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From community resilience to equity-centred technology solutions: Participatory insights from first responders and stakeholders

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A R T I C L E I N F O

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A B S T R A C T

The lack of a universally accepted definition of “community resilience” calls for participatory and multi-stakeholder-based approaches for defining the resilience attributes that are pertinent to the community of interest. This paper presents a participatory, community-resilience–based approach for identifying technology and operational needs that reflect the perspectives of first responders and related stakeholders. Building on a structured methodology developed within the EU-funded Search and Rescue (S&R) project, which integrates literature review, 24 case studies, focus group consultations, and a multi-thematic gap survey administered to 28 organisations—spanning first responders, technology developers, and other expert groups, we provide herein a more detailed analysis of the structure of the gap survey and the feedback obtained.

Findings highlight convergent priorities across respondent groups, including the need for equitable access to training; the safety and well-being of first responders and victims; improved interoperability across actors; and enhanced data integration for shared situational awareness. By explicitly linking community resilience attributes to user needs, the approach enables a shift from generic risk indicators toward context-sensitive and equity-informed design requirements. These insights guided the development and evaluation of multiple S&R technological solutions, including wearable health-monitoring systems, mixed-reality training tools, and shared information platforms supporting cooperative risk assessment.

1. Introduction and scope

Innovation in disaster management should not be an end in itself. What is more important is that it properly achieves its intended goal of increasing resilience, both in terms of the affected infrastructure and the community it aims to protect.

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Due to the lack of a universally agreed-upon definition of “resilience” and the diverse backgrounds of those involved in disaster management (such as rescuers, civil protection, and local authorities) and stakeholders (including civil actors and the scientific community), the interpretation of the term can significantly impact both the management of these events and the effectiveness of operational actions and technologies—whether innovative or not—that support these. Consequently, the answer to questions of resilience for whom, when, why, and where needs to be clearly addressed, agreed and communicated to the entities involved in the management of disasters.

The paper on the participatory methodological framework presented in Ref. [1] established a process for defining resilience features for a community of interest prior to technology development and pilot implementation. Within that broader approach, a stakeholder survey (hereafter, the gap survey) was used to elicit priorities and perceived shortfalls regarding technological and operational features relevant to strengthening community resilience; indicative survey insights were reported previously as part of the methodological reporting. The present manuscript consolidates and extends this survey component by presenting the gap survey and its findings in full.

Within this methodological context, the present article makes a distinct contribution by documenting the gap survey as a fully specified empirical instrument and by reporting its analysis and results. Whereas the study presented in Ref. [1] primarily details the participatory methodology and process. This article: (i) reports the complete structure of the gap survey and its feature questions to support transparency and facilitate adaptation in comparable contexts; (ii) explains the processing of survey responses (importance ranking, classification of implementation status and perceived gaps, and cross-group comparisons) to translate stakeholders’ inputs into actionable requirements; and (iii) synthesises and discusses convergences and divergences across stakeholder groups (First/Early Responders (FR), Technology Developers (Tech), and other expert stakeholders (Other)), drawing implications for equity-aware technologies and operational design in disaster management.

As such, we refrain from going into details on the process and methods of the followed and already published methodological approach; nevertheless, we do provide definitions of key terms and a brief summary of the process that led to the gap survey, which are important for the reader to be able to seamlessly follow the presentation of our research.

Both the process and the gap survey were performed in the context of the EU research and innovation project S&R,[1] which was cited among the EU-funded research success stories.[2] In the context of S&R which was focused in developing technologies for locating entrapped victims during the response phase of a disaster, definitions of “resilience” that emphasised the adaptive, transformative and learning aspects of resilience, such as those implied or emphasised in the definitions of UNDP (United Nations Development Programme) [2], UNDRR (United Nations Office for Disaster Risk Reduction) [3] and AIDR (Australian Institute for Disaster Resilience) [4], were considered by the stakeholders to be more relevant and suitable for the development of technologies and wearables and for the operationalisation of the pilots. The primary drive for this was the need for social change and learning, as expressed by the stakeholders.

In relation to “communities”, a detailed discussion about the different “communities” that exist in the context of disaster management is provided by Ref. [5] (p. 2) and supplemented in Ref. [1]. Three major “community” categories may be distinguished: a) the community of “practice and interest” which refers to networks of specialised professional actors involved in the different phases of disaster management; b) the “interaction-based” community which includes different social groups and networks more visible in the immediate and long-term aftermath of the disaster; and c) the “place-based” (i.e. local) community. In the S&R context, the “community of practice and interest” (i.e. first and early responders and sustained support elements such as infrastructure operators, utility companies, and voluntary organisations active in disaster response) was in scope. Further to the professional–volunteer interactions, this paper emphasises the important role of interactions between the community of “practice and interest” and vulnerable groups in strengthening community resilience.

In the context of this study, equity is understood as the fair and meaningful inclusion of diverse actors in the processes through which resilience priorities, operational constraints, and technology requirements are identified and interpreted. Disaster risk research has long emphasised that risk is shaped not only by hazard exposure but also by social vulnerability, institutional capacity, and how different actors participate in decision-making processes and in defining and addressing risks (e.g. Refs. [6–8]). Accordingly, the methodological approach adopted here integrates equity primarily through participatory engagement of actors occupying different positions within the disaster management ecosystem. By incorporating the perspectives of first responders, technology developers, and other institutional stakeholders in defining resilience attributes and operational needs, the approach supports a more inclusive and context-sensitive articulation of requirements for disaster management technologies and operations. Such participatory approaches have been widely recognised as a key mechanism for addressing structural asymmetries in knowledge production and ensuring that risk-informed innovation reflects the realities of diverse actors involved in disaster management.

In this sense, we found it more useful from a practical point of view to follow suggestions (e.g. Refs. [5,9–11]) that support explicitly defining the elements or attributes/capacities of resilience that were deemed most relevant for enhancing the resilience of the community, as mentioned in the aforementioned paragraphs. In this respect, we need to clarify that in the literature, the term “attributes” may refer to measurable aspects of a characteristic or the mere presence or absence of certain elements, without any assessment of quality, whereas “capacities” may pertain to the evaluation of performance or quality ([9], p. 748). Herein, the term “attribute(s)" will be used more broadly to simplify reading when a clear distinction between attributes and capacities is not necessary.

[1] www.search-and-rescue.eu (last accessed: 28/11/2025).

[2] https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/cutting-edge-tech-helps-europes-search-and-rescue-teams-work-together (last accessed: 28/11/2025).

Hence, the aforementioned considerations need to be kept in mind when interpreting the findings and feedback obtained from the gap survey. Specifically, the aim of the gap survey was to provide high-level guidance for the development of technologies/wearables and the operationalisation of the pilots in relation to improving community resilience, as defined. It is not within the scope of this paper to provide an extensive discussion of how to interpret or define resilience or community; for this, the interested reader should instead refer to the aforementioned previous work, where these are extensively discussed. Moreover, we must also mention that quantification or any assessment of the resulting resilience was not in scope of the S&R project, and neither was it considered within this paper.

Finally, while some intermediate insights were documented in S&R technical deliverables intended for project reporting and implementation, this manuscript consolidates and extends that work into a peer-reviewed contribution by providing the gap survey instrument in full, applying a transparent analytical workflow, and offering an interpretive discussion focused on cross-stakeholder patterns and implications for research and practice.

In practical terms, the paper answers three questions.

1. What does a resilience-attribute–to–needs gap survey instrument look like in an operational disaster-response context?
2. What priorities and implementation gaps emerge when multiple stakeholder groups assess these needs?
3. How do these results translate into actionable and equity-relevant design and operational requirements?

Accordingly, we provide only the methodological context necessary to situate the survey, and focus the paper's core contribution on the design rationale, full content, and analysis of the gap survey, and on the implications of the results for equity-aware technology development and operational planning.

Following this introductory section, the rest of the paper is structured as follows:

Section 2 is divided into three subsections. Subsection 2.1 provides a concise but self-contained summary of the participatory methodological process that led to the development of the gap survey, including the main sequential steps and the equity considerations that informed the assessment design. Subsection 2.2 presents the background literature and case study insights that helped define the study context, clarify the meaning of community resilience in relation to the scope of the paper, and inform the identification of relevant resilience attributes. Subsection 2.3 then summarises how these background insights were translated into the refinement of the survey through Focus Group discussion and associated expert consultation, thereby informing the final survey structure. While the main text presents only the material necessary to support the rationale and interpretation of the gap survey, Appendix A provides a more comprehensive discussion of the literature and case study review, as well as additional background on the Focus Group findings, and Appendix B provides a full view of the survey.

Section 3 presents the gap survey, first describing its structure (subsection 3.1), then reporting the survey results across respondent groups (subsection 3.2).

Section 4 discusses the major findings, study limitations (subsection 4.1), and the validation and operational implications of the results (subsection 4.2).

Section 5 concludes the paper and identifies directions for future research.

2. Methodological approach and methods

2.1. Background methodology

This study builds on a previously published participatory methodological framework developed in the context of the S&R project, but the contribution of the present paper is different. Whereas the earlier publication focused on the methodological development and validation of the overall approach, this paper concentrates on the empirical insights generated through the gap survey and on their implications for technology development and operational planning. To make the present article self-contained, we summarise below

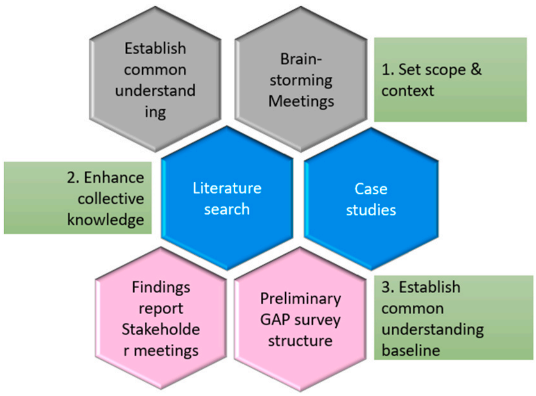


Fig. 1. Initial phase of the participatory process leading to establishing a baseline for common understanding.

the main methodological steps that led to the survey instrument, while keeping the detailed discussion of protocols, workshops, and intermediate analytical decisions to the earlier methodological publication and project deliverables.

The approach was designed to address a practical problem: in disaster management, resilience is widely invoked as a desirable objective, yet its meaning and operational implications vary across actors, institutions, and contexts. In S&R, this challenge was particularly relevant because the project sought to support technology development and pilot operationalisation for a community of practice and interest centred on first and early responders and closely related stakeholders. Rather than assuming a universal definition of community resilience, the adopted approach used participatory steps to identify which resilience attributes were considered most relevant in this specific operational context and how these could be linked to concrete user needs. This background is essential for understanding why the gap survey was structured as it was and how its results should be interpreted.

Figs. 1 and 2 summarise the sequence of methodological steps that led to the gap survey. They are included here to provide the reader with a direct overview of the logic of the process, rather than requiring consultation of earlier work before the present findings can be understood. The first part of the process focused on establishing the conceptual and operational basis of the study; the second part translated that basis into survey design, implementation, and validation.

In practical terms, the process can be summarised in seven (7) major steps.

1. Setting of the context and scope. Meetings, brainstorming sessions, and preliminary desk research were used to clarify the objectives of the work, the disaster-management context of interest, and the terminology to be used. This step was necessary because terms such as resilience, community, and community resilience are interpreted differently by different actors, and these differences can shape both the framing of problems and the perceived relevance of technological or operational solutions.
2. Enhancing collective knowledge. A structured literature review was combined with a bottom-up collection of disaster-response case studies. The purpose of this step was not to produce an exhaustive review of resilience scholarship, but to identify conceptual dimensions, recurring operational challenges, and context-relevant lessons that could inform the survey design. The combination of literature-based and experience-based inputs helped refine the scope and grounded the subsequent methodological decisions in both prior knowledge and practice-based evidence.
3. Establish a common-understanding baseline. The literature review and case-study analysis were discussed in expert and stakeholder meetings, and their main implications were documented in a form that could serve as a shared reference point. At this stage, a preliminary structure of the gap survey was drafted around the main resilience attributes that appeared most relevant to the S&R context.
4. Linking community resilience attributes with key user needs. This was a central step in the process, because it allowed the study to move from abstract discussion of resilience toward targeted identification of needs that matter for operations and technology design. Through expert consultation, interviews, surveys, and brainstorming, the identified resilience attributes were connected with key user needs such as first responder training and safety, interoperability and compatibility, manoeuvrability, sensitivity to environmental conditions, and the scale of the impacted area and victims. This step ensured that the survey would capture specific and actionable gaps rather than generic preferences.
5. Finalising the gap survey structure. The preliminary survey was reviewed through focus group discussions and consultation among project partners and external experts. This iterative refinement helped prioritise the most relevant attribute–need combinations, improve the wording of questions, and ensure that the survey reflected operational realities while remaining analytically coherent.
6. Administering the gap survey. The survey was distributed to S&R consortium partners representing first/early responders, technology developers, and other expert stakeholders. Their responses provided the empirical basis for identifying perceived priorities, implementation gaps, and cross-group differences.
7. Preliminary results were presented in a dedicated expert workshop, where participants discussed the plausibility, usefulness, and limitations of the emerging findings. This final step supported both validation and refinement before interpretation of the results.

Fig. 2. Second phase of the participatory process leading to the administration of the gap survey, validation and final recommendations.

This summary is intentionally concise. It provides the methodological context needed to understand the survey and its findings, while avoiding repetition of material that has already been presented in detail elsewhere. Because the main contribution of this article lies in the structure, analysis, and implications of the gap survey, the text below focuses only on those background elements from the methodological process that are necessary for interpreting the results presented in Section 3.

Equity considerations also informed the design of the methodological framework. In equity-centred risk assessment, it is increasingly recognised that the identification of risks and priorities depends on whose perspectives are included in the assessment process. The participatory methodology adopted in this study intentionally integrates actors with different institutional roles, namely operational responders, technology developers, and other expert stakeholders, so that the identification of technological and operational gaps reflects diverse forms of expertise. This multi-perspective engagement reduces the likelihood that risk assessment is shaped by a single institutional or technological viewpoint and instead supports the joint consideration of operational requirements, technological capabilities, and organisational constraints. The methodological approach, therefore, contributes to procedural equity by enabling diverse actors to shape how resilience attributes and technological needs are identified, prioritised, and interpreted.

2.2. Literature review and case study collection: key insights

This section presents indicative insights derived from the literature review and case study collection undertaken as part of the methodological process used to structure the gap survey. The objective is not to provide a comprehensive review of the extensive literature on resilience and community resilience, but rather to highlight selected conceptual and operational elements that informed the identification of relevant community resilience attributes and the subsequent design of the survey. Additional detail regarding the literature review and the Focus Group discussion and its findings is provided in Appendix A, while the main text summarises only the key findings necessary for understanding the subsequent methodological steps.

2.2.1. Indicative literature review

The literature review examined conceptual and operational uses of the terms resilience, community, and community resilience within the context of disaster risk reduction and crisis management. The aim was to identify conceptual dimensions and operational considerations that could inform the development of the gap survey.

A recurring distinction in the literature concerns how communities are conceptualised. Institutional guidance and policy documents frequently adopt a place-based perspective, reflecting their focus on populations affected by disasters and the development of broadly applicable resilience policies (e.g. Refs. [2,12–15]). More recent research emphasises dynamic and multi-actor conceptualisations of community, highlighting evolving networks of actors and the need to adapt analytical approaches to specific operational contexts (e.g. Refs. [5,11,16–20]). Such perspectives are particularly relevant when examining disaster response systems involving multiple stakeholders, including emergency services, public authorities, volunteers, and civil society organisations.

With respect to resilience and community resilience, institutional guidance, policy frameworks and scientific literature increasingly emphasise adaptive, transformative, and learning capacities (e.g. Refs. [3,4,21,22]) rather than a narrow “return-to-equilibrium” framing favoured by early conceptualisations. At the same time, the literature highlights the diversity of resilience assessment approaches and the absence of a universally accepted operational model [9–11]. This reinforces the importance of explicitly identifying the resilience elements that are most relevant for the operational context under examination.

Broader disaster research also emphasises that disaster risk and response outcomes are shaped not only by hazard exposure but also by social vulnerability, governance structures, and institutional capacity [6,9,10].

In light of these observations, the literature review served to highlight conceptual dimensions and operational considerations of resilience and communities, supporting a context-oriented approach that informed the subsequent identification of community resilience attributes relevant to disaster response operations.

However, most frameworks provide limited guidance on how resilience attributes can be operationalised in relation to technology development and operational practices within disaster response organisations.

2.2.2. Case study collection and identification of resilience attributes and focus group insights

The literature review was complemented by a bottom-up collection of disaster-response case studies contributed by experts with operational experience in emergency management. These case studies were documented using structured templates designed to capture operational challenges, lessons learned, and examples of effective practices observed during disaster response operations [23,24].

The collected cases covered a wide range of hazard types and operational contexts, including earthquakes, floods, fires, infrastructure failures, and chemical incidents. Analysis of these cases revealed several **recurring themes** relevant to community resilience in disaster response contexts.

First, several cases highlighted **communication and information-sharing challenges**, including limitations in communication infrastructure and difficulties in exchanging operational information between responding organisations.

Second, **training and coordination challenges** were frequently identified, particularly in situations involving collaboration between professional responders and volunteer groups. Evidence from recent studies also highlights evolving roles and training needs among volunteer responders in disaster response systems [25].

Third, many cases revealed **interoperability challenges**, including differences in communication technologies, data formats, and operational procedures across organisations involved in emergency response.

Fourth, the case studies highlighted **volunteers as a vital component of community resilience**. Volunteer organisations and community-based actors often provide critical support during disaster response operations, particularly through local knowledge, rapid mobilisation, and proximity to affected communities. At the same time, the effective integration of volunteers into formal response structures requires appropriate coordination mechanisms, training, and compatible communication practices.

Additional observations concerned **information practices and perception differences** between responders and the broader public during disaster situations, including the **increasing role of social media** in crisis communication processes [26–28].

Taken together, insights derived from the literature review and the case studies analysis informed the identification of a set of **community resilience attributes** relevant to disaster response systems. These attributes were subsequently organised into four clusters representing key dimensions of resilience.

i. **Human/Behavioural** attributes, including technical competencies, professional expertise, operational skills, and collaboration/coordination practices;
ii. **Technological** attributes, including the availability and accessibility of software, hardware and equipment, as well as communication, interoperability and data integration capabilities;
iii. **Organisational** attributes, including organisational structures, inter-organisational communication mechanisms, and the presence and implementation of operational standards; and
iv. **Legal/Regulatory** attributes, including the adoption of relevant standardisation frameworks and legal/regulatory conditions affecting deployment and operational use of solutions.

2.3. Linking community resilience attributes with end-user needs and development of the gap survey through focus group discussion

Building on the literature review and case study insights summarised in Section 2.2, the methodological process proceeded by linking the identified community resilience attribute clusters with end-user needs relevant to disaster response operations, in order to structure the gap survey.

The **key end-user needs** were identified through an earlier end-user requirements survey [29]. These needs were grouped into three thematic categories consistent with the subsequent gap survey structure: **Human/first responder needs**, **Technical information needs**, and **Operational information needs**.

Based on the above, a **matrix linking community resilience attributes with the identified user needs** was developed. Project partners were invited to assess the relevance of the different attribute–need combinations, in order to identify the most pertinent pairs for guiding survey design and focusing subsequent analysis [24]. This step ensured that the survey would elicit targeted rather than generic feedback.

A **Focus Group** discussion was then conducted to review the prioritised attribute–need pairs and to refine the gap survey by emphasising operational criteria that participants considered most relevant for strengthening community resilience in disaster response contexts. The discussion converged on five key operational criteria.

i. Community engagement in disaster management
ii. Training and preparedness
iii. Health and safety of first responders
iv. Interoperability of systems and procedures
v. Manoeuvrability and operational adaptability

These criteria were used to refine the wording and focus of survey questions and to ensure alignment between the resilience attribute framework and operational realities of disaster response. The finalised survey structure was subsequently reviewed in a follow-up consultation among project partners before administration [24].

The resulting gap survey structure and the analysis of survey responses are presented in Section 3.

Overall, Section 2 describes a sequential participatory process in which resilience attributes derived from literature and case-study evidence are linked to end-user needs and refined through Focus Group input to structure the gap survey. Section 3 presents the resulting survey instrument and its findings.

3. GAP survey and results

3.1. Structure of the GAP survey

The GAP survey was designed to identify key end-user needs and existing gaps relevant to strengthening community resilience in disaster response contexts. The areas of inquiry were grouped into three overarching thematic categories.

i) **Human/first responder needs**, encompassing education, training, and safety considerations;
ii) **Technical information needs,** focusing on environmental sensitivities, the size of the impacted area, and the number of victims; and
iii) **Operational information needs**, particularly those concerning manoeuvrability, interoperability, and system compatibility.

The survey consisted of 20 feature questions addressing human, operational, and technological dimensions of community resilience. Each feature question was paired with an additional item asking respondents to rank its importance, thereby helping to guide project implementation toward the most critical needs. Of the 20 questions, 15 examined existing and required crisis-management and community-resilience procedures within responders' organisations, while the remaining five focused on the

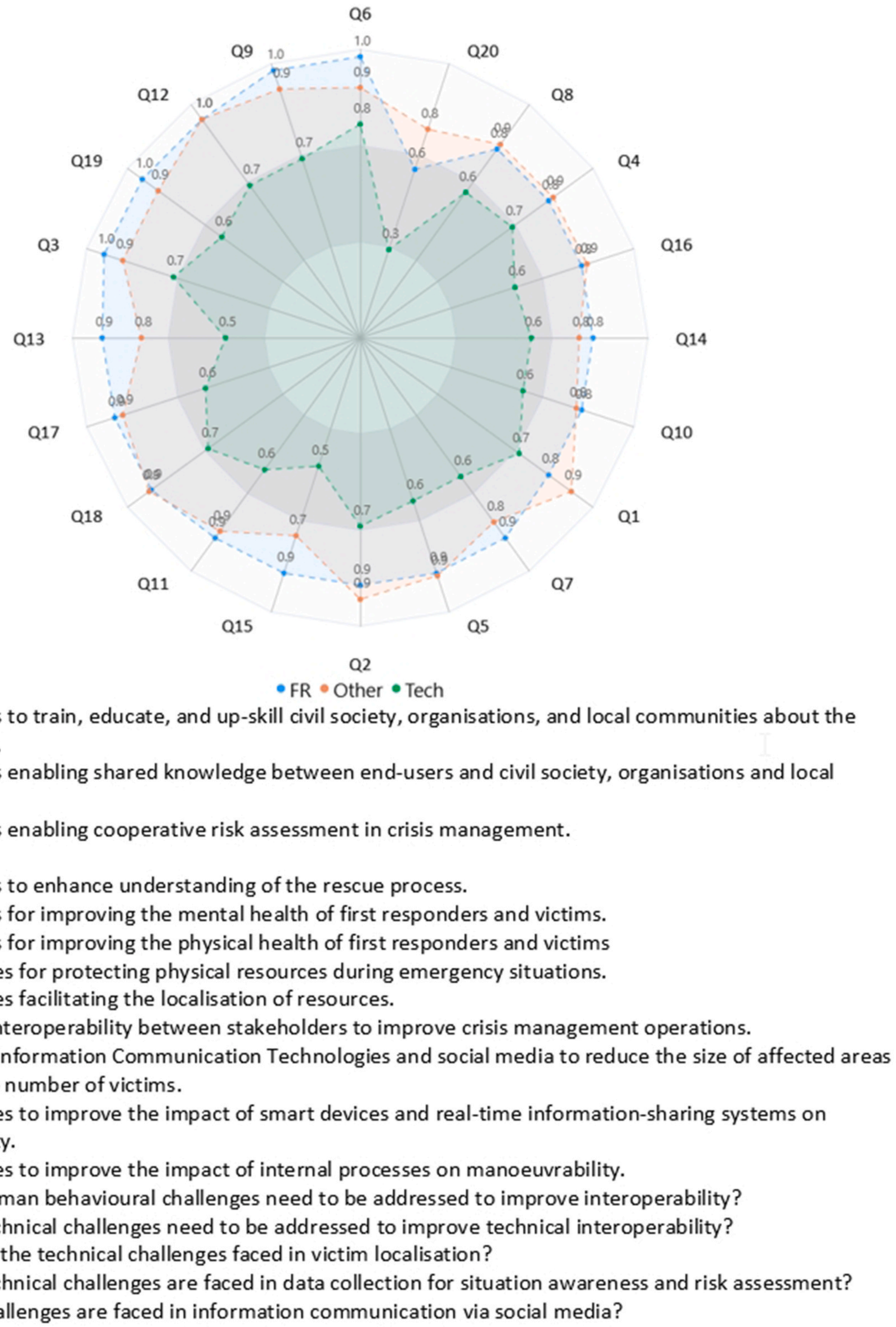


Fig. 3. Standardised importance scores for each feature across the three respondent groups: FR, Tech, and Others.

technical challenges associated with these processes. An additional question asked respondents to rate the importance of all procedures and challenges.

Most of the questions addressing the challenges encountered within first and early responder organisations (Q1–Q15) used a six-level implementation scale.

- Activity/process NOT NEEDED:
- Activity/process not commenced/undertaken BUT NEEDED
- Activity/process commenced, but in outline only
- Activity/process partially completed
- Activity/process almost completed
- Activity/process completed satisfactorily

In contrast, the five questions focusing on technical challenges (Q16–Q20) employed Yes/No response options, with the additional possibility of selecting Not Applicable (NA). The six-level implementation scale was selected instead of a conventional Likert-type agreement scale because the objective was to capture the degree of implementation (i.e., maturity) of specific processes within organisations, rather than respondents' subjective agreement or perception. The scale reflects a progression from absence to full operationalisation, thereby enabling the identification of implementation gaps (e.g., processes that are needed but not yet implemented or only partially developed), which is central to the study's analytical framework.

The full set of 20 feature questions is presented in Appendix B, Table 1. To enable respondents to elaborate on their experiences and perspectives, each question concluded with an open-ended item inviting participants to propose additional solutions or approaches that could help address the identified challenge.

The survey was disseminated to, and completed by, 28 Search and Rescue partner organisations, grouped into three categories: FR – 8 organisations; Tech – 11 organisations; and Other – 9 organisations. This composition enabled the integration of operational, technological, and higher-level systemic (e.g. ethical, legal, academic, dissemination, and exploitation by the industry) perspectives and the considerations of these aspects in the assessment of community resilience needs. From the perspective of equity-centred disaster risk assessment, such diversity is essential because different actors experience and interpret disaster risks through distinct professional and institutional lenses. Ensuring representation across these groups helped prevent the dominance of a single stakeholder perspective and supported a more balanced identification of priorities related to training, interoperability, safety, and data integration. By capturing these multiple viewpoints, the survey contributes to a more equitable and context-sensitive understanding of the operational and technological factors that shape disaster risk and response capabilities.

3.2. Results of the gap survey

This section presents the feedback collected from the gap survey, beginning with general observations that apply across all respondent categories, followed by detailed results for each group. Fig. 3 provides an overview of the standardised attributed importance scores for the three respondent groups: FR, Tech, and Others. These scores were derived by aggregating the importance ratings assigned to each feature within each group and subsequently standardising (i.e., normalising) them to allow comparison across groups with different response distributions. Across all categories, several features consistently emerged as top priorities: the physical health and safety of first responders and victims (Q9), training needs (Q6), procedures enabling cooperative risk assessment (Q3), and the level of interoperability among stakeholders (Q12).

The following sections provide group-specific insights that contextualise the overall results.

3.2.1. First responders

For first responders, the five most important features were: i) the physical health and safety of first responders and victims (Q9), ii) training (Q6), iii) procedures enabling cooperative risk assessment (Q3), iv) the level of interoperability between stakeholders (Q12), and v) technical challenges faced in data collection (Q19). The paragraphs below elaborate on each of these features:

Respondents identified several under-implemented but promising ways to enhance the physical health and safety of first responders and victims, including the use of wearable technologies (Q9_Option6: 8%), the use of new technologies for real-time risk identification systems (Q9_Option5: 7%) and monitoring, recognition, and management of responders' physical well-being (Q9_Option4: 7%) (see Fig. 4). Additionally, decision-support tools were deemed essential for facilitating time-sensitive decisions and reducing cognitive burden and were marked as undertaken but needed activities.

Additionally, the implementation of technology-mediated communication between victims and responders (Q9_Option 9) (8%), alongside joint practical training sessions with stakeholders such as civil protection agencies (Q9_Option 8), were identified as promising procedures to enhance field coordination and safety.

As shown in Fig. 5, a variety of training procedures are already in place within many organisations. However, notable gaps remain. Training on interacting with people with specific disabilities (Q6_Option2) was reported as needed by 62.5% of first responder organisations and implemented by 50%, indicating that 12.5% consider this training necessary but have not implemented it. In addition, 25% of first responder organisations do not sufficiently provide training on the use of new technologies (Q6_Option4), on standards for volunteers and S&R teams (Q6_Option6), and on procedures affecting the speed of professional response (Q6_Option5). Onboarding in new technologies and search-and-rescue standards, as well as training in emergency medical skills, could also be further strengthened.

Furthermore, first responders participating in the focus group discussions preceding the survey emphasised the need to incorporate

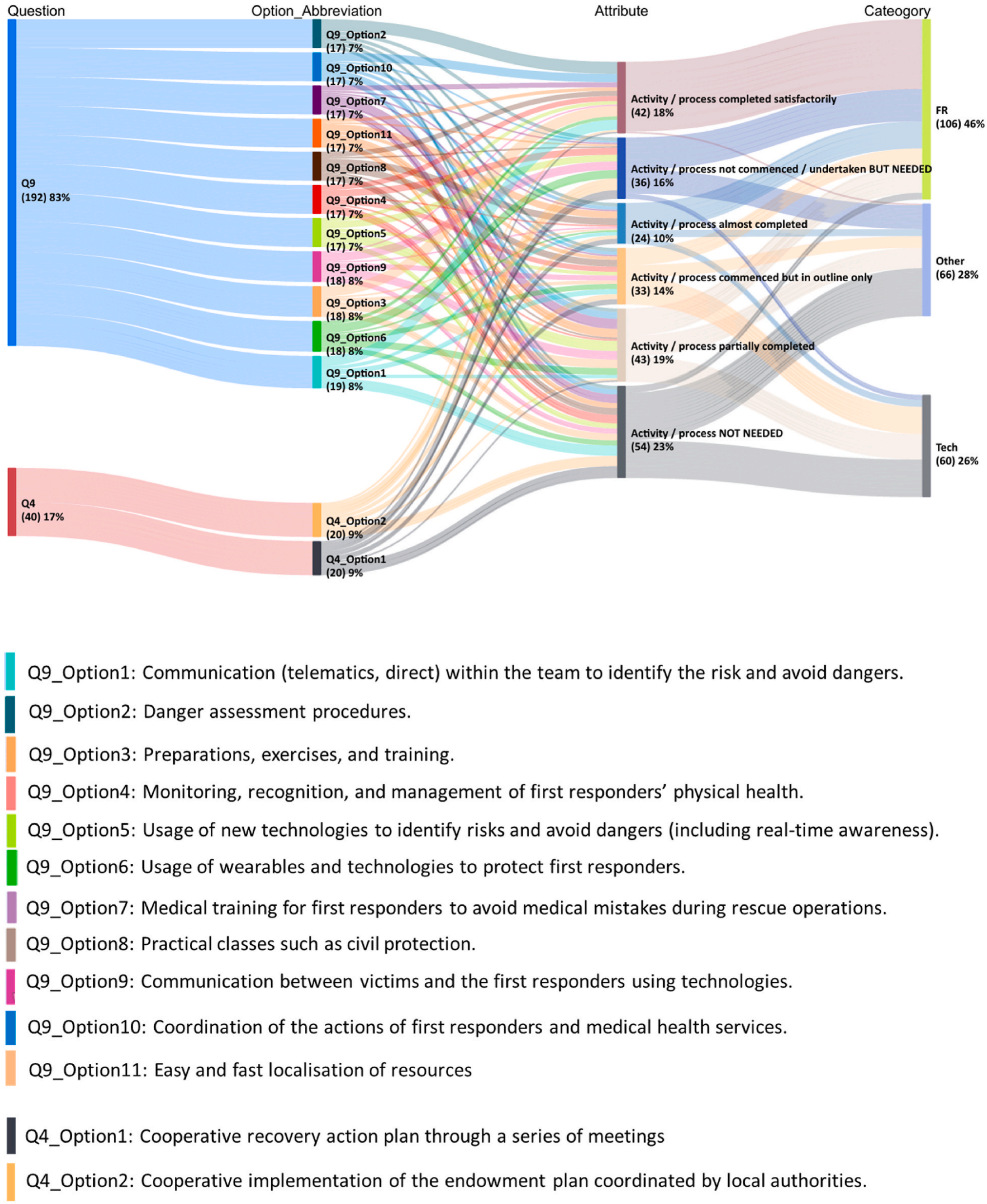


Fig. 4. Potential implementable activities to (Q9) improve the physical health and safety of first responders and victims, and (Q4) enable cooperative preparation of a recovery plan.

training on emergency action plans for Chemical, Biological, Radiological, and Nuclear (CBRN) risks.

The use of sensor technologies during the discovery phase also featured prominently in survey sections regarding protecting physical resources (Q10). Findings indicated that the use of sensor technologies during the discovery (Q10_Option1) is necessary but currently unimplemented in many organisations, highlighting a critical need for such technology and for frequent training on the use of these technologies across diverse operational and environmental conditions (Fig. 6). Enhancing such training would ensure the effective use of technological solutions, thereby improving first responder readiness and reducing response times.

Training (Q7_Option2 and Q7_Option3) was also identified as a key element in enhancing the understanding of the rescue process, as reflected in Question Q7 (see Fig. 7). Responders emphasised the value of simulation-based software for modelling rescue procedures within expected environments and operational scenarios (Q7_Option1), noting its potential to improve preparedness and procedural comprehension. First responders also highlighted the need to analyse lessons learned through cooperative platforms (Q1_Option8) as well as the need for practical (Q1_Option2) and online training (Q1_Option5) as procedures to train, educate, and upskill civil society, organisations, and local communities in the rescue process and to enable shared knowledge (Q1).

Regarding procedures that enable cooperative risk assessment during crisis management (Q3), although the majority of activities were completed satisfactorily. Many activities were marked as needed and undertaken. More specifically, first responders highlighted the importance of cooperative risk identification (Q3_Option1) and risk assessment via a series of meetings (Q3_Option2) and via

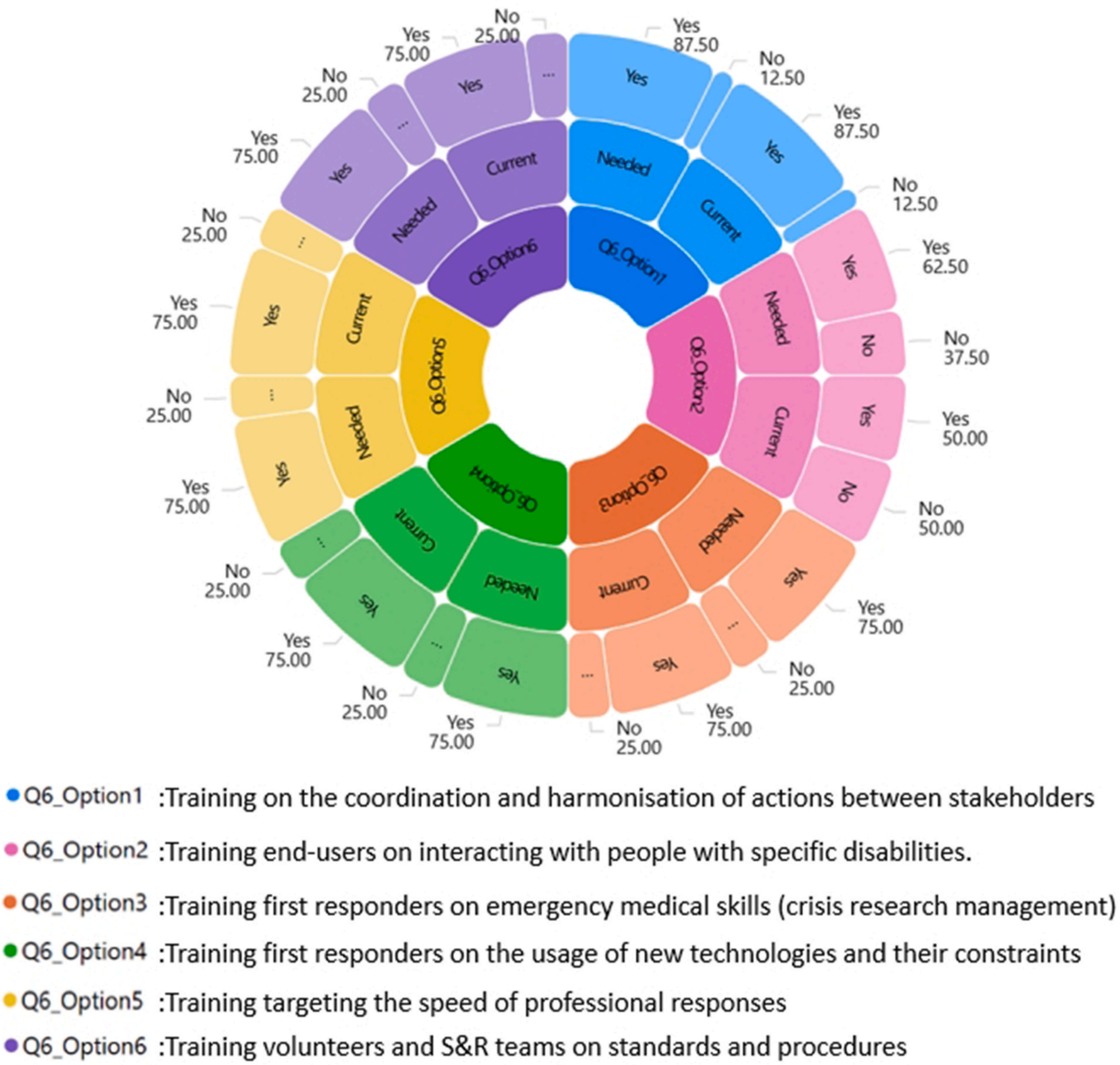


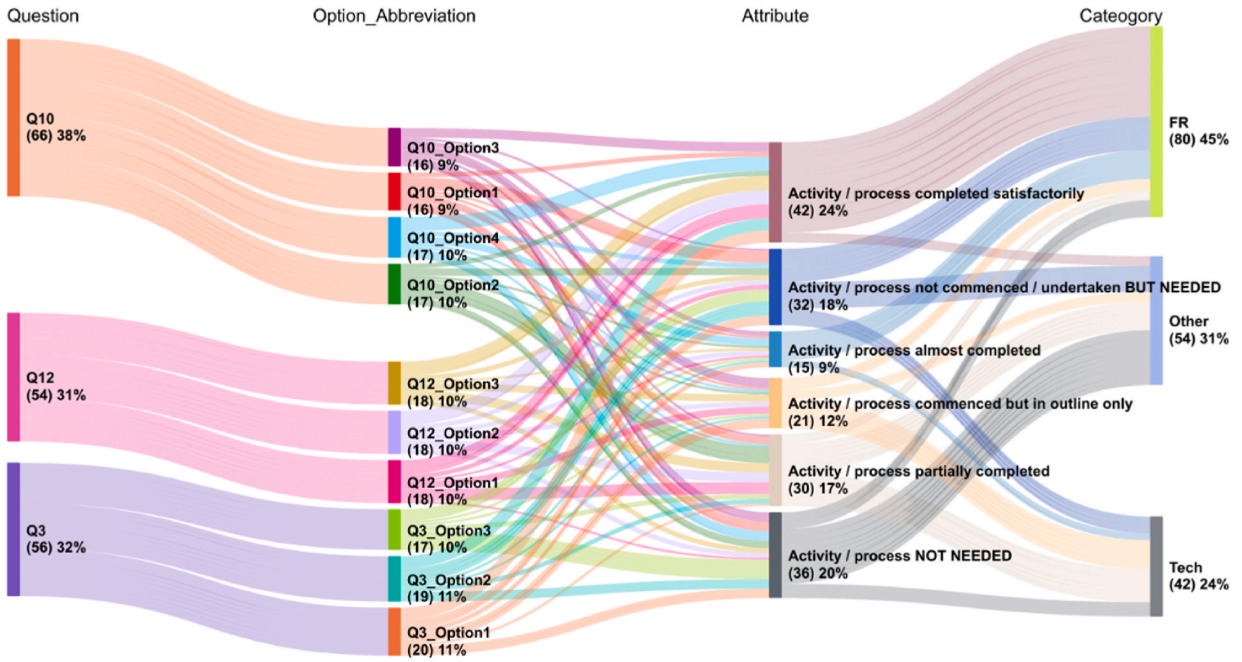
Fig. 5. Implemented and needed trainings across participating (FR) organisations.

gamification (Q3_Option3) (see Fig. 6).

Interoperability (Q12) was identified as the fourth most critical feature for resilient crisis management, encompassing the administrative level for shared protocols, the strategic level for overarching operational planning, and the tactical level for detailed intervention design. Despite its importance, significant implementation gaps persist; specifically, some organisations have yet to initiate strategic or tactical coordination. Other respondents report that administrative standards for communications are only partially implemented. These findings highlight an urgent requirement for the harmonisation of communication tools to ensure effective multi-stakeholder coordination and field readiness (see Fig. 6).

Technical challenges related to data collection (Q19) constituted the fifth most important feature identified by first responders. As illustrated in Fig. 8, respondents reported a range of difficulties affecting their ability to collect, integrate, and utilise data for situational awareness and risk assessment. These challenges include.

- Delays in real-time information, which hinder timely decision-making.
- High financial costs of supporting software, with many effective solutions remaining inaccessible to first responder organisations due to budget constraints.
- Limited access to full-coverage communication resources, such as satellite-based systems.
- Insufficient or delayed integration of real-time field data with platforms and technological solutions used by other stakeholders.
- Difficulties in analysing collected data promptly for risk assessment, accompanied by concerns regarding the accuracy and reliability of the data.



Q3_Option1: Cooperative risk identification.
Q3_Option2: Cooperative risk assessment via a series of meetings
Q3_Option3: Cooperative risk assessment via gamification.

Q10_Option1: Use of sensory technologies during the discovery phase (for risk assessment) and before intervention.
Q10_Option2: Training on the appropriate use of different technologies in different contexts and conditions.
Q10_Option3: Design a comprehensive plan to protect physical resources.
Q10_Option4: Recommendation about a suitable resource to use in a special context from the control centre before intervention.
Q12_Option1: Administrative level: protocols and standards for communication, decision-making, and norms.
Q12_Option2: Strategic level: where stakeholders prepare the big picture plan of the operation.
Q12_Option3: Tactical level: where the stakeholders prepare the detailed plan of intervention.

Fig. 6. Procedures for (Q10) protecting physical resources during emergency operations, (Q3) enabling cooperative risk assessment in crisis management, and (Q12) interoperability needs across administrative, strategic, and tactical levels to improve crisis management operations.

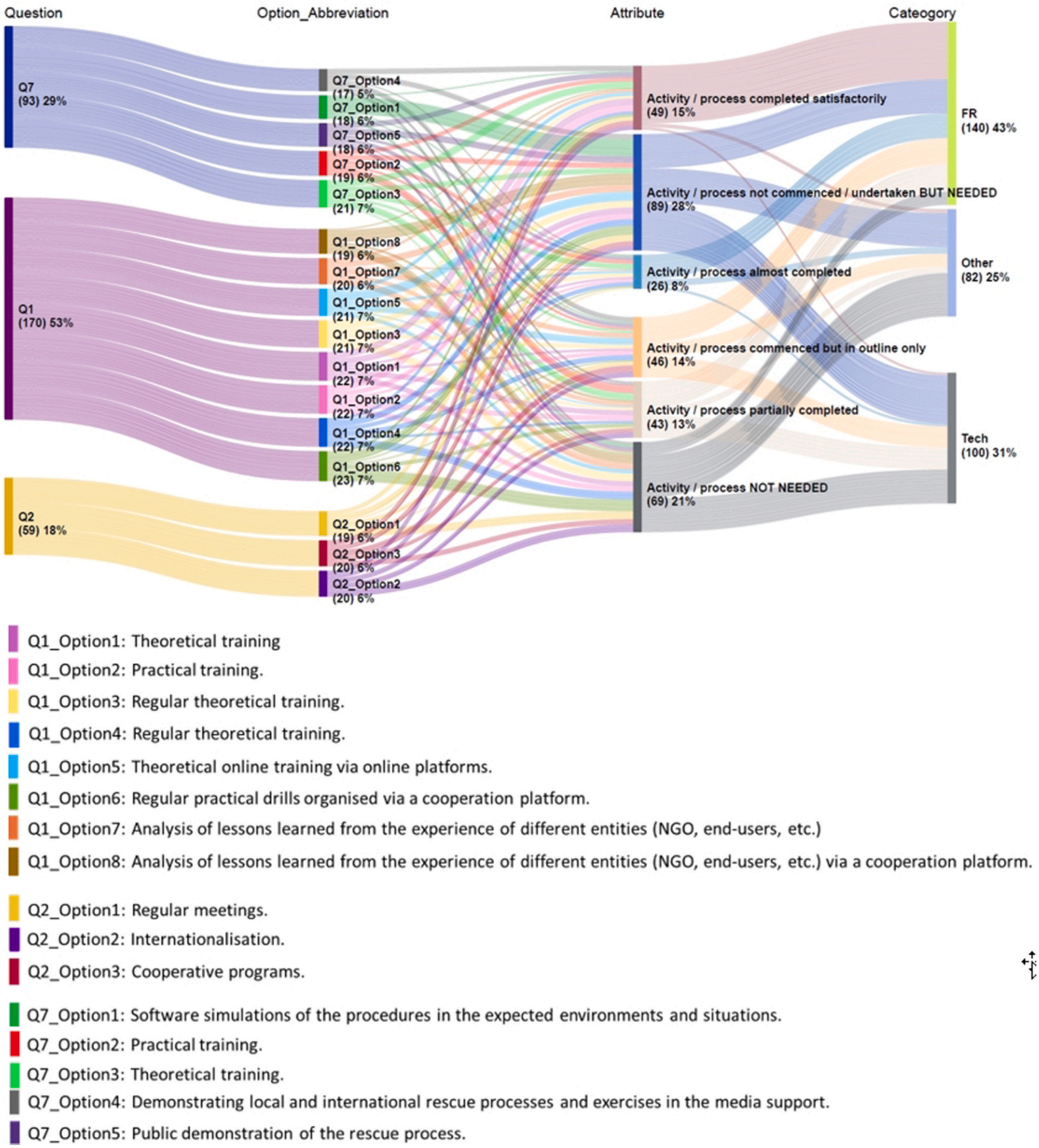
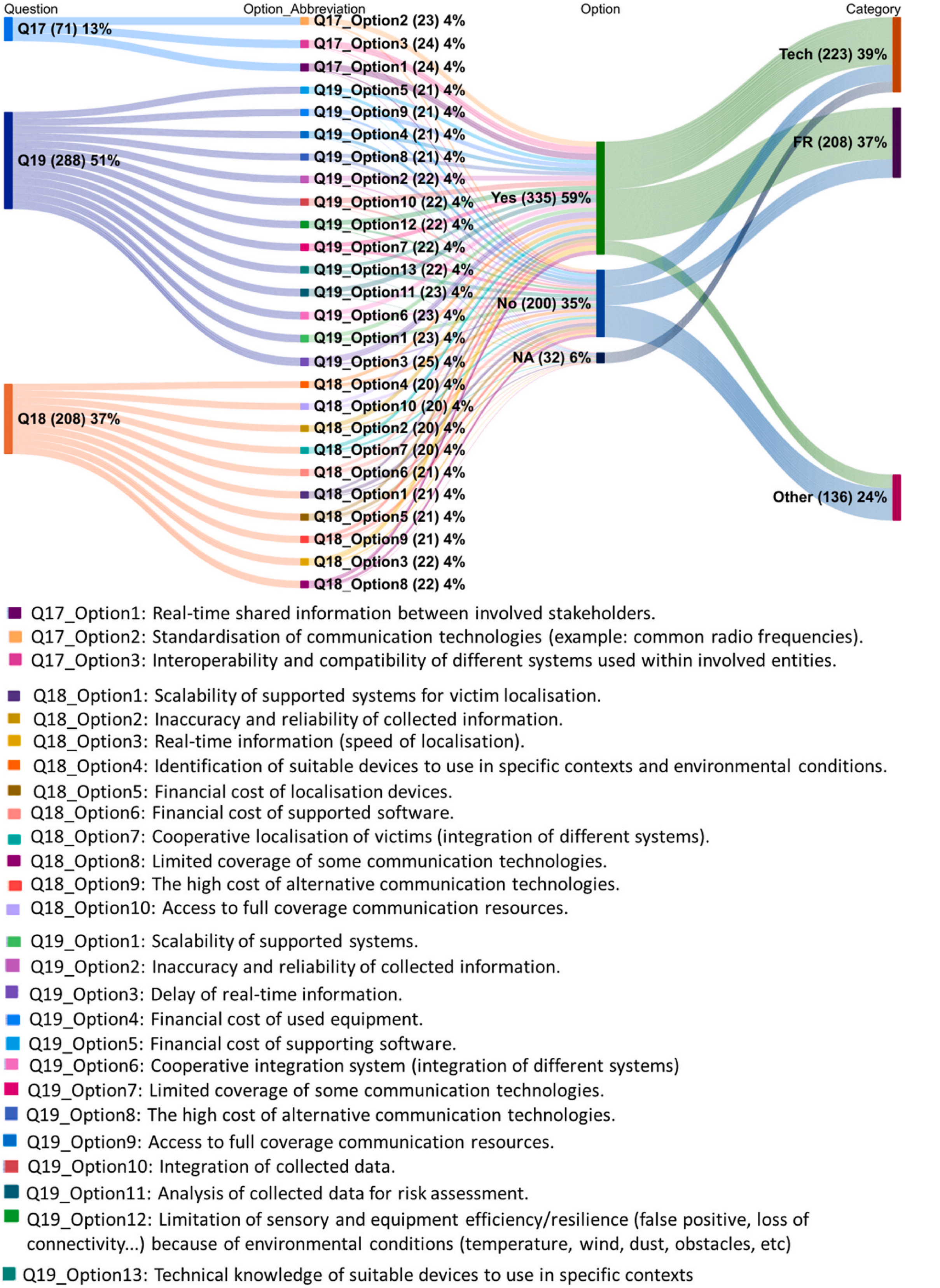


Fig. 7. Suggested procedures to (Q1) train, educate, and upskill civil society, organisations, and local communities about the rescue process, (Q2) enable shared knowledge between end users, civil society, organisations, and local communities, and (Q7) enhance the understanding of the rescue process.

- Reduced efficiency or resilience of sensors and equipment, including false positives or connectivity loss, caused by adverse environmental conditions (e.g., extreme temperatures, wind, dust, structural obstacles). Responders noted the importance of being fully aware of equipment limitations across operational contexts.

To address operational vulnerabilities, technological partners recommend trialling novel systems under diverse environmental conditions and developing malfunction detection algorithms to ensure system reliability. Concurrently, first responders emphasise the necessity of optimised data integration for shared situational awareness, specifically proposing the direct upload of clinical data to



(caption on next page)

Fig. 8. Technical challenges faced in data collection for situation awareness and risk assessment (Q19), encountered in victim localisation (Q18), and challenges that need to be addressed to improve the technical interoperability (Q17) (Yes: challenges faced, No: challenges not faced).

victim medical records to facilitate rapid and seamless information exchange.

In addition to the five most important features discussed above, nearly all first responders indicated that the compatibility of systems used by different entities in crisis management requires further attention to strengthen interoperability (Q17; see Fig. 8). Moreover, respondents agreed that real-time information sharing (Q17_Option1) and the standardisation of communication technologies (Q17_Option2) play a critical role in achieving effective interoperability and must be prioritised for further improvement.

3.2.2. Technological partners

Technological partners prioritised the training of first responders (Q6) to facilitate operational efficiency and the seamless integration of novel technologies. Their secondary focus centred on the upskilling of civil society and local communities about the rescue process (Q1), specifically through the analysis of lessons learned and the execution of regular drills via cooperative platforms. Furthermore, technological stakeholders demonstrated alignment with first responders by emphasising the necessity of cooperative risk assessment (Q3) and the enhancement of physical health and safety for all involved parties (Q9) (see Fig. 3).

Additionally, the feature related to sharing knowledge between end users and civil society organisations (Q2) ranked highly (see Fig. 3) among technological partners. As illustrated in Fig. 7, internationalisation (joint multinational effort enabling shared knowledge between resilience stakeholders, including exchanging expertise, knowledge, and best practices) (Q2_Option2), regular meetings (Q2_Option1), and cooperative programs (Q2_Option3) were viewed as the most promising mechanisms for fostering knowledge exchange among stakeholders, local communities, and relevant organisations. From the perspective of first responders, however, internationalisation and cooperative programs remain unimplemented within their organisations.

Responses from technological partners also highlighted the importance of procedures that enable the cooperative preparation of a recovery plan (Q4), which received an importance ranking comparable to Q9 and Q2 (Fig. 3). From Figs. 4 and 7, first responders and technological partners indicated that a series of meetings is needed to jointly develop a recovery action plan (Q4_Option1). Likewise, first responders and technological partners emphasised that implementing an endowment plan coordinated by local authorities is also needed and potentially valuable for supporting cooperative recovery planning (Q4_Option2).

3.2.3. Other partners

This group, comprising legal, ethical and research experts, mirrored first responders in prioritising interoperability (Q12) and training (Q9). While aligning with technological partners on the necessity of civil society upskilling (Q1) and collaborative knowledge exchange (Q2). This group also emphasised that technical barriers to victim localisation represent a critical gap requiring further attention (Q18) (see Fig. 3).

Analysis of community training procedures (Q1) reveals a strategic divergence. While legal and research experts prioritise the development of theoretical training (Q1_Option1), first responders emphasise the analysis of lessons learned from prior experiences (Q1_Option8). This contrast highlights distinct sectoral perspectives regarding the most effective approaches for educating and upskilling civil society, organisations, and local communities about the rescue process (see Fig. 7).

In alignment with technological partners, legal and research experts identified internationalisation (joint multinational efforts for exchanging expertise) as a critical procedure for facilitating shared knowledge between end-users and civil society (Q2). Furthermore, regular meetings (Q2_Option1) were underscored as a vital mechanism for supporting continuous coordination and the exchange of best practices across diverse stakeholders and local communities (see Fig. 7).

Safeguarding the physical health of first responders and victims (Q9) was another priority shared with both first responders and technological partners. Respondents in this group identified the monitoring of the physical health of first responders (Q9_Option4) and the danger assessment procedures (Q9_Option2) as the most important measures (see Fig. 4), further underscoring a cross-group recognition of the value of technology-supported safety measures (Q4_Option5).

Furthermore, the findings reflect a consensus among the group of first responders and the group of legal and research stakeholders on the priority of interoperability as a critical mechanism for strengthening crisis management operations (Q12). Although both cohorts recognised that most levels of interoperability are currently implemented, an implementation gap persists at the administrative level regarding standardised protocols and communication norms. Distinctly, this stakeholder group identified significantly lower maturity at the strategic and tactical levels concerning collaborative planning and intervention design, indicating that these areas remain underdeveloped (partially completed) compared to the more satisfied assessments provided by first responders (see Fig. 6).

The third group of responders ranked technical challenges related to victim localisation (Q18) as their second-highest priority (see Fig. 3), whereas the feature remained outside the top five for the first responder. This divergence suggests that while the issue is universally recognised, its perceived operational urgency varies across different respondent groups. As shown in Fig. 8, within this group, the primary challenges in victim localisation include data inaccuracy (Q18_Option2) and cooperative localisation of victims (Q18_Option7). In contrast, a majority of these stakeholders do not encounter system scalability issues (Q18_Option1) or perceive financial costs of software as a significant barrier (Q18_Option6). The prevalence of Not Applicable (NA) responses in these responses stems from the technological stakeholder group's lack of direct involvement in field operations, highlighting their unique position relative to first responders. It is noteworthy that many of these issues were also raised by first responders, indicating a shared recognition of the need for enhanced technological capabilities and improved data-integration systems. However, for challenges related to data collection for situation awareness (Q19), a closer examination of first responders' responses reveals that they may face additional or differently weighted challenges in certain areas. For example, first responders reported challenges related to the inaccuracy and reliability of collected information (Q19_Option2), delays in obtaining real-time information (Q19_Option3), and difficulties in achieving rapid victim localisation. In addition, they emphasised challenges associated with cooperative victim localisation, particularly the integration of data across different systems (Q19_Option6) and the lack of full-coverage communication resources (Q19_Option9). Furthermore, they highlighted difficulties in identifying suitable devices for specific contexts and environmental conditions (Q19_Option13), underscoring the operational complexity and situational variability faced by first responders in the field.

4. Discussion, limitations, and implications of major findings

4.1. Summary of major findings

Following the presentation of key survey results, and by also considering expert opinions expressed in focus group discussions that preceded the survey, the major findings can be summarised in the following points.

More broadly, however, the findings reveal a consistent pattern across respondent groups: first responders, technological partners, and other expert stakeholders converged around a relatively stable set of priorities, particularly training, responder and victim safety, interoperability, and cooperative forms of information sharing and risk assessment. At the same time, each group assigned a different practical emphasis to these themes, reflecting their distinct institutional roles and operational responsibilities. This combination of convergence and divergence is itself an important result, as it supports the rationale of the participatory methodology presented earlier in the paper, namely that resilience-oriented priorities for technology and operations cannot be robustly identified from a single stakeholder perspective alone.

I. Need to introduce additional training programs.

Existing training protocols within first responder organisations are currently insufficient to fully address their operational requirements. To significantly enhance the resilience of rescue operations, further training is essential. Immediate priorities should include concrete guidance on interacting with individuals with specific disabilities and comprehensive education on emergency action standards for chemical, biological, radiological, and nuclear (CBRN) risks. Furthermore, first responders underscored the vital need for advanced medical training to reduce errors with potentially adverse consequences for the health of those involved in critical rescue missions. Responders additionally highlighted the importance of integrating training sessions focusing on the effective use of new technologies to identify risks and mitigate dangers associated with advanced real-time awareness systems.

The significance of this finding lies not only in the amount of training required but also in the role that training plays across multiple dimensions of resilience. In the survey results, training emerges as a cross-cutting mechanism linking human competencies, coordination between stakeholders, the safe uptake of new technologies, and preparedness for complex operational contexts. This is reflected not only in the responses concerning first responder training needs, but also in the identified need for better use of sensing technologies in diverse field conditions, in the value assigned to simulation-based understanding of rescue procedures, and in the emphasis placed by other respondent groups on training and upskilling civil society and local communities. In this sense, strengthening training is not merely a capacity-building recommendation; it is a practical means of reducing coordination failures, improving operational readiness, and increasing the effectiveness of resilience-enhancing technologies in real emergency settings.

II. Need to improve the physical health of first responders and victims

Given the paramount importance of first responders' physical and psychological health, survey findings indicate a clear need to enhance their protection. This can be achieved through the deployment of wearables and advanced technologies specifically designed to safeguard them in operational settings, coupled with improved systems for the monitoring, recognition, and management of their physical well-being to prevent serious injuries or psychological wear. Technological developers suggested that existing advanced technologies could be more leveraged for risk identification and danger aversion, including providing real-time awareness during operations. This opinion aligns with that of the third group of responders. Technology developers also highlighted that communication technologies between victims and first responders are not yet fully implemented and that further enhancements are possible for easier and faster localisation of resources needed in emergency response.

Importantly, the protection of first responders should not be viewed only as an occupational or welfare issue, but as a condition for effective disaster response. The findings suggest that responders' safety is closely linked to operational performance through improved situational awareness, decision support, reduced cognitive burden, and more reliable communication under hazardous conditions. This interpretation is also consistent with the earlier Focus Group findings, where health and safety were linked not only to protective measures, but also to organisational procedures, risk assessment, and real-time monitoring of operational environments. Accordingly, investments in safety-oriented technologies and procedures can support both the well-being of responders and the broader capacity of the response system to act quickly, safely, and effectively.

III. Need to consider and enhance interoperability of technological solutions and operations.

Further improvement of interoperability is required to enhance the resilience of emergency response. The level of interoperability most needed was identified at the administrative level, where stakeholders could use the same protocols, standards for communication, decision-making, norms, etc. First responders highlighted the need to share common knowledge about technology and used communication terminology during operations. Learning from past experiences was considered important. The third group marked the need for interoperability at the strategic and tactical levels.

The results indicate, however, that interoperability should be understood more broadly than the existence of common communication protocols or standards. In the present study, it also concerns the timely exchange of reliable real-time information, compatibility between systems used by different organisations, the integration of field data into shared platforms, and the ability to translate information into coordinated action across administrative, strategic, and tactical levels. This broader interpretation is supported by the survey findings on data collection and victim localisation, where respondents repeatedly pointed to delays in real-time information, incomplete communication coverage, and difficulties in integrating information across technological systems and actors. Interoperability, therefore, emerges not only as a governance issue but also as a technical and organisational prerequisite for shared situational awareness, cooperative risk assessment, and timely intervention.

Another important implication of the survey is that resilience-enhancing responses cannot be reduced to isolated improvements in equipment or response procedures. The prominence of cooperative risk assessment, shared knowledge mechanisms, and recovery-oriented coordination indicates that respondents understand resilience as a multi-actor process extending across preparedness, intervention, and recovery. The fact that technological partners and other expert stakeholders placed particular emphasis on knowledge exchange, coordination meetings, internationalisation, and cooperative recovery planning complements the more immediate operational concerns raised by first responders. This reinforces the initial rationale of the paper that resilience should be translated into context-specific attributes and linked to the needs of the relevant community of practice and interest, rather than being treated as a generic or universally fixed concept.

It is also important to be aware of the limitations of the present research. The empirical basis of the gap survey lies within a single EU research and innovation project, involving 28 partner organisations. Although the consortium was diverse, it cannot represent the full variety of institutional, cultural and hazard contexts in which crisis management is practised. The focus on a “community of practice and interest” means that other crucial actors—such as local communities, informal volunteers or particularly marginalised groups—were not directly surveyed, even if their needs were discussed by intermediaries. Furthermore, the survey relies on self-reported assessments of implementation levels and challenges, which may be subject to perception biases and organisational politics.

Another limitation is that the sample size (28 organisations), while sufficient for capturing diverse perspectives within the S&R consortium, does not support statistical generalisation or inferential analysis. The study, therefore, adopts an exploratory and comparative analytical approach, focusing on relative prioritisation and cross-stakeholder patterns. The analytical approach is consistent with participatory and mixed-methods research designs, where structured scoring and normalisation are used to support comparative interpretation rather than hypothesis testing.

These limitations mean that the findings should be interpreted primarily as a structured prioritisation exercise that informed technology development and pilot operationalisation within a defined project setting, rather than as a basis for generalising the prevalence of these needs across all disaster-management systems. In this sense, the findings are context-specific but transferable to similar participatory settings.

4.2. Validation of the findings and implications in equity-centred disaster risk assessment, technology development and operationalisation

To validate the followed approach and its relevant findings, a workshop titled “End-user requirements and beyond” was conducted, which included a roundtable interactive discussion following the presentation of the survey approach and its findings, which allowed interventions from participating experts. In total, 305 experts (peak number) from various organisations attended the workshop.

The roundtable discussion first examined the strengths of the proposed approach as well as potential areas for refinement. Experts highlighted the value of the participatory and flexible design, noting that it effectively engages end-users in developing a shared understanding of key principles and concepts. They further emphasised that the approach fosters constructive communication among the various actors that form the resilience landscape. The use of a resilience definition grounded in multi-dimensional attributes and capacities was regarded as particularly appropriate. As a mixed-method participatory framework, it integrates qualitative and quantitative elements and draws on both top-down and bottom-up knowledge. While its strong reliance on expert contributions increases the required moderating effort, it was also recognised as being highly adaptable to diverse audiences and contexts. The workshop did not simply confirm the relevance of the identified needs but also supported the central methodological premise of the paper, namely that resilience-oriented priorities become more actionable when they are comparatively examined across respondent groups and then used to inform technology development and operational testing in a more targeted manner.

The findings of this study also contribute to the broader discussion on equity-centred approaches to disaster risk assessment. First, the participatory structure of the methodology allowed actors with different institutional roles to influence how risks and operational gaps were identified, thereby supporting procedural equity in knowledge production. Second, several of the priorities highlighted by respondents, such as training related to interaction with persons with disabilities, improved interoperability between organisations, and stronger collaboration with volunteer networks, reflect the need to address inequalities in access to information, resources, and operational capabilities during disaster response. These results suggest that improving disaster resilience requires not only technological innovation but also governance mechanisms that ensure equitable access to training, information-sharing systems, and collaborative decision-making processes. In this sense, the study demonstrates how participatory methodologies can support more inclusive and context-aware approaches to identifying risks and designing technological solutions in disaster management. In the present study, this is visible not only in the inclusion of different stakeholder groups but also in the fact that issues such as disability-sensitive training, access to interoperable information, and coordination with volunteer and community-facing actors emerged as substantive priorities rather than issues of marginal importance.

To support the integration of the survey findings into technical and operational development, experts emphasised the need to present the relative prioritisation of challenges across respondent groups, as these rankings can inform the sequencing and focus of technological and operational solution design. They also underscored the importance of assessing the maturity level of each resilience attribute within end-user organisations, as this understanding is essential for formulating a targeted and priority-based improvement plan.

The insights derived from the case studies, survey, and workshop substantially informed and strengthened the S&R project. Several key end-user needs were directly addressed through the project's developments. A dedicated platform for sharing first responders' lessons learned in crisis management was deployed, and mixed-reality simulations were introduced to support pilot operations, offering a more realistic, adaptable training environment that enabled the simulation of interactions among multiple responding entities. Data integration and knowledge sharing were facilitated through enhanced communication between stakeholder services and the platform developed within the S&R project, thereby supporting cooperative risk assessment and improved shared situational awareness. These developments should therefore be understood not as isolated technological outputs, but as concrete responses to stakeholder-prioritised gaps identified through the participatory process, particularly in relation to more effective and operationally relevant training, responder safety, cooperative risk assessment, and data-supported situational awareness.

Prioritising the physical safety of first responders, the project designed and deployed a wearable monitoring system embedded in their uniforms (including electrocardiograph, electromyograph, and strain sensors) to enhance protection against multiple hazards. Additionally, membrane inlet mass spectrometry (MIMS) technology was integrated into robotic platforms to detect toxic environments and safeguard K-9 (Canine) units. These robots were also equipped with complementary sensing technologies for detecting and locating entrapped victims, further contributing to shared situational awareness among the involved organisations.

As noted earlier, the S&R project was selected by the European Commission as a Research and Innovation (R&I) success story. It was recognised for its significant contribution to advancing EU policy objectives and for delivering tangible scientific and societal benefits. All developed, implemented, and integrated solutions were evaluated through seven major field exercises (pilots), which provided the appropriate conditions for testing and validating them against predefined key performance indicators (KPIs). However, it is important to note that these KPIs pertain to technical characteristics of the developed technologies and do not directly measure their impact from a resilience standpoint, even though these are expected to positively contribute to improving coordination, response and recovery in disaster management operations, which is another limitation of the study. For a comprehensive discussion of the individual technologies, applications, and pilot operationalisation activities undertaken within the project, the reader is referred to the publicly available S&R deliverables on the project's website, as such detail lies beyond the scope of this paper.

5. Conclusions and future research

This paper examined how community resilience considerations can be systematically integrated into the design of technologies and the operationalisation of pilots for disaster management, using the EC-funded S&R project as a case. Building on a previously proposed methodological framework, we combined literature review, case studies, focus groups and a structured gap survey to identify which resilience attributes matter most to the “community of practice and interest” and how these translate into concrete technological and operational needs.

Across first responders, technology developers and other stakeholders, a strong convergence emerged around four core priorities: (i) training and education, for both professional responders and civil society; (ii) the physical (and, to a lesser extent, mental) health and safety of first responders and victims; (iii) interoperability at administrative, strategic and tactical levels; and (iv) the availability, quality and integration of data for situational awareness and risk assessment. These priorities were not derived in the abstract; they were grounded in the lived experience of 24 disaster case studies, refined through expert focus group, and then quantified and ranked via the gap survey.

The findings confirm that community resilience, when viewed from the perspective of a professional “community of practice and interest”, is less about a single indicator or technology and more about the configuration of capabilities that enable actors to anticipate, absorb, respond and learn. By explicitly linking resilience attributes to key user needs, such as safety, manoeuvrability, interoperability and sensitivity to environmental conditions, the methodology made it possible to move from high-level resilience discourse to actionable design requirements for technologies, wearables and pilot operations. At the same time, the approach illuminated how these capabilities intersect with issues of access and inclusion, thereby underscoring the relevance of equity considerations in shaping risk-informed technology development.

The insights were not purely diagnostic. They directly informed several S&R developments, including: a platform for sharing lessons learned among first responders; mixed-reality simulations that support more realistic and multi-actor training; integrated data services that facilitate cooperative risk assessment and shared situational awareness; and protection-oriented innovations such as wearable physiological monitoring systems for first responders and robotic solutions equipped with MIMS and victim-localisation technologies. These implementations demonstrate how a resilience-oriented, participatory process can shape both the conceptualisation and the deployment of technological solutions in disaster management. Methodologically, the approach proved particularly valuable in three respects. First, it offered a structured way to bridge top-down perspectives (policy frameworks, resilience literature, indicator sets) with bottom-up insights from practitioners and other stakeholders. Second, it helped to surface differences in prioritisation between respondent groups (e.g. the stronger emphasis placed on victim localisation challenges by “other” partners compared to first responders) even when the aggregate priorities appeared similar. Third, the process itself functioned as a resilience-building intervention, fostering shared understanding, common terminology and constructive dialogue among actors that will need to collaborate during real events. Collectively, these outcomes reflect not only improvements in technical coherence but also advancements in procedural equity and equity-centred approaches to disaster risk assessment, by ensuring that diverse voices shape risk-related decisions.

A key limitation is that the study does not quantify resilience outcomes. While we link attributes and needs to perceived gaps and technological responses, we do not measure how these interventions ultimately affect resilience in terms of reduced losses, faster recovery or improved well-being. Finally, the methodology is relatively resource-intensive, requiring dedicated facilitation, expert time and iterative engagement, which may pose constraints for organisations with limited capacity. Such resource demands may further influence who can participate, pointing to additional equity implications that warrant attention in future applications.

Despite the aforementioned limitations, the work opens several promising avenues for future research and practice.

There is a need to develop and test maturity models for resilience attributes at the organisational level. Such models could operationalise the notion of “maturity” discussed in the workshop, enabling end-user organisations to assess where they stand for specific attributes (e.g. interoperability, training, data integration, volunteer management) and to plan phased, priority-based improvement pathways.

Future studies should broaden participation beyond the consortium setting and extend it to a wider range of stakeholders, including local authorities, community-based organisations, spontaneous volunteers and representatives of vulnerable groups (e.g. persons with disabilities, migrants, older adults). This would allow examining how perceptions of priorities shift when community resilience is approached from multiple positionalities, and how professional and lay knowledge can be combined more systematically. Such broadening is essential to ensure that resilience strategies meaningfully reflect the needs, experiences, and histories of those most affected by disasters.

There is also considerable scope for integrating advanced analytics into resilience-oriented technology design. Building on the data challenges identified in this study, future work could explore how AI-driven analytics, real-time data fusion and digital twins can support risk assessment, resource allocation, victim localisation, and early warning, while remaining transparent, trustworthy and useable in time-pressured operational environments.

Longitudinal and comparative evaluations are needed to link participatory design processes and resulting technologies to actual resilience outcomes. This implies following organisations over time, across exercises and real events, and comparing contexts where similar methodologies have and have not been applied. Such work could help disentangle which combinations of attributes, capacities and tools are most effective under different hazard types, scales and governance arrangements.

Finally, future research should engage more deeply with governance, ethical, and legal dimensions of resilience-oriented technologies, particularly those involving extensive data collection, physiological monitoring or novel human–robot interactions. Questions of data ownership, consent, equity in access to technology and potential unintended consequences for trust between authorities and communities deserve explicit attention alongside technical and operational performance.

In conclusion, the S&R experience suggests that investing in participatory, attribute-based and user-centred processes is not a luxury but a prerequisite for ensuring that innovation in disaster management genuinely contributes to community resilience. The methodology and findings presented here offer a transferable starting point for other projects and jurisdictions seeking to align technological development and operational planning with the complex, context-dependent realities of those who respond to and live with the impacts of disasters. By embedding equity-aware participation throughout these processes, future efforts can more effectively support fair, inclusive, and sustainable disaster risk reduction outcomes.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author used ChatGPT for text refinement and reformulation during manuscript preparation and revision. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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CRediT authorship contribution statement

Hana Gharrad: Data curation, Formal analysis, Investigation, Supervision, Writing – original draft, Writing – review & editing. **Ioannis Benekos:** Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Ansar Yasar:** Project administration, Supervision, Writing – review & editing. **Evangelos Bekiaris:** Project administration, Supervision.

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.

Glossary

AIDR	Australian Institute for Disaster Resilience.
DG/ECHO	Directorate-General for European Civil Protection and Humanitarian Aid Operations.
EC	European Commission.
EU	European Union
FR	First/Early Responders
KPIs	Key Performance Indicators.
MIMS	Membrane Inlet Mass Spectrometry.
NGO	Non-Governmental Organisations
S&R	Search and Rescue (EC-funded research project - www.search-and-rescue.eu).
Tech	Technology Developers.
UNDP	United Nations Development Programme.
UNDRR	United Nations Office for Disaster Risk Reduction.
WHO	World Health Organisation.

Appendix A. Detailed background on literature review and Focus Group findings

This appendix provides a detailed overview of the literature review and case study collection conducted during PHASE A of the methodological development process. The appendix includes extended descriptions of the reviewed resilience frameworks, relevant EU-funded projects, and the disaster case studies analysed by the consortium. These materials informed the development of the community resilience attribute framework used in the main text, but are presented here to maintain readability and conciseness in the core methodological narrative.

Literature Review Scope and Sources

The literature review examined a wide range of sources addressing resilience, community resilience, and disaster risk reduction, including peer-reviewed publications, policy frameworks, technical reports, and methodological guidance produced by international organisations and research initiatives. Key conceptual guidance on resilience and disaster risk reduction was obtained from institutional frameworks and terminology developed by the United Nations Development Programme and the United Nations Office for Disaster Risk Reduction [2,3,30]. Guidance on community engagement and resilience-building practices was also drawn from institutional resources developed by the Australian Institute for Disaster Resilience [4].

To capture policy-oriented operationalisation and assessment approaches, the review included materials from civil protection agencies and international bodies (e.g., DG/ECHO and related EU guidance), as well as resilience-oriented tools and scorecards [12–15]. Academic studies were reviewed to synthesise core debates on community resilience definitions and disaster management processes, including the multidimensional character of resilience and the need to consider social, institutional, and governance dimensions [5,11]. Finally, research examining resilience indicators and assessment approaches was considered to understand how resilience concepts have been operationalised and to highlight the diversity and limitations of indicator-based approaches across contexts [9,10].

The review also incorporated selected outputs from major research initiatives and practitioner-oriented resources relevant to crisis management and resilience, including EU-funded projects [17,31–33] and practice-oriented initiatives and networks reflecting civil society engagement in disaster risk reduction and response support [18–20].

Communities and Resilience in Disaster Research

The reviewed literature underscores the complexity of defining both community and resilience in disaster risk management. Communities may be conceptualised geographically, institutionally, or as networks of actors involved in disaster response and recovery [5,11]. In institutional guidance and civil protection documentation, communities are frequently framed as place-based, reflecting a focus on affected populations and on generalisable policy tools and assessment approaches [2,12–15].

By contrast, more recent research emphasises the dynamic and relational nature of communities, including “communities of practice and interest” that emerge around disaster management activities and encompass professional responders, infrastructure operators, voluntary organisations, and other stakeholders [5,11,16,17]. This orientation is also reflected in civil society organisations and networks engaged in disaster risk reduction and response support [18–20]. Complementary disaster scholarship further highlights that disaster risk is shaped by social vulnerability, governance structures, and institutional capacity, reinforcing the need to interpret resilience through social and institutional lenses [6–8].

Across institutional frameworks, resilience is commonly framed as a capacity involving adaptation, learning, and transformation within complex socio-technical systems [3,4,12,21,22,30,34,35]. Taken together, these sources support the view that resilience is more actionable when its relevant elements are made explicit and aligned with the operational context under examination [9–11].

Analytical Frameworks for Operationalising Resilience

Several analytical approaches relevant to resilience assessment and operationalisation were examined. Resilience engineering perspectives emphasise core system capabilities—anticipation, monitoring, response, and learning—as central elements of resilient socio-technical systems [36]. Complementary work on measurable resilience highlights the importance of developing operational indicators and metrics that can inform policy and decision-making processes [37].

Work addressing resilience management and guidance for critical infrastructures was reviewed to situate operational resilience considerations within broader systems perspectives and continuity concerns [31]. Related research initiatives addressing crisis management innovation and cyber-enabled support for resilience and response operations were also considered [17,32]. Finally, initiatives focusing on resilience indicators and methodological approaches for critical infrastructure resilience under climate-related stressors were reviewed to capture established approaches to indicator development and operationalisation [33].

Collectively, these frameworks support linking resilience concepts to operational attributes while also illustrating why context-specific translation of "resilience" into implementable elements is necessary in applied disaster management settings [9–11].

Focus Group discussion: operational interpretation of resilience attributes

To complement the literature review and case study analysis, a Focus Group discussion was conducted involving representatives of project partners with operational expertise in disaster response, crisis management, and technology development. The purpose of the discussion was to examine how end users interpret the identified community resilience attributes and how these attributes relate to operational criteria considered important for strengthening community resilience in disaster response contexts.

Five operational criteria emerged from the discussion as particularly relevant for strengthening community resilience in disaster response systems.

Community engagement in disaster Management

Participants emphasised that effective disaster response and recovery depend not only on the capabilities of professional response organisations but also on the active involvement of local communities and civil society actors throughout the disaster management cycle. In this context, community resilience was closely associated with mechanisms that enable meaningful participation of community actors in preparedness, response, and recovery processes.

Examples discussed included engagement of non-governmental organisations (NGOs) and volunteer groups, mechanisms for community-based preparedness planning, and initiatives that promote local awareness and participation in risk reduction activities. Participants also emphasised that local knowledge and situational awareness provided by community actors can significantly enhance operational decision-making during emergency response.

Training and Preparedness

Another major theme concerned the importance of training and preparedness mechanisms for strengthening community resilience. Participants emphasised that training programs should not only focus on technical response procedures but should also incorporate lessons learned from past disasters and emerging operational challenges.

The discussion highlighted the value of joint training exercises and simulation activities that bring together different actors involved in disaster response, including professional responders, volunteers, and relevant public authorities. Such activities were considered particularly important for strengthening coordination and improving the operational integration of different response organisations.

Participants also emphasised that training programs should address the effective use of new technologies introduced in disaster response operations, ensuring that end users are familiar with both the capabilities and limitations of technological tools.

Health and Safety of First Responders

The health and safety of first responders was identified as a central concern in the operational interpretation of community resilience attributes. Participants emphasised that responder safety is influenced not only by the availability of protective equipment but also by organisational procedures, decision-making protocols, and situational awareness mechanisms.

Several participants highlighted the importance of technologies and procedures that support hazard identification, risk assessment, and real-time monitoring of operational environments. In addition to physical safety considerations, the discussion also emphasised the importance of addressing psychological stress and cumulative mental health impacts experienced by responders during prolonged or high-intensity emergency operations.

These considerations were viewed as directly related to the resilience of response systems, as the well-being and operational capacity of responders strongly influence the effectiveness and sustainability of response activities.

Interoperability of Systems and Procedures

Participants also emphasised the importance of interoperability among technological systems, communication platforms, and organisational procedures used during disaster response operations. Lack of interoperability was frequently identified as a major operational barrier, particularly in multi-agency response environments.

Examples discussed during the Focus Group included difficulties in exchanging information across different communication systems, incompatibilities between technological platforms used by different organisations, and differences in operational terminology or procedures.

Participants emphasised that improving interoperability requires not only technological solutions but also organisational coordination mechanisms, common protocols, and harmonised operational practices across response organisations.

Manoeuvrability and Operational Adaptability

A final operational criterion identified during the Focus Group concerned the manoeuvrability and adaptability of response operations. Participants emphasised that disaster response environments are often characterised by rapidly changing conditions, limited accessibility, and complex physical environments.

In such contexts, technologies and operational procedures must be sufficiently flexible and adaptable to function effectively under diverse and unpredictable conditions. Participants highlighted the importance of designing technological tools and operational protocols that remain functional in degraded infrastructure environments and can support decision-making in rapidly evolving crisis situations.

The manoeuvrability criterion also emphasised the importance of selecting equipment and technologies that are compatible with the physical and logistical constraints of disaster response operations.

Implications for the GAP Survey Design

The insights derived from the Focus Group discussion were used to refine the structure of the gap survey and to ensure that the survey questions captured operational challenges and priorities identified by end users. In particular, the five operational criteria identified during the discussion helped guide the formulation of survey questions linking community resilience attributes with operational needs related to training, information management, technological capabilities, and response procedures.

These insights also contributed to the development of the attribute–need matrix described in Section 2.3, which served as the analytical basis for identifying priority gaps in community resilience within the context of disaster response operations.

Appendix B. Survey Questions

Table 1
Survey questions.

Q1: Procedures to train, educate and up-skill civil society, organisations, and local communities about the rescue process	
Options	- Theoretical training - Practical training. - Regular theoretical training. - Regular practical training. - Theoretical online training via online platforms. - Regular practical drills organised via a cooperation platform. - Analysis of lessons learned from the experience of different entities (NGO, end-users, etc.) - Analysis of lessons learned from the experience of different entities (NGO, end-users, etc.) via a cooperation platform.
Q2: Procedures enabling shared knowledge between end-users and civil society, organisations and local communities	
Options	- Regular meetings. - Internationalisation. - Cooperative programs.
Q3: Procedures enabling cooperative risk assessment in crisis management	
Options	- Cooperative risk identification. - Cooperative risk assessment via a series of meetings - Cooperative risk assessment via gamification.
Q4: Procedures enabling cooperative preparation of a recovery plan	
Options	- Cooperative recovery action plan via a series of meetings - Cooperative implementation of the endowment plan coordinated by local authorities.
Q5: Procedures for apprising and improving awareness of vulnerable populations	
Options	- Exploration of the best means of communication with the vulnerable population (technologies, social media, media). - Improve vulnerable population awareness regarding norms and behaviours via organising events, games, and media. - Continuous information distribution of the emergency event and its development. - Training of first responders on communication during personal emergency evacuation plan (targeting people with disabilities). - Exploitation of technologies to improve the awareness of people with special disabilities. - Public demonstration of the rescue process.
Q6: Training	
Options	- Training end-users about interaction with people with specific disability. - Training targeting the speed of professional response. - Training volunteers S&R teams on standards and procedures. - Training first responders on the usage of new technologies and their constraints. - Training about the coordination and harmonisation of actions between stakeholders. - Training first responders on emergency medical skills (crisis research management).
Q7: Procedures to enhance the understanding of the rescue process	
Options	- Software simulations of the procedures in the expected environments and situations. - Practical training.

(continued on next page)

Table 1 (*continued*)

	- Theoretical training.
	- Demonstrating local and international rescue processes and exercises in the media support.
	- Public demonstration of the rescue process.
Q8: Procedures for improving the mental health of first responders and victims	
Options	- Pre-training and preparedness.
	- Monitoring, recognition and management of cumulative stress.
	- Monitoring, recognition and management of incident stress.
	- Mental health training.
	- Psychological care of victims.
Q9: Procedures for improving the physical health of first responders and victims	
Options	- Communication (telematics, direct) within the team to identify the risk and avoid dangers.
	- Dangers assessment procedures.
	- Preparations, exercises and training.
	- Monitoring, recognition and management of first responders' physical health.
	- Usage of new technologies to identify risks and avoid dangers (including real-time awareness).
	- Usage of wearables and technologies to protect first responders.
	- Medical training for first responders to avoid medical mistakes during rescue operations.
	- Practical classes such as civil protection.
	- Communication between victims and first responders using technologies.
	- Coordination of the actions of first responders and medical health services.
	- Easy and fast localisation of resources
Q10: Procedures for protecting physical resources during emergency situations	
Options	- Use of sensory technologies during the discovery phase (for risk assessment) and before intervention.
	- Training on the appropriate use of different technologies in different contexts and conditions.
	- Design of a comprehensive plan to protect physical resources.
	- Recommendation about a suitable resource to use in a special context from control centre before intervention.
Q11: Procedures facilitating the localisation of resources	
Options	- Usage of risk assessment to identify needed resources and provide a better vision of how to locate resources.
	- Cooperative analysis of needs.
	- Communication between stakeholders via one emergency centre (could locate all stakeholders).
	- Allow stakeholders to locate each other and communicate with each other.
	- Cooperative mapping of resources involving different stakeholders.
	- Design of operating protocols to allow local authorities and communities to participate in decisions linked to resource localisation.
Q12: Level of interoperability between stakeholders to improve crisis management operations	
Options	Administrative level: protocols and standards for communication, decision-making, and norms.
	- Strategic level, where stakeholders prepare the big picture plan of the operation.
	- Tactical level, where the stakeholders prepare the detailed plan of intervention.
Q13: Usage of Information Communication Technologies and social media to reduce the size of affected areas and reduce the number of victims	
Options	- Dissemination of information to prepare a protection plan and precaution.
	- Social media can provide information for first responders and allow the population to avoid danger after disasters.
Q14: Procedures to improve the impact of smart devices and real-time information-sharing systems on manoeuvrability	
	- Frequent training on the usage of equipment.
	- Training and learning from previous lessons to avoid the negative effects of new devices on the manoeuvrability of the team.
Q15: Procedures to improve the impact of internal processes on manoeuvrability	
Options	- Frequent internal review of training processes is required to speed up the response and improve the safety of the professional.
	- Learning from previous lessons and adaptation of internal processes.
	- Benefit from the previous lessons of others stakeholder.
Q16: Which human behavioural challenges need to be addressed to improve interoperability?	
Options	- Use of different languages, cultures, and terminologies by different stakeholders
	- Coordination of action plans of involved stakeholders.
	- Standardisation of operational procedures.
	- Identification of key people in different organisations.
	- Training of civil society organisations in relation to technologies.
	- Harmonisation and coordination of action plans via a mediation centre.
Q17: Which technical challenges need to be addressed to improve technical interoperability?	
Options	- Real-time shared information between involved stakeholders.
	- Standardisation of communication technologies (example: common radio frequencies).
	- Interoperability and compatibility of different systems used within involved entities.
Q18: What are the technical challenges faced in victim localisation?	
Options	- Scalability of supported systems for victim localisation.
	- Inaccuracy and reliability of collected information.
	- Real-time information (speed of localisation).
	- Identification of suitable devices to use in specific contexts and environmental conditions.
	- Financial cost of localisation devices.
	- Financial cost of supported software.
	- Cooperative localisation of victims (integration of different systems).
	- Limited coverage of some communication technologies.
	- The high cost of alternative communication technologies.
	- Access to full coverage communication resources.
Q19: Which technical challenges are faced in data collection for situation awareness and risk assessment?	
Options	- Scalability of supported systems.

(*continued on next page*)

Table 1 (*continued*)

	- Inaccuracy and reliability of collected information.
	- Delay of real-time information.
	- Financial cost of used equipment.
	- Financial cost of supporting software.
	- Cooperative integration system (integration of different systems)
	- Limited coverage of some communication technologies.
	- The high cost of alternative communication technologies.
	- Access to full coverage communication resources.
	- Integration of collected data.
	- Analysis of collected data for risk assessment.
	- Limitation of sensory and equipment efficiency/resilience (false positive, loss of connectivity …) due to environmental conditions (temperature, wind, dust, obstacles, etc)
	- Technical knowledge about suitable devices to use in specific contexts.
Q20: Which challenges are faced in information communication via social media?	
Options	- Identification of responsible entities for providing information.
	- Assessment of the reliability of the received information.
	- Identification of solutions to avoid conflictual information.
	- Identification of solutions to resolve conflictual information.

Data availability

Data will be made available on request.

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