Human-Centred Requirements Engineering for Critical Systems: Insights from Disaster Early Warning Applications

Anuradha Madugalla[a,*,1], Jixuan Dong[b], Kai Lyne Loi[b], Matthew Crossman[b] and John Grundy[b]

[a] School of Information Technology, Deakin University, Melbourne, Victoria, Australia
[b] Faculty of Information Technology, Monash University, Melbourne, Victoria, Australia

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ABSTRACT

Critical systems, such as those used in healthcare, defence, and disaster management, demand rigorous requirements engineering to ensure safety and reliability. Yet, much of this rigour has traditionally focused on technical assurance, often overlooking the human and social contexts in which these systems operate. This paper argues that considering human-centric aspects is an essential dimension of dependability, and presents a human-centred RE process designed to integrate social responsibility into critical system development. Drawing from a literature review, we identified a set of guidelines for designing software for vulnerable communities and translated these into sixty-two functional and non-functional requirements. These requirements were operationalised through the design of an adaptive early warning system prototype, which was subsequently evaluated through six interviews and eight cognitive walkthroughs to validate their relevance and applicability. The findings demonstrate that human-centric requirements, when addressed early, enhance the usability and accessibility of systems for all users. The paper concludes by positioning human-centricity not as an ethical add-on but as a defining quality of safe and equitable critical systems.

1. Introduction

Critical systems, such as those used in healthcare, transportation, defence, and disaster management, demand exceptional rigour in their requirements engineering (RE). When these systems fail, the consequences extend beyond technical malfunction; they directly threaten human safety and public trust [1]. Therefore, RE for critical systems has historically focused on aspects such as safety, dependability, and correctness. While these qualities remain essential, this emphasis has often come at the expense of an equally critical dimension: the integration of human-centred concerns. A significant gap exists in ensuring that requirements capture the full spectrum of stakeholder needs, particularly those of vulnerable or marginalised communities [2].

Neglect of these concerns can lead to significant consequences. A healthcare system that assumes expert digital literacy of its users may exclude elderly patients; an emergency transport app optimised for urban connectivity may fail rural users; and a disaster early warning system designed for the “average” user may leave people with disabilities without access to life-saving alerts. In critical systems, these shortcomings cannot be considered as simple usability oversights. Instead, they must be recognised as requirements failures rooted in incomplete stakeholder analysis and non-inclusive elicitation practices.

Focusing on inclusive elicitation not only supports vulnerable communities but also leads to broader improvements in product quality and user experience for everyone. For example, in the broader field of engineering, curb cuts were created to make city streets more accessible for wheelchair users. But this resulted in curb cuts enhancing mobility for many others, including people pushing strollers, pulling suitcases, delivering goods, or riding bicycles and skateboards [3]. A similar pattern can be observed in software inclusivity: captions were first introduced to make videos accessible to people with hearing impairments, but with the rise of social media, they are now used widely [4]. Captions enable quiet or multilingual viewing, showing how accessibility features can evolve into mainstream usability improvements [5]. These examples illustrate that inclusive design is not a constraint but a driver of innovation and universal benefit.

This paper builds on the argument that socially responsible RE is central to the development of all systems, especially for critical systems. We propose an RE process that ensures requirements are elicited, specified, and validated in ways that support social equity. To demonstrate this process, we present a case study in disaster management:

anuradha.madugalla@deakin.edu.au (A. Madugalla)
ORCID(s):

the design of an adaptive early warning application that addresses the needs of vulnerable groups. We show how participatory engagement with vulnerable communities can uncover overlooked requirements, translate them into adaptive design guidelines, and validate them through stakeholder feedback. Our contributions are twofold:

Contribution 1: A case study demonstrating how socially responsible RE practices can be operationalised in a critical domain through participatory stakeholder engagement

Contribution 2: Generalisable insights for integrating inclusivity and equity into RE processes for other critical systems, thereby advancing RE's role in supporting resilience, safety, and social good.

2. Motivation

Most of the critical systems today are designed for a notional "average" user. This one-size-fits-all approach overlooks the needs of vulnerable groups. For example, in a disaster warning system, colour-only alerts may be inaccessible to users with colour vision deficiencies; small interface elements may exclude older adults with vision issues; and reliance on stable connectivity disadvantages rural populations. Such oversights hinder their access to critical early warnings, placing their lives and livelihoods at danger. When warnings cannot be understood or acted upon by the most vulnerable, the system fails in its primary purpose. Such oversights demonstrate the necessity of embedding human-centricity into requirements engineering for critical systems.

This study is motivated by the need to bring human-centricity and participatory principles into the early phases of RE for critical systems. By deriving requirements from participatory design guidelines, modelling them through adaptive prototypes, and validating them with both communities and personas, this research demonstrates a pathway towards human-centred RE that is both socially responsible and technically rigorous. Ultimately, it aims to ensure that no user is left behind due to a lack of representation in the system development process. To achieve this, the paper investigates the following research questions:

RQ1: What are the requirements of vulnerable groups in the context of critical systems?

RQ2: How can these requirements be modelled and operationalised for stakeholder feedback?

RQ3: How can requirements be validated with diverse stakeholders to ensure their needs are effectively addressed?

The rest of the paper is structured as follows. In the next section, we present a review of related work. Section 4 discusses our human-centred requirements engineering process, and sections 5 and 6 contain two steps of this approach: requirements elicitation and specification. Section 7 presents how these requirements were modelled via prototyping, and Section 8 presents the validation. Section 9 includes a discussion of the findings, and Section 10 presents threats to validity. The final section of the paper summarises the study, presenting suggestions for future work.

3. Related Work

3.1. Requirements Engineering for Critical Systems

Requirements Engineering in critical systems has long focused on aspects such as safety, reliability and correctness. Within domains such as healthcare, transportation, defence, and disaster management, these qualities are vital to prevent major failure and to ensure regulatory compliance. This was brought forward by early foundational work, such as that by Van Lamsweerde, which emphasised that correctness and traceability are qualities that are central to the development of critical systems [6]. Over time, these principles have strongly influenced safety system-oriented RE frameworks and compliance standards across critical domains.

Martins and Gorschek's systematic review of safety-critical RE conducted later revealed that RE in safety-critical domains were still largely compliance-focused and heavily constrained by certification requirements [1]. While these methods reinforced rigour, they provided limited mechanisms for usability and stakeholder collaboration. A subsequent interview study with industry practitioners showed that requirements were commonly extracted via formal reviews and spreadsheets, while user engagement and feedback loops remain minimal. These findings highlight a persistent gap: despite decades of methodological refinement, RE for critical systems continued to prioritise technical assurance over human engagement [7]

3.2. Human-Centred and Participatory Requirements Engineering

Recent research has attempted to bridge this divide by significantly broadening RE's scope from designing systems that are functionally correct to those that are socially responsible and inclusive. Early work by Sutcliffe et al. demonstrated that neglecting human workload and task distribution can undermine both safety and performance, introducing the notion that human factors should be integrated to the RE process [2]. This idea later evolved into a broader recognition that RE is a socio-technical process that is shaped by values and relationships among diverse stakeholders. The systematic review by Hidellaarachchi et al. strengthened this perspective, showing that human aspects such as empathy, collaboration, and communication are central to RE success, and yet these remain under-represented in mainstream practice [8] .

More recent research has extended this school of thought to encompass human aspects such as ethics and equity. Perera et al. empirically demonstrated that explicitly embedding human values—such as fairness, dignity, and social justice within the RE processes results in more creative and socially responsible requirements [9]. Their findings show that values can be operationalised through lightweight elicitation techniques. Similarly, Damian et al. redefined participatory RE as an ongoing, relationship-centred practice through the *REConnect* framework [10]. Their work brings forward the idea that empathy, trust, and continuous collaboration are essential RE artifacts showing how long-term partnerships with communities produce requirements that are both technically sound and socially legitimate.

Building on this trajectory, Tizard et al. called for more inclusive RE practices that consciously address the representation of underserved users [11]. This work highlighted how both traditional elicitation methods and modern crowd-based approaches systematically underrepresent vulnerable groups, including people with disabilities, women, and older adults. The authors proposed practical strategies, such as combining diverse elicitation channels and employing tools like GenderMag cognitive-style surveys, to identify whose voices are missing in the process. However, they did not propose an end-to-end RE process to ensure human-centricity.

Despite this progress, most human-centred and participatory RE approaches have not yet been applied systematically to safety-critical domains or to the inclusion of vulnerable groups. Existing frameworks rarely incorporate intersectional factors such as disability, ageing, or digital literacy that directly affect users' ability to engage with these complex systems. As Martins and Gorschek observed, current industrial RE practices still marginalise diverse perspectives under procedural and regulatory constraints [7]. This study extends the participatory RE process by embedding human-centricity into the core lifecycle of RE for critical systems.

4. Methodology

In this study, we followed a four-stage requirements engineering process to ensure human-centric aspects of the requirements are captured (Figure 1).

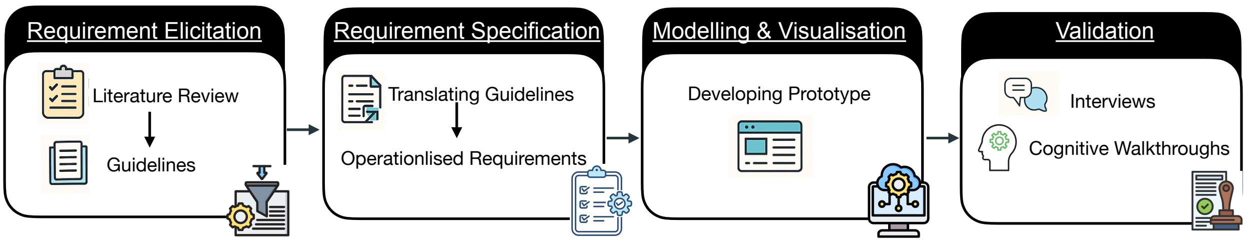

Figure 1: Human-Centric Requirements Engineering Process

The first stage was requirements elicitation, which focused on identifying the needs of our chosen vulnerable user groups. We conducted a targeted review of existing literature, including academic publications and grey literature, to extract guidelines for designing inclusive software relevant to the chosen groups: elderly, individuals with low digital literacy, rural residents, and people with colour-vision impairment.

The second stage was requirements specification, in which we interpreted and translated the extracted guidelines into implementable software requirements for safety-critical systems. Wherever possible, these requirements were expressed as functional or non-functional requirements with measurable criteria (for example, minimum button size, colour-contrast thresholds, or offline caching rules).

The third stage involved requirements modelling, where the specified requirements were represented via a medium-fidelity interactive prototype developed in Figma. This prototype served as both a visualisation of the requirements and as a communication tool for engaging with stakeholders. For the prototype, we chose to design an Early Warning System (EWS) mobile application, which is commonly used in disaster communications to convey safety-critical information.

Finally, the requirements validation stage assessed whether the prototype met stakeholder needs. This evaluation contained two steps: 1) Structured interviews with community members (six participants: two older adults and four rural residents), and 2) Cognitive walkthroughs using personas representing the four vulnerable groups. The insights we gained from both activities were used to validate the requirements and refine the prototype, ensuring that it addressed the needs of these communities.

A key highlight of our methodology is the integration of participatory requirements collection and validation. During the elicitation stage, we extracted guidelines derived from earlier participatory studies in the literature to ensure this knowledge was incorporated in our study without requiring to repeat each of the participant interactions those studies involved. In the validation stage, direct participatory validation was applied by conducting interviews with community members and cognitive walkthroughs with personas.

5. Requirements Elicitation

Following our human-centred requirements engineering framework, we first conducted a targeted, non-systematic review of both academic literature and grey literature (e.g., design guidelines from accessibility organisations, papers in archives, and blogs). This approach prioritised breadth over exhaustiveness, aiming to capture guidelines from previous research and practice. A key feature of this stage was that many of the guidelines extracted from the literature were outcomes of earlier participatory studies, where researchers directly engaged with these communities through interviews, workshops, and field observations. With this, we ensured that the elicitation stage incorporated the lived experiences of vulnerable users without duplicating previous data-collection efforts. We carried out a comparative analysis of the extracted guidelines to prepare them for the requirements engineering process.

1. The extracted guidelines were grouped into our four user groups based on the original literature
2. Examined the guidelines to identify potential overlaps and shared needs.
   This process revealed that while many guidelines were specific to a single group (e.g., high-contrast icons for colour-impaired users), a significant number were common to two or more groups. For instance, large, well-spaced buttons supported both elderly and people with low digital literacy, and a simplified navigation structure helped elderly, rural residents and individuals with low digital literacy as it simplified systems.
3. Present these guidelines as “Guidelines specific to a single vulnerable community" [Table 1], and “Guidelines Shared between Vulnerable Communities" [Table 2]. These tables only show an extraction from the original guidelines, and the detailed guidelines can be found in Appendix A and B.

5.1. Guidelines: Specific to a Single Vulnerable Community

Table 1 shows an extraction of the design guidelines targeted at individual vulnerable groups. The detailed guidelines can be found in Appendix A. The first group, Elderly communities, contain 11 guidelines (E1-11), Low digital communities have 15 guidelines (D1-15), Rural communities have a smaller set of guidelines (R1-5) and lastly color blind communities have 10 guidelines (C1-10). The guidelines for the elderly mostly focus on simplification and readability of the systems to reduce cognitive overload and to address their possible physical challenges (motor control issues, low vision issues). Low digital literacy community guidelines focus on clear information architecture, the use of plain language and consistency to overcome any possible confusion. For Rural residents, the emphasis is on the connectivity constraints and how best the systems can support them. For the colour blind communities guidelines, highlights the need for redundant cues beyond colour — e.g., patterns, icons, and text labels alongside colour coding.

Table 1: Guidelines for Vulnerable Communities

ID	Guideline: Description
Elderly Communities	
E1	**Reduce short-term memory load:** Reducing the cognitive load is important for the elderly who may have decreased working memory and for those who may not be very familiar with digital systems. [12]
E2	**Maintain focus on current action:** Older users have more trouble concentrating. [13]
...	...
	Continued on next page

ID	Guideline: Description (continued)
E11	**Prefer tapping over gestures:** Older users may have motor skill challenges that make gestures difficult, which is compounded by a lack of familiarity. [13]
Low-Digital-Literacy Communities	
D1	**Include short, simple instructions in Help menu:** Ensure help menus are short and easy-to-understand without jargon and are quick to action [14]
D2	**Enable customisation:** Allow users to customise the content, layout, and other settings for the application [14]
...	...
D15	**Error-free operation:** Apps should be as error-free as possible and, when they fail, should fail “gracefully” instead of crashing [15]
Rural Communities	
R1	**Split content into pages:** Pagination enables partial loading to help in areas with poor Internet access [16]
R2	**Promote your app/website – make it easy to find:** Rural-facing content is easily overwhelmed in search results due to poor Search Engine Optimisation or being out-competed by generalised content [17]
...	...
R5	**Rely on telecommunication rather than Internet:** Internet access can be poor, but other connectivity methods like direct sharing are often available [18]
Color-Blind Communities	
C1	**Test against tools:** Use existing accessibility assessment tools such as WCAG tool suites & colour-blindness simulators [19]
C2	**Use more than just colour to distinguish things:** Don’t rely solely on colour to inform users; add other indicators like symbols or shapes [20]
...	...
C10	**Colour-blind users have different preferences:** Colours such as red and green have common meanings for most users, but colour-blind users may interpret them differently [19]

5.2. Guidelines: Shared between Vulnerable Communities

In addition to group-specific guidance, we also identified a significant number of overlapping design guidelines across the four groups. During our analysis, where guidelines targeted similar usability or accessibility concerns, we classified them as shared guidelines. We found 3 guidelines (EC1-3) common to elderly and colour-blind groups, with the focus being on improving colour contrast for better readability. Between elderly and rural communities, there were 8 common guidelines (ER1-8), and for rural and low digital literacy communities, there were 5 guidelines (RD1-5). We also identified 5 guidelines (ERD1-5) that were common to 3 groups: elderly, rural and low digital literacy communities and these focused on providing more feedback and simplifying systems. An extraction of these guidelines are shown based on the shared grouping in table 2 below. The detailed guidelines can be found in Appendix B.

Table 2: Shared Guidelines Across Communities

ID	Guideline: Description
Elderly & Color-Blind Communities	
EC1	**Colour contrast between popups and background:** Ensure that colours used between foregrounds and backgrounds have high contrast to cater for potential vision challenges [21]
EC2	**Design without colour to maintain luminance contrast:** If colours are used to code or contrast two elements, revise the design without colour (i.e., without chromaticity) to compare them in grayscale (luminance or brightness) [22]

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ID	Guideline: Description (continued)
EC3	**Maintain WCAG contrast ratios:** Ideally, follow the AAA standard of 4.5:1 for text, as well as other ratios for different scenarios, to cater to low contrast vision and colour-blind users. Make use of compliance checkers (e.g., Google Lighthouse) to validate that designs meet required contrast ratios [19]
Elderly & Rural Communities	
ER1	**Give time to act and read:** Avoid deadlines or timed events so people with different reading speeds are not rushed or cut off [13]
ER2	**Discoverability – clear purpose and state:** Clear focal points, good visual hierarchy, and transparent navigation so users always know what something does and its current state [23]
...	...
ER8	**Provide text alternatives:** Provide alternatives (e.g., alt-text, large text, or simplified language) for non-text content [24]
Rural & Low-Digital-Literacy Communities	
RD1	**Minimise download times:** Use smaller image/video sizes, compression, and substitute images with text where possible to improve performance on low bandwidth [17]
RD2	**Consider alternative information infrastructure:** Support cases where multiple users share one device and ensure offline distribution of the app if app stores are not accessible [25]
...	...
RD5	**Enable offline access:** Ensure key features remain accessible offline when network coverage is poor or intermittent [26]
Elderly, Rural & Low-Digital-Literacy Communities	
ERD1	**Simplify navigation structure:** Flatten menu hierarchies and prefer linear navigation to reduce cognitive load [14]
ERD2	**Reduce alternative paths:** Ensure navigation paths are simple and consistent; minimise branching or multiple routes that may confuse users [13]
...	...
ERD5	**Understandable error messages:** Provide clear, actionable error messages so users know what went wrong and how to recover [21]

6. Requirements Specification

Following the elicitation stage, we systematically interpreted and transformed the extracted inclusive design guidelines into implementable software requirements using both our knowledge and information in the original research. The goal of this stage was to bridge the gap between conceptual guidance from literature and practical specifications that could be implemented during development. Each guideline was interpreted in terms of what the system must do (functional requirement) or how it must perform/behave (non-functional requirement).

6.1. Translation Process

We followed a structured process to convert each guideline into a precise requirement. This approach ensured traceability from original evidence-based guidelines to system-level requirements, while enabling later validation and visualisation with the prototype.

1. Traceability mapping: every requirement was assigned an identifier (R#) that directly links it back to the originating guideline (e.g., E1 → R01)
2. Requirement type classification: requirements were categorised as Functional (E.g. "provide context-aware help") or Non-Functional (E.g. "achieve WCAG-AA colour contrast")
3. Sub-categorisation of Non-Functional requirements: non-functional requirements were further tagged as Usability, Accessibility, Performance/Efficiency, or Reliability, reflecting the core quality attribute being addressed

Table 3
Distribution of Requirements by User Group and Non-Functional Categories (from final requirements table)

User Group	Total Reqs.	Func.	Non-Func.	Non-Functional Categories			
				U	**A**	**P**	**R**
Elderly	11	3	8	5	3	0	0
Low-Digital-Literacy	15	4	11	7	3	0	1
Rural	5	3	2	2	0	0	0
Colour-Blind	10	0	10	1	9	0	0
Shared Across Communities							
Elderly + Colour-Blind	3	0	3	0	3	0	0
Elderly + Rural	8	3	5	4	1	0	0
Rural + Low-Digital-Literacy	5	2	3	0	0	3	0
Elderly + Rural + Low-Digital-Literacy	5	1	4	4	0	0	0
Shared Total	21	6	15	8	4	3	0
Grand Total	**62**	**16**	**46**	**23**	**19**	**3**	**1**

U = Usability; A = Accessibility; P = Performance/Efficiency; R = Reliability.

6.2. Specification

The full mapping of Guidelines → Requirements → Requirement Type is presented in Table 5 and in Appendix C. This serves as both a traceability matrix and a specification artefact for future design and validation. This final specification consists of 62 requirements with 16 Functional requirements and 46 Non-Functional requirements. Within the non-functional requirements, 23 focused on usability, 19 on accessibility, 3 on performance/efficiency and 1 on reliability aspects. Below is their breakdown based on the community groups. The breakdown of these categories based on each group can be found in Table 3.

Based on the Table 3, the Elderly group shows a relatively even balance between functional and non-functional requirements (4 functional vs 7 non-functional), with usability concerns (5) dominating. The Low-Digital-Literacy group has a slightly higher share of functional requirements (6 of 15), yet still prioritises usability and cultural responsiveness. Rural users are associated with fewer requirements overall (5). In contrast, Colour-Blind users contribute mostly accessibility-focused non-functional requirements (8 of 10). The requirements that are shared between groups had more non-functional over functional (15/6). An extraction of the detailed requirements related to each of these groups can be found in Table 5, the full list of requirements can be found in Appendix C.

Table 5: Guidelines and Corresponding Requirements with Types

Guideline (ID: Name)	Requirement (R#)	Req. Type
Elderly Communities		
E1: Reduce short-term memory load [12]	**R01:** Ensure the system simplifies navigation, uses clear and consistent icons, and provides step-by-step instructions to reduce memory burden.	Non-functional (Usability)
E2: Maintain focus on current action [13]	**R02:** Ensure the interface removes distractions and secondary functions, highlighting the most important or typical action on each screen.	Non-functional (Usability)
...	...	...

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Guideline (ID: Name)	Requirement (R#)	Req. Type
E11: Prefer tapping over gestures [13]	**R11:** Ensure tapping alternatives exist for gesture-based interactions (e.g. sliders) to reduce dexterity demands on the user.	Functional
Low-Digital-Literacy Communities		
D1: Include short, simple Help instructions [14],	**R12:** Ensure help menus provide concise, jargon-free, and easy-to-act-on instructions.	Non-functional (Usability)
D2: Enable customisation [14],	**R13:** Ensure the system allows users to customise layout, content, and settings to fit their needs.	Functional
...	...	...
D15: Error-free operation [15]	**R26:** Ensure the app is stable and fails gracefully with clear recovery options instead of crashing.	Non-functional (Reliability)
Rural Communities		
R1: Split content into pages [16]	**R27:** Ensure long content loads in smaller paginated chunks to improve usability under poor Internet conditions.	Functional
R2: Promote app/website visibility [17]	**R28:** Ensure content is properly indexed (e.g., by search engines) and organised into discrete, discoverable pages.	Functional
...	...	...
R5: Rely on telecommunication [18]	**R31:** Ensure the app supports SMS or offline-friendly messaging for areas with poor Internet connectivity.	Functional
Colour-Blind Communities		
C1: Test against tools [19]	**R32:** Ensure the design is validated using WCAG and colour-blindness simulators.	Non-functional (Accessibility/-Compliance)
C2: Use more than colour to distinguish [20]	**R33:** Ensure redundant visual cues (e.g., icons, text, patterns) supplement colour-coded information.	Non-functional (Accessibility)
...	...	...
C10: Respect colour-blind preferences [19]	**R41:** Ensure designs respect typical user preferences (e.g., favouring blue for clarity) and avoid negative shifts in meaning.	Non-functional (Accessibility)
Elderly + Colour-Blind Communities		
EC1: Colour contrast between popups and background [21]	**R42:** Ensure popup backgrounds and foreground text meet high contrast ratios for readability.	Non-functional (Accessibility)
EC2: Design without colour to maintain luminance contrast [22]	**R43:** Ensure designs work in greyscale by testing contrast without chromatic elements.	Non-functional (Accessibility)
EC3: Maintain WCAG contrast ratios [19]	**R44:** Ensure the design complies with WCAG AA/AAA standards (e.g., 4.5:1 for text) and validates dynamically with tools like Google Lighthouse.	Non-functional (Accessibility/-Compliance)
Elderly + Rural Communities		
ER1: Give time to act and read [13]	**R45:** Ensure time-sensitive actions allow extended durations so slower readers are not disadvantaged.	Functional
ER2: Improve discoverability [23]	**R46:** Ensure clear focal points, strong visual hierarchy, and transparent navigation states.	Non-functional (Usability)
...	...	...
ER8: Provide text alternatives [24]	**R52:** Ensure all non-text content includes descriptive text alternatives (e.g., alt-text).	Non-functional (Accessibility)

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Guideline (ID: Name)	Requirement (R#)	Req. Type
Rural + Low-Digital-Literacy Communities		
RD1: Minimise download times [17]	**R53:** Ensure multimedia elements are optimised or replaced with lightweight alternatives to improve load times on poor connections.	Non-functional (Performance)
RD2: Consider alternative information infrastructure [25]	**R54:** Ensure app design supports shared-device usage and alternative distribution channels (e.g. share app package) when/if app stores are inaccessible.	Functional
...	...	...
RD5: Enable offline access [26]	**R57:** Ensure essential features remain accessible offline or with intermittent connectivity.	Functional
Elderly + Rural + Low-Digital-Literacy Communities		
ERD1: Simplify navigation structure [14]	**R58:** Ensure navigation flows are flattened and linear to reduce cognitive complexity.	Non-functional (Usability)
ERD2: Reduce alternative paths [13]	**R59:** Ensure single, consistent routes for completing tasks to minimise confusion.	Non-functional (Usability)
...	...	...
ERD5: Understandable error messages [21]	**R62:** Ensure error messages are concise, instructive, and reduce user anxiety during recovery.	Functional

7. Requirements Modelling via Prototyping

As the next step of our human-centric requirements engineering for critical systems process, we focused on operationalising the specified requirements by designing a prototype of an Early Warning System (EWS) mobile application. There were two main reasons for choosing EWS as the subject of the prototype.

1. **EWS platforms are archetypal safety-critical systems:** In EWS, delays, inaccessibility, or miscommunication can result in severe consequences, ultimately even leading to loss of lives. This domain provided an appropriate context to model and evaluate our human-centric requirements. It also helped to explore our suggested socially responsible requirements engineering (RE) process, given its reliance on reliable information delivery and inclusive user interfaces.
2. **Global need for more inclusive EWS:** EWS plays a key role in disaster communication and has functions like conveying disaster alerts, helping prepare emergency plans, and providing education on disaster management. The United Nations has recognised the importance of ensuring equal access in EWS via its initiative “Early Warnings for All,” which aims to ensure that every individual globally has access to EWSs by 2027.

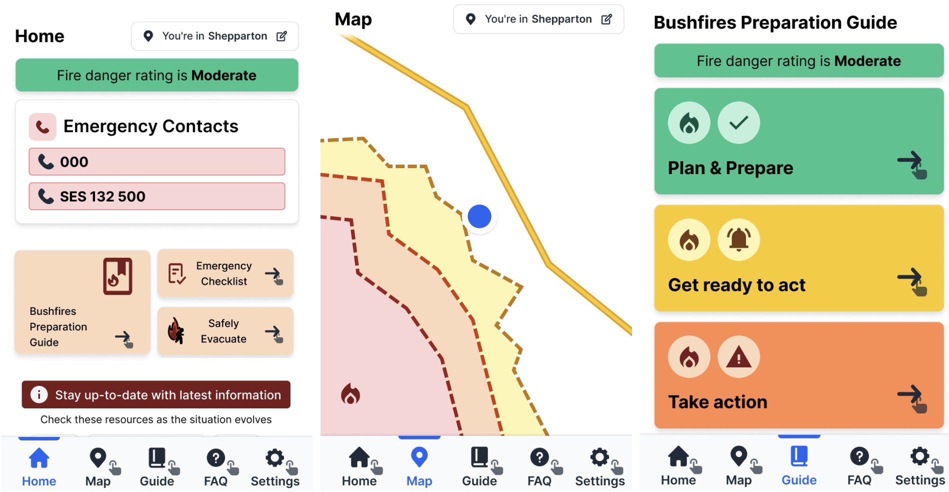
In modelling the specified requirements via this prototype, the first step was to develop a core system prototype that incorporated the essential functions of a standard EWS [27], such as alert notifications, event maps, and preparedness information. Building on this baseline, adaptive versions of the app were then developed for each user group—elderly, low-digital-literacy, rural, and colour-blind communities. These versions integrated the requirements specific to each vulnerable group while maintaining a consistent core architecture.

7.1. Core System Prototype

EWS can focus on a single or multiple hazards, such as floods, earthquakes, and bushfires. For our prototype, we focused on bushfires as this was the disaster that was most relevant to our group of researchers.

The key functionalities of this prototype included 1) real-time, location-based notifications and news, 2) a map displaying nearby fires, 3) disaster preparation guides in various stages of the disaster: Plan and prepare, Get Ready, Take Action, Evacuate, and 4) contacting emergency services for assistance.

As shown in Figure 2(a), on the home page, users had immediate access to emergency services through a speed dial. There were quick links to critical content like the disaster (bushfire) preparation guide, emergency checklists and evacuation guide within the app. Additionally, location-based information retrieval was also integrated, displaying trusted information sources relevant to the user’s current location, e.g. for a user living in Victoria (Australia), it would display information from VicEmergency. It also had a live banner to show real-time updates and warnings e.g Fire



(a) Home Page (b) Map Page (c) Guides Page

Figure 2: Core Prototype

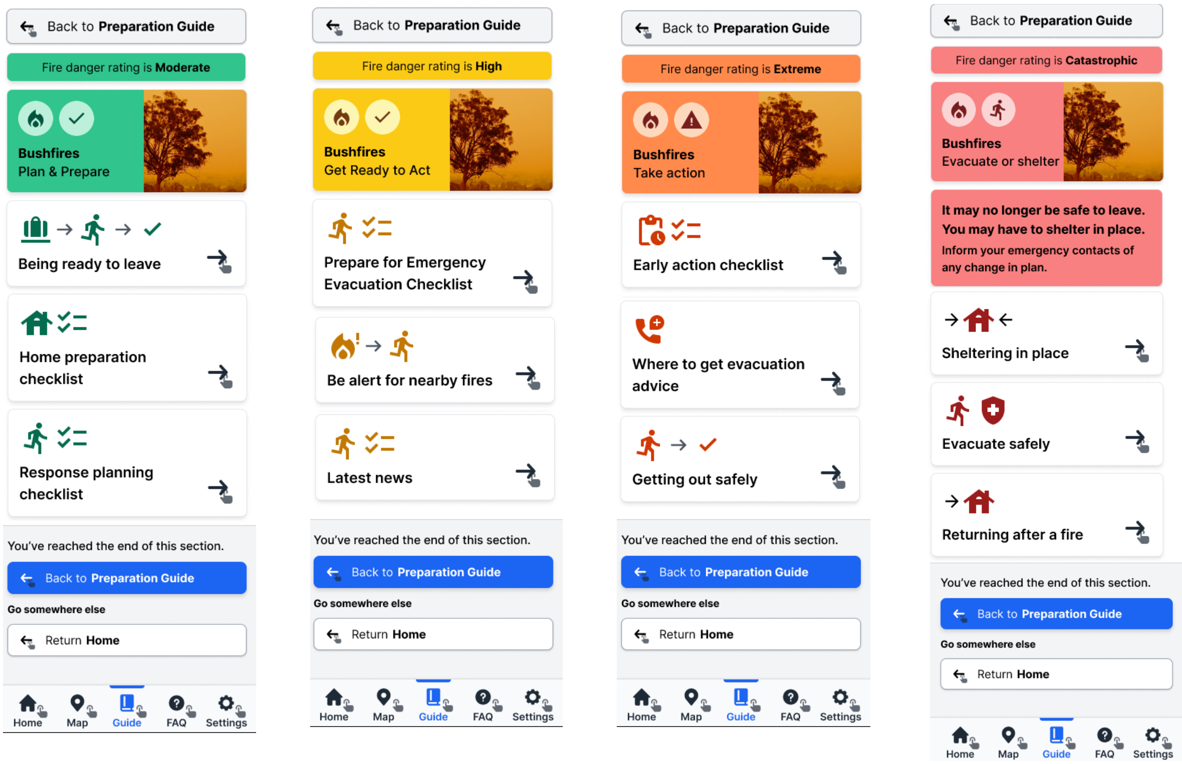
danger rating is moderate. Additionally, the bottom navigation bar facilitated easy switching between different sections such as home, maps, guide, FAQ and settings.

In the map page (Figure 2(b)), the current location of the user is displayed with a blue dot, and they will be able to see the current bushfire danger rating for their current location, and how far they are from the bushfire zones. This would be able to give them an estimation of the distance to danger and the ability to visualise the evacuation routes to avoid running towards fire. Most of the current disaster apps make it very difficult to determine evacuation routes based on the current status of a disaster. Therefore, we added this feature and focused on simplifying the information visualisation. In the final system design, this map page would ideally incorporate road networks and would pull data from a source such as Google Maps.

The disaster preparation guide (Figure 2(c)), a FAQ page with some common questions and contact details for the developer team and a settings page which allowed customisation of the app. The customisations supported in the settings page will be explained in detail in the next section.

The disaster preparation guide was categorised into four: Plan and Prepare, Get Ready to Act, Take Action, Evacuate, and Shelter. Each guide was associated with a fire danger rating ranging from Moderate to Catastrophic, which are standard danger ratings published by the Country Fire Authority (CFA), Australia. We used colors from CFA fire danger ratings as the theme colour for each of the guides, to help users easily distinguish the relevant guides. Information for these guides was sourced from trusted bushfire management agencies such as Australian national and state governments [28, 29, 30, 31, 32]. The list of prototype functions included in each of these guides is listed below.

1. **1. Plan and Prepare Guide:** Provides information on general disaster preparation [Moderate/No Fire Danger] (Figure 3(a))
   (a) Information on how to be ready to evacuate
   (b) A checklist to prepare their home for a bushfire disaster (e.g., cleaning up leaf litter)
   (c) A checklist to help plan the user's response in case of a bushfire
2. **2. Get Ready to Act Guide:** Provides information on preparing for imminent bushfires [High Fire Danger] (Figure 3(b))
   (a) A checklist to prepare for an emergency evacuation
   (b) Information on nearby emergency shelters and routes through Google Maps service to these places
   (c) Next four-day fire danger forecast for users' current area so that they could stay vigilant [33]
   (d) Information on historical bushfire data in the neighbourhood (data extracted from a database created by the government [34])
3. **3. Take Action Guide:** Provides information on preparing to evacuate [Extreme Fire Danger] (Figure 3(c))
   (a) A checklist of early actions E.g prepare an emergency kit, decide on a safe meeting place for your family



(a) Plan & Prepare Guide (b) Ready to Act Guide (c) Take Action Guide (d) Evacuate or Shelter Guide

Figure 3: Guide Pages

   (b) Where to get evacuation advice E.g Radio, links to trusted sources
   (c) Advice on how to get out safely
4. **4. Evacuate or Shelter Guide:** Provides information on evacuating [Catastrophic Fire Danger] (Figure 3(d))
   (a) An evacuation checklist: A streamlined checklist of essential items to minimise preparation time before evacuation [35]
   (b) Guide on how to shelter in their home
   (c) How to evacuate safely
   (d) Post-fire safety tips to protect health upon returning home [36]

7.2. Adaptive Versions

To operationalise the requirements we identified in Section 6, the prototype supported adaptivity. Some of these requirements were specific to user groups, while some were shared between user groups. To accommodate this diversity, users were allowed to self-customise the app, instead of being limited to pre-defined, group-based versions. This approach avoided rigid classification while allowing individuals to tailor features according to their personal capabilities and contexts.

Users could adjust visual, interaction, and content settings directly within the app to match their preferences and accessibility needs. This was important because it was a possibility that some individuals may belong to more than one vulnerable group (for example, an elderly person with colour-vision deficiency living in a rural area). By supporting these intersectional requirements through manual feature selection, we simplified the app logic and enhanced flexibility. It also helped to ensure that the adaptation remained user-driven rather than system-imposed.

Users were able to define the adaptation parameters at the initial setup of the app as shown in Figure 4, and modify them later via the settings page. We supported adapting the app language, font size, and location, ensuring that the alerts and interface were relevant and legible to the users. The app also allowed users to adjust its ease-of-use settings, such as choosing whether to display visual cues or selecting between scroll-based and page-based navigation depending on

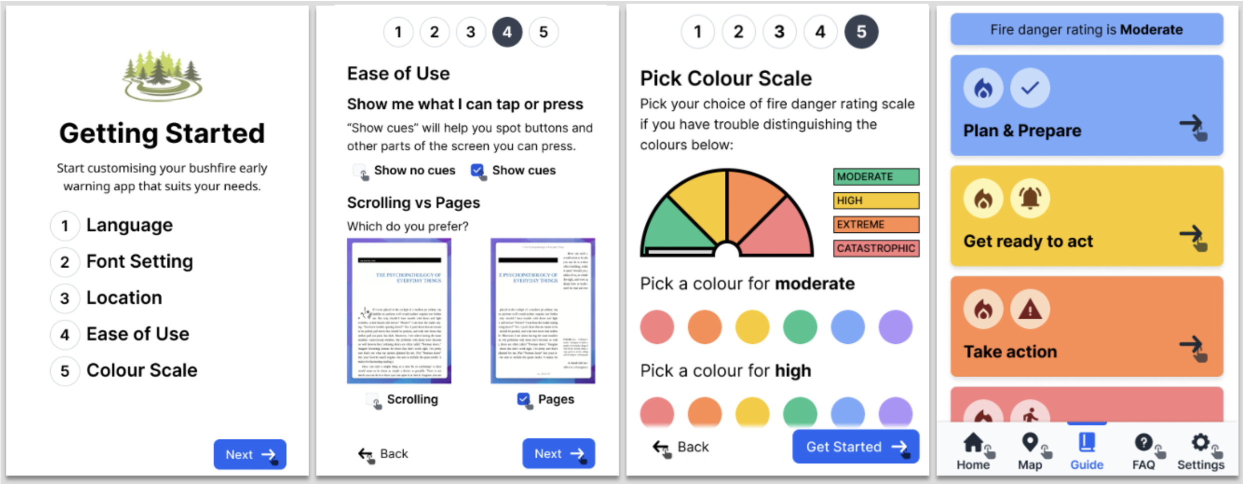


Figure 4: (a)-(c): Adapting the System at Set-up, (d): The adapted system

their comfort and familiarity. For visual accessibility, users could modify the colour scale used for fire danger ratings, selecting combinations that best suited their vision or colour-perception abilities. As these colours were also linked to the visual themes used in fire-danger warnings and preparedness guides, the colour-customisation feature played a crucial role in ensuring that critical safety information was clearly conveyed to every user.

These options were included to reflect the diversity of user capabilities and contexts, while maintaining a single, unified system. Instead of relying on rigid, pre-defined versions for specific groups, this approach allowed individual users to decide which accessibility and usability features mattered most to them, creating a more flexible and inclusive early-warning experience.

8. Participatory Validation of Requirements

Following the specification and modelling phases, we validated the identified requirements through participatory evaluation activities. These validations helped to examine how well the identified requirements were reflected in the prototype and to gather feedback for further refinement. In following this work's inclusive and human-centred nature, the validation process actively engaged end users and realistic user representations. We used two participatory approaches: semi-structured interviews with community members and cognitive walkthroughs using personas.

8.1. Interviews

We conducted semi-structured interviews with our target groups to understand their experiences in using the prototype. This involved using the prototype to complete pre-defined tasks and providing feedback on the experience of using the tool. Each interview took approximately 30-45 minutes. We advertised our study via social media platforms and personal contacts. We received six responses and conducted Zoom-based online interviews with them.

Table 6: Prototype Evaluation Tasks: Interview

ID	Task
1	Open the app and navigate to the home screen.
2	Access the emergency kit preparation checklist and tick some items.
3	Locate and access the Settings.
4	Access the map to see nearby disasters.
5	Access the preparation guide for each of the bushfire danger ratings.
6	Attempt to navigate back to the home page.
7	Evaluate the overall user experience and ease of use.

During the interviews, participants were first introduced to the prototype and were asked to explore its core features, including the home, map, guides, FAQ, and settings pages. They were then tasked with completing seven predefined tasks as outlined in Table 6 by interacting with our prototype tool. These tasks were designed to test the prototype's usability across the different user groups effectively. After the user performed these tasks, we conducted a discussion with them to understand their experience in using the prototype. We audio-recorded each interview, transcribed it later using Zoom's transcription feature and then performed thematic analysis on these transcriptions.

8.2. Cognitive Walkthrough

Due to difficulties in finding a sufficient number of participants to represent all four vulnerable user groups in our interviews, we employed cognitive walkthroughs as a complementary validation approach. As this standard validation method is widely used in HCI and software engineering when direct end-user testing is limited or not feasible, this suited our needs [37, 38]. This allowed us to systematically assess how users with varying characteristics, such as the elderly, rural, low digital literacy, and colour-impaired, would interact with the prototype.

Table 8: Tasks Used in Cognitive Walkthroughs

User Group	Task ID	Task Description
Elderly	1–7	General tasks from Table 6.
	8	Verify if font size adjustments adequately address readability needs.
	9	Evaluate the simplicity and clarity of instructions provided.
	10	Check if the interface design is straightforward and easy to navigate, considering a preference for simplicity.
Colour-Blind	1–7	General tasks from Table 6.
	8	Test the effectiveness of colour customisations in distinguishing interface elements.
	9	Evaluate alternative visual cues (e.g., patterns or text labels) for differentiating colours.
	10	Verify that critical information is not solely conveyed through colour.
Low-Digital Literacy	1–7	General tasks from Table 6.
	8	Evaluate the simplicity and intuitiveness of navigation options.
	9	Verify that the app provides clear and concise guidance for adjusting text settings.
	10	Test the clarity and usefulness of step-by-step instructions, ensuring minimal technical jargon.
Rural	1–7	General tasks from Table 6.
	8	Evaluate the clarity and accessibility of the evacuation guides and map-based information.
	9	Verify that relevant, localised details about disaster and evacuation routes are provided
	10	Assess the usefulness of the app to support the safety of both family and livestock

We developed four personas to represent our four vulnerable communities: elderly, rural, low digital literacy, and colour-impaired. These personas can be found in Appendix D. A cohort of eight participants was then recruited through personal networks to participate in the cognitive walkthrough sessions, with two participants assigned to each persona. At the beginning of each session, participants were first briefed on the characteristics, goals, and limitations of their assigned persona. For the participants assigned to the colour-blind persona, we recommended using a color blind simulator to carry out the cognitive walkthroughs. For this group, a short demonstration was conducted on using a colour-blindness simulator to help them get familiar with the simulator. Each participant then completed ten tasks during the walkthroughs. Seven of these tasks overlapped with those used in the interview study, while three were additional tasks specific to each user group. These tasks are listed in Table 8. After completing the walkthrough, participants were engaged in a discussion to reflect on their experiences. Each session lasted approximately one hour and was conducted online via Zoom. Similar to interviews, we audio-recorded each interview, transcribed it later using Zoom's transcription feature and then performed thematic analysis on these transcriptions.

8.3. Results

In the interview study, we had six participants, two of whom were elderly with an age above 70, and four from rural areas. For the Cognitive walkthrough, we had eight participants, with two participants representing each persona. Upon performing thematic analysis on the discussions, we found that the feedback from both cohorts can be categorised into four main themes, and these are discussed in detail in the next subsections.

8.3.1. Functionality

The majority of the participants from both interviews[INT] and cognitive walkthroughs[CW] found the functions presented in the prototype useful and clear. They found that the checklists in the app were helpful in preparing for a disaster. One rural resident[INT] who works in emergency management observed that the app had "some really good [..] equipment/views and other things to remind people [on what they needed to pack]". Several rural residents[INT] also appreciated the home page's quick links to guide pages, which allowed them to have the most important instructions immediately accessible when the app is opened. They believed this quick access to information would be especially helpful when they are in the middle of a disaster situation, E.g Fire danger rating being Extreme and needing to be ready to evacuate. However, external links to other resources had divided opinions. While some rural users[INT] appreciated direct links to Google Maps for navigation, elderly users [INT] struggled to return to the app after following these links, often requiring assistance to reopen the prototype. In terms of issues in the app, some users were unsure whether any action was needed once a danger rating appeared[CW]; others did not recognise that the blue dot on the map represented their current location[INT]. There was also confusion caused by inconsistent text, such as "You won't be able to get emergency assistance," in the Catastrophic Fire danger guide, which conflicted with the availability of a contact button[CW].

Participants also provided suggestions on improving the app. Some requested more detailed evacuation route information (e.g a map with wind information to help determine evacuation route)[CW] and quick links to safe points and local emergency services[CW]. The absence of such links was seen as a gap in supporting timely decision-making during disasters. Some participants also identified the need for stronger error-prevention mechanisms. This was highlighted by participants[CW] who were concerned about accidentally tapping on emergency contacts without confirmation, which could lead to unintended actions during stressful situations, and by an elderly participant[CW] who suggested restricting users from assigning the same colour to multiple danger ratings. They also suggested adding functions to automatically notify emergency services when the user is in danger[CW], sending reminders for unchecked checklist items[CW], and maintaining a log of recent alerts[CW]. A participant representing a low-digital-literacy persona also suggested allowing the users to personalise content E.g. adding new items to checklists and changing checklist item order. Feedback such as "it would be good to have an option at the beginning asking if notifications are required"[CW] and "a button to call for help straightaway from the fire brigade or police"[CW] also indicated the need for a more integrated, user-centric notification system.

The participants from both groups recognised the importance of functionalities in the current system and also provided several suggestions on how to further improve the prototype.

8.3.2. Content

Both the interview and cognitive walkthrough participants found the app's content useful, clear, and appropriate for disaster preparedness. The interview participants especially found the disaster guides' content meaningful, with one participant[INT] calling the Plan and Prepare section "extremely appropriate", indicating that the app effectively supported readiness before disasters. Participants also praised the app's use of concise, everyday language, noting that this made information accessible even to those with lower literacy levels. One elderly participant[INT] highlighted that functional illiteracy remains high in Australia, and that using familiar, simple words helped ensure inclusivity. Similarly, during cognitive walkthroughs, participants appreciated the clarity of the Take Action section—one low-digital-literacy user[CW] noted, "I like how the content is presented in Take Action as it is very clear for me with not too many choices." These findings underscore that simplicity, directness, and readability are critical strengths of the application. This is particularly vital those who are not knowledgeable about disaster preparation or those who may be under stress during an emergency, where the ability to quickly comprehend and act on information can significantly impact safety and outcomes.

The use of icons and illustrations also received generally positive feedback. Many participants described the visuals as clear, understandable, and not overly complicated. However, while some users found that the icons left "no room for confusion,"[INT] others reported that they "had to think twice,"[INT] suggesting minor inconsistencies in clarity that could be refined. The combination of short text and relevant visuals was appreciated for its ability to make complex evacuation or safety information more digestible [CW].

Despite these strengths, several participants raised issues around clarity and content depth. A number of users found some illustrations or layouts confusing, particularly within the evacuation section. Feedback such as “confusing illustration in evacuation section”[CW] and “issues on illustration of fire—what is the arrow?”[CW] pointed to the need for more descriptive visual aids and clearer graphical representations of actions. Similarly, some users preferred text over icons, expressing that “icons are superfluous; prefer to stick with text. The less there is, the faster it can be conveyed.”[CW] Another participant commented that “the icons used in Shelter in Place (e.g., wavy lines, fire extinguisher, shield) do not make sense”[CW]. These observations highlight the need to balance visuals and text carefully, especially for users with low digital literacy or age-led visual impairments.

Finally, participants identified areas where additional or more actionable content would strengthen the app. One participant[INT] observed that the evacuation section primarily listed dangers but not the corresponding responses, describing it as more appropriate for preparation rather than for real-time action during a catastrophic fire event. Another rural resident[INT] requested that the app include guidance for periods outside the fire season, such as advice for early preparation or maintenance tasks. Together, these comments suggest a need to expand content coverage to support users across all phases of disaster management—before, during, and after an event.

Overall, participants found the content well-written and meaningful, with clear potential for real-world application. However, they also suggested improvements in visual design clarity and actionable content to enhance the system’s effectiveness in communicating critical disaster information to diverse and vulnerable communities.

8.3.3. User Interface

The feedback on the user interface (UI) from both the interviews and cognitive walkthroughs was mostly positive, with participants describing the app as simple, clean, and easy to use. Many appreciated the layout and structure, noting that navigation felt intuitive and that they could easily find where they were in the app. Interview participants highlighted that the quick links at the end of pages as particularly useful for moving between sections, while the bottom navigation bar was found to be familiar and not problematic, even for elderly users. Interviewed Rural residents described it as convenient and practical. Several participants also appreciated the overall visual design, and one elderly participant mentioned that the chosen font, ‘Inter’, was “clean, good looking,” and made the interface feel “simple and well laid out”[INT]. Participants from the cognitive walkthroughs also commented on the layout’s consistency, which they felt made the app easy to learn and navigate. The general view was that familiarity and predictability are essential in an emergency app, as they reduce hesitation and cognitive effort under stress and that this was successfully achieved in the prototype [CW].

However, participants also identified some usability challenges. In interacting with the map, some participants were unsure what specific elements meant. For example, the blue dot representing the current location was mistaken for another feature (“I presume the blue dot is Orange[the closest main town], is it?”)[INT], and the dotted lines for danger zones were interpreted as contour lines. This confusion was caused by the lack of a legend or scale[INT]. Some elderly participants described the app as “not immediately intuitive but easy to learn,” noting that they needed “a couple of goes to understand it” [INT]. In the cognitive walkthroughs, several users found that navigation sometimes required extra cognitive effort, especially when moving between the danger-rating pages and corresponding guides. Participants portraying rural or low-digital-literacy users[CW] were more likely to lose track of where they had come from or how to return to a previous section. One rural participant[CW] commented that the layout might be less suitable for some elderly users unless guided by someone familiar with the app.

Participants also shared several suggestions to make the interface more adaptive and easier to follow. One common idea was to automatically reorder the guide links based on the current fire danger rating—for example, showing “Take Action" first when the risk is extreme [CW]. Others proposed linking the fire danger rating indicators directly to their relevant guide sections so users could act more quickly in emergencies[CW]. A few participants asked for clearer visual aids, such as a vertical scroll bar or a floating navigation tab, to help them track their reading progress through long pages[INT]. There were also aesthetic and layout preferences: some users wanted icons arranged horizontally beside text (rather than vertically) and suggested slightly smaller icon sizes to minimise scrolling[INT]. Several participants expressed a preference for text over icons altogether, saying that “the less there is, the faster it can be conveyed” [CW].

A few participants also highlighted the need for more responsive feedback. For instance, one colour-blind participant[CW] mentioned that the app should provide feedback when a new colour scale is selected, confirming that the

choice was applied correctly. This type of responsive interaction was seen as critical for building trust and confidence, especially in safety-critical contexts.
Overall, participants found the app's user interface visually clean, consistent, and learnable, but their feedback points to further improvement. They identified that enhancing navigational aids, clarifying map elements, improving icon consistency, and adding more feedback mechanisms would strengthen the app's usability and inclusiveness, making it better suited to support users with diverse needs during high-stress emergency situations.

8.3.4. Adaptivity

Participants across both the interviews and CW recognised that the app's adaptive features added real value to the user experience. Overall, they found the adaptive options easy to set up and use, and many appreciated the system's ability to personalise how they received and interacted with information. The initial profiling process was described as straightforward and not burdensome. One elderly participant[INT] commented that "you can actually set it up so eventually you'll be able to become quite comfortable with it," reflecting a sense of gradual confidence-building through familiarity. Similarly, participants appreciated that the app gave them a sense of control over how information was displayed, with one rural participant[INT] noting that the page mode option could help avoid losing focus when reading longer content: "scrolling to me, you can get quite lost when there's a lot of information." The feedback from a rural persona participant[CW] also confirmed that the system's ability to function even with limited Internet connectivity was an important strength for emergency management contexts, as it allowed access to evacuation content offline. Participants with low digital literacy personas[CW] particularly appreciated the clarity of language and the concise instructions used throughout the adaptive menus, describing the tone as easy to follow and unintimidating.
Despite this positive feedback, participants also showed some confusion and inconsistency in how the adaptive features were presented. Some users admitted they skipped certain options, such as disabling visual cues, because they "didn't understand what it meant"[INT]. Others were unsure about the purpose of certain adaptive elements, such as page mode, as they felt that they were not directly relevant to them, which made those features feel unnecessary or even distracting[INT]. Participants[CW] representing colour-blind users noted that the colour customisation options were not intuitive and that it was difficult to find combinations that worked reliably. While some participants felt the buttons and interactive elements were appropriately sized ("large enough to be easily tapped without error"), others described the text, particularly on the home page, as too small[CW]. This tension between readability and interface compactness highlighted the challenge of balancing accessibility and usability across different user groups.
Participants also provided several thoughtful suggestions for improving the adaptivity design. The strongest theme was the need for clearer explanations and feedback. Users wanted the app to explain what each adaptive option meant, either during setup or through short in-context help prompts. Several participants[CW] emphasised the need for confirmation when changes were applied, for example, "Your colour scale has been updated", to make sure their choices had taken effect. Others[CW] asked for simpler terminology in menus, such as using "Push Notifications" instead of simple "Push" as this was confusing for those with lower digital literacy. There were also requests for more dynamic adaptivity, particularly in the context of evacuation information. For example, one rural participant[CW] asked, "What if the fire cuts off the main road during my evacuation?", pointing to the need for location-specific and real-time adaptivity to keep content relevant as situations evolve.
Overall, while some adaptive features were generally well-received, some features could complicate the user experience. This highlights the need for clearer explanations and more intuitive design choices to ensure the adaptive features enhance rather than hinder user interaction.

9. Discussion

Reflections on Requirements for Vulnerable Communities: The four vulnerable communities involved in this study (elderly, individuals with low digital literacy, rural residents, and colour-impaired) showed that while each group had distinct needs, most of the underlying design principles that supported their inclusivity frequently overlapped. For example, simplicity and reduced cognitive load were important for both the elderly and low-digital-literacy communities. However, subtle differences existed in how these requirements should be operationalised—the elderly valued gradual introduction of features and larger visual elements, whereas users with low digital literacy benefitted more from contextual prompts and consistent feedback. Similarly, while colour-impaired communities valued high contrast ratios and customisable colour scales, interestingly, several of these requirements also benefited elderly users, whose visual acuity may be reduced with age. These examples show that designing for vulnerability can indeed enhance usability for all.

Adaptivity in critical systems: Across all groups, participants valued the ability to adapt and personalise the system to suit their individual needs. They particularly appreciated having control over visual and interactional aspects such as colour, font, and navigation modes. However, the participatory evaluation also revealed that adaptive features must be clearly explained and easy to modify. When users were unsure of what a feature did, they either avoided using it or applied it incorrectly—both of which could lead to hesitation or inaction during critical moments. These findings show that while adaptivity helps to achieve varying requirements of user groups, for critical systems, they should also give considerable attention to how understandable and controllable those mechanisms are to end users.

Prototyping for requirements modelling and validation: This study used prototyping to model and validate our identified requirements. Unlike conventional modelling approaches that rely on formal notations and abstract representations, prototyping helped us to prioritise visual/experiential engagement. We found that when interacting with vulnerable communities, this was most effective as it allowed translating abstract requirements into tangible, interactive representations. The visual and experiential nature of the prototype helped participants to better understand the intended functionality and design, which in turn allowed them to provide more effective feedback. For example, users with low digital literacy and older adults were able to comment on layout, readability, and navigation aspects more easily when they could interact with the prototype. Similarly, participants with colour-vision impairments could directly evaluate the effectiveness of colour scales and contrast ratios once visualised, which would not have been possible through text alone. Therefore, prototyping can be recommended as one of the best methods for participatory requirements modelling and validation.

Inclusivity of critical systems: Our study also shows that in critical systems, inclusivity should not be an afterthought added at later stages of system design. System developers need to understand that in these systems, inclusivity is not just about accessibility. Instead, it is also about making the systems reliable and resilient so that “no one is left behind" during safety-critical situations. Therefore, inclusivity must be introduced from the very beginning of the RE process and be continually refined via community-informed feedback. The process followed in this study, from eliciting design guidelines in the literature to specifying requirements, modelling them via a prototype, and validating them with communities, introduces a repeatable pathway for socially responsible RE.

9.1. Recommendations and A Call to Action

We propose some recommendations presented in Table 10 for system designers, requirements engineers, and policymakers. These recommendations aim to ensure a more human-centric and participatory RE process so that vulnerable communities are considered in the equation. They also help ensure that critical systems are accessible for all, especially during safety-critical situations.

Table 10: Recommendations for stakeholder groups to ensure more Human-centric RE

Stakeholder Group	Recommendations
Requirements Engineers	1. Treat human-centricity as a safety-critical property that can affect resilience and user trust 2. Maintain traceability between inclusive guidelines, requirements, and validation evidence 3. Combine qualitative participatory insights with formal requirements documentation (e.g., structured tables, prototypes)
System Designers & Developers	1. Integrate human-centricity checks at the requirements elicitation stage, not as part of later usability testing. 2. Prioritise adaptable and explainable interfaces over one-size-fits-all accessibility solutions. 3. Employ participatory validation cycles (e.g., short, persona-driven walkthroughs) when access to real users is limited.
Policymakers & Funding Bodies	1. Encourage frameworks and funding mechanisms that require human-centric RE in safety-critical domains. 2. Recognise human-centricity as resilience; policies should treat human-centricity not as an ethical add-on but as an operational dimension of resilience in critical systems.

We bring forward a call to action for critical systems. Critical systems exist to protect people, yet they often fail the very communities that need them most. As disasters intensify and technology becomes central to emergency response, human-centricity is no longer optional. It is a fundamental component of safety. This study has shown that participatory requirements engineering can bridge that gap, translating community needs into implementable design requirements that make systems truly life-saving. The way forward is clear and we have presented a summarised version of our recommendations and a plan for future critical system design in Figure 5.

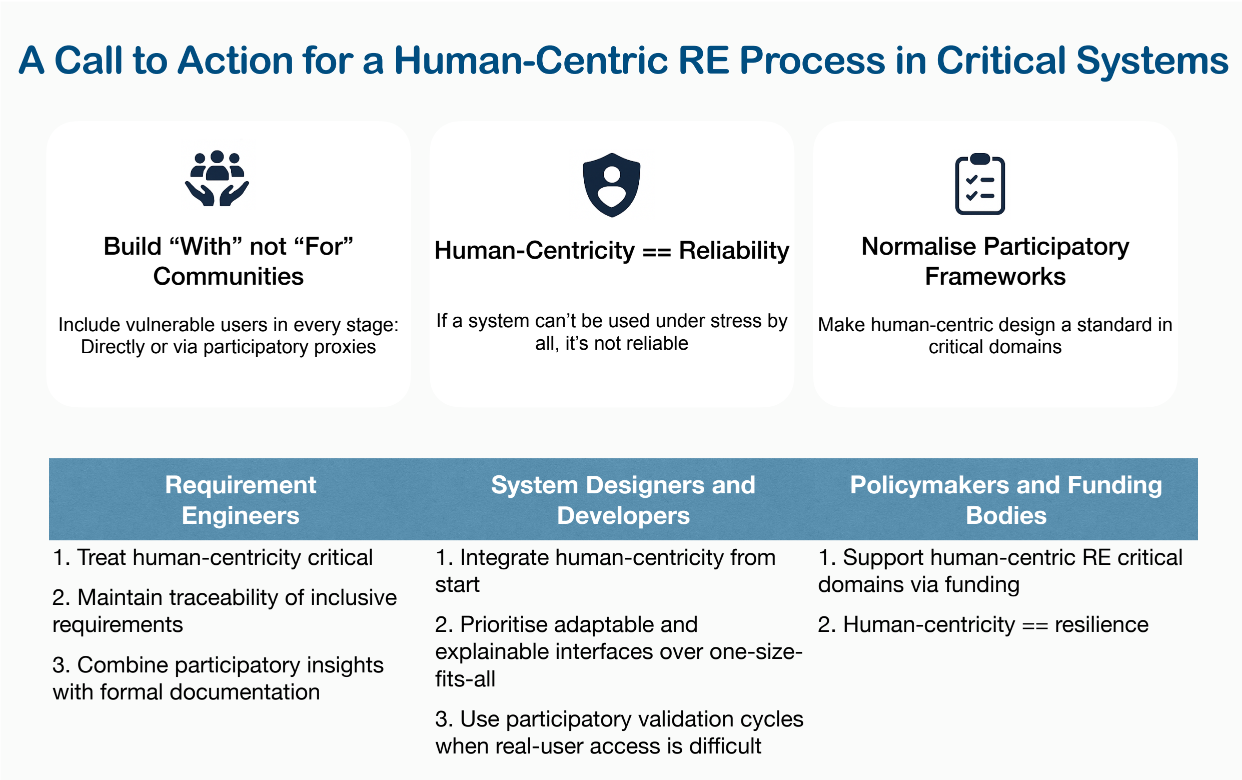


Figure 5: An Action Plan

10. Threats to Validity

Construct Validity: The guidelines analysed in this study were derived from prior participatory work, which ensured that the constructs were grounded in authentic user needs. However, since the guidelines were not systematically reviewed but selected based on relevance to the four target user groups, some bias in guideline inclusion may exist.
Internal Validity: While the adaptive prototype was directly informed by the elicited and specified requirements, participants' feedback may have been influenced by prior familiarity with similar apps or by the demonstration format. To minimise this, the interviews and cognitive walkthroughs used structured prompts. Another threat is the number of participants. We had only six participants for the interviews, and while we used cognitive walkthrough with eight participants to overcome this, a more thorough evaluation with real users would be beneficial.
External Validity: This study focused on four groups of vulnerable communities. Other forms of vulnerability, such as linguistic diversity, cognitive impairments, etc. were not represented and therefore future research can address this.

11. Conclusion

This study illustrated how a human-centred RE process can be applied within a critical domain to make systems more inclusive and socially responsible. Using disaster early warning systems as the case context, we showed how participatory and human-centric RE practices can uncover requirements that traditional approaches often overlook.

The findings highlight that human-centric requirements not only improve access for vulnerable groups but also enhance usability and resilience for all users, emphasising the argument that human-centricity should be a core quality attribute for critical systems.
Our findings demonstrate that when the requirements of vulnerable communities are considered early on, the resulting systems become more understandable and accessible to everyone. The participatory validation activities also revealed that users value adaptive interfaces and information formats that build on their diverse capabilities and contexts. However, the results also revealed that this adaptivity must always remain explainable and controllable, especially in high-stakes environments where misunderstanding or hesitation can have severe consequences.
We argue that human-centricity should no longer be treated as an ethical or peripheral concern in critical systems but as an operational dimension of safety and reliability. Future research should extend the human-centric RE process to other safety-critical domains such as healthcare, defence, and transportation. These should also explore additional participatory methods to involve vulnerable user groups throughout the RE lifecycle. Ultimately, human-centred RE offers a pathway towards systems that not only function correctly but also serve all members of society with equity.

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Appendix A: Guidelines Specific to a Single Vulnerable Community

Link to the detailed guidelines can be found here: https://github.com/anukmd/human_centric_RE_repo/blob/main/Unique_Guidelines.pdf

Appendix B: Guidelines Shared between Vulnerable Communities

Link to the detailed guidelines can be found here: https://github.com/anukmd/human_centric_RE_repo/blob/main/Shared_Guidelines.pdf

Appendix C: Requirements for Vulnerable Community

Link to the detailed guidelines can be found here: https://github.com/anukmd/human_centric_RE_repo/blob/main/Community_Requirements.pdf

Appendix D: Personas used in Cognitive Walkthrough

Link to the detailed guidelines can be found here: https://github.com/anukmd/human_centric_RE_repo/blob/main/Personas.pdf

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