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Safety Implications of Human Readiness Level (HRL) in Drone-assisted Emergency Response Operations

Riana Steen

Department of Business, Marketing and Law, University of South-Eastern, Norway. E-mail: riana.steen@usn.no

FabioA. A. Andrade

Department of Microsystems, University of South-Eastern Norway, Norway. E-mail: fabio.andrade@usn.no

Anthony Hovenburg

Department of Microsystems, University of South-Eastern Norway, Norway. E-mail: anthony.hovenburg@usn.no

Abstract
Unmanned aviation is a central tool in emergency management and protection of critical infrastructure. Fire and rescue services use drones to inspect structural damage, survey hazardous zones, and coordinate operations across multi organizational environments.
While these deployments enhance situational awareness, their safety and effectiveness depend on human readiness and emergency management processes.This paper applies the Human Readiness Level (HRL) framework to drone-assisted emergency response through qualitative document analysis. We reviewed regulations, operational procedures, and incident reports relevant to Norwegian UAS operations, selecting documents according to three HRL phases in our analytical framework. The analysis maps regulatory, procedural, and incident documentation to HRL phases to evaluate and guide improvements in human readiness among drone operators. Findings indicate a progression from formal competence and regulatory compliance (HRL 1–3), through standardized and training-integrated search procedures (HRL 4–6), to operational validation in complex, multi actor incidents where communication
airspace governance, and interorganizational role clarity are decisive (HRL 7–9). We conclude with recommendations to operationalize HRL metrics for interorganizational coordination, cognitive workload, airspace governance, and sustained mission capability.

***Keywords*:**Human Readiness Level (HRL), drone operation, emergency response.

1. Introduction

Emergency response operations take place in dynamic environments. In these constantly changing situations, responders must be ready to adjust to new hazards, work under time constraints, and navigate uncertainties to ensure they perform effectively(Eide et al., 2012; Sommer & Njå, 2012). Success in these operations relies not just on following established procedures but also on the flexibility of both the systems in place and the people involved to meet unforeseen challenges(Cantelmi et al., 2022). Academic literature in safety and reliability context emphasizes that being adaptable and coordinating well across various levels of a system is crucial for maintaining high performance in complex emergency scenarios (Bergström et al., 2016; Dekker et al., 2013).

In this context, unmanned aerial vehicles (UAVs), commonly known as drones, have proven to be valuable resources that enhance the capabilities of emergency response operations (EROs). Drones provide quick access to hazardous or hard-to-reach areas and are used in a variety of tasks, including search and rescue (SAR), logistics, and damage(de Alcantara Andrade et al., 2019). Supplying timely and accurate information, drones improve situational awareness (Eshtaiwi & Ahmed, 2024), help reduce search times during SAR missions(Rattanaamporn et al., 2025). This

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ultimately aids in making informeddecisions during rapidly changing situations (Nasar et al., 2023). For instance, in the 2020 landslide in Ask, Gjerdrum, Norway, drones conducted over 420 missions and provided 200 hours of airtime for SAR operations to locate survivors and assess damage(Steen, Roud, et al., 2024).

However, despite the benefits drones offer, there is still limited empirical understanding of how drone-assisted search and rescue (SAR) adapts to the human and operational challenges encountered in real-world(Wankmüller et al., 2021). Many existing studies tend to focus on the technical capabilities of drones, often overlooking how operators utilize these tools in practice, especially in high-pressure situations. This gap is particularly related to complex environments, such as mountainous and urban areas (McRae et al., 2019), where harsh weather conditions, inadequate infrastructure, and vast distances create additional hurdles for emergency response operations. To meet these challenges, the Police Drone Service in Norway has adopted specialized search techniques to improve detection and align with established SAR protocols (Lundgaard, 2023).

In drone-assisted missions, drone operators encounter cognitive and communicative challenges that set them apart from traditional responders (Steen, Håheim - Saers, et al., 2024) Their roles involve the synthesis of real-time data analysis, aerial technologies, and team collaboration. To fully grasp human readiness in this field, it is essential to adapt the Human Readiness Level (HRL) framework (Handley & Savage-Knepshield, 2020; Phillips, 2010)beyond its technological roots and apply it within the context of field-based emergency response. Therefore, this study seeks to investigate the following research question (RQ):

RQ: How can the HRL framework, as applied to regulatory, procedural, and incident documentation, be used to evaluate and guide improvements in human readiness among drone operators in emergency response?

In this study, HRL assessment refers to mapping documentary evidence to three broad readiness phases: foundational competence and regulatory structuring (HRL 1–3), demonstration and procedural stabilization (HRL 4–6), and operational validation in real emergency contexts (HRL 7–9). The assessment is based on regulations, operational procedures, and incident documentation relevant to Norwegian drone-supported emergency response.

In this work we apply the Human Readiness Level (HRL) framework to drone-assisted emergency response and report a document-based analysis of how HRL relates to safety in such missions. Using systematic content analysis of regulations, operational procedures, and incident reports, we map documented requirements and practices onto three HRL phases—foundational competence, demonstration/simulation, and operational validation. The paper therefore contributes: (1) an HRL aligned drone assisted preliminary mapping of Norwegian regulatory, procedural, and incident documentation to HRL bands, and (3) concrete recommendations and candidate metrics to operationalize HRL dimensions, including interorganizational coordination, cognitive workload, airspace governance, and sustained mission capability.

2. Theoretical background: Human readiness level

The Human Readiness Level (HRL) field has developed as an extension of Technology Readiness Levels (TRL), which have been used since the 1970s across various industries and government sectors, including the Department of Defense (DoD) and NASA. These methods assess technological advancement and readiness for integration into larger systems (Handley et al., 2024). The HRL concept originated in 2010 during a panel discussion at the 81st Annual Scientific Meeting of the Aerospace Medical Association in Phoenix, USA (Acosta, 2010). Phillips (2010) subsequently proposed a nine-level HRL scale in his master's thesis, aiming to complement TRLs by managing risks associated with defense acquisition, in particular regarding human operators and maintainers.

Interest in assessing human readiness has surged among practitioners and researchers, with the HRL concept gaining traction across various fields. Efforts to establish HRL standards began in 2019 with a collaborative working group from the DoD, industry, and academia. In 2021, the Human Factors & Ergonomics Society (HFES) and ANSI endorsed the ANSI/HFES 400-2021 standard (Steelman & Handley, 2022), which outlines nine HRL levels:

- HRL1–3: Basic research
- HRL4–6: Demonstration and simulation
- HRL7–9:Operational performance validation

Johnsen and Aminoff (2024) applied the ANSI/HFES 400-2021 standard to enhance safety in autonomous oil, gas, and maritime operations, addressing HRL challenges such as operator situational awareness and the integration of human factors in fast-evolving technology. In August 2025, the DoD officially adopted the HRL scale for assessing human readiness in defense-related activities, aligning HRL with TRL scales and incorporating human factors into system development.

Building on the HRL framework and ANSI/HFES standard, scholars have investigated their applications in academic and industrial settings. A notable approach is the Human Factors Readiness Level (HFRL), introduced by Hale et al.(2011), which extends TRLs to evaluate human integration throughout development processes. The HFRL provides a structured framework for assessing human factors from identifying capabilities (Level 1) to fully validated operations (Level 9). Garcia et al. (2017) further developed Human Readiness Assessment (HRA) methods to quantify readiness and define exit criteria for each level, addressing challenges in customizing assessments and designing effective questionnaires.

Further, Handley and Savage-Knepshield (2021) explored HRL utility using Human System Integration Assessments (HSIAs), highlighting issues such as aligning HRL and TRL levels and addressing unresolved questions during system development milestones. Recent efforts to formalize human factors integration indicate a shift toward recognizing human readiness as a key component of system maturity. The Human Capability Level (HCL) and Human Integration Readiness Level (HIRL), introduced by Miller et al.(2016), extend System Readiness Levels to encompass human performance, treating human capability as a measurable aspect of readiness. Subsequent research has redefined this metric through various perspectives: Boring (2022) examined it probabilistically via Human Reliability Analysis, while Moens (2021) highlighted organizational and ethical implications of neglecting early integration, using the Boeing 737 MAX case to advocate for broader stakeholder engagement in HRL assessments.

3. Methodology

3.1 *Research strategy and design*

We adopt an interpretive research strategy (Darby et al., 2019), because it is suited to exploring how human readiness is understood and enacted within socio technic contexts. In this study, we limit the empirical work to a document based i reviewed regulations, operational procedures, and incident reports to characterize how HRL dimensions are articulated and validated in documented practice.

3.2 *Data collection*

We conducted a qualitative content analysis of regulatory and practice oriente addressing unmanned aircraft systems (UAS) use in search and rescue (SAR). The purpose of the document analysis was to identify and synthesize documented requirements and recommendations relevant to human readiness (e.g., operator competence, organizational roles, procedures, coordination, and risk controls). Documents were selected for relevance to Norwegian drone operations and mapped to the three HRL phases used in our analytical framework.The document corpus comprised:

- Norwegian Civil Aviation Authority, Forskrift om luftfartøy som ikke har fører om bord mv. (FOR-2015-11-30-1404)
- European Commission, Commission Implementing Regulation (EU) 2019/947
- DJI Enterprise, operational case report on the Norway landslide response
- Losnegård, large-scale Norwegian drone rescue operation report
- Norwegian Police Drone Service, white paper about Drone Search Techniques in SAR Operations

Documents were selected based on relevance to UAS operations, SAR context, and authoritative status. The unit of analysis was a text segment expressing a requirement or recommendation. A hybrid deductive–inductive coding strategy was applied, using predefined HRL domains alongside emergent themes. The analysis followed a specific pedagogical logic to ensure traceability where, first, raw operational requirements, such as "minimum flight altitude,""thermal camera resolution," and "radio frequency protocols", were extracted from the text; second, these requirements were categorized into functional themes such as Pilot Certification, Sensor-Operator Coordination, and Airspace Governance. At the third stage, the HRL relevance of each theme was determined based on a threshold of complexity to align them with specific maturity levels. For example, segments referencing "RO3 certification" were coded as HRL 1–3 because they represent the foundational legal "entry point" for readiness, whereas "JTAC coordination" was coded as HRL 7–9 because it represents the validation of systemic resilience in a live environment. To classify documents into HRL phases, the following criteria were applied: HRL 1–3 was used for documents prescribing formal competence or role definitions to establish a legal baseline; HRL 4–6 was used for documents describing procedural development and practical testing to signify risk mitigation through task-based stabilization; and HRL 7–9 was used for documents reporting actual performance in live, multi-agency operations to provide operational validation of the entire socio-technical ecosystem.

4. Findings

Using the coding categories and HRL phases described in Section 3, a document analysis was conducted of regulatory frameworks, operational doctrine, and documented emergency response operations relevant to Norwegian drone-supported SAR. The material was analytically mapped against the three Human Readiness Level (HRL) phases to identify how human readiness is articulated and validated across regulatory, procedural, and operational domains.

Table 1 presents illustrative examples of documented content that informed the HRL mapping. The excerpts are representative rather than exhaustive and are used to anchor the analytical interpretation presented below.

Table 1. Examples of documented content

Paraphrased Summary	HRL relevance
Regulation defines pilot responsibility, operational categories (RO1–RO3), and authorization requirements for higher-risk operations (Luftfartstilsynet, 2015).	HRL 1–3: Formal competence and regulatory structuring
EU framework introduces risk-based operational categories (open, specific, certified) and competency verification for complex operations (European Commission, 2019).	HRL 1–3: Institutionalized risk-based readiness
Police Drone Service documents structured development and testing of standardized SAR search techniques prior to national implementation (Nilsen, 2024).	HRL 4–6: Demonstration and procedural stabilization
Gjerdrum landslide response involved 420+ drone missions, multi-agency coordination, airspace restriction measures, and sustained deployment (Losnegård, 2021; DJI Enterprise, 2021).	HRL 7–9: Operational validation in complex environme-nts

For HRLs 1–3, representing foundational competence and structured training requirements, the analysis centered on the Norwegian national UAS regulation (FOR-2015-11-30-1404) and its subsequent alignment with the European regulatory framework under Regulation (EU) 2019/947. The Norwegian regulation establishes the legal and operational architecture for unmanned aircraft operations, including definitional clarity (e.g., VLOS, EVLOS, BLOS), explicit pilot-in-command responsibility, and tiered operational categorization (RO1–RO3). This categorization differentiates operational complexity and oversight intensity, requiring higher-risk operations (RO2/RO3) to obtain prior authorization and submit documented operational procedures. In doing so, the framework formalizes competence not merely as individual technical skill, but as documented organizational capability encompassing role allocation, procedural control, and risk management.

For HRLs 4–6 (demonstration and procedural stabilization), the analysis centered on the Norwegian Police Drone Service white paper on SAR search techniques (Nilsen, 2024). The document explains that the search techniques were developed after the 2019–2020 trial period showed that drones were frequently used in SAR operations but had a relatively low success rate in locating missing subjects. It further describes how the Norwegian Police Unmanned Air Support Unit (NPUAS) systematized drone search practice by defining search techniques intended to increase probability of detection and align drone use with the established bike wheel model for SAR operations. The white paper also specifies operational parameters such as gimbal angle, flight altitude, flight speed, and standardized search patterns, and states that these techniques were integrated into the educational program before nationwide expansion.

The white paper itself also notes that the observed increase in successful locations is anecdotal and that comprehensive probability-of-detection evaluation is still lacking, which supports placing this evidence below HRL 7–9.

For HRLs 7-9 (Validation and Real-life operations), evidence ofreadiness is most explicit in the documentation of the Gjerdrum/Ask landslide response, which describes sustained multi-agency, multi-aircraft operations with explicit airspace controls, communication arrangements, and operational data products used in command and field decisions. UAS Norway reports that “sufficient separation was established in distance, height and direct communication on the emergency radio” enabling “both aircrafts” (helicopters and drones) “to operate simultaneously”. The same source describes scale and duration as “over 420 drone missions and 200 hours of airtime collaborating with helicopters”, and documents extended team engagement (“Together they operated for more than 110 hours in the air above the site”) (Losnegård, 2021). Airspace governance is described through explicit measures: “The police established a no-fly zone” (with stated exemptions) and “JTAC… controlled all air traffic in the area” (Losnegård, 2021), indicating operational integration beyond single-team drone use.

Operational capability is also evidenced through sensor-enabled work patterns: drones with “20–80x zoom capability” and “thermal sensors” were used, and flights were “from ground level up to 120 yard above ground” (Losnegård, 2021). DJI’s operational narrative corroborates command-and-control use of outputs, stating that operators “start[ed] mapping out the area, enabling the command center to coordinate the search from a safe distance” and that “drones [were] continuously in the air for the next 40 days” (DJI Enterprise, 2021). DJI further documents night and mapping constraints: the first deployment was “only possible after nightfall,” and thermal payloads were used “to create a high-resolution map in the dark” (DJI Enterprise, 2021). The same account reports rapid data turnaround (“one hour for the infrared images to be processed into a finished 3D map”) and dissemination (“made accessible to all emergency services involved”) (DJI Enterprise, 2021). Finally, the Norwegian government’s recent policy document frames this as institutionalized practice: drones “provide critical support in search and rescue operations” and “coordination guidelines for air resources, including drones, have been developed” to integrate with “helicopters and manned aircraft” (Ministry of Transport, 2025).

5.Discussion

This study advances the application of Human Readiness Levels (HRL) from its original technology-development context into the domain of drone-assisted emergency response. While HRL emerged as a complement to Technology Readiness Levels (TRL) to mitigate human integration risks in defense systems (Phillips, 2010; Handley & Savage-Knepshield, 2020), its operationalization in dynamic, field-based emergency contexts remain underdeveloped. Our findings suggest that HRL offers a useful structuring lens, but its interpretation must be expanded beyond system acquisition logic toward socio-technical performance in high-reliability environments.

In this study, that application was operationalized by interpreting regulations as evidence of foundational readiness (HRL 1–3), procedural doctrine as evidence of demonstration and stabilization (HRL 4–6), and incident documentation as evidence of operational validation (HRL 7–9).

5.1.*HRL as socio-technical maturity rather than individual competence*

At the foundational level (HRL 1–3), regulatory documents primarily institutionalize competence through formal training requirements, certification pathways, and defined pilot responsibilities. In HRL terminology, this corresponds to “basic research” and documented capability definitions (Steelman & Handley, 2022). However, in emergency response settings, readiness cannot be reduced to compliance with codified procedures. As high-reliability theory suggests, safety in complex operations emerges from adaptive coordination and distributed cognition across actors (Dekker et al., 2013; Bergström et al., 2016). Thus, regulatory compliance represents necessary but insufficient readiness.

The transition to EASA’s risk-based framework further reflects this logic: human readiness becomes embedded within structured authorization processes and proportional oversight. Yet, HRL theory emphasizes that validated readiness requires demonstration in operationally relevant contexts (ANSI/HFES 400-2021). Our findings indicate that while formal qualification structures anchor HRL 1–3, they do not inherently address workload management, interagency communication, or decision-making under uncertainty.

5.2.*Bridging HRL 4–6: from demonstration to operational learning*

The Norwegian Police Drone Service’s systematic development of standardized search techniques illustrates HRL 4–6 progression. According to HRL theory, these levels correspond to demonstration, simulation, and structured validation of human-system interaction (Handley et al., 2024). The refinement of search grids, sensor alignment, and detection probability models demonstrates procedural stabilization and learning. Importantly, the documentation of cognitive load challenges aligns with Human Reliability Analysis perspectives (Boring, 2022), suggesting that readiness must incorporate workload thresholds and human performance variability.

Here, HRL intersects with resilience theory. Rather than static compliance, readiness becomes the capacity to adapt within operational boundaries (Cantelmi et al., 2022). The documented pilot phases indicate iterative learning cycles characteristic of resilient systems, where procedures evolve through experience rather than remaining fixed.

5.3.*HRL 7–9: Validation in Complex, Multi-Actor Environments*

The Gjerdrum landslide response provides empirical grounding for HRL 7–9, where readiness is demonstrated under real-world constraints. In HRL theory, these levels require operational performance validation within the intended environment (Steelman & Handley, 2022). The scale of drone deployment, integration with helicopters, establishment of airspace restrictions, and sustained multi-agency coordination represent systemic validation rather than isolated task competence.

This aligns with Human System Integration (HSI) perspectives, where readiness reflects not only operator skill but system-wide alignment between technology, procedures, communication structures, and command frameworks (Savage-Knepshield et al., 2021). The findings reveal that advanced readiness is contingent upon interorganizational communication routines and explicit airspace governance mechanisms. These elements resonate with high-reliability organizational principles emphasizing redundancy, clear role allocation, and sensitivity to operations (Steen et al., 2024).

Notably, HRL theory traditionally emphasizes milestone-based validation. However, emergency responses introduce continuous adaptation, emergent coordination, and dynamic hazard evolution. Thus, HRL in this context must be interpreted as operational readiness-in-use rather than readiness-at-acquisition. This shifts the HRL discourse toward performance under uncertainty, bridging HRL with crisis management literature (Sommer & Njå, 2012).

Although the empirical material concerns UAS in SAR operations, the analytical logic is transferable to other socio-technical emergency response systems in which readiness depends on formal competence, procedural demonstration, and operational validation in multi-actor environments. This includes, for example, ground robotics, situational awareness systems, wearables and other digital response technologies that require coordination, governance, and human-system integration under time pressure.

6. Conclusion and final remarks

This study examined how regulatory frameworks, operational doctrine, and documented incident experience align with the three phases of the Human Readiness Level (HRL) framework in drone-assisted emergency response. The findings indicate a progression from formal competence and regulatory compliance (HRL 1–3), through procedural standardization and structured validation (HRL 4–6), to operational performance in complex, multi-actor environments (HRL 7–9).

While regulations establish baseline qualifications and operational limits, effective drone-supported emergency response depends on standardized search procedures, workload management, shared situational awareness, and coordinated airspace governance during large-scale incidents. Advanced readiness reflects system-wide alignment rather than individual pilot skill alone. Based on the analysis, the following recommendations are proposed:

- **Integrate interorganizational coordination** capacity as an explicit dimension in HRL assessments.
- **Embed cognitive workload** and decision-support considerations within readiness evaluation.
- **Include airspace governance** and communication protocols as measurable readiness indicators at higher HRL levels.
- **Assess operational endurance** and sustained mission capability as part of HRL 7–9 validation.

This study highlights structural patterns of readiness but does not yet capture how these elements are enacted in real-time operational practice. The findings therefore need to be contextualized through empirical investigation of lived experience. Future research should examine how drone operators interpret regulatory constraints, manage workload, coordinate across organizational boundaries, and adapt under uncertainty. Such contextualized inquiry is necessary to refine HRL as an applied safety framework capable of addressing the dynamic realities of drone-supported emergency response.

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