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Future rescue management: Design specifications for a 5G-enabled emergency response information system

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Abstract. Today, access to real-time information from emergency scenes is still limited for emergency medical services, fire departments, and their professionals, also called first responders. Emergency Response Information Systems (ERISs) have recently been discussed in the literature as a potential solution to this problem. Using the Design Science Research (DSR) paradigm, we present a novel 5G-enabled ERIS (5G-ERIS) design that leverages 5G mobile network technologies to offer diverse real-time information. We provide a user-centered examination of design specifications for a 5G-ERIS based on a smart city digital twin. Based on literature and qualitative expert interviews with several first responders in Germany, we derive how emergency medical services and fire departments can improve their decision-making with this 5G-ERIS. Based on existing 5G application architectures, we structure our identified design specifications into four system layers. Our findings provide an essential knowledge base for the successful development, deployment, and long-term use of 5G-ERISs. We stimulate a broader discussion on the design objectives and specifications of 5G-ERISs in theory and practice.

Keywords: 5G, design science research, ERIS, emergency, digital twin

1. Introduction

5th generation mobile network technologies – 5G for short – are attracting attention in research and public policy [1]. Jiang et al. [2, p. 5] envisioned 5G as an "all-dimensional, user-centered information ecosystem". Innovations in the technical infrastructure make this possible. The cornerstones of the 5G infrastructure are high data rates, i.e., enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC) enabling Internet of Things (IoT) communication, and ultra-Reliable and Low Latency Communications (uRLLC) [2]. In addition, 5G networks shall be capable of Highly Precise Localization Everywhere (HPLE) [3,4].

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First responders, such as firefighters and paramedics, are user groups expected to benefit strongly from these innovations. For example, green rescue lanes and indoor localization [5], as well as Unmanned Aerial Vehicle (UAV) support for search and rescue [6], are expected to improve first responder operations triggered by emergency calls.

These user groups are receiving increased attention in the development of 5G-enabled applications as they must make, at worst, life-or-death decisions quickly. First responders have to make decisions under physical stress on top of common stressors, such as information overload, time pressure, complexity, and uncertainty [7]. Therefore, tools are needed to improve the decision quality of first responders through reliable real-time information. 5G promises reliable and high data transfer rates in near real-time. With 5G, information can be processed and distributed among more stakeholders and over longer distances in less time. This infrastructure layer enables improved decision-making during decision tasks characterized by high stress levels.

Any unanticipated deployment of first responders requires decisions to be made under uncertainty, e.g., how many people to deploy, the fastest route to the emergency scene, and an initial set of actions to gain control of the situation upon arrival (mission planning). First responders rely on maps for many of these daily decision-making tasks and communication actions during their operations. A significant amount of research is devoted to improving Geographic Information Systems (GISs) for emergency purposes, especially in disaster scenarios, e.g., rapid evacuation planning [8], better crisis and wildfire management [9,10], and UAV-assisted 2D mapping systems [11].

However, even today, innovative technologies and applications for first responders are rarely integrated into daily operations, which would reduce risks posed to their lives or the lives of victims [11]. Weidinger et al. [12, p. 14] emphasized the need for dynamic GIS applications: "Firefighters still have limited access to real-time information about the emergency scene such as the locations of responding units, the status of available resources, or environmental conditions at the incident scene. Increasing the situational awareness hence continues to be an important goal to make emergency responses more effective." The authors proposed Emergency Response Information Systems (ERISs) to fill this gap as a "versatile, generic platform that facilitates the collection, analysis, and communication of mission-critical information in order to support the dynamic management of resources on-site" [12, p. 14].

Therefore, we identify a lack of innovative GISs that provide first responders with real-time information to support their decision-making. To address this identified problem, we investigated how novel 5G cornerstones and corresponding applications can be leveraged in a 5G-enabled ERIS (5G-ERIS) to add value to and promote the adaptation of ERISs.

In addition to this practical issue, the user perspective and feedback from first responders are not adequately considered in the literature when studying GISs and ERISs [5]. Khanal et al. [13, p. 16] state that "a significant amount of the research papers related to the development of unique simulations lacked adequate testing and validation." Examples of user integration include Volk et al. [14], who study which 5G features and use cases are most desired by first responders but only evaluated two test scenarios with non-functional Key Performance Indicators (KPIs). Weidinger et al. [12] develop a general acceptance model of ERISs without a 5G focus and without defining the GIS solution but explaining the intended use in relation to different possible functions of such an application. Reflecting on this literature gap, Elmasllari [15, p. 1302] points to a discrepancy in ERISs between what users need and what information systems implement due to missing or wrong requirements and that "emergency-related IT systems must be designed with constant and broad participation of users."

We address these shortcomings by utilizing Design Science Research (DSR) proposed by Peffers et al. [16], extended by ex-ante evaluation [17] to integrate user feedback loops. We apply a set of qualitative data analysis methods used in Grounded Theory to the interview data to acquire a rich description of the 5G-ERIS [18,19]. Thus, we focus on the Justified Design Objectives (JDOs) of a 5G-ERIS and its

Validated Design Specifications (VDSs), which we derive from literature and interviews with ten first responders from Germany. We address the lack of first responder feedback as well as the lack of advanced GISs by answering the following research question (RQ):

"How must a 5G-ERIS be designed to support the decision-making of first responders successfully?"

By applying DSR, we can develop a meaningful, problem-solving artifact, i.e., a 5G-ERIS that supports real-world decision-making tasks in mission execution and preparation for first responders [16,20]. This paper provides a knowledge base for an advanced technological solution that enables emergency and rescue professionals to improve the quality of their decisions.

The rest of the paper is structured as follows: Section 2 introduces relevant fundamentals for the envisioned 5G-ERIS. In Section 3, the research design and methodology are described. Section 4 presents the JDOs, followed by the VDSs in Section 5, leading to the discussion and implications in Section 6. We end with limitations, a further research agenda, and the conclusions given in Section 7.

2. Digital twins of cities for decision support

In Section 1, it was elaborated that ERISs are "versatile, generic platforms" supporting emergency responses. Thus, the expected features and user groups of ERISs vary. We differentiate our envisioned 5G-ERIS based on the expected functions, type of visualization, geographic scope, and user group.

Weidinger et al. [12] categorize ERISs in the dimensions of data provision and the degree of decision support. Rudimentary ERISs provide a platform to communicate and present manually updated information during the emergency response. More mature ERISs provide real-time data from sensor networks that are automatically fed into the system and displayed to first responders. Most mature ERISs additionally offer decision-making support based on the received real-time information.

As we investigate a 5G-ERIS, various real-time data sources are envisioned to be integrated into the GIS tool; hence, it will fall into the category of most mature ERISs. Real-time data shall complement static data about the built environment and elevation data. The different data sources will enable landscape visualization, communication, and decision-making support, such as wayfinding.

In the context of the most mature ERISs, Ford et al. [21] study the applicability of smart city and digital twin technologies for disaster management and propose the fusion of these technologies into a Smart City Digital Twin (SCDT). They define smart cities as communities that use Information and Communication Technology (ICT) to autonomously sense, store, and make available up-to-date information about community conditions to community leaders and citizens. Further, digital twins are defined as community images (e.g., visual maps) and simulations of infrastructure that can be used to represent current and projected future conditions to improve decision-making. Thus, an SCDT is defined as a system of ICT sensors that generate data sets that are integrated into digital twin models that provide a dynamic capability to assess the future impacts of current conditions and strategies in ways that improve decision-making to achieve desired outcomes.

Ford et al. [21] explore SCDTs for disaster management to improve evacuations and resource allocation for rebuilding. In their literature review, they identify other SCDT systems that model a specific category of infrastructure, e.g., transportation systems, water utilities, or building and facility management systems. They criticized that no current SCDT incorporates the interdependencies of different infrastructures, although the need to do so has been identified [21]. Further visual examples can be found in [22], where flood simulations, noise levels, or tourist information are displayed in 2D and 3D. In the context of disasters, it has been found that SCDTs can provide executives with decision-making support in several aspects, e.g., providing all the data needed for effective and efficient strategies during the disaster, capturing the current state of the environment, predicting the impact of decisions, and providing an ex-ante simulation platform to test the best-performing strategies in the mitigation and preparation phases of disasters [21]. However, in these studies, the SCDT provides a high-level overview that supports the decision-making tasks of senior disaster managers rather than first responders in the field. An SCDT that provides decision-making support for ground forces is studied in [23]. The authors conduct a first pilot study towards a GIS meant to improve the communication between police and ambulances and explore how to bridge the dependencies between organizations. Their pilot focuses on road congestion levels, navigation, and arrival times. In order to evaluate which expected benefits can be realized during varying daily operations and how first responders in the field can utilize a 5G-ERIS based on an SCDT, more holistic application studies are needed, for which we lay the groundwork in this article. We combine the SCDT with other 5G-enabled technologies to implement a 5G-ERIS that solves real-world problems faced by first responders.

Cities are ideal candidates for creating an SCDT and piloting the envisioned 5G-ERIS artifact, as 5G deployments primarily occur in large urban agglomerations first [24]. Moreover, 5G localization can improve real-time positioning information in urban canyons [25], and the large number of agents in cities makes real-time monitoring and visualization imperative compared to rural areas [26]. Based on this study area, we selected first responders from the firefighting and emergency medical services branches as the most relevant user groups to evaluate the 5G-ERIS. These branches are under municipal responsibility in Germany, allowing us to address personnel operating in cities that are expected to benefit from 5G coverage. Firefighters and paramedics routinely have to work with different organizations, including volunteer forces. This increases the importance of information sharing and a common operational picture aggregated by the 5G-ERIS [27].

3. Research design and methodology

3.1. Design science research paradigm

We highlighted that first responders have limited access to advanced technologies and that the literature does not sufficiently consider the user perspective on decision-making support. DSR in information systems allows the creation of solutions to concrete problems [28]. To declare the solution valid and provide a rationale for the design decision, truth in prescriptive knowledge must be relied upon [17]. Sonnenberg et al. [17] propose DSR with an accompanying evaluation to assign a truth-like value to prescriptive knowledge. This type of evaluation in DSR leads to specific and targeted artifact formation [17] and can mitigate the risk of incorrect or unworkable solutions [29]. These benefits are achieved through ex-ante evaluation in DSR before the artifact is constructed and ex-post evaluation after the artifact is constructed. Activities in DSR include Problem Identification, Artifact Design, Artifact Construction, and Artifact Use. Evaluations are conducted between the activities. We relate our research to ex-ante evaluation, i.e., the first two activities, with the goal of building an artifact [17].

For this purpose, we identify and explain the problem in Section 1 and provide the reader with relevant background in Section 2. Then, in Section 4, we present a scientific literature search to find existing research on these problems and present the results of Evaluation 1, the evaluation of the problem statement to ensure a meaningful DSR problem [17]. The research must be relevant and novel to practice and contribute to the existing knowledge base in the scientific literature. This evaluation justifies the value of a solution and the envisioned artifact [17]. At the end of these first two steps, we obtain JDOs that describe the problems that the solution aims to solve.

In the third step, Artifact Design [17], a first version of the design specifications was prepared based on the literature related to the JDOs. To "provide a rich description of a phenomenon based on a systematic exploration of the accounts of the phenomenon" [30, p. 2], we adapt the architecture overview of 5G for IoT by Chettri et al. [31] and use it as an up-front theory for the SCDT [18].

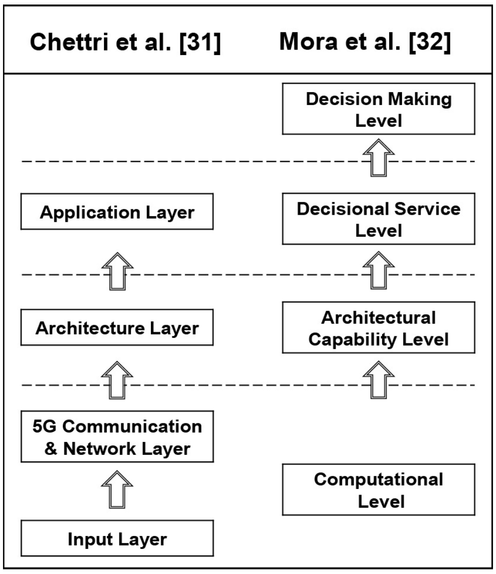

Fig. 1. Architectural layers within our ERIS concept based on Chettri et al. [31] compared to Mora et al. [32].

At the top, Chettri et al. [31] describe an Application Layer where users interact with the system and use its services. It is followed by an Architecture Layer consisting of cloud storage and intelligence to provide data transformation, filtering, and analysis. The Architecture Layer is connected to a Communication Layer and a Network Layer. Chettri et al. [31] distinguish between a 5G Communication Layer and a LowRange (LoRa) or Sigfox network as a bridge to the input hardware. We assume that sensors and other inputs will be directly integrated within the 5G network, hence defining a combined 5G Communication and Network Layer. The Input Layer integrates and interacts with the environment, e.g., through IoT sensors such as wearable devices or smoke sensors, to consistently update the digital twin.

The architecture was chosen as it can be aligned with the Intelligent Decision Technologies System Design and Evaluation Framework described by Mora et al. [32]. This ensures that the design specifications for the architecture are relevant to improved decision-making. In this framework, the highest of four layers, the Decision-Making Level, is supported by a Decisional Service Level that provides algorithmic, analysis, synthesis, and hybrid services. This level builds on the Architectural Capability Level, including the user interface. On the lowest level, the Computational Level, non-intelligent computational mechanisms are placed. Figure 1 shows a comparison of the two architectures.

Evaluation 2, the evaluation of the design specifications for completeness and correctness, leads to the problem's solution, which is documented by the VDSs. Principles for implementation are formulated, the solution design is evaluated, and the design is assessed for understandability and usefulness to stakeholders [17]. VDSs define a description of what an artifact should provide to support problems for solutions that have not yet been addressed. They guide the development of the DSR artifact and assist in its validation [19].

3.2. Literature search for the problem identification

First, in the Problem Identification step, we identified the 5G innovations with the greatest potential to improve emergency response operations. We searched the Scopus and IEEE Xplore databases for 5G applications in the emergency context. We chose these two since the first provides a holistic overview of the literature, and the second has a suitable technical focus. We used the following search string: " '5G' AND 'application' AND ('emergency' OR ('rescue' AND 'forces')) " in title, abstract, or keywords and included all publications published since 2020. We added relevant review articles identified in Google Scholar, i.e., [5,14]. Literature was considered relevant if it envisioned or tested a use case or application that focuses on an emergency and is enhanced by 5G infrastructure. An emergency was defined as a situation in which the health of one or more individuals is at imminent risk or property is endangered by fire, flood, or storm damage. Publications were included if they were peer-reviewed, e.g., journal articles or conference proceedings. Articles that utilized 5G but did not fit the context of SCDTs, e.g., robot-assisted surgery, were excluded from our literature search.

3.3. Interview approaches for evaluation steps

We conducted our initial evaluation with three unstructured expert interviews (I-F-1, I-F-2, and I-F-3) in Evaluation 1. Unstructured interviews provide an initial expert knowledge base [33]. From the analysis of the unstructured interview in Evaluation 1, we derived the interview guide and the JDOs for our artifact, ensuring relevance to practice and novelty to literature.

For the second evaluation in Evaluation 2, we followed the approach of Semi-Structured Interviews (SSIs) according to Adams [33] and Kallio et al. [34], as well as the content analytical coding techniques of Grounded Theory [18,19]. We conducted eight expert interviews after a pretest to develop the VDSs.

The SSI has a balanced mix of structure and openness, allowing experts to consider experiences, opinions, and perspectives [33,34]. The increased flexibility of SSIs, as opposed to structured interviews, allows for broader responses to predefined questions and the ability to respond to those responses. In addition, the order of questions can be changed as needed. SSIs allow for deeper insights through open-ended questions by detailing respondents' thoughts and perspectives. Better comprehensibility, contextuality, and comparability of SSIs are based on interaction with respondents so that patterns and commonalities across respondents can also be identified. SSIs are particularly participant-oriented due to the consideration of their point of view. Open-ended questions and increased flexibility allow SSIs to adapt to the expert in an interview. In addition, SSIs enable discussion. However, SSIs require a high level of experience, expertise in formulating the interview guide, and the identification of focus groups [33]. To address these prerequisites, one author of this paper is an expert in 5G, and one is an expert in first responders (i.e., a firefighter). All authors have already gained various experiences through semi-structured and structured interviews. Drawing on and using prior knowledge also provides a basic understanding, helps identifying research gaps and focus areas, and with the targeted formulation of questions [34].

The interview guide is based on the quantitative literature search of scientific publications, the first evaluation, and a study published by the authors. A preliminary sequence was constructed according to the guidelines of Adams [33] and the framework for the development of an SSI guide according to Kallio et al. [34]. The interview guide consists of four parts, includes questions about the interviewee's expectations, technical and functional requirements, and explores the barriers introduced by the status quo that impede the implementation and use of 5G-enabled capabilities within an advanced 5G-ERIS. It can be found in the online appendix here.

The interview is started with pleasantries and pleasant questions about the person. Next, the interviewees are given a more detailed explanation of the research and the purpose of the interview. This is followed by relevant and non-threatening questions related to the experts' motivation and understanding of their needs arising from their daily tasks as first responders. Considering the previous questions, questions were asked about which functions are most valuable to first responders. Also included in these questions are the data requirements, interfaces, and key stakeholders. At the end of each interview, there are forward-looking questions and opportunities for discussion. The interview guide was tested internally by the authors, who interviewed themselves as experts. This leads to an ethical and responsible way of researching sensitive topics, eliminating bias, and verifying understanding of the questions [34]. After the interview guide was

Table 1
Overview of experts

Expert	Function	Evaluation step
I-F-1	Captain of a fire department	Eval 1, Eval 2
I-F-2	Captain of a fire department	Eval1
I-F-3	Fire Chief of a fire department	Eval1
I-M-4	Head of a medical station at a factory site	Eval 2
I-E-5	Head of emergency and security services at a factory site	Eval 2
I-F-6	Fire Protection Officer at a factory site	Eval 2
I-M-7	Head of special emergency medical services In-House Senior Advisor for ICT	Eval 2
I-M-8	Medical Chief of municipal emergency medical services and disaster management	Eval 2
I-F-9	Fire Chief of a volunteer fire department	Eval 2
I-F-10	Assistant Fire Chief of a volunteer fire department Station Manager of a professional fire department	Eval 2

edited and reviewed several times, a pretest was conducted with I-F-1. We had previously interviewed I-F-1 in an unstructured manner for Evaluation 1. The pretest is necessary to adjust the interview guide, revise it, rearrange questions, or add questions [33]. Pretesting adds validity, legitimacy, and focus to the interviews and the results [33]. Pretesting also promotes the appropriateness and completeness of the content of the interview guide. Thus, the relevance of the questions can also be discussed, and new wordings can be made [34]. After the successful revision, I-F-1 was interviewed a third time, so the third interview with I-F-1 is counted in our analysis for Evaluation 2.

Data collection through interviews for Evaluation 1 and Evaluation 2 occurred between June 2022 and December 2022. Acquisition of new data was conducted until saturation was reached. Theoretical saturation is reached when the collection of additional data is unlikely to provide new insights into the study of a new phenomenon [18]. We reached theoretical saturation after conducting four (follow-up) focus group interviews and four (follow-up) face-to-face interviews. We interviewed ten experts within the stakeholder groups mentioned above. Experts were informed that they would be kept anonymous to avoid biased responses [35]. Expert abbreviations are made up of the experts' titles. For example, I-F-1 represents the first interviewee, who is a firefighter. I-M-4 is the fourth interviewee and works in emergency medical services. I-E-5 is in charge of the general emergency management of company premises. Table 1 summarizes the main information about the interviewed experts.

The interviews lasted approximately 60 to 120 minutes and were all conducted by the authors. All interviews were conducted in German and transcribed afterward. The interviews were edited or summarized at the request of the interviewees or their organizations so that no sensitive information, such as names, locations, or concepts of the services, would be disclosed to third parties. Nevertheless, all interviews were videotaped and were available throughout the evaluation. This allowed us to ensure the validity of the experts' statements. All information has been treated confidentially.

3.4. *Interview data analysis*

Following Strauss et al. [18] and the description of Wiesche et al. [19], we use a set of Grounded Theory methods to evaluate and analyze the interviews as a means of creating a rich description [19]. This ensures the reproducibility of our qualitative research findings from the interviews. We use the data analysis procedure from open coding to constant comparison and conclude the use of Grounded Theory with memoing utilized to discuss our findings [19].

The analysis was conducted by initially labeling the data during open coding, followed by a detailed analysis of one category, i.e., selective coding. Theoretical coding was then applied, relating the substantive categories from selective coding to each other. Our execution of these steps was assisted by the software

Table 2
Methodological overview with references

Procedure	Ex-ante evaluation				References
DSR steps	1st Step: Identify problem	2nd Step: Evaluation 1	3rd Step: Design artifact	4th Step: Evaluation 2	[17]
Literature search	Obtain "knowledge of what is possible and feasible"		Relevant literature specifies the functional design of architectural layers		[16, p. 55]
Interview approach		Unstructured interviews: Acquire expert knowledge by interviewing three experts		Semi-structured interviews: pretesting by the authors and I-F-1 and conducting eight SSIs	[33,34]
Interview data analysis		Evaluation of transcripts		Evaluation of transcripts	[19]
DSR output	Observation of the problem, existing solutions to a problem; Fig. 2	Justified Design Objectives; Table 3	Design specification and stakeholder identification	Validated Design Specification; Tables 4, 5, 6, and 7	[17]

tool MAXQDA 2022 [36]. Memoing was performed on the structures generated from the coding activities to derive a rich description [19]. Furthermore, we constantly compared the labels generated from the coding of the data. As an example of the coding activities, expert I-F-9 stated,

"An empty venue is a completely different building from a firefighting perspective than a venue prepared for a show or exhibition."

This statement was labeled with the first-order code "Real-time data updates." Within this first-order code, second-order themes were identified, e.g., "status quo," "envisioned use cases," or "design specification." The statement from above was classified as "design specification." Identified dimensions, first-order codes, second-order themes, and corresponding anchor examples can be found in the online appendix.

Table 2 summarizes our research design, the relationships and embeddings between methods, and the outcomes at each step.

4. Justified design objectives of the solution

An SCDT is envisioned as the foundation of the 5G-ERIS. To define the objectives of the 5G-ERIS, i.e., its functions, we must obtain "knowledge of what is possible and feasible" [16, p. 55]. We gathered this knowledge by first studying peer-reviewed scientific literature on 5G innovations for first responder organizations, which three members of these forces then evaluated.

Through the literature search, 135 papers were found in the databases, of which 44 papers were full-text screened, and from this, 20 relevant papers were identified. These study 5G-enabled applications for first responders that can be integrated into the 5G-ERIS. Figure 2 shows three dominating research areas. A map feature is envisioned in different articles to display first responders, tracking their location and additional vital parameters, especially for firefighters [5,14,37,38]. A real-time map visualization might be further enriched by video streams from Unmanned Ground or Aerial Vehicles (UxV), improving surveillance, search and rescue, and mapping tasks [5,14,37,39]. These real-time information sources can help commanders manage operations by improving decision-making through relevant and reliable data [37, 39].

Objective monitoring data can also be provided by tracking vital parameters. This type of sensor data is being explored in the context of ambulance patients and continuous monitoring of citizens at risk of diseases. The majority of relevant articles apply 5G technology to monitor individuals, providing

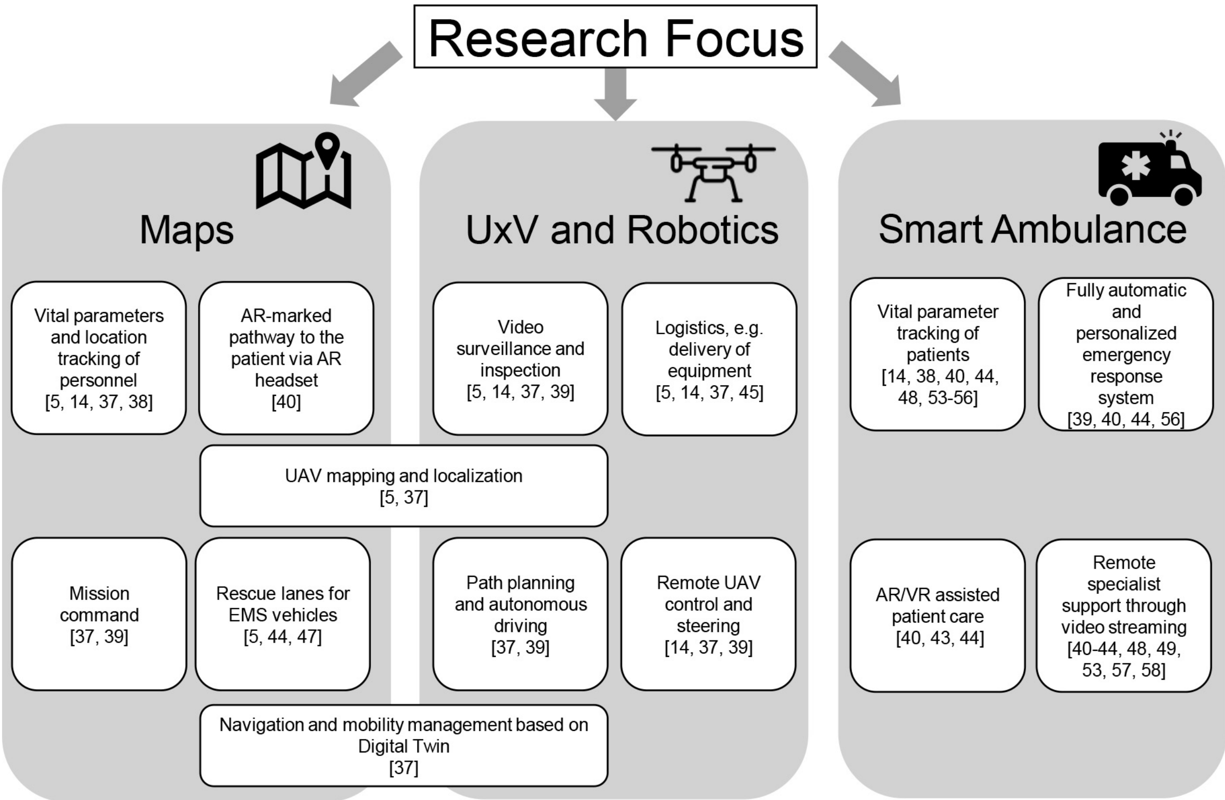

Fig. 2. Research areas identified in the literature search matching 5G and first responders in the context of SCDTs.

real-time data exchange with the responsible hospital, e.g., [40]. Additional studies investigate how paramedics on-site and in the ambulance can be supported by specialists, e.g., through high-quality live video streaming [41] or transmission of ultrasound images [42].

Using the local and global geospatial context, Augmented Reality (AR) applications are considered beneficial to assist first responders and are researched in [40,43]. Furthermore, maintaining a digital twin of the city is considered to enable navigation and mobility management [30]. It shall keep rescue lanes clear for ambulances, e.g., [44], and enable path planning, remote steering, and autonomous UxV trips [14, 39]. The digital twin infrastructure is thus expected to enable the delivery of materials like first aid kits in inaccessible areas or blood bags to ambulances via UxV [37,45].

The dominant research areas from Fig. 2 were discussed in a workshop with the experts I-F-1, I-F-2, and I-F-3. In this workshop, three JDOs were outlined. In the workshop, the experts stated that, based on the research areas in the literature, the 5G-ERIS must be a ‘management support system’ building on integrated sensor data. This digital solution should replace printed maps showing the route to a reported alarm with a predefined point of entry to the building. The 5G-ERIS should include the tracking of persons, especially first responders. Pressure in breathing tanks, vital parameters, and the status of equipment and vehicles were cited as crucial. If additional forces from other departments perform supporting tasks during the operation, they should also be able to log on to the platform. Furthermore, the experts emphasized that digital maps, in combination with localization, would allow the visualization of first responders on a map provided by the 5G-ERIS. To date, firefighters must rely on voice channels. Here, problems arise when parts of a building cannot be accurately described or are undefined, as well as when there is disorientation or loss of connection.

Table 3
Justified design objectives to be implemented in a 5G-ERIS

No	Justified design objective	Description	Workshop	References
1	Maps	Digital, dynamic maps provide monitoring of first responder's location and navigation to target based on SCDT.	x	[5,14,37,38]
2	Supplementary information	Monitoring of patient and first responders' vital parameters. Video streams for surveillance and early emergency detection.	x	[5,14,37,39]
3	Contextual features	Platform for training and emergency operations evaluation.	x	

In addition to the execution of operations, experts envisioned the 5G-ERIS to provide live video streams for early detection of fires or to monitor capacity limits and overcrowding in predisposed areas.

Finally, combining digital maps with first responder location information and video streams was stated as valuable for discussing training sessions and emergency operations in the aftermath to learn from the experiences that were made. Combining camera and location data to create an action-oriented learning platform was seen as very beneficial, a feature we did not find in the identified literature. The findings are summarized in Table 3.

The three JDOs formed the basis for the development of the SSI guideline. In the interviews, the potential users were then able to elaborate on, further specify, or extend the desired functionality around the JDOs and explain which design specifications must be met for the developed artifact to become meaningful for the daily operations of first responders.

5. Validated design specifications

5.1. Application layer

Based on the architectural layers of Chettri et al. [31] in Fig. 1, the VDSs were derived along the four layers Application Layer, Architecture Layer, 5G Network & Communication Layer, and Input Layer. Experts stated in Section 4 that the envisioned JDOs can be used for operations management, training, and evaluation platforms. The three JDOs form the basis for the VDSs as they form three families of VDSs in the Application Layer (c.f. Table 4).

Regarding the map feature, statements were made that locating vehicles, equipment, and fellow crew members remains challenging but is highly desired. Although Global Navigation Satellite Systems (GNSS) are becoming more common, stakeholders lack positioning information when needed. Even today, especially for large factory sites, the exact position of an emergency is often not communicated, making accurate navigation difficult, according to I-M-7. The experts stated that a dynamic, interactive map provided by the SCDT is the most relevant innovation for operations management. The map will enable navigation by displaying closed roads and available routes in real-time and highly accurate localization (VDS1.1, VDS1.2).

I-M-7: "When there is a large event or marathon, then I can throw all my normal routes in the trash (...); the paramedic will turn off his current navigation app, as it won't help anymore."

I-F-9: "If I can see behind the building through a 3D animation, how I can access it from the back, this would lead me to better routes, that I can't see when I'm looking at a 2D map or standing in front of the building."

5G localization can improve the tactical positioning of forces for large-scale fires, indoor coordination for building fires, and information delivery through one digital application.

I-F-9: "When the operations commander first arrives on the scene (...), I need to know where the hydrant is, where I can access the building, where the keys are for the fire brigade. What other entrances are there? Then, when we enter the building, plans of each floor. (...) In large-scale fires, you have to position your

Table 4
Validated design specifications for the application layer

Layer		VDS	Name	Description or examples	Validated via		
					Other VDS	Interviews	References
Application layer	Maps	1.1	Mission planning and management	Deployment selection, initial arrival planning, managing supporting forces		I-F-1, I-M-7, I-M-8, I-F-9, I-F-10	[5,14,38,39,40, 43]
		1.2	Location tracking	Display the location of vehicles, first responders and patients as well as precise navigation to target		I-F-1, I-E-5, I-M-7, I-M-8, I-F-9, I-F-10	[5,14]
	Supplementary information	1.3	Vital sensor tracking	Display vital parameters of first responders and patients to monitor health status		I-F-1, I-M-7, I-M-8, I-F-9, I-F-10	[14,37,38,40,44, 48,54,53,55,56]
		1.4	Live video streams	Processing and sharing of video streams from UxV, attached or fixed cameras		I-F-1, I-M-8, I-F-9, I-F-10	[5,14,37,39,40, 41,42,43,44,48, 49,53,57,58]
		1.5	AR applications	Information display, e.g., victim locations or vital parameters. Training scenarios in AR or VR		I-M-8, I-F-9, I-F-10	[40,43,44]
	Contextual features	1.6	UxV assistance	Remote steering and autonomous trips		I-M-8, I-F-9, I-F-10	[5,14,37,39,45]
		1.7	Ex-post evaluation	Analysis of past trainings and operations		I-F-1, I-M-4, I-F-9, I-F-10	

personnel in an appropriate tactical manner. It is of uppermost importance to know where your firefighters are located, and if it could be implemented that I can see every single person in real-time, that would be truly groundbreaking, that would be amazing."

Today, indoor firefighters' locations are only known by voice communication, and accuracy is affected by stress and visibility, as stated by I-F-1 and I-F-6. Similarly, sensors for vital parameters and equipment could help to reduce voice communication, thereby reducing the mission commander's uncertainty when making decisions (VDS1.3):

I-F-1: "If I also have information about the pressure in the breathing tank, then I have the most important information. If the firefighter inside the building doesn't communicate the pressure level, I have to send, in the worst case, a squad to look after him."

Hospital trauma centers can prepare for an incoming emergency based on patient tracking and live video streams. For example, I-M-8 said medical experts could remotely assist paramedics in treating victims with complex implants. Furthermore, experts I-M-8, I-F-9, and I-F-10 expected to get a clearer picture of the operation and the emergency through the steering of UxVs and corresponding video streams provided by these vehicles (VDS1.4). Expert I-M-8 stated that steering various UxVs from remote operations command centers should also be a feature (VDS1.6).

5G innovations were also associated with AR and Virtual Reality (VR). Some experts (I-F-1, I-M-7, I-M-8, I-F-9, and I-F-10) discussed the value of AR and VR glasses to provide supplementary information. Fighting the fire was considered inappropriate due to the physical strain, but coordination tasks and assessments were seen as an exciting application area for AR and VR. In particular, scenarios that require a lot of preparation, such as staging mass casualty events or training for the initial assessment of a fire scenario, were identified as suitable for AR and VR (VDS1.5).

I-F-1: "A firefighter must feel weight, danger, and heat, I can't simulate the water coming out of the hose."

I-M-7: "Use AR glasses in a mass-casualty event where the medical or organizational head of command is supported by AR. That he can see relevant information on the AR glasses, (...) how many ambulances are on their way, how many are already there, which patients are already registered in my application, how serious are their injuries? So that I don't always have to ask people for that."

I-F-10: "Today, our training sessions for commanders are analog, sitting at a desk, using photos to imagine a fictitious scenario, a computer-based simulation would help there. But for the firefighter inside the building, I'm also skeptical, I think he must sense and feel what he is doing there."

I-M-8 added that staging AR mass casualty events where they occur, e.g., stadiums, train stations, or trade fairs, would significantly enhance the first responders' preparedness.

As stated in Section 4, other experts also see integrating the gathered data into one platform as beneficial to the ex-post evaluation of the actions performed (VDS1.7).

I-F-9: "If all operational actions are already digitally stored somewhere – every information collected and every point of view – then this information is crucial to evaluate the decisions that were made during the operation. If there were a time-lapse, I could also use the data for training purposes."

Our VDSs for the Application Layer, as found in the literature and evaluated by experts, are summarized in Table 4.

5.2. Architecture layer

From the Application Layer, VDSs for the Architecture Layer can be derived, i.e., the data platform must provide object-related data (VDS2.1), geospatial data (VDS2.2), real-time data updates (VDS2.3), and data storage for past, future as well as fictitious events (VDS2.4).

Expert I-M-7 specifically requests a reliable and secure platform that reflects the critical operating conditions of first responders (VDS2.5, VDS2.6): "If the power goes out, I fear I can't use such an application, what will still work then? (...) I have to directly design a redundant system where 97% uptime is not acceptable, but 99.9% is. (...) Our existing communications platform provides encryption, that's not the point, but it has to be built for encryption, and that comes at a price."

Experts pointed out that the data platform must provide different features if it should deliver added value to the operations of first responders, e.g., VDS2.7, that relevant data interfaces to other organizations exist. Isolated applications and data silos were seen as critical constraints.

I-M-7: "We need one platform for everything (...) at least the most important operation data should be automatically exchanged between operations command centers."

Furthermore, a squad resource management system could automatically select the most suitable squad based on available information.

I-M-7: "The status of each squad: Are they on their way to the scene, already there, are they right now treating a patient, how many operations and strain did they already occur today? When was the last break? Such parameters need to be considered in the background."

A 5G-ERIS must ensure that information is available throughout the chain of command and must not be requested via voice channels (VDS2.8).

I-M-7: "If we need to evacuate people because a World War II bomb has been found, there are tools that show who needs help evacuating, but only the operations command center has access to the information, not the personnel on the street."

I-M-8 stated that UxV video streams from emergency scenes or the ability to maneuver UxV from the operations command center remotely would benefit the information overview. The information needs to be available at the operations command center, in mobile command vans, and to squad commanders. I-M-8 added that on a macro level, knowing the number of patients, their health status, and symptoms, especially in mass-casualty events, could improve the distribution of patients to hospitals, and patterns in the symptoms of individuals could be identified faster.

Potential users (I-M-7, I-F-9, and I-F-10) highlighted several focus areas during the emergency operation, summarizing that interfaces and integrated communication between the command levels are crucial. It was also emphasized that the data platform approach has the potential to reduce workload and increase operational efficiency through automated documentation (VDS2.9).

I-F-9: "From the first view on the building, what type of building is it, where do I get my water from, where do I position my vehicles and then during the ongoing mission, the documentation. This could be implemented by providing the operations command center with a digital report because we have to write a report for the municipality on every operation. This is a legally binding document that is archived in case damages occurred or something went wrong."

I-M-7: "That the system is all-encompassing, that is crucial for me. I have a pile of paper from the last operations. This is where the operation ends for me. If I could save time there. You have to think about all the tons of paper we have to archive."

The resulting VDSs for the Architecture Layer are listed in Table 5.

5.3. 5G communication and network layer

The characteristics of this layer are defined through standardization processes of infrastructure providers, e.g., the 3GPP consortium, which unites various standards organizations [46]. These specified cornerstones of 5G enable our envisioned 5G-ERIS. To better understand the cornerstones of 5G, the experts were presented with applications from the literature. This procedure allowed them to evaluate the technical capabilities and state required features. The application examples from the literature are shown in Fig. 2. Thus, the experts rarely stated technical requirements for the Communication & Network Layer but expected technical features to be given and delivered by 5G out of the box. We derived the need for 5G

Table 5
Validated design specifications for the architecture layer

Layer		VDS	Name	Description or examples	Validated via		
					Other VDS	Interviews	References
Architecture layer	Data functionality	2.1	Object-related data	E.g., mission, first responder, patient, or vehicle data	1.1, 1.2, 1.3	I-M-7, I-M-8, I-F-9, I-F-10	[14,38,39,40,43, 45,53,55,56]
		2.2	Geospatial data	E.g., streets, buildings, parks, construction sites, or events, demonstrations combined in SCDT	1.1, 1.2, 1.3, 1.5	I-M-7, I-F-9, I-F-10	[5,14,40,43]
		2.3	Real-time data updates	E.g., position changes, video streams, accidents, temporary road closures, traffic jams	1.1, 1.2, 1.3, 1.4, 1.5	I-F-1, I-M-7, I-M-8, I-F-9, I-F-10	[5,14,37,40,42, 43,45,53,55,56]
		2.4	Information storage	Past, future, and fictive events	1.1, 1.3, 1.5, 1.6	I-F-9, I-F-10	
	Security and reliability	2.5	Reliable data access	System availability aligned with uRLLC: 99.999%	1.1, 1.2, 1.3, 1.4, 1.5	I-F-1, I-M-7, I-M-8	[14,42]
		2.6	Voice chat, patient and mission data	This data is sensitive and must be protected against abuse, unauthorized access, and changes	1.1, 1.2	I-F-1, I-M-4, I-M-7, I-M-8	[14,42,45,54,53, 55]
	Services	2.7	Relevant data and access interfaces	Interfaces with other authorities and organizations	1.1, 1.2, 1.3, 1.4	I-F-1, I-M-7, I-M-8, I-F-9, I-F-10	[43,54,53]
		2.8	Micro to macro	Information provision from mission commander to operations command center		I-F-1, I-M-7, I-M-8, I-F-9, I-F-10	[39,43]
		2.9	From alert to legal report	Automated operation documentation in one digital solution		I-M-4, I-E-5, I-M-7, I-F-9, I-F-10	

cornerstones predominantly from the literature and the functional requirements of the Application Layer, Architecture Layer, and Input Layer. For example, data security (VDS2.6) implies secure communication channels (VDS3.5), and reliable data access (VDS2.5) is only feasible given ultra-reliable networks (VDS3.4). AR applications (VDS1.5) require latencies well below 100 ms [40,45], implying uRLLC (VDS3.4) and Mobile Edge Computing (VDS3.6). As an example, I-M-8 stated that only a reliable mobile communication network (VDS3.4) that allows high data rates via eMBB (VDS3.1) would generate added value for AR glasses and that AR applications with high downtimes would be considered useless. Additionally, only if large diagnostic data files or video streams inside ambulances can be sent quickly to remote specialists, they offer value during the transport to the hospital (VDS3.1).

As another example, it was highlighted by I-M-7 that green rescue lanes have failed in the past because the used systems did not respond fast enough.

I-M-7: "Green Rescue Lanes have already been tried; the same system they use for buses was tested, but the result was that by the time the light turned green, the ambulance had already crossed the intersection."

This implies the value of the 5G cornerstones HPLE (VDS3.2), mMTC (VDS3.3), and uRLLC (VDS3.4), which can be combined to turn traffic lights green for ambulances in an adequate time [5,44]. Also, as quoted in Section 5.1, I-F-9 called the visualization of firefighters' position in real-time a breakthrough, emphasizing HPLE (VDS3.2). Table 6 summarizes these findings for the 5G Network and Communication Layer.

5.4. *Input layer*

To enable paths for UxV (VDS2.1), the environment needs to be constantly updated (VDS4.1). I-M-7 also pointed out that the entire digital twin needs to be updated at least several times a day, as data that was valid in the morning may have changed during the day. However, first responders must be able to rely on the fastest route to an emergency. VDS4.2 summarizes patient diagnostics that require high data rates. I-M-8 refers to application studies of mobile computed tomography as an example of a desired use case that requires eMBB. Further applications include ultrasound [42] or video assistance (telemedicine) [40].

Various sensors have been proposed to monitor the vital parameters of patients and personnel (VDS4.3) as well as the equipment and environment of firefighters (VDS4.7).

I-R-10: "The pressure in the breathing tank, also the vital parameters of the firefighter, the temperature under the protective suit, the pulse and the respiratory rate, parameters that we track during physical stress tests."

I-M-7 also suggested transmitting electrocardiogram data. VDS 4.4, location sensors, are required for mapping applications (VDS1.1, VDS1.2). These use both 5G and GNSS technology, depending on the surroundings and thus on which provides better accuracy [5]. AR and VR glasses (VDS4.5) are imperative for AR visualizations (VDS1.5). Traffic sensors (VDS4.6) enable intelligent transportation systems necessary for the implementation of green rescue lanes [47].

To improve the accuracy of the digital twin through environmental sensors (VDS4.7), I-F-1 and I-M-7 suggested monitoring large gatherings of people to identify congested areas or when capacity limits are exceeded in buildings. I-E-5 desired the integration of sensors that monitor if windows are broken. In [14], acoustic gunshot, fire, and smoke detection are listed to increase the amount of information available to first responders.

The experts pointed out that the devices that provide the maps, supplementary evaluation, and other contextual features of the Application Layer must be suitable for the conditions under which operations take place. I-M-8 stated that, while a tablet computer is an appropriate hardware (I-F-1, I-M-8, I-F-9, and I-F-10), alternative input options must be available when hands or gloves are covered in blood or touchscreens malfunction in heavy rain. Therefore, I-M-8 suggested that voice input channels should be explored (VDS4.8).

Table 6
Validated design specifications for the 5G communication and network layer

Layer		VDS	Name	Description or examples	Validated via		
					Other VDS	Interviews	References
5G communication and network layer	eMBB	3.1	High data transfer rates	Required for high-quality video streams and continuous update cycles of SCDT	1.5, 2.2, 4.1, 4.2	I-M-8	[14,39,40,41, 42,44]
	HPLE	3.2	Mapping services	Highly precise localization everywhere enables localization indoors as a key feature of 5G networks	1.1, 1.2, 1.5, 4.3	I-F-1, I-M-7, I-M-8, I-F-9	[5,14,40]
	mMTC	3.3	Sensor connectivity	mMTC allows to log a very large number of devices into the 5G network in a small area (high density of devices).	1.1, 1.2, 1.3, 4.3, 4.4, 4.5, 4.6, 4.7	I-E-5, I-M-7, I-M-8	[5,14,39,40,43, 44]
	uRLLC	3.4	Mission-critical reliability and low latency	Reliability of first responder systems and data streams	1.1, 1.2, 1.3, 1.5, 1.6, 2.3, 2.5, 4.6	I-M-7, I-M-8	[5,14,39,40,41, 42,43,44,45,49]
	Network security	3.5	Secure communication channels	Secure communication for first responder organizations	2.6	I-M-7, I-M-8	[14,42]
	Mobile edge computing	3.6	Computational power on the edge	I.e., in close proximity to users to reduce latencies	1.5		[14,37,40,43, 47,56]

In addition, manual data updates must be possible in a fast and intuitive manner (VDS4.9). If errors occur, data is missing, or personnel wants to enter notes about the current operation, it must not take a long time to edit the data, which underlines the need for VDS4.1.

I-M-7: "For example, mobile fences, I should be able to draw a line, do a camera scan, or have the information added in an automated fashion. (...) The system could automatically ask the driver: 'Why did you turn left here instead of turning left the intersection before as suggested?'."

Lastly, to ensure VDS2.9, i.e., that the system connects micro and macro perspectives, it must be able to run on various screen sizes and operating systems. I-F-1, I-M-8, I-F-9, and I-F-10 pointed out seamless information sharing between tablet computers at the emergency site and large screens in the operations command center. At the same time, I-M-7 also added the inclusion of PCs in mobile command vans. The VDSs from the Input Layer are highlighted in Table 7.

6. Discussion and implications

The interviews revealed that first responders place the highest value on applications that address the shortcomings of the systems and tools they rely on today. To improve decision-making under stress, frequently updated maps that provide relevant and reliable information from multiple data sources in a single platform are most important. Today, these are often only available analog and not maintained at sufficient time intervals. We have found that map visualizations at the operation scene or for navigation purposes while approaching the scene is a priority. Data collected directly from or around the personnel is considered particularly important, e.g., the location of vehicles and first responders as well as sensors that allow remote stakeholders to assess the health of persons at immediate risk, i.e., firefighters or patients.

5G technologies can provide the foundation for these applications, e.g., sensor data transmission [37,48] and live video streams [39]. With 5G, more devices can be connected and more data can be transmitted much faster to relevant decision-makers, with higher reliability than with current network technologies. In the literature, uRLLC is dominantly seen as a major improvement in terms of latency [40,43,44,45,49]. However, the experts emphasized that reliability in these applications is more important for all planned applications. Thus, a key finding is the importance of the 5G cornerstone of 99.99% network uptime.

Critically assessing the results furthermore indicates that when evaluating our implemented 5G-ERIS, it must be reviewed which time intervals for updating the data of the SCDT are appropriate in terms of costs and added value, i.e., whether a full-scale digital twin of a city updated in real-time, is strictly required to meet the current needs of first responders. While the route to an emergency requires the latest information on road closures and congestion levels, navigation solutions available on the market could potentially serve this requirement more cost-efficiently than a digital twin. Localization technologies like inertial measurement units and GNSS exist today. Making these available to first responders appears more relevant than narrowing down on 5G HPLE. In line, I-F-9 emphasized that frequently updated information is desired, but considering that today's sources are outdated: "If I know in which part of the building and on which floor that person is, and I could also see in the ERIS that two persons are about close to each other, then with some communication, they should be able to find each other in time. (...) Combine the position with a dynamic map and not public satellite images from three years ago, and add the direction the fire is heading. That would be the ultimate goal."

Similarly, based on the results, we consider it more relevant for emergency operations to share drone footage across all hierarchical levels and remote operations command centers rather than implementing an unmanned aircraft traffic management system [50], which enables UxVs to be steered autonomously or remotely from long distances.

As first responder organizations seek their own 5G spectrum to build an independent 5G network [14], reliability (uRLLC) must be of the highest importance, followed by eMBB and the ability to integrate

Table 7
Validated design specifications for the input layer

Layer		VDS	Name	Description or examples	Validated via		
					Other VDS	Interviews	References
Input layer	Imaging	4.1	Create and update the 3D model	Through, e.g., UxV-mounted cameras or LiDAR	1.1	I-F-1, I-M-7, I-F-9, I-F-10	[14, 37, 39, 44]
		4.2	Patient diagnostics	Through, e.g., cameras, MRI, ultrasound	1.4	I-M-7, I-M-8	[14,39,40,42,43,45,49,54,53,58]
	Wearables	4.3	Sensors for vital parameters	e.g., heartbeats per minute, breathing rate	1.3, 3.2	I-F-1, I-M-7, I-M-8, I-F-9, I-F-10	[14,37,38,39,40,43,45,54,53,55,56]
		4.4	Location sensors	5G, GNSS, or IMU	1.1, 1.2, 1.5, 1.6	I-F-1, I-M-8, I-F-9, I-F-10	[5,14,43,40,55,39,56]
		4.5	AR/VR glasses	For emergency management or training	1.5	I-M-8	[14,39,40,43]
	Traffic and environment	4.6	Traffic sensors	To enable intelligent transportation systems	1.1	I-M-7	[5,44]
		4.7	Environmental IoT sensors	To capture not documented events and states of the environment	1.1	I-F-1, I-F-6, I-F-9, I-F-10	[14]
	User input devices	4.8	Voice and text input channels	Input options that are mission-suitable, e.g., in the rain		I-M-7, I-M-8	[14,37]
		4.9	Fast and intuitive input options	To manually insert or update information		I-M-7, I-F-9, I-F-10	
		4.10	Access	On different user devices	2.9	I-F-1, I-M-7, I-M-8, I-R-9, I-F-10	[43]

many sensors and devices (mMTC). Building on the significant progress that has been made to provide mission-critical reliability to first responders through 5G networks [14].

Our findings underscore the need to incorporate user feedback in the development of new products and solutions for first responders, which has rarely been done in the relevant literature. Table 7 demonstrates a lack of literature addressing requirements for user input devices (VDS4.8, VDS4.9, and VDS4.10). This is highly relevant for first responders to accept novel applications, otherwise they will not use the tools to improve their decision-making. Acceptance of ERISs was studied in [12], who reported that acceptance research can be found in the healthcare domain but rarely in the emergency response domain. The authors' results support our findings, as they find that GNSS positions on a situation map are most desired, that an emergency power supply should back up an ERIS, and that an ERIS can be used on desktop PCs, notebooks, and tablet computers but smartphones are not required.

Another point of acceptance covers data privacy. In the interviews, the experts stated that acceptance could be hindered by concerns about ensuring that personnel are not located outside of operations.

I-M-4: "I am afraid that mistakes or bad behavior could be directly archived, e.g., losing the right way, going to the toilet, or smoking a cigarette."

I-F-10: "As far as volunteer first responders are concerned, we should not track them off-duty, but once the operation starts, no one will question the collection of data and the need to collect it."

Mandatory location tracking has been found to have a negative impact on the trust and relationship between police officers and their employers [51]. Furthermore, I-F-10 pointed out that large factory sites may resist sharing 3D data scans of their precise indoor floor plans, resulting in areas without data in the 5G-ERIS.

Interviews with first responders also revealed that different user groups have different priorities. Paramedics emphasize the route to the victim and the potential time saved on the road. Firefighters, on the other hand, were most concerned with having the right knowledge of the emergency scene, potential hazards, and how to extinguish the fire as quickly as possible.

Lastly, controversy arose in the interviews about the use of AR and VR. Experts stated that, on the one hand, there are different training scenarios where AR and VR are suitable. On the other hand, they also expressed their opinion on using AR in emergency operations. I-M-7 envisioned an overview window of available and arriving forces in mass-casualty events provided by AR glasses as welcome support and suggested further research. I-F-9 and I-F-10 were skeptical about the durability of the hardware and its usability during physical work on site. These results are supported by [52], who find that some firefighters appreciate an AR visualization of the pressure in their breathing tanks in order to be able to focus on other tasks. In contrast, others fear technical problems while working in hazardous conditions.

From the interviews and the corresponding results in Sections 5.1 and 5.2, it became evident that first responders need a large amount of information quickly and reliably. Recognizing that information overflow, complexity, and time pressure impact decision-making [7], an appropriate level of information provision must be found in the envisioned 5G-ERIS. In [12], for firefighters, it is noted that in time-critical situations, the display of current information in an understandable way is demanded, with firefighters appearing to tolerate unnecessary information if none of the required information is missing, negatively evaluating 'compact' versus 'extensive' ERISs. The difficulty in providing the appropriate level of information is supported in [52], where interviewees stated that digital maps should provide information from different databases, e.g., hazardous materials, while others stated that digital plans should not be too overloaded.

We conclude from the literature and our interviews that the envisioned 5G-ERIS should focus on the map visualization of the SCDT. Based on the wide variety of proposed 5G innovations in Fig. 2, first responders identified the seven most valuable features documented as VDSs in the Application Layer. All of the envisioned VDSs, with the exception of ex-post evaluation, share the goal of increasing the situational awareness for decision-makers and improving the provision of information on route to or at the emergency scene. Our findings implicate that the lack of relevant information is more critical for practitioners than, e.g., fully autonomous deployment processes and UxV logistics [37], thus pointing to a subset of 5G research for emergency management, e.g., [14,52]. These features provide the most added value, while other applications explored in the literature appear too distant from today's used technologies. Our VDSs contribute to the existing literature on map visualizations and information display for first responders a set of relevant information that is highly prioritized by first responders to improve their decision-making. Our research identifies application scenarios for AR and under-researched areas in data privacy, acceptance, and user interaction with dynamic maps in the emergency context. For example, first responders are likely more resilient to information overflow and more concerned about lacking the information they need. Practitioners can use our VDSs to implement such a system and validate the JDOs. In addition, it became apparent that in practice, increased digitalization and connectivity activities must be undertaken, and barriers to information sharing, e.g., data silos, must be broken down.

7. Limitations, further research agenda, and conclusions

We identified design objectives for a 5G-ERIS based on an SCDT by searching the existing literature. We then refined these design objectives and derived VDSs based on expert interviews. Thus, we obtain a list of VDSs along four architectural layers. This architectural blueprint is the foundation for developing a meaningful artifact that solves real-world problems such as analog maps, squad management, and insufficient mission planning and evaluation. Most importantly, a subsequent implementation of the examined VDSs and an ex-post evaluation are necessary for further research [16].

We encourage fellow researchers to follow up with their application studies as we identified several underdeveloped research areas. In particular, the appropriate amount of information to display on digital maps for first responders appears promising. To improve decision-making, the right information is needed at the right stage of the operation. In the literature search, artificial intelligence and machine learning were found to be used in hospitals to diagnose and forecast diseases, e.g., [53]. However, no application studies of these technologies as decision support for first responders in the field could be identified, and the interviewed experts did not address the use of this technology. Further research should investigate the acceptance of decision support based on artificial intelligence, e.g., predicting and simulating the direction a fire is heading. Also, based on the interviews, we see a more in-depth differentiation of the utility of AR glasses in the context of decision-making in emergency responses as a promising research aisle. Finally, assessing what performance is required in terms of acceptable data rates, latencies, positioning, devices in an area, and reliability of 5G network technologies to enable these applications is another further research direction.

Our research is limited in that it did not include the perspectives of police departments as the third major branch of first responders. Our selection of fire departments and emergency medical services is limited and does not cover all organizations with security roles. Many, but not all, findings can be generalized to police departments, as supported by experts and the literature, e.g., data privacy [51]. We excluded police forces because they have different command structures. Police forces tend to have tightly organized command and control structures. Furthermore, the responsibility for the police forces or technical relief organizations lies with the state or federal governments. As a result, the distribution of information is handled differently compared to fire departments and emergency medical services, including the respective volunteer forces, which are organized under municipal governments, as explained in Section 2. Further research would be able to identify commonalities and differences between these organizations.

All of the experts are from Germany and have worked in Germany. As a result, our findings may not be generalizable or transferable to other countries due to the different structures of the organizations. We also did not differentiate between the hierarchy levels of the experts we interviewed. Finally, there may be a lack of technical standards in operational sections, particularly in the use of software, data protection, and respective interfaces. Therefore, our findings may not apply equally.

To examine user perspectives on the 5G-ERIS for first responders, we conducted a literature search and qualitative interviews with participants from these organizations. The experts emphasized that a 5G-ERIS provides more frequently updated information. 5G infrastructure innovations offer improved localization, increased amounts of data that can be transmitted, connectivity to many sensors and devices, and a highly reliable network with low latencies. By implementing user-centered 5G-ERISs, emergency managers will be able to improve on targets like time to the victim, lives saved, and first responder safety. Practitioners can use these 5G-ERIS VDSs to assess whether their organization can develop or adapt such a system and what needs to be done to implement it. We contribute to a meaningful foundation for the successful development of a 5G-ERIS to improve the decision-making of first responders.

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