First In, Left Out : Current Technological Limitations from the Perspective of Fire Engine Companies

Katelynn A. Kapalo
University of Central Florida
katelynn.kapalo@ucf.edu

Pamela Wisniewski
University of Central Florida
pamwis@ucf.edu

Joseph J. LaViola Jr.
University of Central Florida
jjl@cs.ucf.edu

ABSTRACT

The cognitive demands and skills required of a fire engine company when assessing the scene of an incident and the systems they use to manage this information are a matter of life or death. We conducted a case study with an entire fire battalion in Florida (35 firefighters at varying levels of command) to assess their routine technology needs. Using a cognitive work analysis approach, we found that the firefighters in our study relied on mission critical systems that often failed, as well as disparate secondary systems that lacked integration. Capability gaps and inaccessible data also increased the likelihood of errors, creating frustration in the systems that both helped and hindered these firefighters in their daily job tasks. We describe what firefighters need from technology in its present state and we outline usability issues for technology designers and practitioners to leverage in the design of future systems.

Keywords

Fire service, case study, sociotechnical analysis, work analysis, information systems

INTRODUCTION

Every 23 seconds, a fire is reported in the United States (Haynes & Stein, 2017). From the time of the call, fire response teams must be on the move within 80 seconds for a fire call and 60 seconds for a medical emergency. This fast-paced response requires careful planning and coordination involving input from multiple sources, information from multiple devices, and communication from multiple people. With such a tight timeline for response, firefighters must be prepared to arrive on scene and successfully complete their mission, sometimes without accurate information or adequate time for pre-planning.

Despite a common need for accurate and real-time information, the fire service is very diverse in how it obtains, manages, and handles data due to variations in response areas and budgeting (Haynes & Stein, 2017). Consequently, firefighters may not have access to state-of-the-art equipment or facilities. For example, 15% of stations in the region we evaluated were over 40 years old according to the most recent National Fire Protection Association survey (NFPA, 2011). Additionally, aging equipment is also a concern. Recently, two firefighters in Massachusetts faced potentially fatal conditions after their radios failed to convey the "mayday" signals, indicating they needed aid in escaping the burning building (Firefighter Nation, 2017). These near-miss accidents require careful consideration of the system in which firefighters must operate, but more importantly warrant a closer look at the systems firefighters depend upon for conveying and obtaining information. Ideally aging equipment and outdated facilities would receive more attention, but the diversity in fire service conditions warrants a closer look to understand the holistic needs of each region and district.

Towards this end, our work focuses on better understanding the needs of 35 firefighters across the command structure from probational (newly trained) firefighters to fire chiefs with over 30 years of experience.

We conducted a case study in which the first author accompanied fire engine companies for an entire day to better understand the sociotechnical context surrounding the fire service. In this paper, we define *sociotechnical* as the interaction between the firefighters, the environment, and the systems/technology they use to operate in those environments. Our research was guided by the following questions:

- How does the sociotechnical system as a whole influence the behavior of the firefighters in our sample?
- More specifically, what are the main tools used by fire engine companies and rescue teams? Do these tools differ across ranks?
- How do these tools and technologies impact job tasks, job functions, and organizational values?

To better design technology to meet the needs of the fire service, we evaluated the broader sociotechnical system across all ranks of the fire service. To do this, we met with firefighters in six different stations (an entire battalion). We also interviewed three emergency operations center personnel responsible for sending information to first responders county wide, spanning over 40 fire stations. Drawing from the Cognitive Work Analysis framework as the theoretical a foundation for our research, we uncovered that the technology and systems used in our sample did not match the needs of the fire service (Vincente, 1999). Our key contributions include:

- An assessment of current systems and technology utilized by a fire battalion that services a large, metropolitan area in the Southeastern United States
- Translation of findings from cognitive systems methods into information that illustrates a richer understanding of the *sociotechnical environment* that firefighters work in
- Identification of areas where further investigation is required to create an effective system that can support firefighters across the command structure

RELATED WORK

Designing technology for emergency management and crisis response poses challenges due to the diverse number of stakeholders involved (Gomez & Turoff, 2007; Moynihan, 2009; Palen, 2007). The field of crisis informatics emerged from a need to better understand the perspectives of these stakeholders in a variety of disaster scenarios and emergencies by leveraging a multidisciplinary approach. Thus, this field has studied the implications of information dissemination across a variety of categories such as collaboration, community response, and information generation (Palen et al., 2007; Shklovski, 2008).

Efforts to better support first responders and emergency management personnel have largely developed from information sciences and decision-support tools. Research in this area has focused on ways to optimize tools and implement new systems at all phases along the system lifecycle. For example, previous work has focused on eliciting information requirements of first responders using a variety of approaches from sociology, grounded theory, and team performance research (Denef et al., 2009; Jul, 2007; Li et al., 2014; Prasanna et al., 2009; Toups & Kerne, 2007). The development of communication tools and systems has also been one of the defining research thrusts in this area (Dawkins et al., 2018; Groner et al., 2012; Jiang et al., 2004). Within the last year, research has assessed the attitudes of German fire departments on the acceptance of newly emerging technologies (Weidinger et al., 2018).

Due to the parallels between military operations and fireground command decision-making, the fireground was chosen as a domain to explore some of the most influential theories and models for decision-making in critical situations (Klein et al., 1989). More recent work in human factors has demonstrated the utility of focusing specifically on the fireground commander to better understand the barriers that impede successful mission management and ways to mitigate these through best practices (Gasaway, 2009). Similarly, work in HCI has focused on designing configurable systems that support the information requirements of four firefighter roles (Prasanna et al., 2013).

This paper directly addresses the role of technology for fire response in the United States. While we recognize that conducting a work domain analysis for firefighting is not novel, we provide a novel approach to the interpretation and presentation of key issues relevant to fire engine companies. We expand upon previous work that identified some of the problems that incident commanders face by addressing the team across all ranks and updating it to be current with the advancement of technology (Dawkins et al., 2018; Jiang et al., 2004; Kapalo et al., 2018). The goal of our paper is to provide a *critical and current evaluation of the sociotechnical needs within current fire teams in the United States*.

We seek to summarize some of the important feedback to better inform the design of future technologies and to draw attention to the needs of firefighters, in our sample, who depend upon these systems in life or death situations.

METHOD

Participant Profiles

The participant sample consisted of n = 35 (32 male, 3 female) firefighters and n = 3 (3 male) emergency management personnel; n = 38 total. The fire service, while grounded in a para-military structure, has local and regional variations across the United States. All participants in this study are career firefighters and personnel. Although volunteer firefighting is prevalent in other parts of the United States, volunteer firefighting is uncommon in this particular area and state, since it is well populated. Participant quotes are denoted with their rank. Due to the possibility of potentially compromising participant anonymity, the term "chief" denotes any of the chief ranks such as battalion, district, assistant, or division. See Table 1 for an overview of ranks in the fire service.

Table 1. Firefighter ranks across the command structure

Rank	Role
Probational Firefighter	Newly Trained
Firefighter	Fire Suppression
Engineer	Driver/Operator of Equipment
Lieutenant	Crew Supervisor
Captain	Direct Operations
Battalion/District Chief	Highest Ranking Officer On-Duty
Assistant Chief	Operations
Division/Fire Chief	Operations/Administration

In this study, an engine company is composed of at least one firefighter, one lieutenant, and one engineer that all ride in the engine cab. The rescue team drives an ambulance separately and is generally composed of an emergency medical technician (EMT) and a paramedic. In this case, the firefighters all at least met basic EMT requirements, since it is common for firefighters to fill different roles depending upon their shift and response area needs.

Recruitment and Data Collection

The study occurred in two phases. Participants for the first portion of the study were recruited via email after Institutional Review Board approval was obtained. In the first phase of the study, the first author conducted focus groups with three Emergency Management Personnel and a group of five fire chiefs at the county Emergency Operations Center (EOC). This aligns with the recommended practice of conducting theoretical sampling in grounded theory-based research (Strauss & Corbin, 1994).

Following these two sessions, approval for a ride-along was granted to the first author through the fire rescue headquarters administration. The first author accompanied a battalion chief for five hours and a captain for five hours. Throughout this 10-hour ride-along, both the chief and captain were required to make stops at six different fire stations. The first author conducted eight additional ad-hoc focus groups throughout the duration of the study by obtaining verbal face-to-face consent from the firefighters at each fire station. The groups were formed based upon staff availability and interest. The first focus group was transcribed from an audio recording. Subsequent focus groups were not audio recorded due to the nature of incident response. All medical calls are subject to Health Insurance Portability and Accountability Act (HIPPA) regulations and patient privacy protections. Therefore, the first author took field notes for the remaining groups (2-10).

Table 2. Summary of data collection groups with participant counts and roles included

Study Number	Data Source	Participant Count	Group Constellation
1	Focus Group	3	Emergency Management Personnel
2	Focus Group	5	Assistant and Fire Chiefs
	RIDE ALONG (Conducted ad-hoc at fire stations & incident scenes)		
3	Interview/Observation	1	Battalion Chief
4	Interview/Observation	1	Captain
5	Focus Group/Observation	5	Fire Engine Company 1
6	Focus Group/Observation	4	Fire Engine Company 2
7	Focus Group/Observation	4	Fire Engine Company 3
8	Focus Group/Observation	6	Fire Engine Company 4
9	Focus Group/Observation	5	Fire Engine Company 5
10	Focus Group/Observation	4	Fire Engine Company 6

Data collection was informed by a cognitive work analysis approach (Rasmussen et al, 1990; Vincente, 1999). Cognitive work analysis developed from a need to understand the work of actors, the information behaviors surrounding the work, the environment in which work is performed, and the reasons behind the work performed (Fidel & Pjtersen, 2004). Our work employed this framework to guide the direction and scope of the studies conducted and the interactions with participants. A sampling of some of the questions asked during participant interactions mapped to major work analysis dimensions are captured in Table 3 below. Please note this is not an exhaustive list and meant to demonstrate how data was collected beyond observations on scene.

Data Analysis Approach

The first author coded all of the interview data. This coding process was completed by uploading all of the transcripts into MAXQDA 12. Two senior researchers reviewed samples of this coding to ensure agreement. The data was coded in three iterations, using the sociotechnical themes (people, technology, incidents) as an initial framework since these reflect the main tenants of the fire service work domain (Fidel & Pejtersen, 2004; Ramussen et al., 1990). These themes were chosen since they captured the broader dimensions of the cognitive work analysis framework: *environmental, organizational, social, activity, and individual*. However, because these dimensions are interdependent, the organizational, social, and individual dimensions were consolidated into a single code, categorized more broadly as *people*, since firefighting requires an understanding of how the command structure drives the social and organizational aspects of fire departments (Monynihan, 2009). As necessary, the interviewer performed sweeps to ask clarifying questions in order to capture information about a particular concept or term. Further sub-codes were added to better understand the three broad themes, leveraging the grounded theory approach (Goggins et al., 2013; Strauss & Corbin, 1994). Finally, a third coding iteration was used to check for accuracy and to ensure statements were categorized meaningfully and completely.

RESULTS

The structure of this section aligns with the themes emergent from our data and categorizes some of the end-user feedback we received to better understand the routine needs of firefighters in our sample. We first grouped these dimensions across three broad categories that comprise the sociotechnical environment of the fire department: people, incidents and technology. The revised coding structure, based upon the three code iterations, is captured in Table 4 below.

Table 4. Coding Structure

Sociotechnical Dimension	Sub-codes
People (Actors)	• Rank and expertise • Values • Expectations • Resource allocation
Incidents (Environment and Organizational)	• Operational constraints • Job tasks and activities • Responsibilities
Technology (Activities and Objects)	• Attitudes • Usability Concerns • Coping strategies • Constraints and failures

Table 3. Samples of Questions Scaffolding Data Collection Sessions

Framework Dimension	**Sample Question(s)**[1]
Analysis of User Characteristics	1. What information do you need to perform your job well? Can you provide me with some specific examples? Are you responsible for sending information to another teammate? a. What is their role? b. What kind of information is necessary for you to provide to them? 2. What kind of tools/equipment are available to you and which tools do you primarily rely upon? a. What information do these tools provide? If they do not provide information, what are their main purposes or functions? b. Are these tools located in the station, on the vehicle, where are they? c. How frequently do you use this set of tools during the day? Are there some that are rarely used?
Activity Analysis	3. From the time dispatch alerts you to the time you arrive on scene, walk me through an example call. What do you do first, and what information do you need to proceed and get to the scene? (may be real-life or a simulated training scenario) a. What are your goals in these scenarios and how do you plan your response? b. What do you prioritize first? ("size up") c. How do you know what to prioritize first? d. At a given moment, how many displays/devices are you obtaining information from? e. Can you explain to me in a few steps what that sequence of information gathering is like? Which device/interface do you look at first? f. Who are your teammates, and do they provide you with information? What does that sequence of information look like?
Organizational Analysis	4. Does your role change as situations change or do you generally perform certain tasks? Could you elaborate on this, if possible? Is it situation dependent or is it determined before your shift who will fill which role?
Work Domain Analysis	5. What are some actions that are taken to make sure a size-up is done correctly? Are you monitoring yourself or does leadership play a role in this? Who is in charge of making sure the team and plan adapt if the scenario changes? 6. In addition to your on-call responsibilities, what are some examples of other tasks you may be responsible for on-shift? (Administrative, maintenance, etc.)

[1] **Please note this is not an exhaustive list of all questions posed due to space constraints. Please contact the authors for the complete list of questions.**

People

Because our approach is grounded in understanding the dimensions of expertise and the self-organizing social structure driven by incident command, we sought to understand the unique roles across the fire engine company (LaPorte, 1996). We contend that within the company, there are prototypical roles each team member must fill, creating an opportunity to better understand the profile, values, and expectations of these team members. For example, the chief conceptualizes the engine company and arriving units as a sports team, with the incident commander acting as a coach. This organization structure provides further insight on how responsibilities are distributed and shared. It also provides context surrounding values and expectations more broadly:

> *"The IC [incident commander] is like a football coach who is calling the plays, absorbing the whole scene, delivering out the task in a priority fashion, their information is more global: where are all my units, what are the changing conditions, what are the needs that I have to address, what are the resources I have, and how do I get the resources I need?"- Chief*

Rank and Expertise

The above statement provides some insight into the challenges the incident commander faces regarding the amount of information they are required to process. In contrast, the crew on the engine has different priorities. They were likened to athletes carrying out plays, and take more of an offensive approach:

> *"I care about what is in front of me, what is overhead, what is in the room, I'm listening to what's around me."- Firefighter*

Despite these conceptualizations, there are some nuances in understanding the rank (social) structure on the fireground. One chief succinctly explained that there are multiple types of supervisors on the fireground to ensure that incidents move swiftly and quickly, but that those roles require different things from technology and tools. He stated:

> *"There are two types of supervisors in incident command: The first is somebody who is commanding a crew and navigating in the truck with them, a lieutenant. The second is somebody [like a battalion chief or captain] who generally is alone and arrives as an individual unit. So, they are navigating, orienting, and planning by themselves."-Chief*

Thus, the role of the battalion chief can be potentially more demanding due to the added requirements of navigating to an incident scene alone, while operating the vehicle, listening to the radio, and monitoring the MDC for changes in incoming information. They may also be required to access documents such as pre-incident plans. This details a richer understanding beyond that of the "prototypical" user in the sense that chiefs and company officers have different priorities than the engine crew when responding on scene. When considering the technical system and incident scene, it is clear that officers have different information needs.

Job Expectations and Resource Allocation

Expectations are emphasized as important, each member has a role to fill and as the incident progresses, it may become necessary for others to join the team. As a consequence, *flexibility and accountability* were two concepts that were consistently referenced in participant responses.

> *"The expectation for the IC [incident commander] is that he/she prioritizes accountability. They need to know where everyone is and what they are doing at the scene from start to finish." –Chief*

In addition to accountability, team members also explained how they coordinate tasks, sometimes with an implicit level of *trust*. For example, one engineer explained how he makes decisions regarding the appropriate amount of water flow. He recognized that this sort of behavior bounds the system, but not explicitly. Instead, he uses his judgement and understanding of his teammate's job tasks to fulfill the requirements of getting the water on the fire in a timely manner.

> *"There's an understanding there. I know that if I put out the maximum pressure required on the line [hose] it's going to knock the guy at the end of the line around and that would piss him off and slow us down. So, I use my judgment, it's not always by the book."- Engineer*

These values of *accountability and flexibility* were prevalent across all interviews but were typically emphasized at the higher levels of command, where the ranks become more supervisory and thus, more critical in terms of ensuring the team's safety.

Incidents

Generally, an "incident" is defined as an instance of a particular activity in which observations can be made and there are directly measurable consequences based upon the actions taken (Flanagan, 1954). In the fire service domain, an incident is any sort of call in which emergency medicine or fire suppression activities are involved. Although incidents vary in nature, in this paper we consider all incidents to be emergencies requiring a time constrained response that involved *protocols and action* among individuals belonging to the engine company. According to our sociotechnical approach, the incident represents the operational environment in which people are present and technical systems are utilized.

From our study observations and interactions with participants, we noted that the most prevalent themes surrounding incident response involved being *adaptable* to rapidly changing scenarios and the ability to think forward and plan ahead, regardless of role or incident. All firefighters had to be prepared to encounter situations that are time-sensitive and require methodical preparation. Across all of the themes in the incident category all participants emphasized the ability to adapt to the incident as one of the main values in this fire department.

Operational Constraints

Participants made frequent references to "playbooks," "thinking ahead," and time constraints. This theme of adaptability stems from a need to embrace the dynamic details of the situation in order to successfully complete the mission.

> *"There's not just one playbook, once one plan is null, we move to a back-up plan, and then we have another back-up plan if that one fails."-Lieutenant*

> *"I'm always thinking half an hour ahead."-Chief*

> *"As an incident commander I am already thinking about where the hydrants are, where to stage, how much room we need to leave, whether we have a decent water supply, where the trucks are going to go, all of this decision-making has to happen quickly."-Captain*

An emergency management center employee captured this requirement well in the following statement:

> *"Essentially there are three levels of response—task, tactical, and strategic. Our responders are filling different roles during the course of an incident; however, these levels determine the scope and perspective of each role." -Emergency Manager*

Despite this need for quick decisions, our study revealed that the systems firefighters rely upon do not necessarily meet their needs, and in some cases can constrain incident response. We describe this idea in more detail below.

Specific Job Tasks, Activities, and Constraints

Incident response is dictated by decision-making of commanders as well as team coordination, but it is also dependent upon other factors outside the control of the firefighters. For example, a demanding and challenging situation arises when a water supply is not readily available. The tanker shuttle is a strategy and protocol implemented when water sources are scarce or not accessible. In one instance, a recently developed community in the area did not contain enough fire hydrants to supply the hoses for a house fire. For this reason, a tanker shuttle is established to provide support for the water supply. However, the logistics of this protocol can be daunting. There is often not enough water on one tanker truck, so portable tanks and a system for replenishing this water needs to be established. Typically, one captain or senior officer is in charge of managing this process while the other serves as incident commander of the entire scene.

> *"One major concern with recently developed communities is the lack of fire hydrants. They are typically expensive, and some developers complete the bare minimum for coding and zoning. As a consequence, the logistics of putting out a routine house fire may be compromised by lack of water and you have to move to plan B." –Engineer*

Technology and Equipment

To support incident response, firefighters need information about the emergency at hand. Firefighters rely on technical systems to understand and react to the dynamic nature of incidents. Often this information is incomplete and lacks detail. Therefore, technology can convey what little information is known.

The Mobile Data Computer (MDC) represents a central component in the system as it facilitates the two-way exchange of information between the Computer Aided Dispatch (CAD) system, the system that transmits emergency information from dispatch, and the firefighters on duty (see Figure 1 and Table 5). While the MDC is equipped with navigational capabilities, these capabilities are augmented by separate devices, such as a Garmin (GPS). Because of this central role, we elaborate on this device further to explain its implications in later sections of this paper. The MDC represents the hub for information in which firefighters of all ranks access incident data, create reports, and log information. Despite its theoretical utility, in practice it is often the source of frustration and error due to connectivity issues, usability problems, and general lack of functionality. These themes were introduced by participants in the quotes below:

> *You have 45 seconds to understand information from several disparate systems, you are flipping screens, switching back and forth from the mapping screen and the incident screen..."-Lieutenant*

> *"The MDC printout has more information than someone can read in 30 seconds..."-Firefighter*

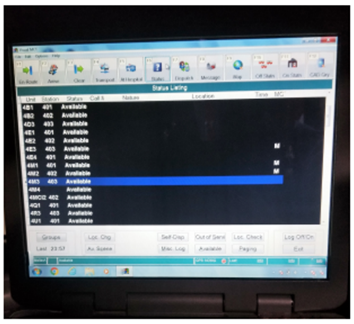

Figure 1. Example of a Mobile Data Computer (MDC) or Mobile Data Terminal (MDT) used by fire engine companies.

In addition to the MDC, firefighters rely upon several different technologies in their routine job tasks. Some of these technologies are listed in the table below. Please note that due to local variations, some technologies such as automated dispatch systems and tablets may exist in other departments. Additionally, there is other equipment stored on the fire engine that may be considered a major tool or technology (e.g. hydraulic tools). However, the goal of this table is to summarize the core technologies routinely used by engine companies.

Table 5. Summary of Core Technologies Used by Firefighters Daily

Device	Usage/Purpose	Users
Mobile Data Computer (MDC)	Information, Logs, Reports	All
Global Positioning System (GPS)	Navigation	All
Paper Map book	Navigation	All
Radio	Communication	All (In-Vehicle)
Camera	Crew Surveillance/Monitoring	All (In-Vehicle)
Mobile Phone	Communication	Officers
Portable Radio	Communication	All
Thermal Imaging Camera (TIC)	Mission Tasks	Lieutenant/Team
Self-Contained Breathing Apparatus (SCBA/" Air Pack")	Mission Tasks/Protective gear	Mission Team
SCBA Tracker	Mission Tasks/Monitoring	Incident Commander

Attitudes Toward Technology

Contrary to the need for flexibility that we noted from both the dynamic nature of incident response and the changes in staffing that may occur, we noticed that participants did not express that current technology reflected these values. Instead, much of the participant frustration stemmed from the inability to use technology that was flexible and mobile to fit with the dynamics of incident response.

> *"Usually we are given a system and it's not perfect. We make the best of it. We have to use it even when it slows us down."-Firefighter*

Some participants felt that these technologies were not appropriately tailored for their job tasks as exemplified below:

> *"Much of the technology we have was created for the S.O. [Sheriff's Office]. They just put a firetruck icon on it and hand it to us. There's not really much consideration about what we do."-Firefighter*

Generally, attitudes toward technology indicated ambiguity surrounding needs. On one hand, firefighters across all ranks expressed that technology was necessary to carry out their job tasks. However, some company officers indicated annoyance and irritation with new systems since they were often unreliable. Although there are electronic rosters, one chief felt that the traditional methods were more reliable since there was less of an opportunity for error:

> *"I prefer to stick with the things that work. My whiteboard with all the staffing details does not fail."-Chief*

Additionally, new technologies such as the automated dispatch system tended to fall short of expectations due to flaws with the system, causing negative perceptions of some of the newly integrated technologies.

> *"The automated voice that provides dispatch information is irritating at times. She often mispronounces things like the abbreviation for "drive" as "doctor." -Captain*

Usability Concerns: Data Inaccessibility and Capability Gaps

A majority of the devices the firefighters used in this sample were not entirely mobile or portable, see Table 5 above. The MDC is not actually completely mobile; it is typically mounted in the vehicle. Therefore, it presents issues with regard to functionality. For example, one Lieutenant commented:

> *"A command tab exists on the MDC for planning. But since the MDC is not portable, no one uses it. It would also require maintenance of another module." - Lieutenant*

A seemingly useful opportunity for planning or visualizing information is missed when a tool is not functional in the environment for which it will be used in. This command tab is not useful if the computer cannot be removed from the truck or if the MDC loses connectivity since new information cannot be added into the system.

Some of the participants on shift expressed that their needs were not currently met due to lack of features related to current technology. It was apparent that the radio was a source of frustration, but also a necessary form of communication. The lack of multiple input capabilities made it challenging since only one person at a time can "talk" on the radio. The quote below indicates that firefighters sometimes struggle with this bottleneck in communications.

> *"It's like talking through a straw [on the radio], one at a time, that makes it impossible."-Firefighter*

To illustrate another example, the officers on scene indicated a need for higher level information. Chiefs and captains expressed a desire for streamlined information that could be quickly visualized.

> *"Something that gives an overhead view would be important, but it does not exist. I can pull an overhead view on Google maps, but it's usually a picture from two years ago..."-Chief*

> *"Give me a report, I can send more stuff that way if it sounds like that is where the threat is, I need this kind of [summarized] information..."-Captain*

"It would be beneficial to have a quick picture and summary for size-up. If there was a way to summarize this information, more people would use it. It's also an issue of accessibility. I have to pull up a separate network just to access these plans. You don't have that kind of time to spend 15 minutes trying to get to a plan."-Captain

It was apparent from the field study observations that firefighting involves tasks that require heavy reliance on visual information. This includes line of sight information, as well as signaling and artifacts that manage the number of people on scene, air pack utilization, etc. Despite this, much of the technology used in firefighting does not present information in a way that easily consumed visually. For example, the MDC presents information in paragraph form and radio communications are exclusively auditory. Of the technologies that do present information visually, they are often cumbersome and difficult to use. Most notably, the MDC map only shows directions from a northward orientation. This means that when navigating, the firefighters must translate all the directions from north to get to the scene. This is a poor allocation of resources and visual attention because there is technology readily available to mitigate this capability gap. As one participant captured, there are too many interfaces for the incident commander to allocate attention to:

"You really need someone like a scribe or assistant to monitor the pack tracker (Self Contained Breathing Apparatus, SCBA) interface" –Engineer

Additionally, some participants identified capability gaps related to a lack of visual information. For example, dispatch can describe a picture of a motor vehicle accident scene taken through a red light camera to the incident commander over radio, but currently, in this department, there is no capability to send the picture to any arriving units or line officers directly.

"[For traffic accidents] Dispatch has control of the red-light cameras but they cannot send us the picture. So, they have to describe what they see. It would be nice if we could see the accident scene before we get there." –Chief

This also affected the ability for officers to plan strategies and prioritize tactics since information could not be easily accessed via the MDC interface.

System Failures and Coping Strategies

All (35) of the fire team participants reported at least one technology/device failure that is routine and occurs daily. Of these reports, the majority cited the MDC is as the piece of equipment most likely to fail. From observations, one call was missed by leadership due to lack of signal in the fire station. Additionally, the MDC experienced connectivity issues the entire shift. Judging by the more experienced leadership's reactions, it was completely normal for these failures to occur. Many firefighters expressed frustration with the failing tools and recently implemented technology. The more experienced leaders found methods of their own for coping with repeated issues.

"I have to keep a separate flash drive with information about local schools on them. Relying on technology that typically fails [the MDC] is not a good plan." -Chief

System failure emerged as one of the most frequent and rich codes in our analysis. Relying on errant technology creates a frustrating and stressful user experience. Using outdated technology or equipment that continuously fails does not support their mission and increases opportunities for error. We noticed this theme to be prevalent due to the disjointed systems that the entire fire battalion uses.

"When I can pull the information up, it is nice, but that is rare." -Chief

In addition to the implications for incident response (slower response times, less accurate coordination), these points of failure seemed to suggest that the firefighters in our sample believed their job functions came as an afterthought rather than a priority.

"For mass casualties/large scale incidents with 5 or more people wounded, it [the MDC] will usually provide you with a list of available hospitals. This feature [hospital suggestion] is sometimes down which complicates situations. Now I have to radio all the hospitals."-Chief

Several team members came to accept that sometimes failure was inevitable, and they needed to rely on other means for getting updated information, such as the radio.

"No way to know when system connectivity is lost because the MDC does not alert you."- Chief

This is also apparent when the radio and MDC provided conflicting information. For example, there was one instance during the observation shift in which the chief was canceled on the call. The MDC connectivity was lost, so the computer did not update this information. When you are operating a vehicle at sixty miles per hour and also listening to the radio and reading the MDC, this poses significant risks for not only the officer operating the vehicle, but also for the civilians on the road. Consequently, technology has the potential to compromise scene safety.

DISCUSSION

Emergent themes surrounding the lack of cohesion with the technical system provided support for the idea that both the *social* and *operational* environment place demands on the *technical systems*, which are not sufficient in their current state. We noted that the technical system comprised of disparate systems that evoked feelings irritation or annoyance, negatively impacting user perception. This theme was pervasive across all ranks, but more so at the higher-ranking end of the command structure. We interpret this as an artifact from expertise, since captains and chiefs typically have years of experience and have witnessed the changing dynamics of emergency management technology over a large period of time.

Based upon our findings, our contributions are two-fold. First, we contend that identification of existing problems can lead us to better understand the needs of firefighters *independent* of current systems, which is important for understanding how to create new technologies that support the work domain of firefighting. Second, we contend that a richer understanding of the sociotechnical structure surrounding the fire department's operations allows us to better address the *gaps and deficiencies* identified in this paper:

People (Individual & Social)

Upon analysis, our data is aligned with the idea that multiple users have different needs from the MDC. In its current state, the MDCs in this department were not sufficient for incident command and often frustrated the engine companies who were attempting to perform simple tasks such as navigation or pulling up planning information. The use of GIS-based systems has been suggested as a lower-cost solution for displaying information to crews and increasing interoperability (Abdalla et al., 2007). However, we recognize each department will have different needs.

Additionally, one of the major findings of this study indicated that back-up systems typically did not involve technology and were sometimes preferred over the use of current systems, depending upon user attitudes and values. One of the ways to mitigate negative attitudes toward these technologies is to consistently gather user input and provide ways to leverage existing, reliable, and lower-cost technologies that can be adapted for the fire service. For example, replacing MDCs with tablets, or augmenting MDCs with tablets, is an easier way to increase functionality. Small solutions such as implementing tablets or changing the mobility of the MDC could have a positive impact on user experience, enhancing productivity and safety. However, due to the complex nature of funding, such changes are not easily implemented. This is particularly true when a department is navigating several risks at once, they must choose between updating MDCs or purchasing a second set of turnout gear to reduce risk of carcinogen exposure. Additionally, environmental factors such as increasing resources, connectivity, and interoperability could increase trust in these technologies, thus aligning user values to match the system and reducing frustration or error. We elaborate on these points below.

Environmental

Incident response requires the ability to quickly adapt to changing conditions. Additionally, now more than ever before, firefighters are dealing with what are known as potentially violent situations (PVS). As a consequence, protocol now requires firefighters to wear protective gear on scene and stage where necessary. This fundamentally impacts operating procedures since scene safety must be conceptualized differently and prioritized in a way that has not been previously addressed. More importantly, the current technologies used by the fire engine companies created tension due to the conflicting information needs and the multiple functions the MDC must fill. Not only must it update with current information, but static information, such as planning or inspection data, also needs to be accessible on scene. Increasing connectivity and providing further resources such as unmanned aerial vehicles and other emerging technologies could enhance user experience and support firefighters operating in complex and dangerous situations. The use of dedicated broadband networks and increased connectivity could facilitate more reliable technology. Finally, we elaborate on this at the organizational level as well, since firefighters are dealing with increasingly different and dynamic incidents.

Organizational & Activity

Although there have been strides made in understanding firefighter communication and coordination across the team, relatively few papers have exposed the research-practice gap that exists in a majority of the United States. That is, although we are designing and evaluating emerging technologies for use in the fire service, the majority of departments are severely understaffed with limited budgets. Although the necessary capabilities may exist, little work directly acknowledges the fact that most departments are not even operating with current technologies available.

For example, the department we evaluated consistently cited cost and budget as one of the limiting factors preventing the use of certain functions on the MDC and the use of upgraded technologies. Once a software product is purchased, much of the budget is spent on maintenance, rather than increased functionality. As a result, this department suffers from a lack of interoperability and is challenged with making the best of the resources available to them. In addition to technology, we also found that staffing/administration, time, response area type, and budget all play a role in the adoption and maintenance of technological systems. Perhaps one of the more interesting findings has to do with the way modern dispatch systems and technologies were developed from the needs of law enforcement (Brenner & Cadoff, 1985). This is still a current issue and these technologies are often later transitioned by manufacturers and implemented in fire departments without much consideration for fire-rescue teams who ultimately serve a different function than law enforcement. One common pattern that emerged in our research was the reiteration that fire response and law enforcement have two separate job functionalities. Despite this, there has been a movement to increase interoperability between law and fire in the form of rescue teams (Marino et al., 2015). As a consequence, these changes require reevaluation of current systems, to accommodate the changing interagency and multiagency response needs.

There are several limitations of this study that impact the generalizable content of our results. First, we did not survey multiple fire departments across the United States. While we recognize that this does not necessarily mean our work generalizes to all U.S. fire departments, we can say that our study supports prior work and seems to be aligned with most common practices in major fire departments (Dawkins et al., 2018; Jiang et al., 2004). Additionally, we were able to assess two different agencies within the same region, which enhanced the findings. However, it should be noted that in more rural parts of the country, volunteer firefighters are more prevalent. This poses safety and training challenges beyond the scope of this paper. Further research must be conducted to determine how the needs of volunteer fire departments can be addressed. We plan to leverage this data to inform the design process for both hardware and software prototypes in the next iteration of our study. By focusing on all ranks in the command structure, this work has directly pointed out where HCI practitioners, designers, and researchers can focus further investigations to enhance the user experience of firefighters across all ranks using the same systems.

CONCLUSION

In our study, we found that the technology firefighters depend upon is not reliable or configurable in its present state. The results of our work suggest that the dynamic and frequently changing operational environment needs to be reflected in the systems firefighters use to better support them in their day-to-day tasks. Furthermore, we noted the perceived needs of the firefighters across all ranks did not necessarily match the current systems they depend on. We contend that by using a cognitive systems driven approach that themes emergent from observations and qualitative data collection provide valuable insight. The goal of this work is to leverage this data set as a foundation for further research in building more resilient and adaptive systems for first responders.

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