CO-ADAPTIVE SYSTEMS IN URBAN FIREFIGFHTING:

A SYSTEMS ANALYSIS OF COORDINATION BREAKDOWNS

A Thesis

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ABSTRACT

The management of complex systems can be quite difficult given the dynamic nature of systems and due to a large web of interdependencies. Nearly all domains will utilize some sort of joint activity, but the coordination across the different aspects of joint activity becomes increasingly difficult when the situation is high tempo, high risk, and constantly changing. It is important to understand the problems that can arise from such a system in order to help those within the system perform better and safer.

The overall goal of this project was to observe coordination problems in a specific kind of co-adaptive system in order to develop design concepts and principles. Urban firefighting was chosen because the domain exemplifies many of the challenges of coordination in high tempo and high risk situations.

Incident Reports were gathered from a major metropolitan fire department and interviews were conducted with the Columbus Fire Department to assemble a collection of case studies that displayed breakdowns in coordination during actual incidents. Based on an analysis of these cases studies, the following were found to contribute to coordination problems: communication problems, poor control, information overload, loss of situational awareness, and poor adaptation to new events. Key requirements for developing a system to combat these problems include supporting – integrating different

perspectives, proving shared location knowledge, facilitating anticipation, facilitating adaptation to new events, and providing multiple forms of communication under highly constrained conditions.

With these improvements, the people, teams and functional roles will be able to collaborate and perform more effectively. The key performance goal is to reduce conditions where teams act in locally adaptive ways but miss changing interdependencies so that their behavior is maladaptive from a more global perspective. Urban firefighting, however, is not unique and the challenges of coordination in these complex systems are ubiquitous to any domain that involves joint activity under pressure. Therefore, key requirements identified in this study can be applied in multiple domains.

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CHAPTER 1

INTRODUCTION

Highly integrated, fast paced and constant change are all phrases used quite frequently to describe systems in our world today. Consider the worldwide economy where it is a large system with interdependent entities that have to respond to changes quickly. Just the virtually instantaneous availability of information about new events, means that critical data such as the stock prices of companies all over the world can be tracked every second by individuals, and the prices of stocks can fluctuate almost in real time to events happening around the world.

Managing these complex systems with a large web of interconnections can prove to be quite difficult given the dynamic nature of these systems (Woods and Branlat, 2010). Almost all domains will have some sort of joint activity that occurs or activities that are distributed over a multi-echelon network of interdependent human-machine roles, but the management of this joint activity becomes increasingly difficult when the situation is high tempo, high risk, and constantly changing (Klein et al., 2005). Given the numerous interconnections and the difficulty of managing joint activities, it is important to understand the problems that can arise and develop new designs to support their joint activities and prevent breakdowns.

Urban firefighting is one domain that involves high tempo, high risk and constantly changing situations in fighting fires or responding to a disaster (Fern et al., 2008). Firefighters have an interesting challenge as Branlat and colleagues describe the main purposes of urban firefighting as follows (2009): "Fire operations aim at fulfilling two main goals: saving lives and protecting property. Given the nature of the environment, managing the risks to which firefighters are exposed becomes another fundamental goal. These three goals are highly intertwined, as difficulties or failures to fulfill one of them have important consequences on the others." There is a potential for goal conflicts and working at cross purposes within urban firefighting. Such conflicts arise especially when coordination breakdowns occur, such as when companies lose track of their respective positions on the scene or when they no longer have a shared understanding about the situation at hand (Branlat et al., 2009). When these occur, time is lost and opportunities for improvement are lost and this could lead to potentially fatal consequences.

This study shows that urban firefighting is a kind of co-adaptive system where interdependent activities must remain synchronized as new events occur in the situation and the coordination of this joint activity has to occur in a very demanding environment given the special challenges fires and hazardous materials create.

Urban firefighting, however, is not unique and the challenges of coordination and resilience in these complex systems are ubiquitous to any domain that involves joint activity and widespread interdependencies (Voshell et al., 2008). Therefore, the findings from this study can be applied to similar domains, though urban firefighting provides many case studies that demonstrate how coordination problems arise because the interactions play out on a manageable spatial and temporal scale.

The overall goal of this research project was to observe coordination problems in one kind of co-adaptive systems in order to develop design concepts and principles to combat observed problems. The methodology for the research project consisted of a series of steps. The first step was to first gain an understanding of co-adaptive systems and joint activity through reading textbooks and technical papers that describe the principles and philosophy of understanding such systems (e.g., Klein et al., 2005; Woods and Hollnagel, 2006).

Next a domain was to be identified that exemplified problems in coordination of co-adaptive systems. Urban Firefighting was chosen due to the high tempo high risk, high variability, and constant change associated with each incident as well as the large availability of information about incidents that had occurred. Also, the high risk/high stake nature of urban firefighting increases the cost and impact of failure where any improvements could be significant and save lives, therefore any progress towards a safer system would be meaningful towards any stakeholder in the system. The high tempo of each situation creates a system where problems will occur very rapidly and therefore more easily observable than other domains due to the small temporal scale. The high variability of each incident and the constant change during the incident forces fire fighters to adapt to every situation which reiterates the importance of this research and determining what coordination problems can occur. Each level of the response system demonstrates some ability to use their skills, standard operating procedures (SOPs), and physical resources to adapt their behavior to handle the changing demands of the situation. Each firefighter, each team, and the Incident Commander are all adapting at different levels in order to pursue their goals based on their own knowledge and awareness of the situation. These interdependent activities make this a co-adaptive system.

Third, Columbus Fire Department SOPs, training manuals, technology guides, and strategy books were reviewed to learn the domain of urban firefighting. Incident reports from a major metropolitan fire department were gathered and interviews were conducted with the Columbus Fire Department in order to identify specific examples of coordination breakdowns within the domain. A subset of the cases was chosen that exemplified coordination breakdowns and were analyzed further. From this analysis, design requirements were developed to help combat the identified problems that occur within this kind of co-adaptive system.

This paper documents the research process used to identify existing coordination problems within the domain of urban firefighting, and the findings about methods, technologies, and requirements that can be used to overcome these problems. The problems in coordination arise because each entity within the system needs to be able to adapt locally to the situation in front of them, but then there is a need to synchronize and connect their responses with what other teams are doing and with the actual situation to create a globally adaptive response to the overall fire situation. The requirements produced by this research project can then be applied to other domains that involve joint activity as well.

CHAPTER 2

SYSTEMS

This chapter will describe the properties of systems and briefly describe how those relate to urban firefighting.

2.1 What is a System?

Classically, there are three main aspects to modeling how a highly coupled system functions. First, a system's behavior emerges from the interactions between its parts. Second, important interactions occur across levels or scales. Third, how the system of interest is defined depends on the perspective and purpose of the analyst.

The first aspect of a system is that it cannot be composed of a single entity in isolation but a collection of entities that synergize their actions to perform work that is more than just the sum of the system's parts. Systems are dynamic in that the entities are changing and sometimes unpredictable. This leads to interactions that emerge from the collective actions of these entities and it is this emergence that defines the system.

The interactions in the system, however, can be across multiple levels or scales. There are multiple levels or echelons that consist of the entities within the system all of whom are stakeholders of the system. The multiple scales of interactions mean that interactions can occur at one level between individuals within a team or another broader level between multiple teams. Each of the levels of entities has a goal for the system because they are stakeholders and these goals can be consistent or conflicting. Since there are multiple objectives, the people who have a stake in the performance of the system will want to control the system to meet their objectives. However, this can be difficult because systems can be quite complex and without a good knowledge of the whole system it cannot be completely controlled.

Since stakeholders would like to control a system to meet their goals, proper perspective is required. However perspective is limited: “the view from any single point of observation simultaneously reveals and obscures” (Morison et al., 2009). This means that there is no one single perspective that is best to fully understand a system, the contrast between multiple perspectives must be considered. Having multiple perspectives is important when the goals of different stakeholders can conflict because the multiplicity of views will provide a systems perspective to reveal what is globally adaptive behavior and to avoid local behaviors that work at cross purposes.

2.2 Agents and Cognitive Agents

There is a clear difference between an agent and a cognitive agent. Orlin Vakarelov, describes cognitive agents very elaborately: “Cognition is the set of the mechanisms/organizational constraints of an autonomous agent that allow lowering of the conditional information entropy of selected important informational sources in the environment on the control structure of the agent, so that the agent can improve the selection of actions to produce successful behavior in light of its information gathering and carrying limitations” (Vakarelov, 2009).

Essentially, an agent is an entity that can interact with the system creating some effect. A cognitive agent on the other hand has the ability to learn from previous behavior, to adapt and use its knowledge in the pursuit of goals. Firefighters would then be classified as cognitive agents in this system.

2.3 Emergence

Emergence is the behaviors and patterns that appear in complex systems whether through reactions to other entities actions or coordination of activities. Jeffrey Goldstein defines emergence: "the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems." He continues to say the common characteristics are, "Radical novelty, coherence or correlation, a global or macro level, it is the product of a dynamical process, and it is ostensive" (Corning, 2002). Those characteristics define emergence, but a more important question is how and why emergence occurs?

Emergence occurs because of the interconnectivity between entities within a system. These connections, though, can be intricate and complex which makes predicting the emergent behaviors difficult. Consider an ant colony with thousands of ants and all the interactions that occur between the ants. It would be impossible to predict exactly where the ants will create the tunnels in their colony but there is still the emergent behavior that occurs when they collectively work together to build these tunnels.

However, Herbert Simon would say otherwise in that the ants only appear to be complex creatures. He describes a situation where an ant is walking along the beach in a winding complex path. One could say that the ant is performing a complex task of trying to cover the most ground in search of food or is trying to find its way home. However, the ant could be instead performing a much simpler task of walking in a straight line and if something is in its way, it must turn to keep walking. The ant's emergent behavior is quite simple and it is the environment that proves to be quite complex (Simon, 1969). This example shows how a relatively simple way of thinking helped the ant through the complex environment.

The complexity of the interconnections or the number of interconnections can still make it difficult to view emergent behavior. If we look at a table, we may just see a table, but the table exists due to the emergent behavior of the interactions from the atomic particles. Mark Bickhard and Donald Campbell discuss this saying: "Perhaps the properties of the table, and even the existence of a distinct object that we call a table, are all just *epiphenomenal* to the fundamental particle interactions" (Bickhard & Campbell). So even though we cannot physically see the interactions occurring, we see the emergent behavior of those interactions between particles which constitute the properties of the table.

Essentially emergence is the perceived properties and patterns during the process of self-organization in systems. These properties and patterns are due to the complex interactions between entities that can be random, reactionary, or coordinated. Interactions can also occur across different levels of entities in the system. It is still difficult to observe interactions and emergent behaviors on a small or large scale because the properties or existence of the object are more easily observable.

2.4 Surprises

The hardest part of controlling complex systems is that no one can fully understand the complexity of the system. The numerous interconnections means there can be multiple variables influencing the behavior of the system and you cannot take into account all of these variables when trying to predict what will happen in these systems. This is when surprises are most likely to occur in complex systems, when people don't fully understand the interconnections.

However, the cause of surprises is the unpredictable nature of a system due to the variation and the complexity of the interconnections within the system. Variation amongst entities, variation of the interactions between the entities, and variation within the variation makes it impossible to fully predict but also control the system.

Surprises can be difficult to handle depending on how much of a surprise the event really was or how much it actually varied from expectation. The thing is we will never know how people will react to a surprise because that is by nature what a surprise is, something that is unknown. We can prepare and predict and try to control complex systems as much as we want but because of the inherent variability of our world there will always be surprises.

CHAPTER 3

URBAN FIREFIGHTING AS A SYSTEM

From the previous section we discussed how a system is a collection of agents with emergent properties due to the interactions between the agents. These interactions occur across scales but which are important depend on the perspective and purpose of the agent. Now, I will discuss how these systems properties relate to urban firefighting.

3.1 Goals

Firefighters and Incident Commanders are agents at different levels within the system each with their own goal and perspective on the situation. The overall system goals as seen by from the Columbus Fire Departments SOPs are:

> "1. LIFE SAFETY: (first priority) The Incident Commander must consider life safety issues for all fire fighters, other emergency workers, occupants and bystanders at an incident. No property is worth the risk of even one life. Life safety must come before all other considerations.
>
> 2. INCIDENT STABILIZATION: (second priority) The Incident Commander must develop the command structure and strategy to stabilize the incident. The command structure must match the complexity of the incident, not the size.
>
> 3. PROPERTY CONSERVATION: (third priority) Property conservation at an incident means achieving our goals and objectives while minimizing property damage. No incident can be considered successfully managed if property conservation is not given proper consideration and implemented in a timely manner." (Columbus Ohio Division of Fire, 1998)

The stakeholders within the system all share these common goals between each other, but the priorities across them can vary from situation to situation or during a single fire response. The next section will discuss how the goals at the individual level may come into conflict because each firefighter has an individual role that requires synchronization with others to avoid working at cross purposes.

3.2 Individual Company Roles

At an incident there are multiple teams or companies working together to complete smaller goals in an attempt to accomplish the overall systems goals described above. Roles are broken down into engine and ladder companies where engine companies work to extinguish the fire by managing the delivery of water to the fire and ladder companies perform search and rescue, ventilation, and forcible entry.

The order in which units arrive on scene determines what roles the team is supposed to fulfill. The first engine on scene is in charge of laying out hose and beginning to attack the fire while the first ladder on scene is in charge of working on the fire level floor, with the first responding engine company, venting and performing search and rescue operations. Subsequent arriving units are given separate roles either supporting the companies already working at the scene or working in a different area than the other companies. For example, the second arriving engine company supports the first arriving engine company in stretching their hose line before they set up a second hose line and the second arriving ladder company will perform search and rescue operations on the floor above the fire level.

Within each company there are four to five firefighters as well as an accompanying officer who is in charge of making decisions for the company and keeping in contact with the incident commander. Each individual is assigned a role that they are responsible for in order to accomplish the higher team goals. The engine companies have individual roles such as chauffeur, nozzle, and backup nozzle that help with accomplishing their higher unit goal of water management and putting out the fire. The ladder companies have individual roles such as roof, hook, and irons that work towards their higher unit goal of forcible entry, venting and search and rescue.

This isn't to say though that the engine roles are independent of the ladder roles. For example, the engine company cannot put water on a fire inside a building until the ladder company has completed forcible entry if it is required. Therefore, there are interconnections and interdependencies that exist between not only individuals within a team but between teams as well. In fact, there are numerous interconnections between other levels or echelons of the system where the individuals interact at the lowest level between each other, teams interact with each other, teams interact with the incident commander, and the incident commander interacts with any outside entities such as dispatch.

The incident commander is a unique role though because they are an individual role but the types of goals connect to higher level system goals. Incident managers are in charge of managing the goals and emergent behavior of the system through constant assessment and reassessment. Typically, the first officer on the scene of an incident will assume the role of incident commander until a superior officer arrives on scene and command is transferred. Sometimes, though, due to staffing limitations the first officer must go with his team and perform his individual role while still being the incident commander. This is not deemed a safe practice but still happens because of the resource limitations. The importance of having an incident commander is shown in the Columbus Fire Department's SOPs,

"The one function that will always be filled at every emergency incident, regardless of size, is the Incident Commander's (IC) position. The IC has the responsibility for overall management of the incident.
Incident command procedures are designed to accomplish the following:

A. Fix responsibility of command with a designated division member through a standardized identification system, based on arrival sequence and other variables.

B. Insure that visible, direct, effective command be established as early as possible upon arrival at the incident scene.

C. Establish an effective framework within which the activities and responsibilities assigned to the Incident Commander can be properly addressed.

D. Provide a system for accomplishing the orderly transfer of command from the initial Incident Commander to later arriving division officers."
(Columbus Ohio Division of Fire, 1998)

Incident command is an important role to be filled but each firefighter also has a role as well such as nozzle man, chauffeur, or door man, which they are expected to perform in conjunction with other firefighters to accomplish the higher level goals. Each individual and team has the ability to adapt but it is through each individual's constant assessment and reassessment of their current status and the system status that they are able to adapt effectively.

3.3 Goal Conflicts

Problems with coordination can be seen here because the potential for goal conflicts exist. Cross purposes are described by Woods and Branlat as the "inability to coordinate different groups at different echelons as goals conflict. As a result of miscoordination the groups work at cross-purposes" (Woods and Branlat, 2010). The Columbus Fire Department SOPs even infer the potential for goal conflicts and specify the need for coordination to reduce them. They state: “The timing of ventilation becomes extremely important and must be coordinated with fire attack activities. Ventilation should be provided in advance of attack lines.” (Columbus Ohio Division of Fire, 1998) This coordination is also made more difficult due to the high tempo of the situations and the multiple levels within the system where the interconnections may not be apparent.

These goal conflicts may not be visible in every situation because the SOPs have been developed as a resource for matching tasks with demands within normal operations, but as stated in the previous chapter, surprises are inevitable in complex systems especially when operating at the boundaries of a system. Therefore, goal conflicts are inevitable because of the adaptive behavior that is built into the system with the training and SOPs firefighters utilize to combat the variability of each situation. The high risk associated with each situation makes being prepared for surprises important because it could mean that lives are saved.

3.4 Managing Emergent Behavior

The incident commander’s role could be better described as managing the emergent behavior of the system. The best way to control the system, so the system goals are met, is through coordination and collaboration of the interdependencies and goals of the agents, roles, and teams that make up the response system. Therefore, the incident commander needs feedback from the system in order to anticipate all the potential consequences. The feedback available to the incident commander, as described by the Columbus Fired Department SOPs, is as follows:

“There are three basic sources of information available to the Incident Commander during an emergency.

1. PRE-PLANNING AND FAMILIARITY INFORMATION: These factors include intelligence that is gained by inspections and general familiarization activities. Such intelligence increases the information initially available to the Incident Commander.

2. VISUAL INFORMATION: These factors include those obvious to visual observation. This visual information is categorized as the type that can normally be gained by actually looking at a situation from the outside. This form of intelligence involves the perceptive capability of the Incident Commander.

3. RECONNAISSANCE INFORMATION: These factors include information that is neither preplanned nor visually available to the Incident Commander. This information must be gained by actually sending someone to check out, go see, etc., or by gaining the information from other personnel on the scene."
(Columbus Ohio Division of Fire, 1998)

This information is not readily available to someone who would have just arrived on the scene. There is local knowledge but the lack of sharing that knowledge leads to fragmentation and is a source of coordination breakdowns. Any complex system performs more effectively when there is synchronization across all levels of agents.

In order to allow for highly synchronized joint activity, firefighters therefore have to rely on coordination mechanisms that will help maintain or restore this type of shared knowledge" (Branlat et al., 2009). The research on joint activity (Klein et al., 2005; Woods & Hollnagel, 2006, chap. 8) describes fundamental coordination principles through various concepts (e.g., common ground, observability, inter-predictability) that directly point to these information needs.

All entities in the system must be able to recognize the signals that things are deteriorating and relay this information to the rest of the system. This allows the rest of the system to adapt to this new information and stay synchronized. This is especially important when operating near the boundaries of the system because SOPs cannot describe what to do in every single situation. The system can be described as brittle because it falls apart quickly when it operates near the boundaries of the system. It is important then that the incident commander must not fear new situations or problems but realize that there will always be problems and that they are ready to adapt and find solutions to the problems.

Griffiths describes: “The first-level chief must use his resources effectively, whether personnel, equipment, services, or pre-planned procedures… No matter what the assignment, the battalion chief is the initial focal point of fireground management, and he must know his resources and be prepared to use them effectively in a changing environment” (Griffiths, 2005). So in being able to manage, adapt, and create the desired emergent behavior of the system, the higher system goals can be met more effectively.

CHAPTER 4

CASE STUDIES

This section will provide summaries of 3 cases from incident reports and 2 cases from the interviews that exemplify the kind of problems that exist within a co-adaptive system. A collection of quotes, that did not pertain to a specific case but were still deemed relevant and within the scope of the project, are included from an interview with an incident commander. All 8 summaries of the cases from the incident reports, the 3 cases from the interviews, and the quotes from the interview with the incident commander are included in Appendix A. Interviews were conducted with the Captain and firefighters at Station 34 of the Columbus Fire Department according to the cognitive task analysis methods described in Working Minds (Crandall, Klein, & Hoffman, 2006). The incident reports were gathered from a major metropolitan fire department but specific references to those involved are omitted. Also, the systems principles each case highlights are briefly summarized after each case.

4.1 Cases from Incident Reports

This section contains the cases summarized from incident case reports gathered from a major metropolitan fire department. They are the result of a rigorous in depth investigation of incidents that resulted in serious injuries or death of firefighters.

Incident Report Case 1:

Two teams of firefighters, Engine 1 and Ladder 1, initially entered the front of a building to fight a fire. The Engine 1 team was then redirected to the rear of the building to attack the fire from a different angle. Ladder 1, in the front of the building, was unaware of this change in tactics which should have prompted them to evacuate the front of the building as well. This, however, resulted in heat being pushed to the front of the building where the Ladder 1 team was still operating. With the rising temperatures they tried to evacuate the building but one firefighter was knocked back and became unconscious, thus trapped in the heat. Engine 1 was still operating in the back pushing heat forward, unaware that a firefighter was trapped inside the front of the building. The firefighter was rescued but sustained severe burns.

There is a miscommunication between the teams that leads to a failure to synchronize activities. The ladder team would not have stayed in the front of the building if they had known that the engine team was moving to the rear of the building to operate. Also without proper knowledge of the locations of the agents neither the teams nor the incident commander was able to adapt behavior in time. They were under the assumption that all entities were performing their roles according to the same operational plan, but shared knowledge about the strategy and about each other was actually not maintained.

Incident Report Case 3:

A fire was occurring in the cellar of a hardware store which was connected to another building next to it. The two buildings had been modified and opened up to each other on the first floor and cellar levels. Two Engine teams were operating at the scene and stretched one hose lines to an interior stair well to the cellar staircase, whereas the *other hose line was stretched to a rear exterior cellar door. The rear cellar door was deemed to be a safer path to attack the fire but it was unconventionally secured which required a Ladder team to force entry. The Ladder team spent 25 minutes to open the door, all the while no water was being put on the fire. Shortly after the door was opened, an explosion occurred causing the exterior wall to collapse on two fire fighters outside the building killing both. Another firefighter inside the building was thrown down the cellar staircase and rescue efforts were unsuccessful to reach him before he succumbed to his injuries.*

The incident commander was stuck in same course of action and unable to adapt to change his plan according to new information that was available. One possible interpretation of this scenario is that he had an opportunity to find out more about the fire from the team operating on the inside the building but failed to utilize this. Due to the struggle with gaining access through the outside door, more than 20 minutes elapsed before any change to the plan occurred and more importantly this delay allowed the fire to grow because no water was being put on the fire. This is a rather large amount of time for events to occur compared to other fire incidents where events happen in a matter of minutes. Since the incident commander insisted on waiting to enter the basement from the outside route, he showed persistence to stay in the same course of action even though there was a possibility to observe what was occurring in the basement from the inside and adapt by modifying the current course of action to better fit the actual circumstances.

Incident Report Case 8:

A fire was occurring in the cellar of a two story house with two Ladder and two Engine teams operating. The two members from the first due Ladder team moved into the *cellar to find the fire while the first due Engine team worked on stretching the hose to the cellar. The Ladder team made its way to the bottom of the staircase, which had a half landing where the Engine team began operating the hose. The Ladder team decided to leave the cellar but had difficulty doing so due to the congestion on staircase from the Engine team. At this point the both team left the cellar because in the congestion some of the firefighter's masks had been knocked off. However, once outside the Ladder officer realized one of his firefighters was still in the building. They found him unconscious still in the stairwell but he eventually succumbed to his injuries.*

Goal conflicts between the ladder and engine companies emerged which lead to a poor outcome. The ladder team began to search for the fire in the basement but their only egress route was up the staircase which had a half landing. They did this though without giving consideration that the engine company would have to come down the same set of stairs to put out the fire. When the engine company began to operate from the half landing on the staircase, it made the difficult route up the stairs partially blocked as well. So the goals of the ladder team to find the fire conflicted with the goals of the engine company in putting out the fire because the environment did not provide a safe egress route for the ladder team.

4.2 Cases from Interviews

This section contains cases summarized from interviews conducted with firefighters from the Columbus Fire Department. The interviews followed the cognitive task analysis methods described in Working Minds (Crandall, Klein, & Hoffman, 2006). The interviewees were asked to describe situations that they had encountered where things went wrong or not according to plan and adaptation was needed to achieve their goals.

Interview Case 1:

The Engine team had responded to an incident but the Ladder team had not arrived yet. The Engine team then had to return to their apparatus to get tools to force entry instead of waiting for the Ladder team to arrive.

The Engine team had to adapt because they were operating at the boundaries of the system which was a different scenario than the SOP describes. This shows that there is an assumption with the SOPs that each entity is performing their role but the SOP doesn't account for adaptation that occurs or needs to occur when someone is not capable of performing their role. The incident commander needs to be aware of this and able to reassess the situation in order to reallocate resources to still meet the system goals. In this case, this meant the engine team would have to force entry before the ladder team arrived. This shows that synchronization is necessary for the system to perform effectively, because the engine team loses valuable time in trying to put out the fire by having to go back to the truck to get tools to force entry.

Interview Case 2:

An Auto body shop was on fire and the responding Ladder team had begun to perform a search. Under very limited visibility and following SOP for searching a room under these conditions, a firefighter was crawling along the wall and discovered the fire in offices and radioed this information to the Engine team. He continued his search along the wall but could hear the fire growing behind him; this meant he could not return that way to escape the building. If he tried to return to his entry point the only available route *was to make a left and go across the middle of the room, but it is easy to get lost under the reduced visibility conditions. Given the situation, he needed to find an alternative exit route. He started to hear pounding on a door in the rear, so he continued to crawl along the wall towards the noise which was a back door being opened by other firefighters.*

The firefighter had to adapt to the situation because the fire was blocking his route of egress. The information update about the location and extent of the fire also told him and, critically, told the other firefighters that his expected route of egress was blocked. The others could then anticipate that he would be looking for and would need an alternative route as he completed his search task. Given how search tasks are supposed to be performed and given the building layout, the other firefighters expected him to behave a certain way – in completing his search he would be along the back wall of the structure. They acted both to provide a way to exit the building and were pounding on the back door to provide a signal so he could find that exit. This case shows the connections between groups carrying out tasks as they adapted to the changing situation (fire in the office area), to new events and information (exit route is blocked), and to the expected response of other agents (he would be along the back wall) so as to anticipate and adapt to prevent risks of injury to the one firefighter.

4.3 Findings from Interview with Incident Commander

This section contains a collection of findings (in the form of direct quotes) from an interview with an Incident commander from the Columbus Fire Department. The interview was conducted in the same manner as described in the previous section. The results did not take the form of specific cases but rather identified different factors that are important to coordination and adaptation in urban firefighting.

As chief on the scene,

-*"All you can do is observe and the radio is very inefficient."*

There is a communication problem due to the technological capability of the system which results in the chief not receiving timely and accurate feedback on the situation and activities underway.

-*"Being the chief on the job is frustrating because guys will do what they want and there is no way to keep track."*

Difficulties keeping track of activities, progress or difficulties encountered and how they teams are adapting creates risks for breakdowns in synchronization. The commander encodes this as if being disciplined about sticking to SOPs would allow him to better track what each team is doing (the SOPs would provide a plan structure that could compensate for the difficulties in obtaining timely information updates about progress). However, from the perspective of the ladder and engine teams, they are using SOPs as a resource to handle the actual situation and difficulties they face, as is clearly illustrated in the cases studied. Discipline also could be defined as adapting in a predictable manner and undisciplined could be adapting in an unpredictable manner. This is the requirement for interpredictability defined in previous research on coordinating joint activity (Klein et al., 2005). The information gap this comment illustrates cannot be solved simply by presenting data on where firefighters are located or moving in or around the structure. The key information to be relayed is about how they have to adapt to the situation and which goals are taking priority.

-*"If I have to go into the building I am carrying the TIC, radio, tools, and the hose but I only have two hands."*

There is a resource bottleneck and technology bottleneck. This shows that simply adding another device or technology may not actually expand a firefighter's capability. It is critical to evaluate the new device in the context of all of the demands on a firefighter, role, or team. Evaluating a technology change in terms of potential workload bottlenecks is a standard technique in human-computer interaction and cognitive engineering (Woods and Hollnagel, 2006). When new designs are driven only by technology capability, interconnections can be missed and inadvertent side-effects may arise such as unanticipated workload bottlenecks that produce surprising and negative results that counter balance or undermine the intended benefits of the new technology (automation surprises; Woods and Hollnagel, 2006, chapter 10). In these cases, the new technology may hinder rather than support performance.

-*"I also have no way to track who is on scene or in reserve without sending someone around to get the info or calling dispatch."*

The lack of information about current activities and resources to handle the next event or difficulty that could arise (reserves) limits the chief's ability to adapt to the situation and keep things under control. The information is not readily available and requires an active element where he must seek out the information which competes with other tasks creating potential bottlenecks for IC.

-*"There are 200 channels on the radio but I only use 2."*

There is a problem with information overload, and the chief's ability to monitor all of the channels is nearly impossible.

-*"Try to keep radio use to a minimum and use only when you have completed tasks. However, when something bad happens like someone falling through a floor, the radio chatter gets loud."*

The system does not work well at the boundaries, because the SOPs indicate to stay off the radio as much as possible but when something wrong happens, everyone wants to help or relay information. This information is not being relayed in a meaningful and useful way and contributes to information overload. This information overload bottleneck has been observed before and studies have shown how overhearing systems can be designed to solve the problem (Patterson et al., 2007).

-*"The SOPs are just patterns and we just try to follow the patterns."*

This is one of the main findings from this research project where firefighters adapt to the system by matching patterns to aspects of the situation and then finding workarounds to handle impasses and to take advantage of opportunities to achieve goals. People can recognize patterns very well and firefighters try to operate within these patterns of actions to adapt to the variable types of situations they encounter.

CHAPTER 5

SYSTEMS PROBLEMS FROM THE CASE STUDIES

5.1 Communication Breakdown

One of the main problems as seen from the case studies reviewed in the previous section is that communication is difficult in a high tempo and high risk situation. However, communication is one of the main sources of information for incident commanders. Communication is also hampered by the technology available to the firefighters where it is either not reliable enough or too cumbersome on the firefighter who already has multiple other tools or things to carry around. The radios they use creates an inadvertent consequence of creating a resource bottleneck, however the radio is the main source of information for all agents. The design of any equipment should be to not only to be helpful but useable by the firefighter in all the variations of scenarios that may occur. But the cases show the communication breakdown is more than passing data; the critical information concerns is about how demands are being handled – Are things progressing according to SOPs? Is the situation deteriorating? What new or unexpected demands are being encountered? Are all teams operating on a common understanding? Are the teams synchronized and able to stay synchronized or at risk of fragmenting their activities? Answering these questions requires more than just better clarity or reliability of communication channels. Sharing information runs into the bottleneck that updating others on what you are facing competes with the activities and workload required to actually handle those demands.

5.2 Control

Another problem was not having effective control of the situation because the incident commanders were not the first on the scene. “This unsafe practice occurs when the first-arriving company officer does not take command when he first gets on the scene. This action orientation, instead of initial command orientation, happens because the urgency the fire is creating in the initial stage outperforms the standard operating procedures (SOPs), training, and personal discipline of that officer” (Brunacini, Filing a Flight Plan, 2010). As Brunacini describes in another article, “Having the first arriver become IC #1 eliminates any zero impact period or ZIP. We grab control in the beginning, maintain control throughout, and never lose control” (Brunacini, SOP for Command Function #1, 2010). Control is pivotal in a system because you want to know what the system is doing. With good control you can anticipate what the system is going to do and prepare for it in advance. Good control also means you are weary of over controlling as well. Over controlling means you are being too reactive to each new piece of data just as one can over steering a car swerving from side to side in the road as a series of traffic obstacles are encountered. However, being in good control means you are anticipating and adapting to the changes in order to more effectively manage the coordination within the system.

5.3 Information Overload

The United States Fire Administration states the dangers of information overload by saying, “It is not possible for a single individual to manage the scene, ensure accountability, make strategic and tactical decisions, and monitor one or more radio channels. Even at routine fires the potential for information overload is very real. Chief officers should be provided with aides early in the incident to help them manage communications and other tasks” (USFA, 1999). Managing the flow of information becomes a difficult task when time pressures are added into the situation. As shown in the incident cases, there can be a cascade of events where one event quickly causes another event which causes another event. The demands presented by the specific fire sets the tempo and can quickly lead to information overload because the agents cannot keep up with pace being set by the flow of events. Therefore, making sure that the flow of information is managed so that only the important useful information is presented to the user in sync with the pace of events is pivotal to these kinds of situations (Woods and Branlat, 2010).

5.4 Situational Awareness / Perspectives

Each case study encompasses the idea of maintaining situational awareness and connecting the different perspectives at each level of the system from the individual firefighter to the incident commander. As stated earlier, the firefighting domain is closely related to numerous other fields with high tempo and risk. For example, the United States Coast Guard operates under many of the same principles in high tempo and high risk situations and they teach situational awareness to their recruits to help them with maintain a broad perspective on the changing situation. They define situational awareness as, “the ability to identify, process, and comprehend the critical elements of information about what is happening to the team with regards to the mission” (United States Coast Guard, 2011).

They go on to say how the loss of situational awareness can directly lead loss of control of a system. “When we lose the bubble (i.e., Situational Awareness) we increase the potential for human error mishaps. Coast Guard analysis of navigational mishaps for cutters and boats revealed that 40% were due to a loss of situational awareness. Effective team situational awareness depends on team members developing accurate expectations for team performance by drawing on a common knowledge base” (United States Coast Guard, 2011). The most important part of the previous quote is that maintaining situational awareness means maintain the common knowledge. The only way to do this is to effectively communicate which also requires changing perspectives to gain a better systems view.

They also mention “Clues” to help identify the loss of situational awareness.

“The loss of Situational Awareness usually occurs over a period of time and will leave a trail of clues. Be alert for the following clues that will warn of lost or diminished Situational Awareness:

- Confusion or gut feeling.
- No one watching or looking for hazards.
- Use of improper procedures.
- Departure from regulations.
- Failure to meet planned targets.
- Unresolved discrepancies.
- Ambiguity.
- Fixation or preoccupation”

(United States Coast Guard, 2011)

All of these “Clues” match the ideas and principles previously discussed though in different words. This is highlights that the ideas discussed in this paper can be applied to multiple domains besides firefighting.

5.5 Adaptation

As the case studies showed, in some cases the firefighters were trying to adapt to the situation but were either hampered by the technology they were using, the physical environment, or some other situational factor. In other cases, the firefighters were stuck in one of the adaptation traps where they were failing to revise plan in progress when disruptions/opportunities arise (Woods and Hollnagel, 2006). Firefighters need to be able to adapt to the situation at hand as the potential for surprise is high in this domain. An important part of being able to adapt is always being aware of what not only you are doing but what others around you are doing. Being able to recognize opportunities and change plans to exploit that opportunity is pivotal, but as stated above, it may be even more important to be able to recognize the risk of falling into an adaptation trap. Supporting adaptation and the recognition of adaptation traps in a system will help the incident commander reevaluate and reassess risks as well.

CHAPTER 6

DESIGN PROCESS RECOMMENDATIONS

In identifying new requirements for future designs, one can use the design cycle from Roesler, Woods, and Feil (2005) illustrated in Figure 1. In listening to the stories from the interviews and reviewing the case studies, I have been following the "Innovator" side of the design cycle (the Northeast passage of the cycle). "Innovators as design researchers plan observational studies, collect data records from protocols, cognitive task analyses, and other process tracing techniques. Functional decomposition in the analysis of observations leads to an abstract model of conditions and relationships behind the observed concrete situations and allows designers to recognize patterns, provide explanations, and propose alternative scenarios" (Roesler, Woods, Feil, 2005).

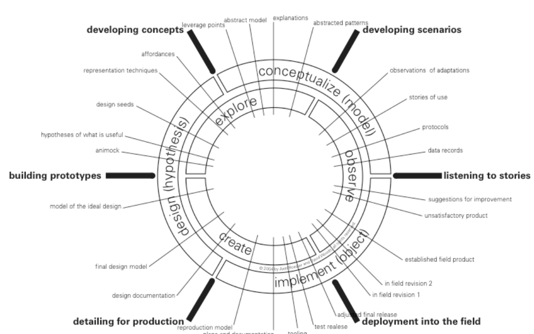

Figure 6.1: Design Cycle (from Roesler, Woods and Feil, 2005).

These models of demands and expertise provide the basis for a shift into developing promising new directions (the Northwest passage of the cycle). Innovators “are proficient in interpreting formulated insight into design seeds--concepts that capture and reveal promising directions” (Roesler, Woods, and Feil, 2005). Figure 2 details this portion of the cycle focusing on how “design seeds” can specify requirements and guide prototyping and early testing.

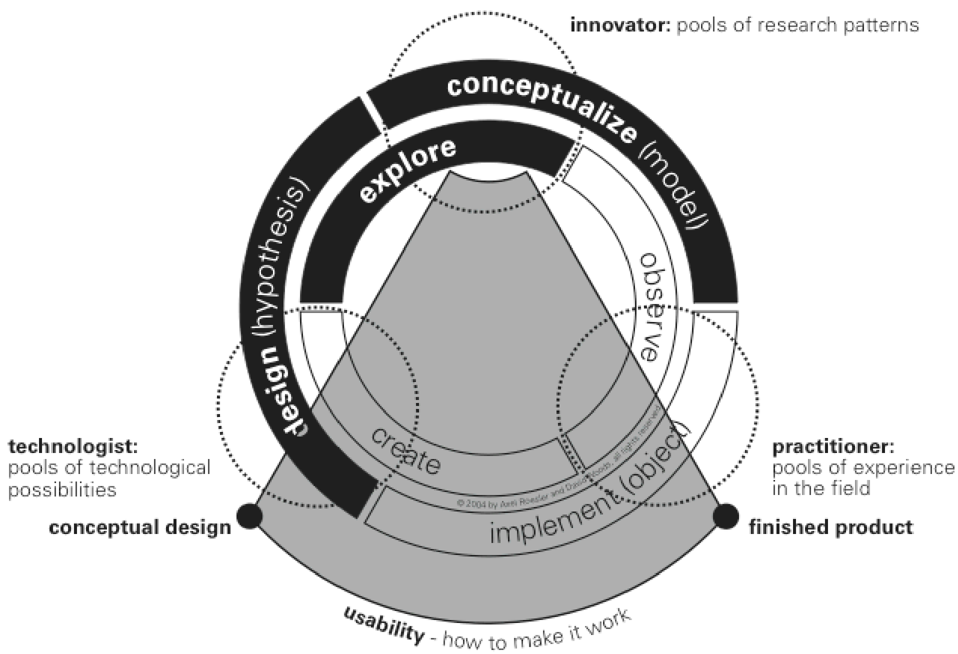

Figure 6.2: Usability as the Relationship between Practitioner and Technologist Relative to the Innovators Perspective (from Roesler, Woods and Feil, 2005)

6.1 Support Different Perspectives

From this systems analysis of urban firefighting, an incident command system is not just for the incident commander. It should be a system that involves both echelons of agents because “Effective, safe fireground communication is a two-way process” (USFA, 1999). The system should be able to provide all agents a variety of perspectives according to their role and function. The display should be able to provide information in a meaningful manner and avoid information overload. This will help all entities build better models of the system because they will have a systems perspective and be able to coordinate their activities to meet higher system goals. This will help with creating observability of interdependencies as situations change.

6.2 Support Shared Location Information

Halls and Adams (1998) describe the importance of keeping track of personnel at an incident as well as important elements of doing this.

"One of the most important functions of an IMS is to provide a means of tracking all personnel and equipment assigned to the incident… To handle these and other differences in the resources available, the Incident Action Plan must contain a tracking and accountability system with the following elements:

- Procedure for checking in at the scene
- Way of identifying the location of each unit and all personnel on scene
- Procedures for releasing units no longer needed"

(Hall & Adams, 1998)

Coming up with a way of identifying the location of each unit and personnel can be difficult. Precision Personnel Location System (Dittmar, 2010), is in development to show personnel location to the incident commander. However, these systems should provide shared knowledge of location to all entities because as was shown in the case studies. Not knowing where a firefighter is located is one of the greatest sources of frustration and confusion when coordinating activities. This is because location data is a critical input to the sensemaking activities of ICs and others if it is combined with other data about the context to understand how demands are being handled, is the response going according to plan, what reserves are available, where synchronization could break down and other aspects of staying on top of the total situation as captured in the cases.

New designs also have to find a way to deal with the information sharing bottleneck -- updating others on what you are facing competes with the activities and workload required to actually handle those demands. Current technologies used by firefighters make use of only one of the physical senses and rely on active participation by all entities. It is hard to communicate where you are located over a radio because you sometimes lack the visual cues to know where you are located and it requires active participation by the firefighters to inform others where they are located. A good incident command system would make this information common knowledge without requiring active participation by firefighters because this would take firefighters focus away from more important issues. Passive reporting of a firefighter's location would need to be in real time for it to be effective, however, and would also need to work in a variety of situations.

6.3 Support for Anticipation and Adaptation

Several software systems are available on the market which attempt to support the ability to anticipate such as the Situational Awareness - Virtual Environment (SAVE) being developed by Kutta Technologies, or Preplanning Software (Kovalcik, 2010). This software creates 3D building visualizations from databases of blue prints and floor plans. This information supports anticipating what kind of situation you are going to be in from a structural/ spatial standpoint, but does little with helping you anticipate the actions or adaptations of agents within the system. However, this spatial information can be used in determining routes of ingress or egress of not only yourself but other entities as well which would support anticipation.

Key principles for sharing information through displays require moving from elemental data displays to displays that are transition-oriented, future-oriented and pattern-based (Woods & Hollnagel, 2006, chap. 10). Humans are good at recognizing patterns from data and can anticipate what will happen very well. An incident command system should be able to give information to all entities that supports anticipation and adaptation. This information should include the current or planned operating locations of teams, the role or function of the team or individual displayed as some recognizable symbol, the location of the fire, someway of indicating that a team is struggling in their current role perhaps as a color indicating how long they have been operating or should have been operating at their current task, as well as possible ingress or egress routes through the building. Now this list does not encompassing of all the necessary information, but it points to what is needed to support situational awareness.

The information displays and sharing systems should also take into consideration the limitations that firefighters face while fighting a fire in that they most likely could not stop and try to type a message into a computer. So each agent will need an interface tailored to their role and the multiple physical, perceptual, and cognitive demands they face in order to avoid creating new workload bottlenecks. Whatever the specific technology or modality used, the designs should make it easier for each firefighter to recognize the patterns that signal an outcome so that they are able to adapt given the new information and synchronize or re-synchronize their activities to others.

6.4 Support Multiple Forms of Communication

As stated previously, effective communication is the means to an effective system. Effective communication requires active participation which is difficult in highly demanding tasks such as firefighting. Effective communication means you need to utilize both active and passive forms of communication and different modalities not just verbal or visual forms of communication.

Multiple forms of communication are especially important in firefighting because essentially firefighters are blind due to environmental conditions when they are operating inside a building. With visual information outside of the mask nearly gone, utilizing the other senses to communicate is a promising area to pursue to enhance communication. The military has even gone so far as to begin developing a system to communicate using only our minds (Piore, 2011). Other senses could be used as well, such as tactile feedback from vibrations on a belt that could point you in the right direction to move to nearest safe haven or escape route. Another possibility is to use heads up displays inside their breathing masks as another way to relay information to the firefighters.

The next question, however, is how exactly do you relay that information to the firefighter in a way that is not only meaningful but also not distracting when their attention is needed elsewhere. Sometimes the information may be important but other times it may not be important. Also, how would they interact with this system or send messages/signals? Could they receive a text message inside their mask to alert them to certain conditions in the room or outside of the building? Also, they have limited use of their hands because of the tools they are carrying or they are trying to carry someone out of a building. Designing a system to meet these interacting requirements is quite difficult and many apparently good designs for a subset of roles or scenario may turn out to be quite brittle when situations do not match the assumptions the designers made.

The best answer to the question of how to communicate effectively during this kind of situation is to provide multiple forms of communication that allow perspectives to be viewed and do not distract the user from task at hand. Active communication should be utilized to make people aware of changes to the system, whereas passive communication should be used for things like location, direction, and role and is accessible only when needed by other firefighters.

CHAPTER 7

CONCLUSION

Urban firefighting exemplifies many challenges of coordination which are present in any domain that involves joint activity. Through a rigorous systems analysis of multiple cases studies within urban firefighting, the study identified the following factors contribute to coordination problems: communication problems, poor control, information overload, loss of situational awareness, and poor adaptation. The following recommendations should be followed when developing a system to combat these problems. The system should be able to support different perspectives, shared location knowledge, anticipation and multiple forms of communication. System designs that incorporate all of these principles should be tested to assess how brittle or resilient they are in supporting firefighter teams under a wide range of scenarios that challenge coordination. The cases studied in this project provide a basis for developing these test scenarios. In particular new designs should help the incident commander manage the interactions between the different teams and activities and be able to intervene to keep the system coordinated and synchronized by anticipating the threats to successful joint activity.

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APPENDIX A

CASE STUDIES SUMMARIES

Incident Case 1:

Two teams of firefighters, Engine 1 and Ladder 1, initially entered the front of a building to fight a fire. The Engine 1 team was then redirected to the rear of the building to attack the fire from a different angle. Ladder 1, in the front of the building, was unaware of this change in tactics which should have prompted them to evacuate the front of the building as well. This, however, resulted in heat being pushed to the front of the building where the Ladder 1 team was still operating. With the rising temperatures they tried to evacuate the building but one firefighter was knocked back and became unconscious, thus trapped in the heat. Engine 1 was still operating in the back pushing heat forward, unaware that a firefighter was trapped inside the front of the building. The firefighter was rescued but sustained severe burns.

Incident Case 2:

A Ladder team of firefighters was operating on the second floor of a building venting and searching for a fire on that level. The officer of the Ladder team could not account for one of his firefighters and told another firefighter to search for him on the floor below. The officer continued to search on the second floor and believed he had *located the missing firefighter and communicated that message across the radio. Upon gathering at the street, the officer realized that the person he found was not the missing firefighter and that he was in fact still unaccounted. They began a new search and found the missing firefighter after 8 or 9 minutes. The firefighter died shortly after arriving at the hospital.*

Incident Case 3:

A fire was occurring in the cellar of a hardware store which was connected to another building next to it. The two buildings had been modified and opened up to each other on the first floor and cellar levels. Two Engine teams were operating at the scene and stretched one hose lines to an interior stair well to the cellar staircase, whereas the other hose line was stretched to a rear exterior cellar door. The rear cellar door was deemed to be a safer path to attack the fire but it was unconventionally secured which required a Ladder team to force entry. The Ladder team spent 25 minutes to open the door, all the while no water was being put on the fire. Shortly after the door was opened, an explosion occurred causing the exterior wall to collapse on two fire fighters outside the building killing both. Another firefighter inside the building was thrown down the cellar staircase and rescue efforts were unsuccessful to reach him before he succumbed to his injuries.

Incident Case 4:

A fire was occurring on the top floor of a four story building with two Ladder teams and two Engine teams operating. The first due Ladder team began operations on the fourth floor while the first due Engine team stretched the hose to the fourth floor. Once the Engine team reached the fourth floor the Ladder team moved out of the way of *the hose line but one firefighter's mask was knocked off during this process. Without his mask on he began to inhale heavy smoke and eventually lost consciousness while trying to put his mask back on and reach the staircase.*

Incident Case 5:

Three Ladder firefighters were operating in the cellar of a building with a fire on the floor above. They were utilizing a search rope to guide them back to the cellar entrance when they were ready to exit. One firefighter's air began to run low and was instructed to go outside and replace his air tank outside. He lost grip of the rope and couldn't find it so he tried to make his way out of the cellar on his own. During this process his mask was knocked off when he bumped into a pillar or wall. He was now disoriented and couldn't put his mask on right away. He transmitted a MAYDAY over his radio but it was ignored because another firefighter had accidentally transmitted a MAYDAY at the same time. So the firefighter removed his facemask to verbally transmit the MAYDAY for a second time which was responded to this time. He, however, did not put his facemask back on because he could not get airflow. He became unconscious and was found by one firefighter who was unable to move him. Once another firefighter arrived, they were able to move him out of the building through a new opening other firefighters had created.

Incident Case 6:

Two Ladder teams had responded to a fire at a four story building. The fire was on the fourth floor and the first and second due roof men from the Ladder teams had climbed onto the roof to perform venting operations. They climbed onto a bulkhead on the roof in order to vent the skylight there. The first firefighter lowered himself back down to the *roof successfully but the second firefighter had multiple tools he was handling and shifted his weight cause him to fall off the roof of the building where he died from his injuries.*

Incident Case 7:

A fire was taking place in a building that had multiple alterations to it that were not consistent with architectural plans. The fire spread to the roof and caused the ceiling to catch on fire. Then the first floor unexpectedly collapsed due to a failure by a column in the cellar plunging ten firefighters into the cellar area. After an hour and forty-one minutes, the last firefighter was pulled from the wreckage, however, the last two firefighters pulled from the wreckage succumbed to their injuries.

Incident Case 8:

A fire was occurring in the cellar of a two story house with two Ladder and two Engine teams operating. The two members from the first due Ladder team moved into the cellar to find the fire while the first due Engine team worked on stretching the hose to the cellar. The Ladder team made its way to the bottom of the staircase, which had a half landing where the Engine team began operating the hose. The Ladder team decided to leave the cellar but had difficulty doing so due to the congestion on staircase from the Engine team. At this point the both team left the cellar because in the congestion some of the firefighter's masks had been knocked off. However, once outside the Ladder officer realized one of his firefighters was still in the building. They found him unconscious still in the stairwell but he eventually succumbed to his injuries.

Interview Case 1:

The Engine team had responded to an incident but the Ladder team had not arrived yet. The Engine team then had to return to their apparatus to get tools to force entry instead of waiting for the Ladder team to arrive.

Interview Case 2:

An Auto body shop was on fire and the responding Ladder team had begun to perform a search. The firefighter was crawling along the wall and discovered the fire in offices and radioed to the Engine team. He continued his search along the wall but could hear the fire growing behind him, so he could not return that way to escape the building. He started to hear pounding on a door in the rear, so he continued to crawl along the wall towards the noise. Couldn't do left turn in the middle of the room or he could lose his way trying to go across the middle of the room.

Interview Case 3:

There was a fire in house at night and the Engine team had knocked down the fire and the Ladder team was conducting search operations. Once the incident commander arrived he called for PAR but there were pitch black conditions inside and no way to account for officer to account for all firefighters.

Generic Elements from Interview with Incident Commander:

As chief on the scene,

-*"All you can do is observe and the radio is very inefficient."*

-*"Being the chief on the job is frustrating because guys will do what they want and there is no way to keep track."*

-*“If I have to go into the building I am carrying the TIC, radio, tools, and the hose but I only have two hands.”*

-*“I also have no way to track who is on scene or in reserve without sending someone around to get the info or calling dispatch.”*

-*“There are 200 channels on the radio but I only use 2.”*

-*“Try to keep radio use to a minimum and use only when you have completed tasks. However, when something bad happens like someone falling through a floor, the radio chatter gets loud.”*

-*“The SOPs are just patterns and we just try to follow the patterns.”*