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Abstract

Resilience is considered an essential capability of an Incident Management Team (IMT) in planning for and responding to disasters and catastrophes. While IMTs have been studied as a decision-making unit, few attempts were made to view them from a Joint Cognitive System (JCS) perspective that highlights the interplay among humans and technical agents and demands imposed by the incident. To that end, this paper presents a JCS model of the IMT grounded in findings from the existing literature and naturalistic observations of simulated IMT's incident action planning, which functions in a cyclic manner across multiple scales. Using this model, three metrics for measuring resilience of the IMT, recovery time, resource status, and interactions, are discussed. By providing a few examples for the interaction aspect, this study provides proof-of-concept for objective assessment of the resilience characteristics of the IMT. The proposed JCS-based IMT model can be used for descriptive modeling of similar systems to investigate resilience behavior and performance.

Keywords	emergency management; cognitive systems; resilience engineering; disaster response; incident action planning process
Taxonomy	Large-Scale Systems, Systems Engineering Evaluation, Engineering Design Process, Model-Based Systems Engineering, Disaster Management, Accident
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File Name	**[File Type]**
Highlights.docx	[Highlights]
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Highlights:

- Incident management teams can be modeled as multilayered joint cognitive systems
- Resilience in incident response depends on time, resources, and interactions
- Recovery time can be measured as time to perceive, to decide, to act, and to recover
- Status of requested, deployed, stocked, and procured resource should be visible
- Interactive episode analysis can be used to model interaction among system elements

Modeling an Incident Management Team as a Joint Cognitive System

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ABSTRACT

Resilience is considered an essential capability of an Incident Management Team (IMT) in planning for and responding to disasters and catastrophes. While IMTs have been studied as a decision-making unit, few attempts were made to view them from a Joint Cognitive System (JCS) perspective that highlights the interplay among humans and technical agents and demands imposed by the incident. To that end, this paper presents a JCS model of the IMT grounded in findings from the existing literature and naturalistic observations of simulated IMT's incident action planning, which functions in a cyclic manner across multiple scales. Using this model, three metrics for measuring resilience of the IMT, recovery time, resource status, and interactions, are discussed. By providing a few examples for the interaction aspect, this study provides proof-of-concept for objective assessment of the resilience characteristics of the IMT. The proposed JCS-based IMT model can be used for descriptive modeling of similar systems to investigate resilience behavior and performance.

Key words: emergency management, cognitive systems, resilience engineering, disaster response, incident action planning process

1. Introduction

Disasters have persistently challenged societal capabilities of managing risks from technical, natural or civil threats (Jain, Pasman, Waldram, Rogers, & Mannan, 2017; Mendonça, 2007). This challenge has been repeatedly observed through extreme loss events, for example, Hurricane Harvey (Harris County Fire Marshal's Office, 2017), Great East Japan earthquake and tsunami in 2011 (Yu et al., 2017), Macondo well explosion (Birkland & DeYoung, 2011; Skogdalen, Khorsandi, & Vinnem, 2012; Sylves & Comfort, 2012), Hurricane Katrina (Comfort, Birkland, Cigler, & Nance, 2010; Cruz & Krausmann, 2009; Wise, 2006), and September 11 World Trade Center attack (Comfort, 2002a, 2002b). In order to address this persistent challenge, the U.S. Department of Homeland Security has launched the National Incident Management System (NIMS) in 2004, to provide a standardized and integrated incident management template for all hazards and for all levels/types of organizations (Anderson, Compton, & Mason, 2004; Federal Emergency Management Agency, 2004).

Prior to NIMS, the Incident Command System (ICS), based on the provision of fire services, was the predominate system used for cross-jurisdictional operations (Perry, 2003). While ICS worked well for organizations with similar functionalities, its efficacy for inter-organizational coordination and collaboration was limited. Moreover, its functioning has been shown to hinder under unplanned conditions (Bigley & Roberts, 2001). To rectify these issues, NIMS was developed to incorporate a comprehensive, interoperable and adaptable incident management framework. In addition, NIMS was designed to manage high-consequence events that necessarily involve multiple agencies, jurisdictions, organizations, and disciplines. Such events can span from local emergencies and planned events (such as sports) to larger natural and man-made disasters. Moreover, a life cycle of incident management in NIMS includes all the mission phases such as prevention, protection, mitigation, response and recovery (Keybl, Fandozzi, Graves, Taylor, & Yost, 2012).

NIMS is characterized by joint operations among multiple actors who are temporally and spatially distributed across different organizational levels. A core component of NIMS is the Incident Command Post (ICP), a temporary on-site facility in which an Incident Management Team (IMT), formed *ad hoc* of multiple operators with different expertise, supervises and supports tactical operations (Vidal & Roberts, 2014). Organizationally, an IMT is positioned between Emergency Operations Center (EOC) that coordinates support among multiple ICPs and field responders.

While NIMS was devised to improve coordination and collaboration among different organizations, its fundamental structure followed that of the ICS. IMTs in the ICS structure typically consist of five functional sections: Command, Operations, Planning, Logistics and Finance & Administration. The Command Section defines incident objectives of the overall operations and directs resource allocation and coordination among participating agencies. The Operations Section performs specific tactical actions to achieve the incident objectives established by the Command Section. The Planning Section gathers incident data including situation assessment and resource status, integrates them into meaningful information and intelligence, and disseminates them within the IMT as well as across other organizations. The Planning Section also prepares Incident Action Plans (IAPs) for continued operations over multiple periods through an incident action planning process. The Logistics Section provides necessary services and resources for incident management such as equipment, supplies and facilities. Lastly, the Finance & Administration Section tracks costs and manages financial matters arising through the course of an incident (Federal Emergency Management Agency, 2004). A generic structure of an IMT is illustrated in Fig. 1.

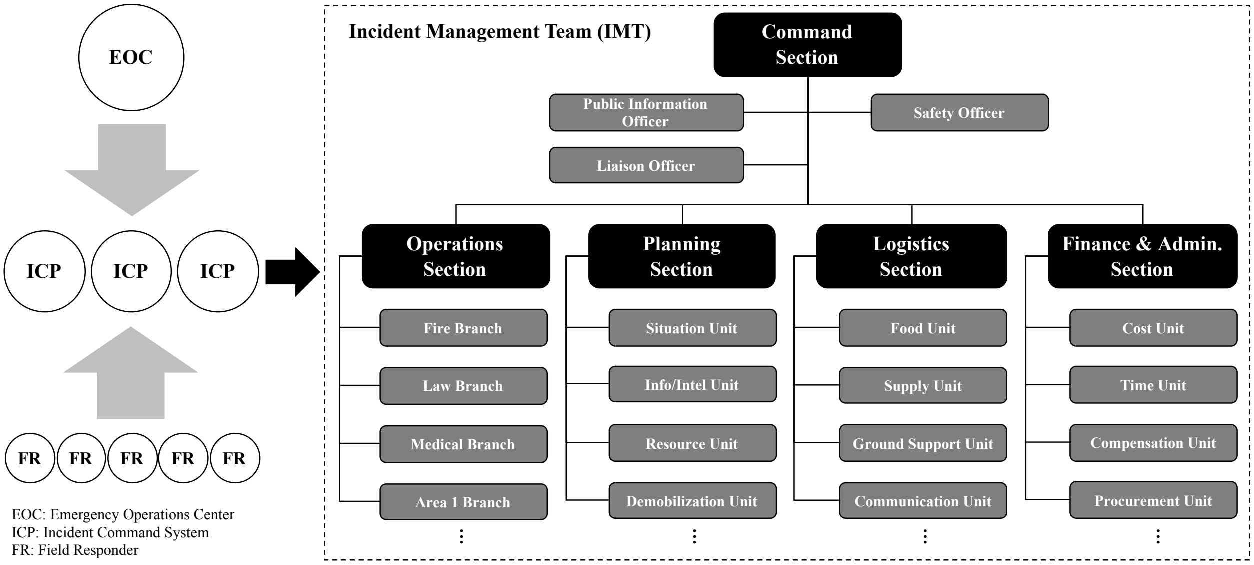

Fig. 1. Generic organization structure of IMT based on the ICS

Previous research has examined the limitations of such centralized, hierarchical ICS structure. Buck, Trainor & Aguirre (2006) claimed that the ICS functions well for like organizations having clear goals but suffer when these goals are ill-defined and conflicted due to multiple hazards and among heterogeneous organizations in large-scale disasters. Similarly, Lutz and Lindell (2008) pointed out the weakness of the ICS for non-fire incidents which require more functions (e.g., evacuation, mass care) than simply controlling hazard sources (e.g., fire). In recognition of these limitations, Bigley and Roberts (2001) stressed the ICS's flexibility and proposed three factors that enhance such flexibility: structuring mechanism, constrained improvisation, and cognition management. Structuring mechanism indicates how rapidly an incident management organization changes its structure. This is facilitated by structure elaboration, a prompt construction or alteration of the organizational structure as incident evolves. This structure-elaborating process is also facilitated by authority transfer and role switching. Constrained improvisation is denoted as developing and applying creative tactical activities to local, unexpected situations in order to achieve given tasks from higher authority. Finally, cognition management of ICS requires a cognitive structure that helps establish 'common operational representation' as the two preceding factors largely rely on this. The cognition points to both what happens within the organization and in its environment. While individual emergency responders' cognitive processes have been emphasized and investigated (Comfort, 2007), investigating incident command teams from the perspective of a Joint Cognitive System (JCS) remains as a general gap.

A JCS is a system in which human practitioners (*e.g.*, incident managers and operators) work with technological tools and modify what the system does to maintain control (Hollnagel & Woods, 2005). Resilience is a unique property of a JCS (Woods & Hollnagel, 2006) and as implied above, the need for resilience in incident/emergency management is evident (Comfort, Boin, & Demchak, 2010; Harrald, 2006). To that end, this study aims to model an IMT as a JCS using theoretical grounds and to propose potential measures for resilient performance with some examples as a proof of concept. In what follows, we describe theories of JCS, Resilience

Engineering and JCS modeling, present methods used for the modeling and understanding of resilient behaviors of the IMT (Section 2), and propose three metrics for resilience of the IMT in Section 3.

1.1. Joint Cognitive Systems

JCS theory emphasizes ‘co-agency’ or ‘ensemble’ of a human and a machine and seeks to define a boundary that surrounds the co-agency (Hollnagel & Woods, 2005). Using the JCS framework the CSE research has focused on helping practitioners’ problem-solving in complex real-world systems (Woods & Roth, 1988) by taking into consideration three inter-relational components termed ‘JCS triad’: (i) cognitive agents (e.g., human and machine), (ii) demands from the world on cognitive work, and (iii) artifacts that represent or manipulate the world (Hollnagel & Woods, 2005; Roth, Patterson, & Mumaw, 2002; Woods, 2003). Observations of coping with complex works in natural settings have revealed that the interplay among this JCS triad has led to adaptations to changes and anomalies in the world (Sanderson, 2017; Woods, 2003). In this vein, Hollnagel and Woods (2005, p. 22) define a JCS as “a system that can *modify* its behavior on the basis of experience so as to achieve specific anti-entropic ends”. Furthermore, Woods and Hollnagel (2006) propose three relational properties of a JCS: affordance (fit among the triad), coordination (joint functioning over distributed, multiple agents and artifacts) and *resilience* (dealing with challenges and changes that go beyond designed competence).

Among the three properties, resilience is emphasized since it is a whole-of-system’s ability to meet the work demands based on affordance that the artifacts possess and coordination among the cognitive agents (Woods & Hollnagel, 2006). As the work demands in modern systems become more complex and thus require adaptation, the CSE’s focus on resilience has given rise to an area of research called Resilience Engineering (Woods, 2017).

1.2. Resilience Engineering

Due to variability of a system’s internal sources or external environment, it is inevitable and necessary for the systems to be resilient in order to cope with complexity of the real world (Hollnagel, Woods, & Leveson, 2007) . In that sense, resilience is defined as “the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances…” (Hollnagel, 2011, p. xxxvi). Resilience is difficult to measure as it is a tacit property of the system (Mendonça, 2008). As such, factors that contribute to resilience are often measured. Such measures include buffering capacity, flexibility (vs. stiffness), margin & tolerance, and cross-scale interactions (Woods, 2006). Buffering capacity indicates the degree to which a system can withstand impact without collapsing its fundamental structure. Flexibility refers to the system’s ability to alter its structure to match work demands. Margin and tolerance are concerned with how the system is operating near its capacity boundary over which the system breaks down or gracefully degrades (Woods, 2015). Cross-scale interaction highlights reciprocal influence between sharp end and blunt end of the system; local adaptations affect managerial policies or strategies, and *vice versa*.

The factors of resilience are also explained by four abilities of a resilient system, namely: monitoring, anticipating, responding and learning – or *MARL'ing* (Hollnagel, 2011). Monitoring consists of making sense of what is happening in the environment as well as in the system itself. Anticipating represents forecasting what challenges and opportunities to emerge. Responding indicates knowing what actions to take and how to execute such actions. Finally, learning refers to gaining lessons both from failures and successes. The ability to learn lessons from what went wrong as well as what went right characterizes 'Safety-II' approach that views failure and success as two different outcomes of the same adaptive process (Hollnagel, 2014).

Resilience engineering research has investigated the aforementioned factors and abilities in safety critical domains such as oil and gas industry (Azadeh, Salehi, Ashjari, & Saberi, 2014; Cabrera Aguilera, Bastos da Fonseca, Ferris, Vidal, & Carvalho, 2016; Dinh, Pasman, Gao, & Mannan, 2012; Jain, Pasman, Waldram, Pistikopoulos, & Mannan, 2017; Shirali, Motamedzade, Mohammadfam, Ebrahimipour, & Moghimbeigi, 2012), nuclear power generation (Carvalho, dos Santos, Gomes, & Borges, 2008; Gomes, Borges, Huber, & Carvalho, 2014; Vidal, Carvalho, Santos, & dos Santos, 2009), and maritime (Tveiten, Albrechtsen, Waero, & Wahl, 2012). While few previous efforts have attempted to create a cognitive system model of nuclear power plant control (Carvalho et al., 2008; Vidal et al., 2009) and oil and gas (Cabrera Aguilera et al., 2016), these studies addressed emergency management as a component of the system under investigation. To our knowledge, no model for the IMT as a JCS has been developed to date. With regard to measuring resilience, a number of measurement methods have hitherto been developed (Hosseini, Barker, & Ramirez-Marquez, 2016). However, none of them rendered quantitative measurement that can be applied to a JCS. To that end, this study offers a JCS model of an IMT and to present several metrics for resilient performance of the IMT.

1.3. Modeling a Joint Cognitive System

Two cyclic models for a JCS were proposed by Hollnagel and Woods (2005). By accounting for the context in which cognition takes place, the two models describe how a system dynamically adapts its functions to maintain control. First model, the Contextual Control Model (COCOM), explains the adaptive process connecting actions, events and constructs of a single entity (e.g., individual, organization). COCOM represents a control loop in which a current understanding of the situation, evaluating encountered events, and choosing actions to deal with those events take place in a cyclic manner. If such understanding is informed by the currently occurring event and previous understanding, the system behavior is *reactive based on feedback*. If the actions are selected by the current understanding and expected consequence, it becomes *proactive based on feedforward*. Second model, the Extended Control Model (ECOM), expands this basic cyclic model to multiple layers allowing for interactions across different levels. For example, goals and targets of a higher layer become action plans for a lower layer, and then these action plans guide specific courses of action for its subordinate layer. In ECOM, therefore, the higher layers orient towards targeting and monitoring based on feedforward and the lower layers lean towards regulating and tracking based on feedback.

An IMT's structure makes it a suitable platform for incorporating these models and studying measures for resilience. The IMT operations occur in a cyclic manner called an 'incident action planning process' (Federal Emergency Management Agency, 2010). In addition, this cyclic planning process occurs across different layers of the IMT. For example, field responders generally implement the plan to respond to an individual adverse event while a higher-level organization such as the Command Section establishes or modifies the plan based on the actions taken by the field responders. Finally, the performance of the IMT is largely situation- and context-dependent. That is, the IMT is highly likely to adjust its operations even with the identical structure and composition as it encounters different situations. For instance, the Operations Section focuses on putting out fire in wildfire; the same section, however, may perform search and rescue activities in earthquake disasters.

In order to create a JCS model for the IMT and to identify resilient performance of the IMT, naturalistic observations were conducted in a representative IMT simulation as detailed below. When necessary, several relevant government documents (e.g., NIMS, Comprehensive Planning Guide (CPG)) were consulted to inform the modeling approach.

2. Material and Methods

A naturalistic observational study was conducted in high-fidelity emergency response simulation provided by the Emergency Operations Training Center (EOTC), managed by Texas A&M Engineering Extension Service (TEEX). The EOTC training programs impose realistic work demands on participants allowing for observations of resilient performance in the context of a naturalistic emergency response. A typical training course invites 40 to 45 trainees under the supervision of about 20 highly skilled instructors in a simulated Incident Command Post (ICP). Two training courses conducted through 2017 were selected for data collection.

2.1. Participants

Participants in this study were recruited on the first day of a scheduled training course in the EOTC. A majority of participants had moderate to high level of emergency operations experience since the prerequisite for this training includes the basic to intermediate level ICS certificates such as ICS 100, ICS 200, IS 700 and IS 800[1]. For the first observation, 39 out of 44 trainees consented, and 32 out of 46 consented to participate in the second observation. Participants also included the instructors who were present throughout the training. Participants were diverse in terms of their discipline (e.g., firefighting, law enforcement, emergency medical) and their geographical location (e.g., different States and municipalities). The research protocol received approval from authors' Institutional Review Board[2].

2.2. Equipment, Facility and Scenarios

The training facility is equipped with laptop and desktop computers, telephones, printers, photocopiers, white boards, large displays, microphones and two meeting rooms. Overall, four incident scenarios were given during each training course: three half-day sessions and one full-day session. Three half-day scenarios were identical for both observed courses, namely, a mass

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[1] A full list of training requirements is available in https://training.fema.gov

[2] IRB No.: IRB2016-0489D

shooting, hurricane and aircraft crash into a populated area. The full-day scenario differed (the first observational study: earthquake, the second observation study: civil disturbance). In order to make these exercises more immersive, experienced and skilled role-players provided ‘injects’ which indicate pieces of virtual incident information fed into the IMT (e.g., fire containment status, number of casualties, request for perimeter setup, a report from field observation, and a call from the mayor). Scripts for injects were prepared in advance but they were often adapted to match with situations as they evolved.

2.3. Data Collection

To collect multifaceted data, various tools including a mobile application and video/voice recorders were used to record behaviors of participants and interactions among participants and technical artifacts. The primary source of data was direct observation. Four to six observers were present in the exercises. To supplement the direct observation, and investigate internal communications, observers used a mobile application named ‘Dynamic Event Logging and Time Analysis (DELTA’) that allowed registration of events using codes from four categories: initiator of communications, receiver of communications, technologies used for communication, and content of communication. The coders used discussion of pilot data for consensus coding.

2.4. Data Analysis

Data entered in DELTA and audio/video recordings were shared among the research team for further discussion and analysis. Several rounds of meetings were conducted subsequently to exchange each other’s findings and elicit themes relevant to the JCS modeling and resilience of the IMT. Through these meetings, the research team attempted to identify:

- How the overall incident action planning process is managed within the IMT.
- How the IMT is structured and how constituent sub-teams and individuals work with others as well as different technologies.
- What types of information are collected, communicated and disseminated.
- What challenges emerged and what resilient behaviors were conducted by the IMT and its personnel to overcome such challenges.

3. Results

Based on the collected data and subsequent analysis, co-agency of human actors and technical tools and their respective boundaries was analyzed and summary of the IMT’s incident action planning processes were documented. Using such co-agency and cyclic incident planning processes, a JCS model for the IMT incorporating multiple layers of JCS’s is proposed.

3.1. Co-Agency and Boundaries in IMT

Among the JCS triad, basic human/technological agents and boundaries of an IMT were examined as the first step because this provided an understanding of the multilayered nature of a JCS. The observed IMT was indeed comprised of the abovementioned five core sections (Command, Operations, Planning, Logistics, Finance & Administration) and each section had several task-specific units. For example, the observed ICP had a Situation Unit and a Documentation Unit in the Planning Section. In addition, tasks assigned to each unit were accomplished by single or multiple operators. Each entity interacted with tools at different levels such as personal computer (at operator level), radio (at branch level), white board (at section level) and large displays (at team level). For instance, the Deputy Planning Section Chief mainly used a white board for maintaining up-to-date incident information but often received paper forms from other members as well as watched other members' computer to exchange information and to communicate with them. Similarly, Information/Intelligence (I/I) Unit member mostly used paper forms to document new pieces of information but he/she also used other sources of information such as telephone calls from the field and other sections' white board. The interactions among co-agency and its pertinent boundary are depicted in Fig. 2.

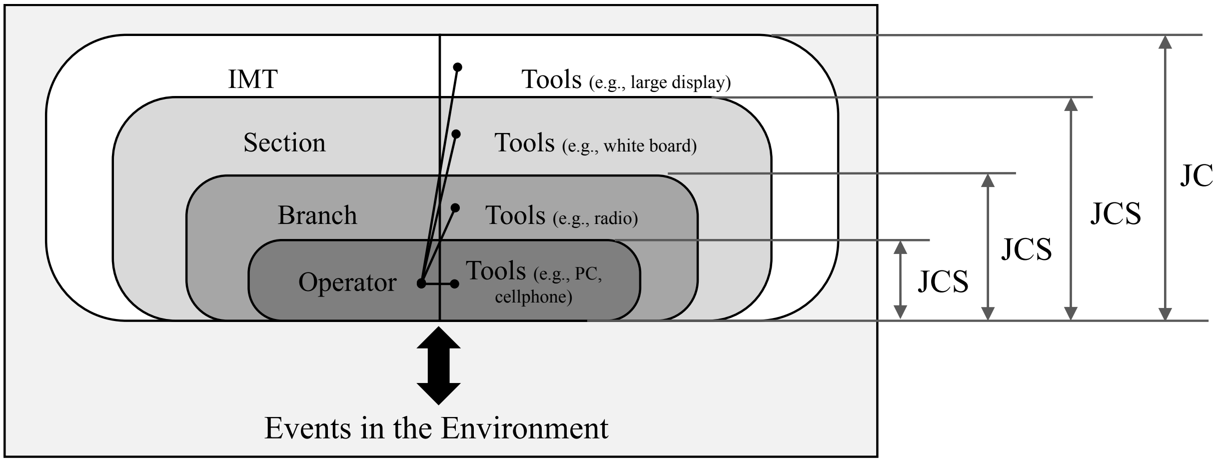

Fig. 2. Multilayered JCS's of IMT: This figure shows co-agency of an entity at different levels and its corresponding tools.

3.2. IMT Action Planning Processes

Incident action planning is a crucial process of an IMT that facilitates incident management. From the JCS triad standpoint, this is a process during which human and technical agents cope with demands from the world through continuous adaptation. A formal incident action planning cycle was comprised of the following steps and reoccurred in each operational period, either in part or in full. An operational period indicated a unit time during which one IMT assumed the incident command. This incident planning cycle was observed in the exercises and summarized as 1) initial response and situation assessment, 2) developing incident objectives, 3) planning strategies and tactics, and 4) executing plans and re-assessment of situation. A respective description for each step is provided as follows:

1) Initial response and situation assessment: When an incident occurs, field responders arrive at the scene and perform an initial response and assessment of the event. Based on this initial assessment, an incident commander (e.g., fire marshal, police chief) determines whether more resources should be deployed and a larger incident management organization such as an IMT should be established. After the IMT is established, an incident briefing is provided to the initial incident commander or unified command (IC/UC) formed of multiple incident commanders.

2) Developing incident objectives: After the IC/UC assumes the overall incident command, they start by deciding priorities and objectives for the initial operational period given constraints and concerns identified in the initial situation assessment. As the incident evolves with new threats and demands, the incident objectives are reviewed and modified for ensuing operational periods.

3) Planning strategies and tactics: Once the incident objectives are established or revised, pertinent strategies and tactics are developed to attain the objectives via meetings with Command/General Staff and other key members (e.g., Resource Specialist). As a result, an Incident Action Plan (IAP) for the next operational period is generated and agreed upon. An IAP typically consists of several key documents that specify the incident objectives, work assignment, and work protocols, for example, communication, safety, transportation and scheduled meetings.

4) Executing plans and re-assessment of situation: When the next operational period begins with a new set of emergency supervisors and responders, they are presented with the IAP during the incident briefing. With this briefing, they apprehend what their incident objectives are, what is current situation assessment and what specific tasks they are assigned to perform. Based on the results of these actions, the situation is re-assessed and reflected on new or modified incident objectives. This cyclic incident action planning process continues until the incident is controlled and the situation reaches a ‘new normal state’.

The naturalistic observations revealed that the IMT sought to ‘muddle through’ difficulties that it faced representing characteristics of a resilient JCS. Participants formed different co-agencies by using or being supported by different technologies. Although information was originated from various sources (e.g., incident briefings, field observations, documents produced in other sections) and often flawed, the IMT attempted to maintain the awareness of the evolving incident through coordination and collaboration across different levels of organizations. Based on this team cognition process, the IMT anticipated future states of the incident and developed both proactive and reactive measures that guided ensuing operations. These findings then informed the development of a JCS model in the following section.

3.3. Joint Cognitive System Modeling

3.3.1. JCS model of IMT

Grounded in the COCOM model consisting of *event*, *construct* and *action*, and the incident action planning process, a JCS model of the IMT was created (Fig. 3). In this model, primary functions occur via interactions among the Operations, Planning and Command Sections. Firstly, ‘uncontrolled or adverse incidents (*event*)’ are typically responded to and perceived by the Operations Section, for example, fire suppression unit. Then, the Planning Section gathers the perceived situations and integrate incident data into useful and meaningful information/intelligence. Based on the integrated understanding (*construct*), key collective decisions including defining incident objectives and strategic and tactical plans are made. Then, the Command Section reviews and authorizes the plans with adequate resources (e.g., workforce, equipment and materials) so that the Operations Section implements the plans by taking actions to compensate the demands from the adverse events (*action*). The Logistics Section provides those resources to support other sections in carrying out assigned tasks. These resources include workforce, equipment, facility and materials. The Finance & Administration manages financial aspects of the incident such as costs of resources (e.g., personnel time records, expenditure on supplies and supports) so it works closely with the Logistics Section. This cyclic incident response and planning process occurs until the overall incident is kept under control.

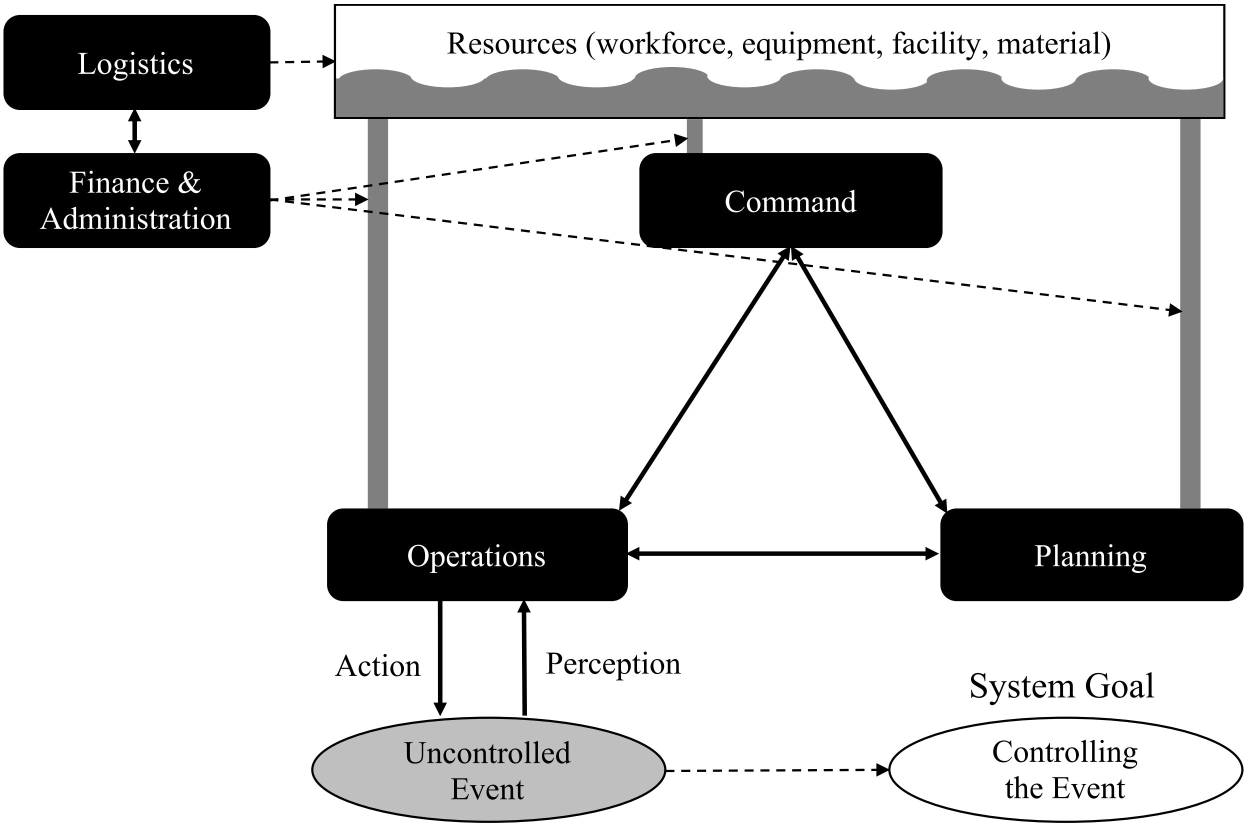

Fig. 3. Joint Cognitive System Model of an IMT: This model illustrates a cyclic incident management process in which the IMT adjusts its functions through interactions among the five major sections.

3.3.2. Multilayered Model of JCS

While Fig. 3 illustrates a cyclic process that occurs at the section level, Fig. 4 represents a multilayered model of the IMT that is situated across multiple levels based on ECOM. Four levels were incorporated in the multilayered IMT model: system, section, branch and unit/responder levels. At the systems level (e.g., IMT), the cyclic process results in incident objectives by anticipating future needs and opportunities. The incident objectives are specified as action plans at a section level. At branch and unit/responder levels, these action plans are implemented as tactical activities by mobilizing resources. In turn, the effects of resources mobilized inform tactical decisions on which specific resources are to be further allocated. These tactical decisions are fed into the performance status of each section. Finally, this status serves as a basis for incident action planning for future operations. In this cross-scale IMT model, anticipatory performance takes place at higher levels (e.g., system and section) and compensatory actions occur at lower levels (branch, unit and responder).

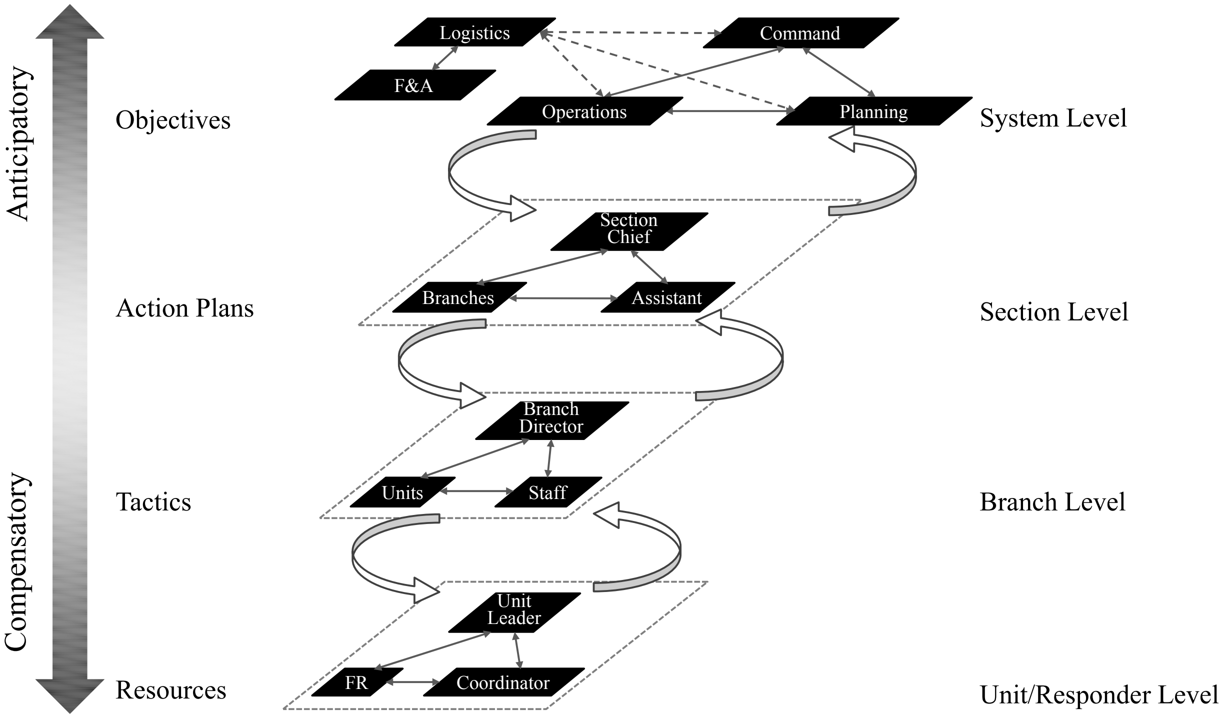

Fig. 4. Multilayered JCS model of an IMT: This model shows how the JCS model above is situated along different levels of incident management.

3.4. Potential Measures for Resilience in IMT

Previous research provides an array of qualitative, semi-qualitative or quantitative measures for resilient performance (see Hosseini et al. (2016) for a review of definitions and measures for resilience). Qualitative measures are mostly based on the provisions of anecdotal evidence of characteristics associated with resilience (e.g., MARL’ing). Semi-qualitative measures largely rely on subjective rating and expert judgment. For instance, Shirali, Mohammadfam & Ebrahimipour (2013) analyzed survey results asking six resilience indicators: top management commitment, just culture, learning culture, awareness and opacity, preparedness and flexibility. Quantitative measures for resilience were mostly based on highly abstract models that hardly consider the aforementioned characteristics of JCS. For example, Bruneau et al. (2003) proposed an equation that measures the resilience loss of community infrastructure after an earthquake. In this equation, resilience was described as a relative degradation of infrastructure quality to the planned or expected level during the recovery time. This measure, however, did not consider how cognitive systems including human and technical agents contribute to such performance. In recognition of this gap, this paper proposes three metrics for the measurement of resilience of IMT using the JCS-based model presented: recovery time, resource status, and interactions and provides some examples to show proof of concepts.

3.4.1. Recovery Time

One factor that typifies resilience of a system is how quickly it returns to a normal state after a perturbations (Dinh et al., 2012). To be resilient, a system must be quick in resolving disruptions and restoring its control. Nevertheless, system thoroughness is sometimes compromised in order to gain efficiency (Hollnagel, 2009). A breakdown of the system may occur when this trade-off is not adjusted well, for example, being thorough usually results in sluggish response in situations where prompt response is necessary.

Four measures of recovery time adapted from Hollnagel and Woods (2005) are proposed in the present work (Fig. 5): time to perceive (T_P), time to decide (T_D), time to act (T_A) and time to recover (T_R). T_P measures the time between the onset of an adverse event or meaningful change in such event and its perception by emergency personnel. In the IMT, T_P indicates time needed for the Operations Section to perceive an event after its onset (e.g., a fire reported to Fire Branch Director). T_D measures the time taken from the point of perception to the development and selection of decisions (e.g., time taken until the Command Section approves a relevant plan after perceiving the event via the incident action planning process). Following this, T_A measures the time lapsed from the choice of decisions until the action is actually carried out at the scene. Finally, T_R measures the time needed to gain control (characterized as recovery) after the action is taken. In the IMT, T_R can indicate time from the establishment of the IMT to its deactivation.

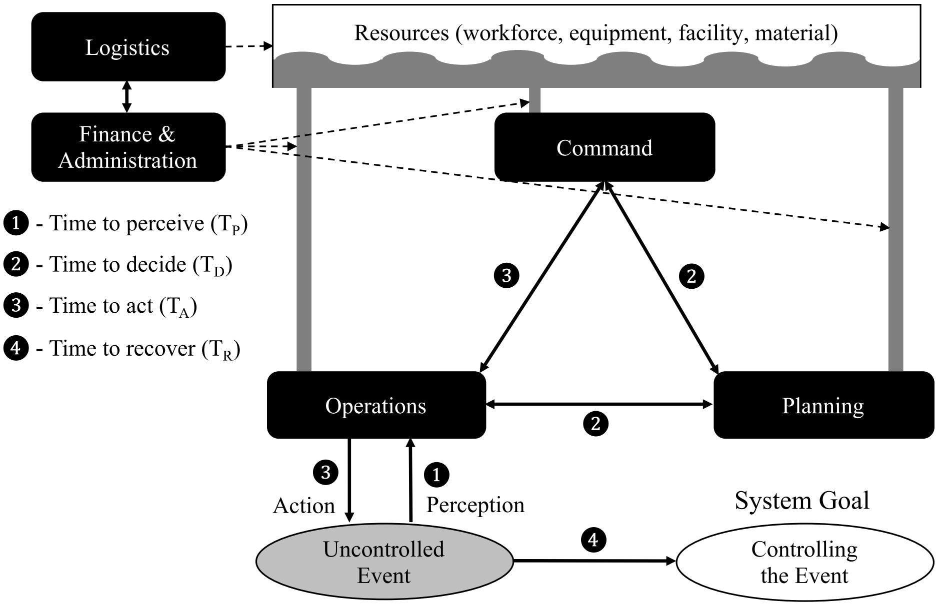

Fig. 5. Four components of Recovery Time as a measure for resilience

3.4.2. Resource Status

When the type or quantity of resources such as workforce, equipment and material are insufficient to match demands from the incident, the IMT may fall into a state of 'decompensation' (Sarter, Woods, & Billings, 1997). Often common resources are shared and conflicted among different sections of the IMT. Hence, the JCS-based IMT model assumes that there is a common resource pool that each section and its subordinate organizations draw upon. In actual emergency operations, the Logistics Section procures and delivers these resources. Different types of resources are accounted by equivalent monetary value and the Finance & Administration Section calculates the rate of resource utilization in order to keep track of budget and cost. Arguably, information about the status of resources should be documented and shared within the IMT to improve resilience. Four types of resource statuses are proposed for measurement (Fig. 6): requested resource (R_R), deployed resource (R_D), stocked resource (R_S), and procured resource (R_P). R_R indicates the amount of resources requested from the field operations (e.g., tactical units and field responders). R_D means the quantity of resources dispatched at the scene thus in use. On the other hand, R_S refers to resources in stock that are available for deployment. Lastly, R_P represents resources that are being purchased or transported.

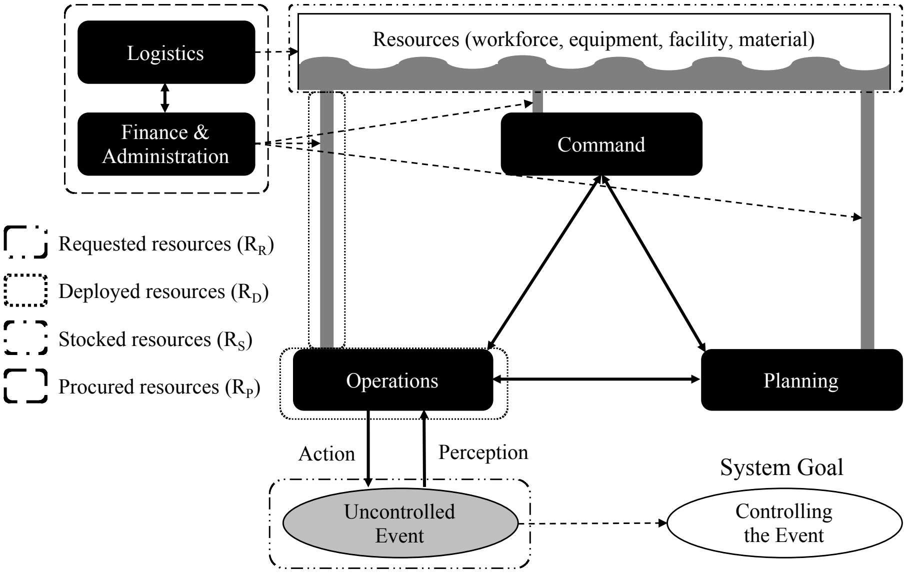

Fig. 6. Types of Resources in IMT: This figure shows four types of resources in terms of their status.

3.4.3. Interactions

Interactions among different human and technological agents within an IMT are an essential aspect of a system's resilience (Nemeth, 2008). Two types of interactions are proposed for the measurement of resilience: interaction between a human actor and a technological tool and interaction between JCSs (e.g., a human actor-*cum*-technical tool). We propose a 'three C's' framework for capturing interactions in IMT: Context, Content and Characteristics (Table 1). Context measures an initiator, a receiver of interaction and technological mediators. Content indicates a description of what is communicated and actions taken. Lastly, Characteristics specify frequency and duration of the interaction.

Table 1
Three C's of Interaction

Context			Content	Characteristics	
Initiator	**Receiver**	**Technology**	**Content**	**Frequency**	**Duration**
Who initiates an interaction?	With whom?	Which technology is used in that interaction?	What is communicated for what purpose?	How often does the interaction occur?	How long does the interaction occur?

3.5. Proof of Concept via Interactive Episode Analysis

While validation is of the proposed metrics is subject of future publications, the observational data at EOTC were used to illustrate the operationalization of interactions as a resilient performance metrics in the simulated IMT. To represent such resilient performance of the IMT, 'Interactive Episode Analysis (IEA)' adapted from Korolija and Linell (1996) was conducted. An episode is defined as a chain of sub-events that are bounded towards a common meaning (Rankin, Dahlbäck, & Lundberg, 2013). In the IMT, an episode means a trace of interactive performance of human operators and technological tools following an inject until the IMT accomplishes a given goal. This inject typically requires further actions to meet some specific demands that the incident imposes to the human operators (e.g., dissemination of incident information within the IMT). Thus, an episode would consist of interactions from the reception of an inject until actions are taken to compensate such demands. Fig. 7 depicts how an episode represents the IMT's interactive performance given an inject. It involves human-to-human interactions that have a direction (from a white box to a black solid box), duration and frequency of those interactions, and a type of technology used in that interaction. In addition, this episode incorporates actions performed by single personnel with a technological device (a gray box). A total episodic time measures time needed to satisfy the demands of the inject from the time it is given. Also, a sub-episodic time is measured for individual interactions.

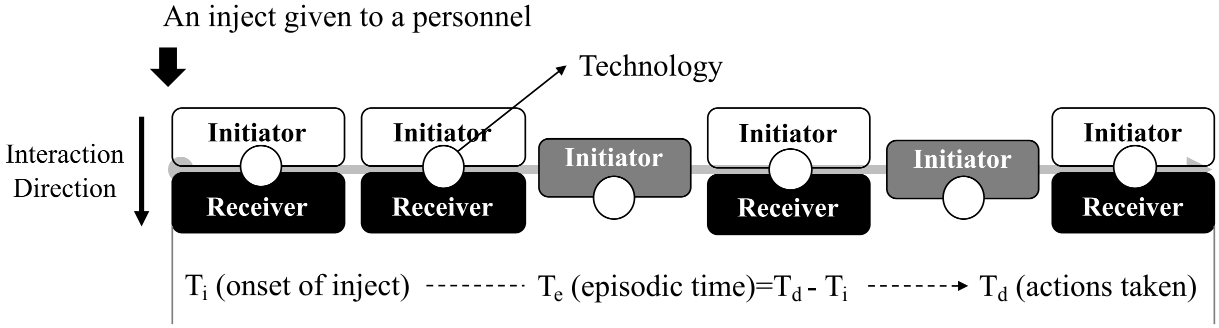

Fig. 7. Schematic of Interactive Episode Analysis: This figure represents essential components (e.g., three C's) of interactions incorporated on a timeline.

Two episodes were extracted from the collected data and presented to discuss the JCS model of an IMT. Fig. 8 and Fig. 9 illustrate each episode following an initial inject given to I/I

Unit Leader (I/I Lead) in the Planning Section. During the aircraft crash scenario (El Diablo), a virtual character, role-played by a skilled staff, reported a field observation that contains information of the incident (e.g., location and consequence of the incident). The communication occurred via telephone. Next, I/I Lead took some follow-up actions in a series, for example, taking a note of what he heard from the field observer on paper, communicating it with another I/I member face-to-face, and making copies of what he wrote down. Following this, I/I Lead delivered each of the copies to other members including Documentation Unit Leader (DOCL), Situation Unit Leader (SITL), Public Information Officer (PIO), Operations Resource Specialist (Ops. Res.), and Operations Section Chief (Ops SC). In the tornado exercise (Needland), a similar pattern was observed. Following an initial field report providing notification on the degree of damage in different locations, I/I Lead had a verbal dialogue with another I/I member, printed copies of the field report, and handed them over to other roles.

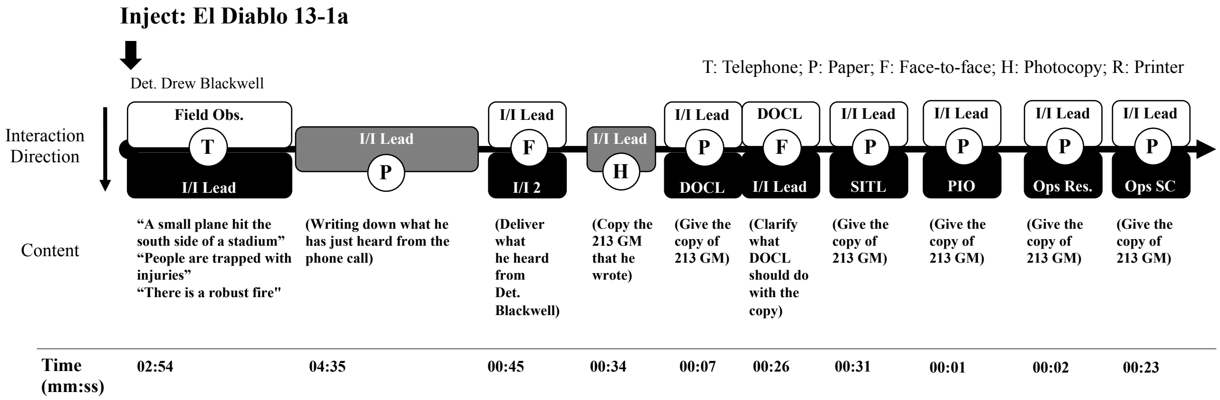

Fig. 8. An Episode following an Inject El Diablo 13-1a: This episode begins with a field observation about airplane crash.

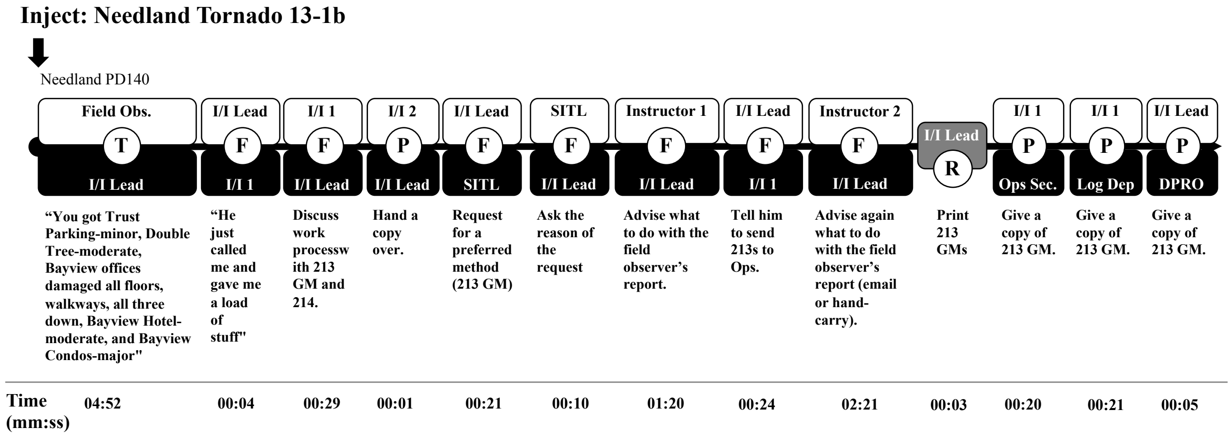

Fig. 9. An Episode following an Inject Needland Tornado 13-1b: This episode begins with a field observation about tornado damage.

The episodic time was 11 minutes and 58 seconds for the first episode, while the second episode was twice as long, taking 23 minutes and 35 seconds. With respect to frequency of interactions, eight human-to-human interactions among eight roles and two human-to-technology interactions were captured for the first episode whereas 12 human-to-human interactions among 10 roles and one human-to-technology interaction were identified for the second episode.

By looking at these episodes, it is possible to investigate the performance of the IMT that adjusts its behavior to accomplish a given goal through interactions among human actors and technical tools. As indicated in Efficiency-Thoroughness Trade-Off (ETTO) principle (Hollnagel, 2009), resilience should be understood in the context of how a balance between efficiency (e.g., quick decision and action) and thoroughness (e.g., more information and less risk) is maintained. Therefore, the measure of interaction is neutral. That is, fewer interactions may not necessarily mean more resilient performance. On the contrary, more interactions may lead to more resilient performance. Likewise, quicker actions and use of less resources may not necessarily mean that the system is resilient. Hence, such neutrality indicates that time, resource status and interaction are not measures ‘of’ resilience per se, but measures ‘for’ resilience that help in understanding this abstract construct.

4. Discussion

As Woods and Christoffersen (2002) postulate, engineering a JCS occurs in a cycle that begins with observation of field practices and abstraction of common patterns from those practices. The common patterns then serve as a model in which new ideas are hypothesized and new designs are discovered. While anecdotes and stories of resilience in the incident/emergency management domain have hitherto been accumulated and contributed to better understanding of resilience engineering, few models are available that explain the real-world resilience behavior of complex IMT systems to facilitate new findings. Traditionally, disaster response and emergency management research has been approached from higher and lower levels of complex socio-systems hierarchy (Leveson, 2004; Rasmussen, 1997). Studies at the higher level have leaned towards social system, public administration and policy (cf. Bissell, 2013; Rodríguez et al., 2007). On the other hand, studies for the lower level have focused on how field responders behave and make decisions (cf. Klein, 1993). To our knowledge, this is the first study investigating the intermediate level of disaster response that focused on the IMT as a JCS. Our work in modeling a JCS for an incident management organization may inform addressing real-world complexities through making dynamic interplay among cognitive agents, technological artifacts and demands that the incident creates more tangible. In particular, incident management systems such as NIMS or ICS in the U.S. can benefit from descriptive models using the JCS perspective given the persistent threats from disasters.

While the JCS model presented in this paper showed promise in facilitating the descriptive modeling of IMT’s resilience, further work is warranted to advance resilience engineering knowledge of incident management systems. For example, resilient performance of the IMT can be traced by investigating how the organization perceives and copes with an input. This input can be manipulated in the sense that whether it is routine and planned (therefore expected) or not. Tracing such coping behavior may include observing how resources are utilized, the timeline of such behavior, and how cognitive agents interact across different boundaries of the IMT. In other words, future studies should highlight communication and information flow that may reveal resilience of the IMT on how it monitors on-going situations, anticipates future states, learns from past experiences, to contribute to an informed response.

While the present work was the first attempt to model the IMT as a JCS and to provide operationalizable measures for resilient performance, several limitations need to be addressed in the future research. First, in this study, data were collected in a simulated setting. While the EOTC environment is similar to real-world emergency response operations in many aspects, evaluating models derived from a simulated setting against real response scenarios is warranted. To that end, work is currently in progress to support this model with empirical evidence through interviews with subject matter experts in this domain, and observation and data collection from real disaster responses. Second, while Interactive Episode Analysis showed promise in operationalizing the three resilience metrics proposed, the scope of episodes collected to date are limited. Sufficient number of episodes should be collected in the future such that they can provide a full inventory of resilient IMT performance patterns. Such inventory may inform a normative model that acts as a reference for comparing resilient performance among different scenarios or IMTs using the proposed measures. It may also provide basis for developing a computational model which can render a predictive study for the IMT. Third, while this study showed a proof of concept for the one of the measures for resilience, namely the interaction, more research is warranted to incorporate and further validate interactions and the other two measures. Finally, experimental research is needed to manipulate these measures in isolation without severely compromising the real-world complexity. This can be managed by careful development of scenarios for experimental studies that incorporate the incident action planning process in a reduced scale and design of injects that impose different levels of high or low demands while investigating cognitive support tools and displays that facilitate adaptations.

5. Conclusions

An IMT is a core element of the U.S. NIMS that deals with complex and high-impact incidents. Prior research identified the needs of resilience in the centralized incident management approach for unexpected and unplanned situations. Considering that resilience is a defining property of a JCS, the present work presented a JCS model of the IMT based on theoretical grounds as well as findings from empirical, naturalistic observations of high-fidelity emergency exercises. This research realized a cyclic incident action planning process and furthermore three measures for resilient behavior in complex IMTs were suggested and qualified through observational cases. While this work documented our preliminary attempts at modeling an IMT as a JCS, future work is necessary to further instantiate aspects of the model as well as the measures presented. Regardless, the models presented address an important gap in understanding resilience behavior of IMTs and provides a venue for fostering new ideas for future measurement efforts.

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Glossary

COCOM	Contextual Control Model
CSE	Cognitive Systems Engineering
ECOM	Extended Control Model
EOC	Emergency Operations Center
EOTC	Emergency Operations Training Center
IAP	Incident Action Plan
ICP	Incident Command Post
ICS	Incident Command System
IC/UC	Incident Command/Unified Command
IEA	Interactive Episode Analysis
IMT	Incident Management Team
JCS	Joint Cognitive System
NIMS	National Incident Management System

Declarations of interest

none

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Fig. 1

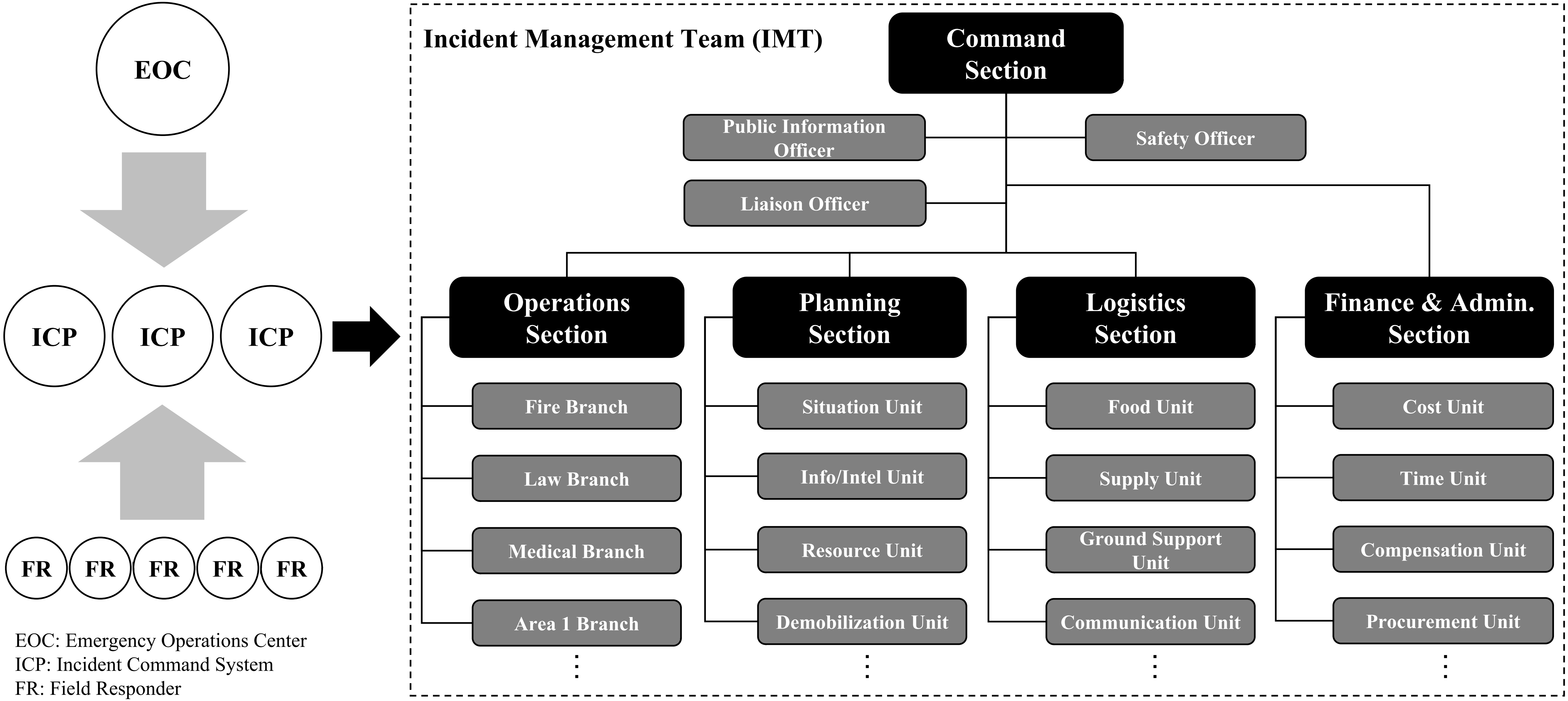

EOC
ICP
ICP
ICP
FR
FR
FR
FR
FR
EOC: Emergency Operations Center
ICP: Incident Command System
FR: Field Responder
Incident Management Team (IMT)
Command Section
Public Information Officer
Safety Officer
Liaison Officer
Operations Section
Fire Branch
Law Branch
Medical Branch
Area 1 Branch
Planning Section
Situation Unit
Info/Intel Unit
Resource Unit
Demobilization Unit
Logistics Section
Food Unit
Supply Unit
Ground Support Unit
Communication Unit
Finance & Admin. Section
Cost Unit
Time Unit
Compensation Unit
Procurement Unit

Fig. 2

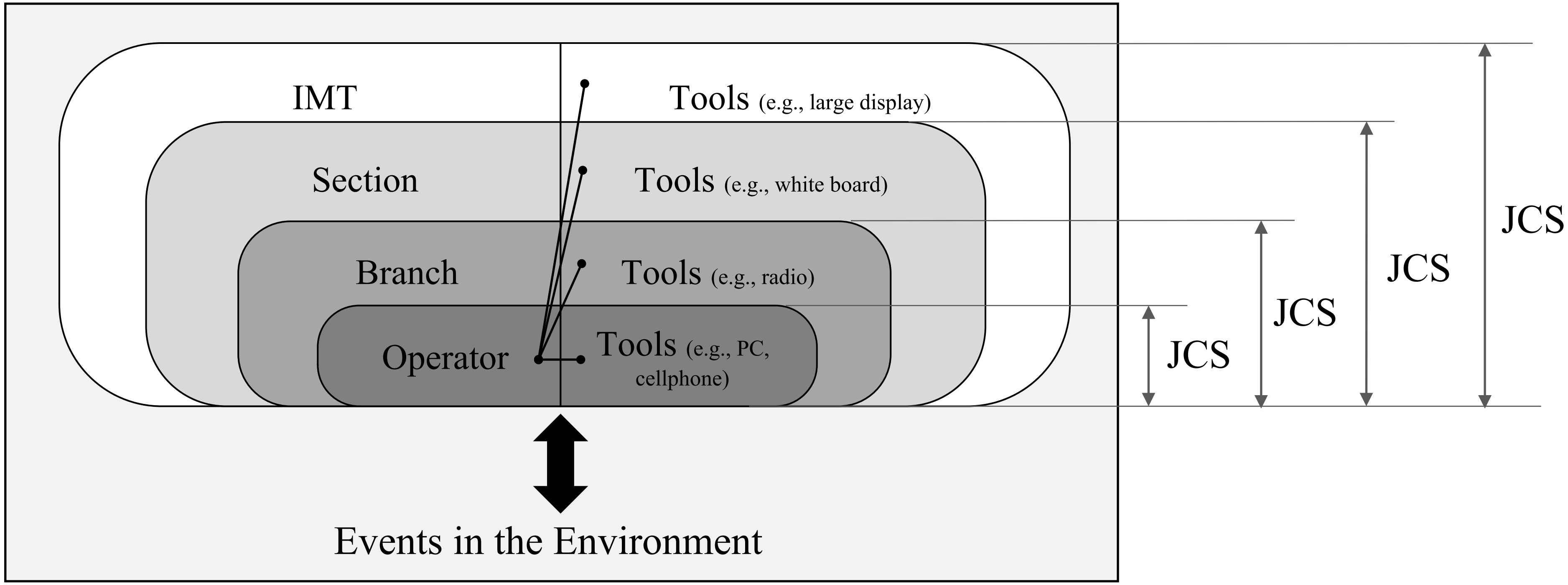

IMT
Tools (e.g., large display)
Section
Tools (e.g., white board)
Branch
Tools (e.g., radio)
Operator
Tools (e.g., PC, cellphone)
JCS
JCS
JCS
JCS
Events in the Environment

Fig. 3

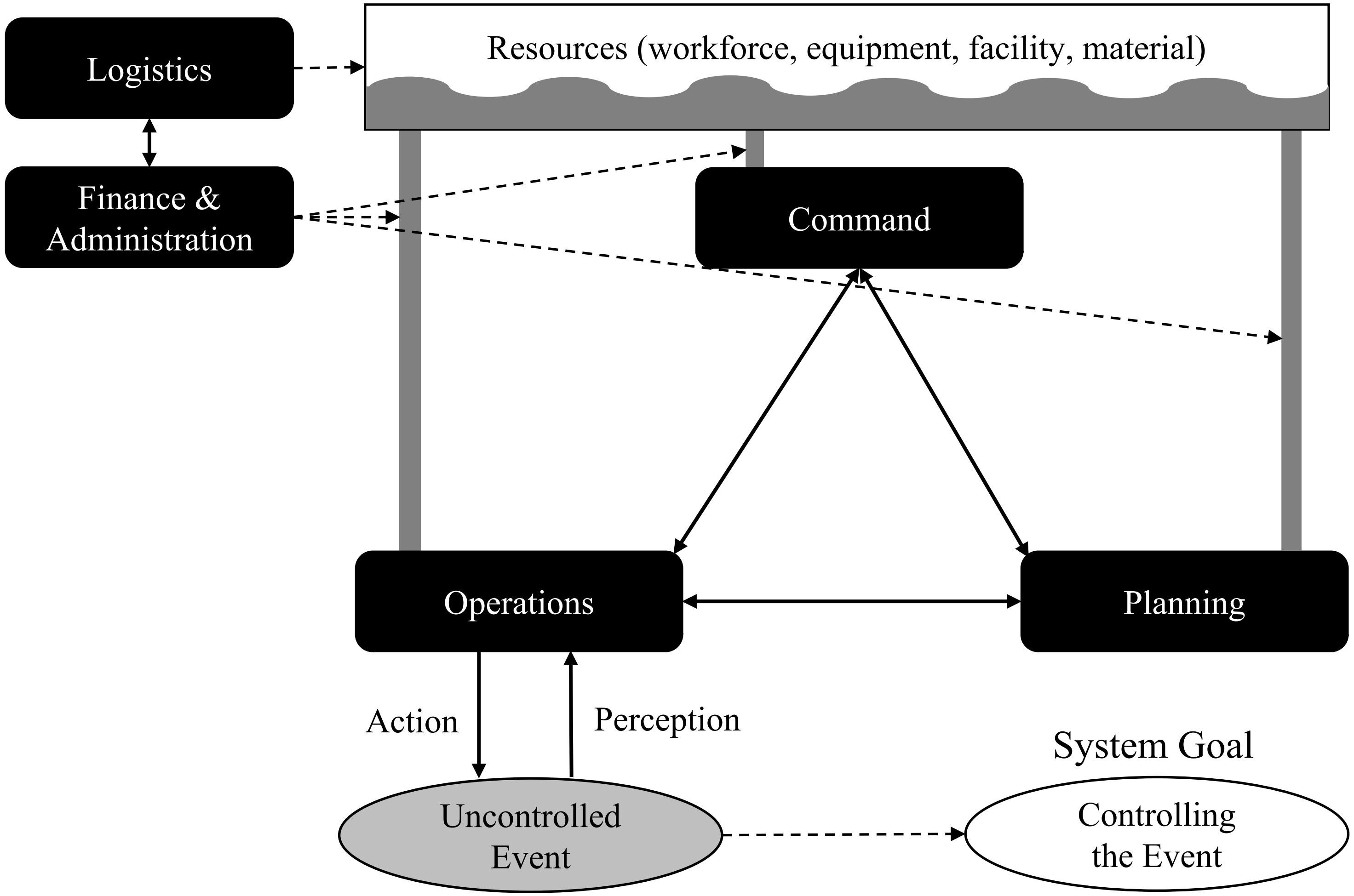

Logistics
Resources (workforce, equipment, facility, material)
Finance &
Administration
Command
Operations
Planning
Action
Perception
System Goal
Uncontrolled
Event
Controlling
the Event

Fig. 4

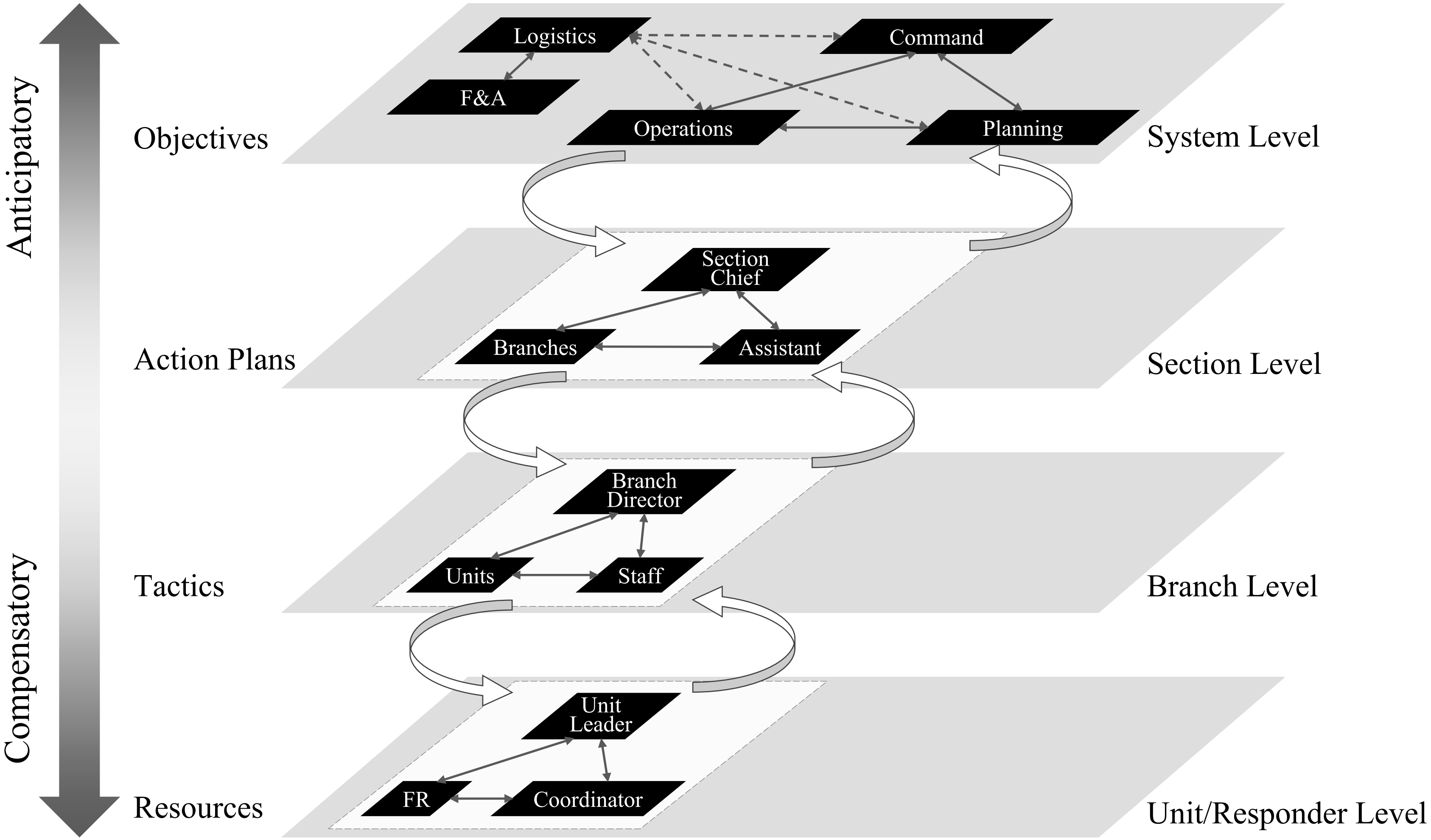
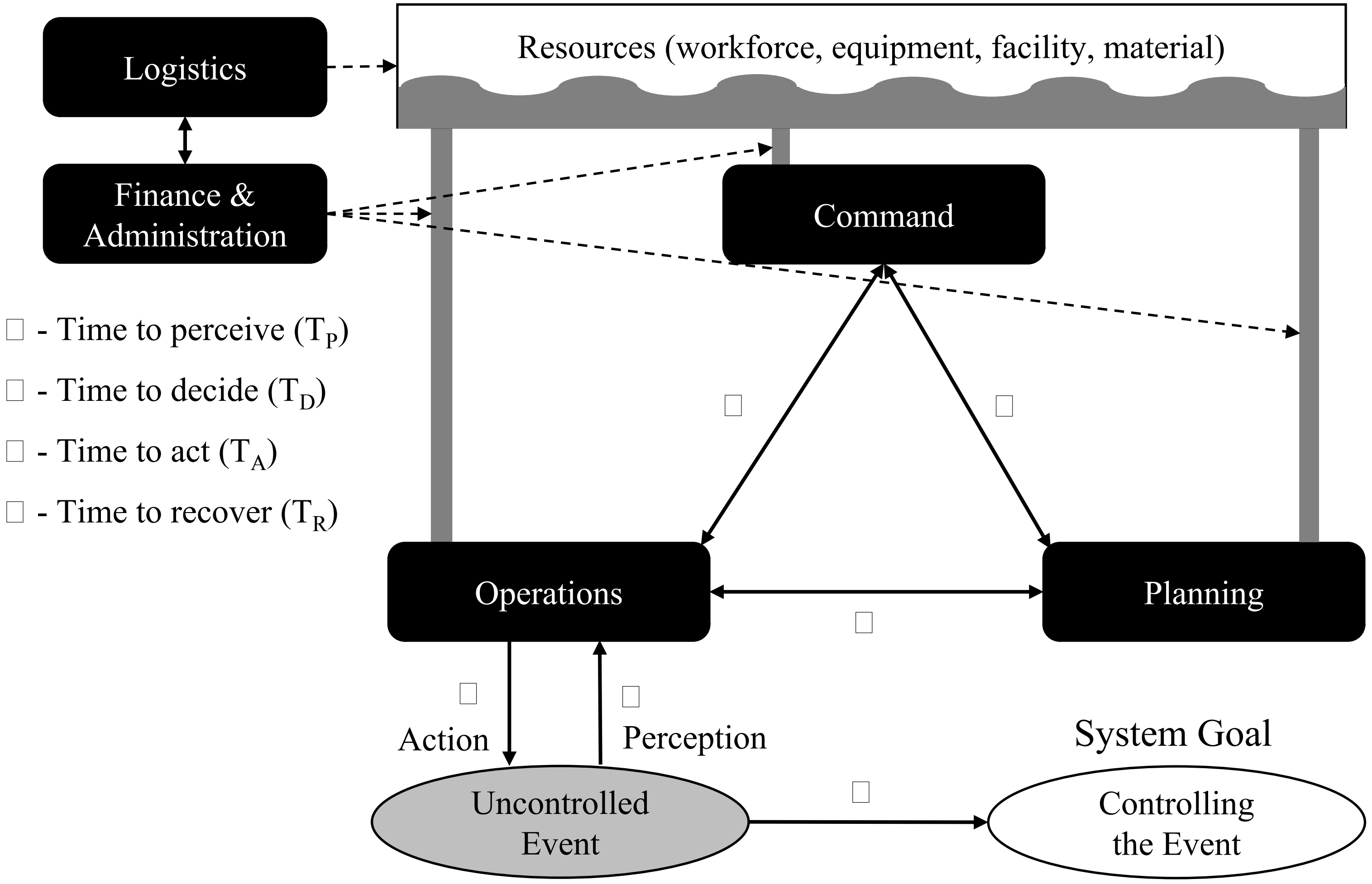

Anticipatory
Compensatory
Objectives
Action Plans
Tactics
Resources
Logistics
Command
F&A
Operations
Planning
System Level
Section Chief
Branches
Assistant
Section Level
Branch Director
Units
Staff
Branch Level
Unit Leader
FR
Coordinator
Unit/Responder Level

Fig. 5



Resources (workforce, equipment, facility, material)
Logistics
Finance &
Administration
☐ - Time to perceive (T_P)
☐ - Time to decide (T_D)
☐ - Time to act (T_A)
☐ - Time to recover (T_R)
Command
☐
☐
Operations
Planning
☐
☐
☐
Action
Perception
System Goal
Uncontrolled
Event
☐
Controlling
the Event

Fig. 6

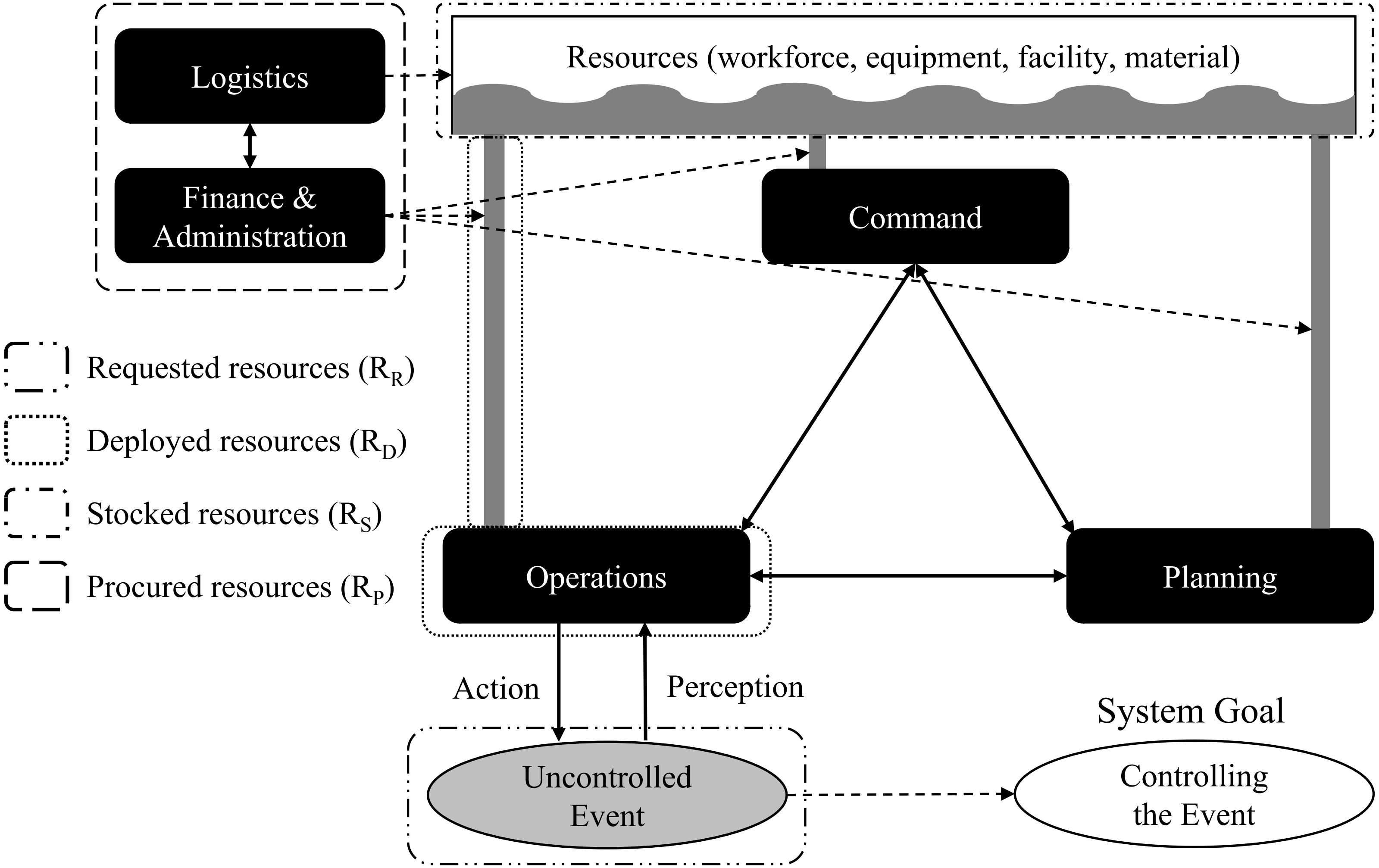
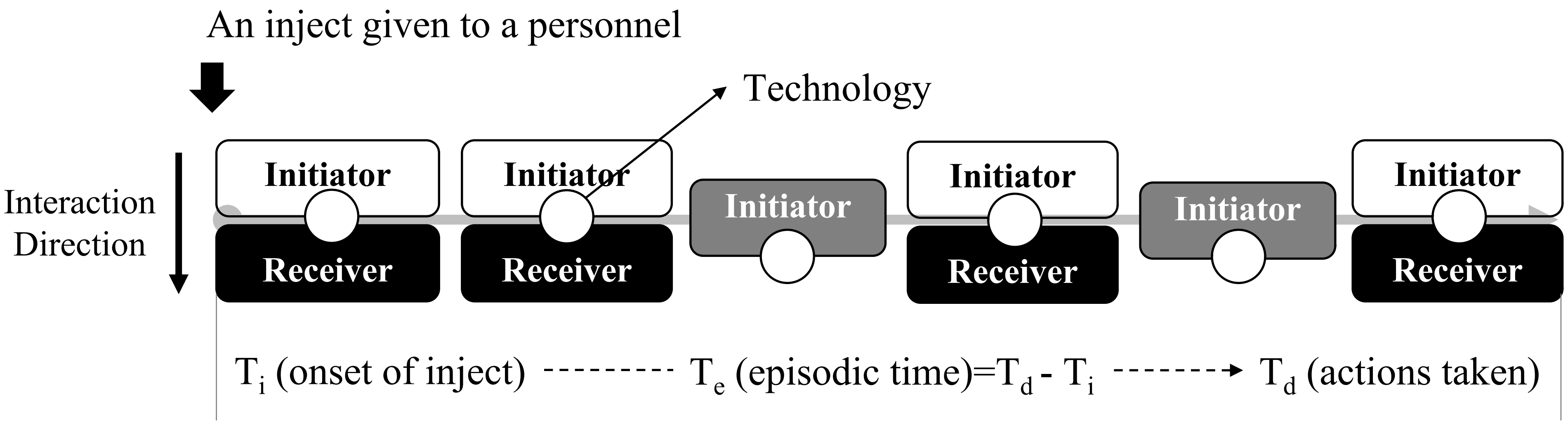
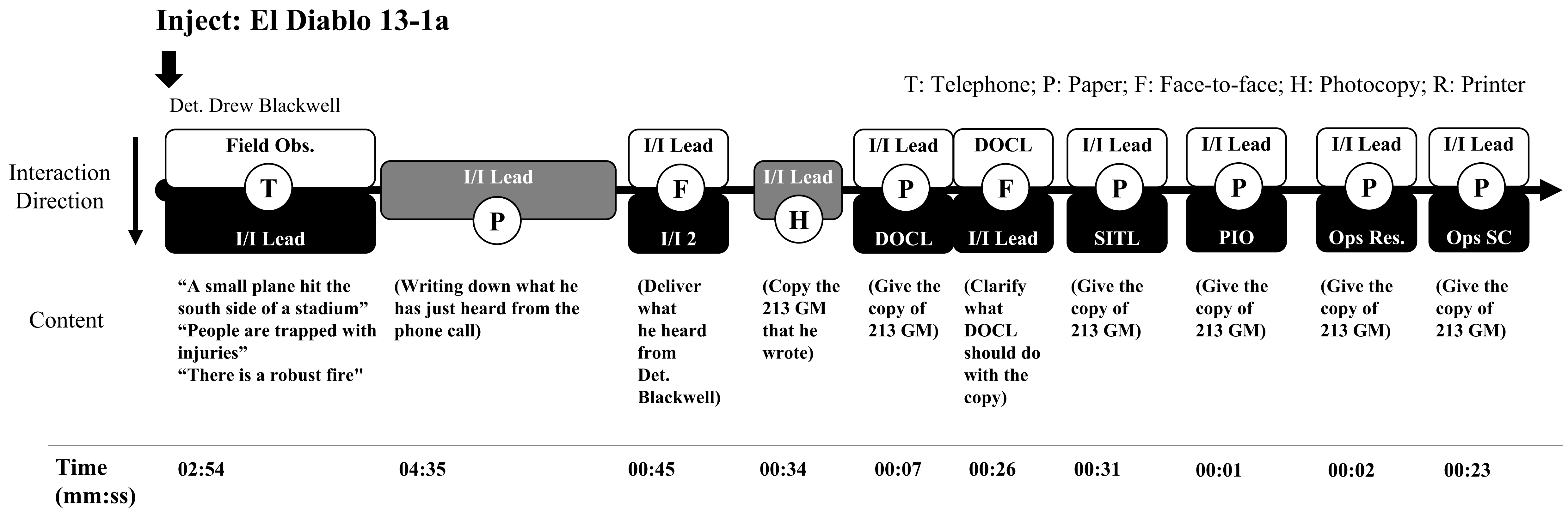

Logistics
Finance & Administration
Resources (workforce, equipment, facility, material)
Command
Operations
Planning
Requested resources (R_R)
Deployed resources (R_D)
Stocked resources (R_S)
Procured resources (R_P)
Action
Perception
Uncontrolled Event
System Goal
Controlling the Event

Fig. 7



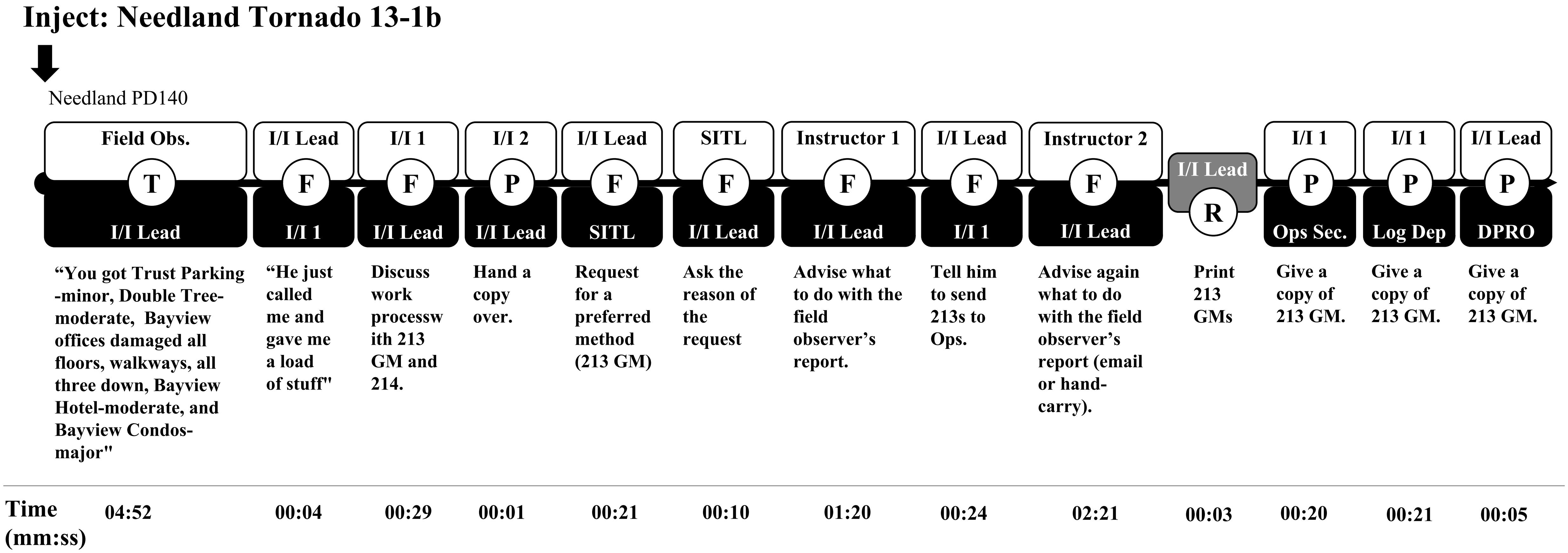
An inject given to a personnel
Technology
Interaction Direction
Initiator
Receiver
Initiator
Receiver
Initiator
Initiator
Receiver
Initiator
Initiator
Receiver
T_i (onset of inject) --------- T_e (episodic time)=T_d - T_i -------→ T_d (actions taken)

Fig. 8



Interaction Direction	Field Obs. T I/I Lead	I/I Lead P	I/I Lead F I/I 2	I/I Lead H	I/I Lead P DOCL	DOCL F I/I Lead	I/I Lead P SITL	I/I Lead P PIO	I/I Lead P Ops Res.	I/I Lead P Ops SC
Content	"A small plane hit the south side of a stadium" "People are trapped with injuries" "There is a robust fire"	(Writing down what he has just heard from the phone call)	(Deliver what he heard from Det. Blackwell)	(Copy the 213 GM that he wrote)	(Give the copy of 213 GM)	(Clarify what DOCL should do with the copy)	(Give the copy of 213 GM)	(Give the copy of 213 GM)	(Give the copy of 213 GM)	(Give the copy of 213 GM)
Time (mm:ss)	02:54	04:35	00:45	00:34	00:07	00:26	00:31	00:01	00:02	00:23

Fig. 9


Inject: Needland Tornado 13-1b
Needland PD140
Field Obs.
T
I/I Lead
"You got Trust Parking -minor, Double Tree-moderate, Bayview offices damaged all floors, walkways, all three down, Bayview Hotel-moderate, and Bayview Condos-major"
I/I Lead
F
I/I 1
"He just called me and gave me a load of stuff"
I/I 1
F
I/I Lead
Discuss work processw ith 213 GM and 214.
I/I 2
P
I/I Lead
Hand a copy over.
I/I Lead
F
SITL
Request for a preferred method (213 GM)
SITL
F
I/I Lead
Ask the reason of the request
Instructor 1
F
I/I Lead
Advise what to do with the field observer's report.
I/I Lead
F
I/I 1
Tell him to send 213s to Ops.
Instructor 2
F
I/I Lead
Advise again what to do with the field observer's report (email or hand-carry).
I/I Lead
R
Print 213 GMs
I/I 1
P
Ops Sec.
Give a copy of 213 GM.
I/I 1
P
Log Dep
Give a copy of 213 GM.
I/I Lead
P
DPRO
Give a copy of 213 GM.
Time (mm:ss)
04:52
00:04
00:29
00:01
00:21
00:10
01:20
00:24
02:21
00:03
00:20
00:21
00:05