Adaptable socio-cyber physical systems for supporting disaster response

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Abstract

Effective disaster response highly depends on disaster types, scale, and attributes of disaster affected regions. Although deeply interconnected, social, cyber and physical aspects are usually not considered together when shaping an appropriate disaster response strategy. We introduce a conceptual framework in which disasters are socio-cyber-physical systems that codify attributes impacting effective responses. The framework enables rigorous analysis and evaluation of response plans by disaster managers. We inform our conceptual model through a range of disaster-response case studies and our personal disaster first-responder experiences.

Keywords: *disaster management, disaster response, socio-cyber physical system, situational awareness*

Disasters, either natural or man-made, are destructive events with disruption to infrastructure, and society. *Disaster management* is a catch-all phrase that includes all phases of a disaster: mitigation, preparedness, response and recovery (Lettieri et al., 2009). Indeed, the goal of mitigation and preparedness phases is to ensure a systematic response in the event of a disaster. In this paper, we outline a methodological approach to specifying a *socio-cyber-physical (SCP)* system which is designed to aid decision-making for specific operational activities within the disaster-affected region.

The recent significant increase in the frequency and severity of disasters (Madanian et al., 2020; Ogie & Pradhan, 2019) has been leading to an increase in research studies, investments in technology utilisation and improving disaster management systems, especially for the disaster response phase. To have a better response to the requirements and demands of disaster casualties, the use of technology is inevitable. Technology utilisation helps in improving overall disaster management, facilitating response when a disaster occurs, enhancing support after a disaster, and keeping records for better future preparedness. In order to accomplish this, different Information and Communication Technologies (ICT) can be utilised and integrated to enhance the overall response missions' effectiveness. This integration needs a systematic framework that is discussed by (Madanian et al., 2020) with the main aim of facilitating finding out where and in what way technologies can be practised and integrated within disaster management. Among all phases of disaster management, this research concentrated on disaster response, exclusively.

Disaster mitigation, preparedness and recovery possess a critical role in managing disasters. However, they have the convenience of longer time scales allowing for detailed plans. Contrasting these phases to the unpredictable nature of disasters, has necessitated an increased focus on disaster response. While disaster preparation and recovery are planned over longer timeframes, disaster response must be accurate and in real-time in order to save lives.

In disaster response every second counts which highlights the importance of leveraging the advancements in ICT. In this regard, ICT can play an important role in supporting disaster managers, and disaster response activities. Using different technologies assists disaster responders and managers by providing more real-time information about the disaster affected region, preparing more organised responses, and effectively and efficiently controlling and leading disaster response operations. This helps in minimizing the probability of further disturbance occurring, wasting of resources, delivering inappropriate services and amortization.

The current challenges in disaster response and resource distribution are covered in the following section. To address these challenges and to further support disaster managers and authorities, in this research, we propose a methodology based on socio-cyber physical systems which is integrated with system adaptability, and situational awareness concepts for supporting disaster response missions. These concepts are explained and discussed before their usage in disaster management are explained through a case-study in the subsequent section. The modelling of Disaster Management Life Cycle using this methodology is discussed in the final section of this paper.

Disaster Response and the Current Challenges

Large-scale disasters have increased in frequency and intensity over the past few decades and have wrought substantial damage to the livelihoods of populations across the globe (Ogie & Pradhan, 2019). This includes financial, psychological and social burdens on households (Leung). Based on the available literature, there is a long list of disaster response difficulties and challenges and by referring to disaster damage statistics, it can be concluded that this is not an area specific problem and affects both developed and underdeveloped nations alike (Biddison et al., 2018).

Response missions have always been negatively affected by factors such as disasters' unpredictability of location, time, number of injured people, and the severity and types of injuries (Latifi et al., 2007). This leads to further challenges often including accessing those most affected by the disaster, response prioritization, equitable distribution of resources and communication between stakeholders, in regional, national and international levels. These factors specifically affect search and rescue missions as well as providing health support for victims. From the recent catastrophes, it is evident that disaster management and medicine response activities have been far from perfect operations. Poor coordination and communication, information fragmentation, lack of preparedness, and frequent failures in sharing vital information among response agencies result in poor disaster management and responses, both within and between response agencies, which cause unnecessary loss of life (Madanian et al., 2020; Norris et al., 2015).

When disasters occur, there is a heightened need for immediate emergency response in order to save lives and minimize damages (Bürkle et al., 2012). To accomplish this emphasis should be placed on the allocation and distribution of resources to the affected areas. In this regard, disaster managers primarily consider plans coordinating personnel and first-responders to distribute scarce resources within the disaster-affected region. Resource allocation plans form the basis for disaster management, disaster medicine and more recently, disaster healthcare (Madanian et al., 2020).

For effective resource allocation, disaster management and planning should be placed in a holistic setting, and new initiatives are found in order to ensure that a disaster is viewed as a shared responsibility (Trim, 2004). Once the decision has been made as to what resources to allocate to affected areas, the next challenge lies in the distribution of those resources and in doing so posing many other strategical challenges. However, in volatile environments affected by disasters, this leads to extra challenges (Biddison et al., 2018; Chacko et al., 2014). These challenges are often centred around the information availability and their quality, and decision-making process between those managing the situation on the ground and how command chains are formed.

It is also known that gaining access to resources in post-disaster settings can be extremely challenging (Biddison et al., 2018), especially in locating required resources and matching them with the level of demands. In resource allocations, many factors should be considered such as methods of resource allocation, the participants' organisation in rescue missions and their role, and the required types and amount of resources based on individual and community needs. However, the availability of infrastructure and accessibility to disaster-affected areas is required to deploy resources.

This resource allocation is a part of operation managers' responsibilities not just to manage the allocation of resources, but real-time managing the gap between available resources and resources necessary at the disaster-stricken locations (Gabdulkhakova et al., 2012). Additionally, the availability of resources is dynamic and constantly changing which creates logistical challenges for all the involved parties. Incoming information can also be unclear, obsolete and outdated, subjective and even contradictory further burdening the decision making of those in charge (Gabdulkhakova et al., 2012). Therefore, it is concluded that in any disaster response mission, having or collecting the right information, sharing them with the right responsible organization in a timely manner can significantly enhance disaster response, and resource distribution (Kuo et al., 2007). According to (Chacko et al., 2014) some of these could be mitigated utilizing different technologies. For example, social media and social media mining (Pohl et al., 2020) and their usage in emergency dispatch (Grace et al., 2019), different types of decision support systems for resource allocation (e.g. COVID-19 vaccine (Baharmand et al., 2021)), auto-identification technologies for resource management (Madanian & Parry, 2021), big data analytic (Ragini et al., 2018), or delay-tolerant network for gathering and disseminating resource needs (Basu et al., 2020).

Research Gap and Research Objectives

Despite all the recent technologies' enhancements, there are many risks and uncertainties when preparing for and responding to disasters. Many factors have to be taken into consideration and those factors are fluid and constantly chaining (Amendola, 2004). Both the occurrence and consequences of each disaster are quite difficult to anticipate. Following the occurrence of a disaster the uncertainty of each response holds inherent risks due to the precarity of the disturbed environment, the potential for continued impact of weather events and uncertainty of the affected population and volunteers on the ground (Liberatore et al., 2013). These risks exist for both the individuals (or victims) affected by the disaster as well as the first- responders, volunteers and field workers responding to it. Uncertainty affects the victims being responded to as it is often unclear if or when a responder will arrive. This can lead to fear and anxiety in addition to any physical ailments they are suffering as a result of the disaster. Also, for the responders the location of the victims is often unclear, as are hidden obstacles inhibiting their access and what resources are required when they arrive.

These issues have necessitated enhancements in disaster response and managing its supply chain. Although the number of studies in the area of technology and ICT utilisation for disaster response have been growing significantly, resiliency in the disaster supply chain should be improved. According to the National Academy of the Sciences (2020) resilience should be embedded in disaster supply chains and is crucial in maintaining the consistent delivery of goods and services to the affected populations.

The challenges associated with resource allocation could be mitigated utilizing strategic systems (Chacko et al., 2014) that can best determine interventions that provide the best possible outcome. This is the case for both single hazard events, but even more so for multi-hazard events which often stretch resources well beyond demand (Chacko et al., 2014). Utilization of strategic systems to assist in resource allocation has grown substantially over the past few decades and has seen a significant amount of growth and improvement. The use of spatial partitioning has been utilized in recent years in order to locate the best segmentation of an area for optimal resource allocation (Kolomvatsos et al., 2013). However, most of the available or proposed systems have been inflexible and constrained by capacity (Underwood, 2010).

Different field response works following disasters such as Hurricane Irma in Central Florida uncovered several response limitations concerning the use of cyber systems in disaster response. In our research, we are looking for the potential of technology and theory integration to optimize response activities and integrate the physical world to the digital using a self-adaptive system. The objective is the conceptualisation and re-developing disaster management and disasters as a socio-cyber physical system (SCPS) and software engineering theories such as self-adaptive systems and incorporating situational awareness concepts to further support disaster response missions. With this new angle into disasters and disaster management context, disasters can be viewed as a socio-cyber physical system, and its requirements can be viewed as system requirements that should be satisfied. In this concept, disaster affected regions and disaster preparedness can be represented by systems' configurations and system constraints that should satisfy the defined system requirements.

This new approach to disasters as SCPS helps us in developing self-adaptive systems, especially useful for disaster response. As SCP systems are dynamic (components can be changed), they are layers and can be managed in a way to maintain and meet the system requirements. For example, in pre-disaster phases, sufficient resources, based on the response strategy and plan, are allocated at every location in the region to satisfy resource demands. Finding a suitable allocation essentially corresponds to a constraints solving problem $\alpha \models K$, where resourcing demands are formalised as logical predicates K and an allocation is modelled by the satisfying assignment function α (Johnson et al., 2020). However, due to a disaster's inherently uncertain and unpredictable nature, disaster managers must assume that the scenario evolves: i.e., more resources are required at a location, initial resourcing is inadequate and new locations arise and must be resourced. In response, plans must be continually devised to transport resources to the locations where they are needed.

Adaptable Socio-Cyber Physical Systems

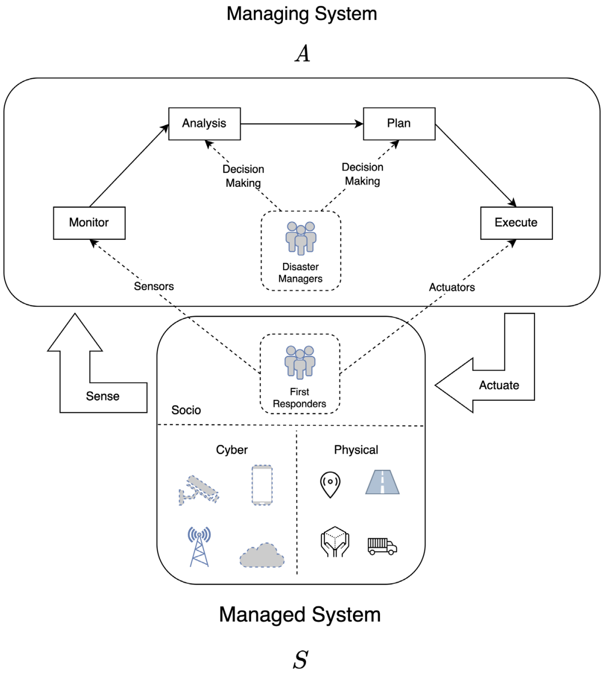
Cities are evolving into *cyber-physical systems*, a complex mixture of software and hardware embedded within the physical environment. Cyber-physical systems that also represent humans as part of the system are called *socio-cyber-physical (SCP)* systems (Paterson et al., 2019). This is an important class of systems for which we may reason with, and understand, human roles within cyber-physical systems and how they interact with technology. This section develops a socio-cyber-physical system to represent resource allocation and distribution within a disaster-affected region. The sorts of resources needed during a disaster scenario are ranging from emergency medicine and sustenance to supplies and disaster first responders. This section introduces key mathematical notation used throughout the paper, summarised in Table 1.

Resource allocation during a disaster is a challenging problem since demands for resourcing frequently change. Disaster could cause ongoing damage to road infrastructure, making resource distribution by the first-responders difficult. The topmost portion of Figure 1 presents the *managing system* A, comprising Monitor, Analyse, Plan and Execute components which sense the situational state of the *managed system* S. The disaster management team maintain situational awareness of S to effectively command and control transport workers tasked with resource delivery.

Table 1
Mathematical Notation for the Algebraic Model of the Adaptive SCPS

Symbol	Meaning
S	SCPS of the Disaster-Affected Region
A	MAPE Loop Managing S
P	Resourcing Policies (Requirements)
σ	Current state of the SCPS S
σ'	Updated state from observing physical event
$\sigma_{good} \models P$	State σ_{good} is a state satisfying resourcing policies P
$\{\mathbf{a}, \mathbf{b}, \ldots\}$	Unique names referring to locations within the disaster-affected region
p_b	Quantity of resources specified by $\sigma_{good}(\mathbf{b})$
q_b	Quantity of resources needed at location **b** to satisfy P

Figure 1
Adaptive Socio-Cyber-Physical System for Resourcing a Disaster-Affected Region



Managed System Components and Requirements

The goal of the managed system S is to support the disaster management team in their decision making process for resourcing within the disaster-affected region. The required amounts of resources and their location within the region are typically expressed in terms of a policy P and are outlined during the mitigation and preparedness phases of disaster management.

The bottommost portion of Figure 1 depicts scp system S components impacting disaster preparedness within the region, delineated by dashed lines, including:

Physical components which correspond to characteristics of the geographical region, such as road infrastructure, physical attributes of the resources being distributed to locations within the region and reliability of the vehicles used.

Cyber components which comprise disparate ICT contained within smart cities, to be utilised to improve the ability to retrieve, compute and visualise information from the region that is relevant to resource distribution within the region. This category of components may include drone technology, computing devices, cameras and CCTV, cloud-based technologies, and telecommunication infrastructure.

Socio components comprising human first responders and medical teams who play the most important role during a disaster response to distribute resources as they are needed.

Situational State of the Managed System

Key to our approach is defining the *situational state σ* of *S*, an object which defines the current situation of every real world element represented by a component of *S*, such as the quantities of resources allocated within a region, the position of first-responders and their current status. The situational state *σ* can be represented using high-tech and low-tech ways. For example, using a physical map and radio communication, a disaster manager team can track resourcing in the region, maintaining a rudimentary situational state of *S*. We expect that resourcing policies also change depending on the severity of the disaster and the updated policies are also reflected as part of the managed system's situational state.

When using a modelling approach, *σ* is a mathematical object, meaning that *formal verification* tools such as constraint solvers can be used to automatically check current resourcing properties of the system. In symbols, we write $\sigma \models P$ to mean that the system state σ satisfies all resourcing policies in *P*, e.g. no resources are needed to be transported within the region represented by *S*. We say that *σ* is a *good* state of *S* whenever $\sigma \models P$. We outline this approach in the final section of this paper.

Self-Adaptive Capabilities of the Managing System

The components of the managed system *S* are subject to change and this is especially true when the region represented by *S* experiences a disaster, where outstanding resources may be required at one or more locations. To support the disaster management team in keeping the system in a good state, *S* is coordinated via the managing system *A* which comprises a MAPE control- loop (Kephart & Chess, 2003) depicted on the topmost part of Figure 1. The adaptive functionality is delineated into four distinct *Monitor*, *Analysis*, *Plan* and *Execute* phases. These phases act as a feedback loop performed continually by the disaster management team to maintain resourcing across the region.

Human Roles and Responsibilities. Humans play a critical role in both the managed scp system *S* and its managing system *A*. There are two specific roles for humans, *first responders* and *disaster managers*. It is the role of disaster managers to command and coordinate first-responders in *S* during the disaster response. They are responsible for decision making based on analysing the current situational state of *S*, and developing a resource allocation and distribution plan informed from the *Analysis* results. These responsibilities are depicted in Figure 1 by dashed lines from the Disaster Managers component of *A* to the *Analysis* and *Plan* phases of the MAPE loop. For the scp *S*, *first responders* act as sophisticated *sensors*, denoted as a dashed line that acts as input to the *Monitor* phase. This means first responders report back on road conditions, resourcing quantities at locations within the region in order to form information to update the disaster manager's situational state of the system *S*. In turn, first responders also perform resource transportation and distribution according to plans made by disaster managers, which alters the situational state *σ* of the managed system *S*. These actions are denoted by the dashed line from the *Execute* phase to the first-responders component within the managed system *S*.

Sensing and Monitoring. In the first phase of the MAPE loop, system components are perceived by *sensors* from the SCP system and input to the *Monitor*, to be synthesised into the situation state σ of *S*, as denoted by the vertical arrow on the left-hand side of Figure 1.

In the *Monitor* phase, disaster managers build up a current snapshot of the region, particularly:

- kind and location of resourcing,
- updated resourcing policies, brought about from e.g. increased demand, and
- status and location of first responder staff working within the region.

Sensors are defined as any system component whose perception give usable information for decision-making. Broadly speaking, this can be high-tech solutions which are helpful automating the collection of sensor data, or it could be human-centric, such as situation reports from first responders (on-going via radio or upon return to the command centre), healthcare workers or other people in the region deemed as a reputable source of information to base decision-making upon.

High-tech solutions depend on communication infrastructure within the region. Technological sensors such as cameras and drones can record and transmit pictures to communicate digital images to the management team. Devices can be commanded from a distance and observe parts of the region impossible for humans to safely access. In most cases, and especially during a disaster, it is too difficult and expensive to instrument the region with sensors to extract useful information.

For resource allocation during a disaster, it is vital to keep track of resources, and how they may be distributed within the region. Physical components such as the roadways, locations, resources and vehicles can become affected by a disaster at any time. For example, roadways may be negatively impacted by adverse weather conditions, which make travel slow and difficult. In some cases, a disaster may damage a roadway, making it completely impassible and therefore must be avoided. As a result, locations may become impossible to reach, making resource distribution difficult.

Our approach accounts for uncertainty in sensing the situational state σ of S. For example, it is usually impossible to obtain full information of resource needs and changing requirements through the disaster-affected region. However, if hospitals and clinics operate auditing software for their on-site resourcing, then it can be utilised, capturing very accurate resource usage information.

Analysis and Planning. The *Analysis* phase takes the completed situational state σ of S as input and applies analytic processes to determine whether or not there is a need to deploy first responders to transport resources as required within the disaster-affected region. The situational state keeps track of a finite number of unique locations {a, b} of interest within the region and, broadly speaking, if σ_{good} represents a *good* state of the system before the disaster hit, then $p_b = \sigma_{good}(\mathrm{b})$ is the ideal quantity of resources available at the location b. To simplify the presentation, let p_b be a single number. In real-life disaster scenarios, p_b would be a list of resources: sustenance, first-aid supplies etc.

The management team computes current resource needs at **b** by the difference equation

$$q_b = \sigma_{good}(\mathbf{b}) - \sigma(\mathbf{b}).$$

If $q_b > 0$, then the quantity q_b of resources needs to be transported to **b**. Otherwise, **b** currently satisfies it's resourcing requirements as determined by the situational state σ against the resourcing policies *P*. These resourcing policies may have been updated as a result of changes in demand or addition of new kinds of resources, as perceived during the monitoring phase.

Formal verification techniques automate these calculations during a disaster scenario, where logic and mathematical models to encode resourcing requirements. The final section of this paper outlines the kinds of models and techniques used in our previous work (Johnson et al., 2021; Johnson et al., 2020).

Determining resourcing needs is carried out by the management team with uncertainty about how many resources are needed. The *Analysis* phase yields quantities of resources to be distributed to locations within the disaster-affected region. The next phase is the *Plan* phase which works out the logistics for moving resources where they are needed. Disaster managers must consider the health and safety of the first responders. They take into account their team's personal circumstances, such as competencies, capabilities, capacities and level of fatigue. Once a responder is given a quantity of resources, they mainly select a shortest path route through the region, typically computed by GPS, when available. Alternatively, the route may be selected according to the most reliable and least affected by the disaster. At times, the first responder may not know the exact location where the resources and simply drive in the general direction where resources are likely needed.

Execution and Actuation. In the *Execution* phase, the plan considered by the disaster management team is realised. For a disaster scenario, this means that resources are secured and loaded onto an emergency response vehicle. We denote this *source* location by a, which represents the staging area from which resources are supplied to locations within the disaster-affected region. In general, there may be one or more source locations, where resources are either strategically prepositioned during the disaster preparedness phase or transported to a centralised location to be distributed as part of the disaster response.

The first responder team sets out to their target location, such as **b** to deliver the resources. In this sense, the first responders are system *actuators* which alter the current state σ to a new state $\sigma' = \mathit{transport}(\sigma, q, \mathbf{a}, \mathbf{b})$, where

transport is an algebraic operation on situational states yielding σ', satisfying the equations

$$\sigma'(\mathbf{b}) = \sigma(\mathbf{b}) + q_b$$

$$\sigma'(\mathbf{a}) = \sigma(\mathbf{a}) - q_b.$$

In some cases, it may be possible to utilise high-tech solutions for distributing resources across the region. For example, drones may be useful for quickly reaching areas that are impassible via the ground. Often times however, humans play a critical role in actuating resource distribution since technology may simply be unavailable to the disaster responders. Deliveries of resources and other changes to S update its situation state, which are sensed by future iterations of the MAPE loop.

Integrating SCP Design and Operation into the Disaster Management Life Cycle

Table 2 associates disaster management life cycle phases[1] with corresponding SCP system engineering steps. The mitigation phase coincides with component and requirement specification of the SCP system S. In this step, disaster managers work together with engineers to specify key components and translate disaster requirements into policies P. At the end of this step, we define the situational state σ of the system S.

In the preparedness phase, disaster managers distribute resources (according to policies P) to locations in the region to help the community prepare for a disaster. Non-perishable resources are typically stored on-site either in the building or in nearby storage containers. This includes the majority of equipment, electronics and safety/rescue vehicles. During this phase, S becomes operational and is initialised in a good situational state σ_{good} satisfying all resourcing policies. In symbols, $\sigma_{good} \models P$.

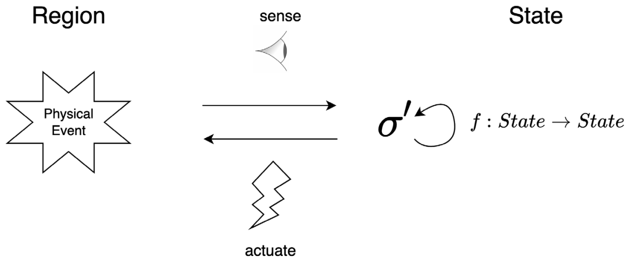
Figure 2 presents the functionality of managing system A, logically delineated into MAPE control loop phases, and continually managing changes in S to inform planning during the disaster response phase. For example, depletion of resources at location **b** might be perceived by

- first-responders
- healthcare staff, or
- automatically by auditing eHealth software.

Table 2
Disaster Management Phases and SCP System Engineering Steps

Disaster management Phase	SCP System
Mitigation	Component and Requirements Specification
Preparation	Situational State Initialisation
Response	MAPE Control-Loop
Recovery	

Figure 2
Translating Physical Events in the Region to Algebraic Operations on the Situational State σ of S



The *Monitor* updates the situational state σ_{good} with an operation f corresponding to the physical event. For example, the updated state

$$\sigma'(\mathbf{b}) = \sigma_{good}(\mathbf{b}) - q_b'$$

for the quantity q_b' of used resources at **b**. The *Analyse* part of the MAPE loop analyses σ' to determine if $\sigma' \models P$ If so, actions are formulated by *Plan* to be approved by the disaster management team and actuated by *Execute*, including transporting enough resources to **b** to put S into a good situational state again.

The recovery phase can synthesise knowledge from the operational logs from S that describe behaviour of the SCP system during a disaster, to inform future disaster response policies.

Case-Study

To demonstrate the applicability and functionality of our proposed methodology and considering disaster as the SCP system, we develop a case-study based on Hurricane Irma. The attempt is to specify the socio, cyber and physical aspects of Irma disaster response operations and how we can conceptualize disaster management into SCP system.

Despite the fact that different categories of disasters (such as earthquakes, flooding, and terrorist events) lead to different consequences, most disasters have many common elements (Uchida et al., 2004). Therefore, as storms and floods are the two most prevailing disasters in the Asia Pacific region (Alisjahbana et al., 2021), in terms of fatalities and the affected people, cyclone/hurricane disaster type was chosen. With this in mind, we developed a case-study based on first hand response to Hurricane Irma considering the wealth of the available knowledge and our first responder's experience deploying to Southern Florida for disaster relief efforts following Hurricane Irma in 2017.

Based on our field experience in responding to Hurricane Irma, there is a long list of ad-hoc types of response challenges that are different in nature, types and root causes. This makes disaster response adherence to the pre-defined strategies and plans challenging, especially due to constant changes in disaster affected regions while disaster managers often have outdated, or inaccurate information about the region.

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[1] disasterphilanthropy.org/issue-insight/the-disaster-life-cycle

Hurricane Irma

Hurricane Irma made landfall on the continental US over the Florida Keys as a category 5 hurricane on the morning of September 10, 2017[2][3][4]

The majority of the damage was caused by hurricane strength wind reported to have reached over 180mph and flooding that caused the evacuation of nearly 6 million Floridians (Hong & Frias-Martinez, 2020). The category five storm ripped off roofs, flooded coastal cities, and knocked out power to more than 6.8 million residents. By Sept. 11, Irma weakened to a tropical storm and as it moved North the storm lost power causing substantially less damage over time. By Sept. 13, it had almost completely dissipated and the majority of the major damage was over. Affected residents were left with an immediate and desperate need for resources all across Florida. According to a preliminary estimate Hurricane Irma cost as much as 42.5 to 60 Billion (USD) in wind and flood damage to both commercial and residential property (LaVito, 2017).

When our disaster responder deployed with the Red Cross, the Southern Florida region of Naples was strategically chosen as one the main hubs for response and resource distribution due to the disaster impact on a densely populated area and it's ease of accessibility by main roadways and a major airport. In disaster response, main hubs are usually positioned in a larger city due to their heightened access to valuable resources, resupplies via their access to a multitude of transport options, and accommodation for responders and volunteers. Access to an airport is also critical for any disaster response hub as it allows all responders, volunteers and replacements easy access to the disaster stricken region and expedites medical evacuations for those in need. Cities also have better access to technology-based systems, internet, and access to hospitals and other localized emergency response teams and equipment.

Irma Disaster Response

Our fieldwork expert was deployed in response to Hurricane Irma as a Red Cross disaster responder and Emergency Response Vehicle Driver (ERV). ERV teams main responsibilities during disasters are centred around resource distribution, risk communication and health services throughout the disaster- affected region. Tangible resources on response vehicles include supplies such as food, water, blankets, medical kits, clean up kits and tarpaulins for sheltering and coverage. ERV teams typically deploy in pairs, however when available, teams are accompanied by a nurse or other medical professional to attend to any medical needs during the days responses.

Figure 3

Disaster Relief Vehicle Traversing City Roads

RV teams responding to victims of Irma were briefed each morning by a disaster manager in the main staging area. The location of the briefing is typically the same location as the main staging area for all supplies, logistics personnel, responders, volunteers and response vehicles. The morning briefing broke down a situation report (SITREP) containing the day's chain of command, available distributable resources, and established teams and their vehicle assignments. STRIP is a periodic status report with a quick understanding of the current situation for decision-makers. Weather forecasts and updates on any further road closures or road openings from the past twelve to twenty-four hours were also discussed. These briefings usually ended with a question and answer session to clarify any details or misunderstandings about the days proceedings.

Following vehicle assignments, each team loads their ERVs based on any specific needs they were briefed on concerning the location of their morning assignment. Selecting and loading various resources also depended on the availability of hot meals from predominantly elderly volunteers from a local church and the availability of bulk supplies from the previous day's restock. Some locations were without power and grocery stores had been closed so getting them meals was of most importance, other areas had flooding damage (shown in Fig. 3) that contaminated their water source and just needed clean-up kits and fresh water.

For Hurricane Irma's response, each ERV team was assigned to a disaster- affected location which would range in distance from the main staging area. Sometimes a team would be deployed within a kilometre of the

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[2] www.worldvision.org/disaster-relief-news-stories/2017-hurricane-irma-facts#timeline-path

[3] en.wikipedia.org/wiki/Hurricane Irma

[4] www.fema.gov/sites/default/files/2020-11/fema florida-hurricane-irma-recovery case-study. pdf

staging area, or deployed as far away as a two-hour drive or more. An ERV team could expect to respond between two to eight times every day depending on location, conditions and distance. It was rare that specific drop-off points were assigned for resource distribution, rather the majority of responses entailed driving through the most affected areas and assessing and reacting to their needs face to face.

Different challenges such as the unpredictability of the resource drop-off areas, nature of the required resources and the types of casualties' requirements, made resource distribution difficult. It was especially difficult to know what supplies might be needed for each response region, and often it was based on the ERV team's guess with limited communication between those affected, the responders and the disaster managers. Utilizing a basic loudspeaker with a dash-mounted communication system enabled the response team to announce their presence on each street and would stop if someone came out and waved them down. Unfortunately, this was often the only way victims could communicate their needs with the responders as all stakeholders in disaster response were overwhelmed with requests.

Having limited even or no communication was a regular occurrence during daily responses, which reflects back on the importance of relaying information to the disaster manager after returning to the staging area for teams to stay informed of what supplies were most needed on the ground. This information could be directly fed to each ERV team through handheld radios or disseminated at the following days' morning briefing. Flexibility was also key for ERV teams as they were often the first responders on-site and their role frequently expanded to differing forms of comforting and counselling. This flexibility was key as communication was difficult for those affected by the Hurricane due to power lines and cell towers being damaged and rendered inoperable. This caused heightened anxiety, panic and fear as they could not reach out for help or contact loved ones.

Communication wasn't only difficult for the victims of the Hurricane but also for the disaster responders and managers. Much of the information at the morning briefing was found to be inconsistent or unreliable as communication of information was not consistently gathered or received from established and reliable sources and was also heavily reliant on word of mouth from responders' direct experiences in the field where often resources are needed immediately. Communication also inhibited effective resource distribution as communication between different ERV teams and the Disaster Management team was also inconsistent.

Lacking communications, advanced technological support systems and a clear vision of the disaster-affected area and casualties' requirements leads to delivering supplies that were often not in need. Without appropriate communication of supply needs an ERV loaded with hot meals could easily respond to an area in need of fresh water and clean up kits. This mostly created an issue as ERVs would regularly carry hot meals which, for health and safety purposes, had to be distributed within a certain time frame. If enough disaster-affected households were not identified by the ERV team, food supplies would often go to waste.

Situational awareness was also of the utmost importance for the involved agencies as it helps them understand 'what is going on in the disaster field', stated by (O'Brien et al., 2020). Road damage, downed power lines and flooding frequently complicated or inhibited access to certain areas that had not been identified or discussed at the morning briefing. This caused logistical issues for the ERV teams as to whether a flooded road was beyond the impasse (Figure 2). This often lead to on the spot judgement calls by the ERV team who for the most part were not trained to do so or waste of precious response time or resources. While most of the issues could be addressed using better communications technology, either through local informers on the ground communicating information to authorities, or satellite technology relaying the information to stakeholders on the ground.

Socio-Cyber Physical System of Hurricane Irma

Based on what has been explained in the Irma case-study, in this section we conceptualised the scenario into the form of a SCP system and its components. This helps disaster management field experts to breakdown disaster response activities into Socio, Cyber and Physical elements that may reduce the complexities of their management in dealing with response operations, especially for resource distribution.

We envision the region affected by Irma as an SCP system. The goal of this system is to maximize the efficiency and effectiveness of field workers and first-responders endeavours and efforts when responding to disasters. Efficiency is absolutely critical in disaster response as every second lost can put lives at risk. This SCP system is equipped with the adaptive MAPE control-loop and by integrating all the elements, the solution potentially improves situational awareness, required a disaster response mission.

As discussed in the third section of this paper, our SCP system can be translated as disaster- stricken area and with the analysis of ’Physical’ components such road access based on flooding, downed power lines, and most efficient routes of travel supports the situational awareness in the system. The ’Socio’ elements includes all human activities, behaviour, roles and responsibilities in disaster management. Therefore in the Irma case-study, once disaster response workers and disaster managers are mobilised and assembled at the required staging area, disaster response tasks are primarily centred around resource distribution, addressing the socio aspects. The socio aspect, manage or handle the physical elements including resources for distribution (food, water, clean up kits, and tarpaulins), and manage basic medical assistance, and counselling services, as well as any manual labour required (e.g. furniture moving and assembly, etc.). To support relief efforts, disaster managers often rely on a collection of low and high-tech solutions to keep track of resources in the region. In an ideal situation, resources can be digitally tracked and traced and specialised software applications can accurately determine current resource allocations to each location. This approach has the benefit of automatically checking current allocations against requirements to determine what resource is needed, and where. However, as discussed in earlier, in responding to Irma instead of cyber systems, disaster responders were responsible for such task using a manual counting system which is time-consuming, and less reliable with minimum room to perform the MAPE loop and boot the efficiency.

Different cyber systems can be used to report on specific supply needs of different disaster-affected areas (e.g. a particular area may have sufficient water but require tarpaulins, whereas another area might be in need of water or medical supplies), availability of supplies for distribution to disaster-affected areas, and location of available supplies. In relation to situational awareness this same cyber system would also monitor incoming inclement weather for purposes of evacuating affected citizens, disaster responders and field workers. Currently, information around road access and supply-needs is communicated to mobilised disaster response workers and emergency managers in face-to-face briefings as there is no centralized cyber system for disaster managers at the staging. This constrains disaster and operational managers’ ability to efficiently communicate information, updated news, or report to the ERV drivers and first responders. The current reality in the field highlights a communication issue where disaster managers do not necessarily have access to what resources are needed at disaster affected locations, often leaving them in the position of guessing what might be required. This is the same for those in disaster affected regions that cannot communicate specifically what resources are needed for their particular situation, and in their particular region. Due to the aforementioned communication issues the distribution of resources in this SCP System lacked organization. Due to these basic communication issues the distribution of resources lacked organization.

Therefore, the ability for disaster field workers on the ground and disaster managers at the main staging area to access and update the system in real time would be optimal in order to support disaster response efforts. If the system was also able to be accessed and updated by other emergency response groups, such as the police and the fire brigade it would provide additional support. Integration with other emergency response groups would corroborate existing information as well as providing additional information around such things as evacuations in progress, casualties, etc.

Current cyber technologies being utilized in Red Cross ERV’s are basic dash mounted communications systems with a roof mounted loudspeaker similar to what is utilized in most police vehicles. When available ERV teams will also be equipped with a hand-help radio to communicate with disaster managers in the staging area. Navigational tools are often extremely limited, and Red Cross responders are often limited to use of their own cell phones, or ones issued by the Red Cross.

Run-time Formal Verification of SCP Systems

Formal verification refers to the class of processes that check whether a formal, mathematical model M of a system satisfies the formal specification P of a property or requirement. Model checking is an automatic formal verification technique that accepts formal behavioural models of systems in the form of state machines or automata, and property models in the form of temporal logic formulas or automata. Formal methods like model checking guarantee that, as long as the system and requirement models are correct or true representations, if M satisfies P (written as $M \models P$), the system will satisfy the given property. Alternatively, and perhaps more importantly, model checking can automatically identify paths in system execution, called counter examples, that do not satisfy the given requirement. Other formal methods, such as SMT solvers, can comprehensively determine if a given problem, posed as a Boolean or first-order logic formula, can be satisfied under a given set of system constraints. The ability of formal verification to comprehensively and unambiguously answer questions relating to the satisfaction of requirements is highly desirable in planning a disaster response.

This section focuses on run-time verification, where the key challenge is to ensure models are updated according to changes in the system, and are simple enough so that analysis can quickly yield actionable plans for the management team during a disaster scenario.

SCP Models and Requirement Specifications

Our previous work (Johnson et al., 2021; Johnson et al., 2020) formalises system components and their requirements as mathematical models such that

- region is modelled by the graph G comprising locations in the region represented by a finite set of nodes, labelled $\mathbf{a}, \mathbf{b}, \ldots$ and directed edges $\mathbf{a} \rightarrow \mathbf{b}$ representing routes between locations
- resources requirements are specified by logical formulae K translated from the policies in P
- a resource allocation α satisfying K.

Together, these models specify the situational state $\sigma = (G, K, \alpha)$ of the socio- cyber-physical system S.

Resourcing Requirements as Logical Formulae

At the heart of our approach is the translation of resourcing requirements from P into a set of logical formulae formalising constraints, denoted K. For example the formula

$$\phi_{\mathbf{b}} \equiv (bMed \geq 15) \wedge (bSus \geq 10) \wedge (bSup \geq 20) \quad (1)$$

$$\wedge\ (bMed = bSup) \quad (2)$$

in K specifies resource requirements for the location labelled **b** in the disaster- affected region. The formula comprises four propositions connected by the conjunctive operation $\wedge$. The propositions on Line (1) specify the least amount of each resource type needed at the location. e.g. $bMed \geq 15$ specifies at least 15 units of medical supplies are needed at **b**. The expression on Line (2) adds a further constraint on the resources; particularly that the amount of medicine must equal the amount of medical supplies at **b**.

A resource allocation satisfying all the resource requirements is solution α of $\phi_{\mathbf{b}}$ assigns a number to each variable such that its evaluation is true. For example $\alpha(bMed) = 21$, $\alpha(bSus) = 10$ and $\alpha(bSup) = 21$ is a number assignment to the variables in a way that satisfies $\phi_{\mathbf{b}}$. We write $\alpha \models \phi_{\mathbf{b}}$ if, and only if, α is a solution to $\phi_{\mathbf{b}}$. We use Satisfiability Modulo Theories (SMT) solvers (de Moura & Bjørner, 2008) which are advanced software tools to automatically and efficiently compute an assignment α of values to variables, satisfying a given input formula $\phi_{\mathbf{b}}$. In symbols,

$$\alpha = smt(\phi_{\mathbf{b}})$$

Formulas for disaster resourcing may be designed per-location or also depend on proximity constraints, such as *any location within 10KM of location* **b** *must have more than 50 units of sustenance.* As a result, formulas quickly become very large with complex inter-dependencies that make them difficult to manage. Therefore, it is preferable constraints be generated automatically using high-level English language templates to select standard resource requirements. This approach benefits disaster managers by

- providing instant feedback when requirements are incompatible, making a solution satisfying impossible to obtain, and
- being easily adaptable to change in resourcing policies during or after a disaster since only the high-level English language templates need to be updated to generate a new set of constraints.

Modelling Stochastic Properties of SCP Components

During a disaster, the best route for first-responders to take is the easiest and most reliable route, which is not necessarily the shortest one. In our previous work (Johnson et al., 2021), we modelled reliability of the disaster-affected region's transportation network as a *Markov Decision Process (MDP)*. Stochastic models such as MDP have been used to calculate best routes based on changing travel infrastructure conditions within the region (Paterson et al., 2019; Rashid et al., 2020). Underlying these models is a graph whereby nodes represent locations and edges represent routes between locations. Each edge is labelled with probabilities measuring the likelihood of failure; e.g. unsuccessfully traversing the route. In (Paterson et al., 2019), transition probabilities are continuously updated by sensing adverse events on routes using natural language processing techniques on social media data. Transition probabilities are updated according to rules defined by domain experts, governing how initial probability values should change depending on the kind of event. Other sources of information for calculating transition probabilities may include data automatically collected from one or more sensors. Analysis of Markov Decision Processes to compute route reliability leverages software such as a *probabilistic model checker pmc*, which automatically verifies a probabilistic temporal logic formula T on an MDP P such that

$$\pi = pmc(M, T) \quad (3)$$

computes the path π through the MDP M satisfying T.

Figure 4 presents a fragment of the MDP M written in Prism's (Kwiatkowska et al., 2011) high-level programming language. Each line represents a transition between states of M that model locations within the disaster-affected region. The first line of the fragment represents one possible directional choice labelled [a_to_b], to travel to location **b** from location **a**. This choice succeeds with probability pb and fails with probability 1 - pb. If successful, the MDP is in state b and only one transition labelled [succ] is available from b to the succ state, representing the successful execution of the *transport* (σ, **a***,* **b***,* q) operation. Otherwise, if the transition to b fails, then we transition to, and stay in, the fail state. This models the failure of *transport* (σ, **a***,* **b***,* q). Alternatively, [a to c] represents the directional choice to travel to **c** from **a**, which succeeds with a probability of *pc* and otherwise fails with probability 1-*pc*.

Probabilistic model checking in Equation (3) checks the MDP M against the probabilistic temporal logic formula $T = P{=}?[F(s{=}succ)]$, to determine the *strategy* π of directional choices from the source location to target with the maximum probability of success; e.g. reaching the succ state.

Disaster managers may suggest π first responders to maximise the likelihood of resources to be delivered within the disaster-affected region and the safety of the first-responders. Markov models can be automatically synthesised from the graph structure G of the transportation network. Sensors, including both humans and high-tech cyber systems to monitor traffic and other travel conditions are used to measure the probability of successfully traversing a route.

Modelling Stochastic Properties of Humans in the SCP

Figure 4
Fragment of the Markov Decision Process M

```
[a_to_b] (s = a) -> pb:(s'=b) + (1-pb):(s'=fail);

[a_to_c] (s = a) -> pc:(s'=c) + (1-pc):(s'=fail);

[succ] (s = b) -> 1.0:(s'=succ);

[fail] (s = fail) -> 1.0:(s'=fail);
```

Certain task critical attributes of humans can be modelled in the SCP system S to enhance decision making. The Opportunity-Willingness-Capability (OWC) model was first developed in (Eskins & Sanders, 2011) and used in our work (Johnson et al., 2021) to measure the likelihood that a first-responder can successfully complete a resource transport task according to:

- *opportunity* : access to an appropriate vehicle and adequate resources
- *willingness*: they are not fatigued, and
- *capability:* they have correct training and experience.

The OWC attributes can be modelled using Markov models and anal- ysed in parallel with the MDP M to maximise the probability of successfully transporting resources within the disaster-affected region.

Challenges. Furthermore, like many other muti-disciplinary work, the common challenge would be the gap and lack of common language between technical people vs first responders and disaster managers. this might negatively impact the project implementation on the early stage when technical people intent to extract the requirements and constrains for modelling. While domain experts can assist disaster managers to design and implement models during the disaster preparedness phase, the key challenge in using formal verification techniques to support decision making is maintaining these models. This means that changes in the socio-cyber-physical system S are sensed and translated into algebraic operations on the situational state of the system S. This inherently involves much uncertainty, as disaster responses typically involve limited communications and lack high-tech sensors. However, advanced probabilistic model checkers such as Prism are able to verify probabilistic systems that are only partially observable (Norman et al., 2017).

Concluding Remarks and Future Directions

In this paper, we developed a conceptual framework in which concerns about locations, infrastructure, actors and resource management raised by disaster managers during the mitigation phase are represented as components in a *socio-cyber-physical* system. The process of articulating these issues as components help to simplify requirements in a way that disasters managers could easily put into play and explain to responders. The process also delineates the roles and responsibilities of first responders during a disaster.

The SCP systems designed during disaster mitigation and preparedness phases are managed systems, adapted according to the four phases of the MAPE loop. This is a control feedback loop which monitors the current state of the system components. If analysis deems the system to be in an unfavourable state, then a plan is devised to adapt, returning the system to a good state. System adaptation strategies for the SCP correspond to disaster-response plans for resource distribution within the disaster-affected region to satisfy resource requirements. Using formal verification, Mathematical models of system components can be used to largely automate analysis steps to provide irrefutable evidence of the effectiveness of adaptation plans. We applied our approach by designing an adaptive SCP system for a real-life case study using our first-hand experience as emergency responders during Hurricane Irma.

Our research programme (Johnson et al., 2021) aims to develop a generic and re-usable self-adaptive framework for socio-cyber-physical systems where components and phases of the MAPE loop are extended with standardised interfaces. The interface for components name operations that provide functionality, with axioms that govern its behaviour. The component interfaces may be realised with one or more implementations which can help disaster managers plan for alternatives to key tasks during the disaster-response, such as sensing the environment or actuating delivery of resources. Although this sensing requirements could be interrupted because of the dependency on networking infrastructure, different technologies are available to address the issue. For example, satellite connectivity, or using Internet of Things (IoT) sensors to capture data and retransmit when the connection is re-established, are seen as a promising solution to overcome network interruption and sensing in disaster response.

The conceptual SCP system framework in this paper will form the basis for developing simulations based on formal verification techniques which optimise the assignment of resource distribution tasks to first responders, based on their location and the current resourcing of the disaster-affected region.

Conflicts of Interest

The authors declare no conflict of interest.

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