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Drones for disaster response and relief operations: A continuous approximation model

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ABSTRACT

This paper proposes a Continuous Approximation (CA) model that designs the potentiality of drones as a mode of transportation to supply emergency commodities in a disaster-affected region. The model determines the optimal distribution center locations and their corresponding service regions and ordering quantities to minimize the overall distribution cost for the disaster-relief operation. We propose a two-phase CA approach that solves the model efficiently. We conduct extensive sensitivity analysis to reveal insights into how system design varies with key drone design parameters. We use three disaster-prone coastal counties of Mississippi as a testbed to visualize and validate the modeling results.

1. Introduction

Between 1995 and 2015, *Emergency Events Database* (EM-DAT) of *The Center for Research on the Epidemiology of Disasters* (CRED) recorded a total of 6457 weather-related disasters, which claimed over 606,000 lives and left 4.1 billion people injured, homeless, and/or in need of emergency assistance. More specifically, between 2005 and 2014, EM-DAT recorded an average of 335 weather-related extreme events which is approximately 14% higher than the number recorded between 1995 and 2004 and twice the number between 1985 and 1995. Scientists predict that we will witness a continued upward trend in weather-related extreme events in the decades ahead (UNISDR, 2015).

Among all the countries in the world hit by the highest number of weather-related disasters, United States (US) comes first, with 472 disasters occurring over the past 20 years (Shaw, 2015). In recent years, natural disasters such as flooding, wildfire, hurricane, tornadoes, and many others hit frequently in different parts of the US and cause significant damages to both economy and human life. The most devastating natural disaster that shocked the entire country in recent years was Hurricane Katrina which rampaged the Gulf Coast of the US in the morning of August 29, 2005. It had a *Category 3* rating on the Saffir-Simpson Hurricane Scale and it brought sustained winds of 100–140 miles per hour.[1] The storm itself did a great deal of damage, but its aftermath was even more catastrophic. Many people charge that the federal government reacted slowly to meet the needs of the disaster affected people. The main reason behind this is that the government, particularly the federal government, seemed unprepared for the disaster. It took the Federal Emergency Management Agency (FEMA) days to establish operations in the disaster-affected regions, and even then did not seem to have a sound plan of action. People suffered significantly because of the scarcity of clean water, food, and medical aid. A proper plan regarding facility location and inventory policy of emergency products as well as deciding on which mode of transportation to use would have been much more beneficial during the recovery phase of the disaster and helped people in the affected region significantly.

Logistics activities in response to a disaster are commonly known as *humanitarian logistics*. Humanitarian logistics can be defined as the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from a point of origin to a point of consumption for the purpose of meeting the end beneficiaries requirements (Thomas and Mizushima, 2005). The aim is to deliver the right commodity at the right time, to the right place, and to the right people. Although the basic methodology behind humanitarian logistics is the same as classical logistics operation, the effect of decision making holds more significance for humanitarian logistics. Note that while planning a robust logistics network, decisions regarding where to place emergency

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[1] Available from: http://www.cnn.com/2005/WEATHER/12/21/katrina/.

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facilities from where all the commodities will be transported to the demand sites is of significant importance as it has a direct impact on how fast disaster-affected points can be served. Simultaneously, inventory policy decisions are equally important since they determine whether enough commodities are available to serve all the disaster affected regions.

In this study, we propose an integrated facility location-inventory allocation model for a disaster affected region where drones can be considered as a potential mode of transportation to transport emergency supplies to the demand points. Drones can become very useful as a mode of transportation in humanitarian logistics since they do not need any preexisting path to fly. Thus, if a natural disaster strikes and roads are blocked, drones can easily be used to serve a disaster affected region. Nowadays drones are used in a diverse range of civilian activities, primarily humanitarian aid and rescue actions in various natural disasters which include earthquakes, hurricanes, flooding, volcanic eruption, tsunamis, and many others. The crisis management of these natural disasters poses very critical decisions related to the well-being of the affected people. Integrating drones into emergency and disaster response protocols can be considered as an effective tool to provide immediate relief benefits needed by civilians, communities, and first responders. The disaster relief life cycle can be split into four major stages: prevention, preparation, response, and recovery (Center for Disaster, 2016). Drones have the potential to play a major role in all four stages, though currently are used overwhelmingly in the response stage. Unfortunately, even though they have the potential to respond quickly in a critical situation, drones are surprisingly under-utilized.

When a disaster strikes, drones are able to provide support with risk assessment, mapping, and planning for the affected region (Measure-Red cross, 2015). Al-Tahir et al. (2011) present an overview and assessment of the technology relevant to low cost cameras and platforms to acquire aerial photographs of a disaster-affected Caribbean region. The authors suggest that drones can be employed further to establish temporary communication structures, creating up-to-date maps of the affected region, and searching for hot spots where the rescue teams may have more chances of finding victims. There are a number of cases where drones have already been used in humanitarian settings. For instance, in 2013, a US start-up company called *Matternet* announced that it had tested humanitarian aid drone prototypes in Haiti and the Dominican Republic (Cohen, 2014). Drones were further used to create up-to-date maps of the devastated areas following Typhoon Haiyan in 2013 where the mapping efforts were coordinated between multiple aid and drone organizations (Greenwood, 2015). Similarly, when the earthquake and Tsunami hit the Fukushima area of Japan, the nearby nuclear power plant named *Fukushima Daiichi plant* was highly affected. A drone was launched to fly around the Fukushima plant to gauge the radiation levels. It took off around six kilometers away from the damaged power plant in Namie City. It had a flying time of 30 min and it was able to collect radiation levels in real-time and went back to the scientists safely (Pamintuan-Lamorena, 2014). Table 1 summarizes the application of drones in response to natural disasters in recent years between 2005 and 2015 (Murphy, 2014).

In situations, where transportation network is highly impacted by natural disasters, obvious mode of transportation e.g. trucks often can't be used in response operations. Despite high expectations of the role of drones to serve in humanitarian logistics, there is not yet a comprehensive design framework on how to economically deploy a drone that is capable of serving a disaster affected region considering the restrictions provided by Federal Aviation Administration (FAA)[2] (Federal Aviation, 2016) and the technological limitations (e.g., limited battery and weight carrying capacity) that the existing drones hold. This paper proposes a continuous approximation (CA) model for determining the optimal configuration of a humanitarian logistics system, including the location of distribution centers and the corresponding emergency supply inventories at these centers under stochastic demand and drone flying range constraints. This optimal configuration shall minimize the overall system cost including the costs of opening distribution centers, ordering and holding costs of emergency supplies, and the expected transportation costs of using trucks and drones to serve a disaster affected region. We approximate the nonlinear drone transportation cost by considering a number of routing specific factors such as climbing, hovering, descending, turning, acceleration and deceleration, rotational, and constant speed cost into account. We then propose a two-phase continuous approximation approach to solve this nonlinear programming problem efficiently. Finally, we apply this model to three disaster prone coastal counties of Mississippi i.e., Hancock, Harrison, and Jackson counties and draw interesting managerial insights into the optimal system design and the total system cost (Table 2).

Table 1
Drones used in response to natural disasters between 2005 and 2015 (Murphy, 2014).

Year	Natural disaster	Name of drone	Application			
			A	B	C	D
2005	Hurricane Katrina Response (USA)	AeroViroment Raven	✓	✓		
		Evolution	✓	✓		
		iSENSYS T-Rex	✓	✓		
		Silver Fox	✓	✓		
2005	Hurricane Katrina Recovery (USA)	iSENSYS IP3			✓	
2005	Hurricane Wilma (USA)	iSENSYS T-Rex		✓	✓	
2007	Berkman Plaza II	iSENSYS IP3			✓	
2009	Laquila Earthquake (Italy)	Custom		✓	✓	
2009	Typhoon Morakot (Taiwan)	Unknown		✓		
2010	Haiti Earthquake (Haiti)	Elbit Skylark		✓		
2011	Christchurch Earthquake (NZ)	Parrot AR. Drone			✓	
2011	Tohoku Earthquake (Japan)	Pelican			✓	
2011	Fukushima Nuclear Emergency (Japan)	Custom		✓		
		Honeywell T-Hawk		✓	✓	
2011	Evangelos Florakis Explosion (Cyprus)	AscTec Falcon		✓	✓	
		AscTec Hummingbird		✓	✓	
2011	Thailand Floods (Thailand)	FIBO UAV-1		✓		
		FIBO UAV Glider		✓		
		SIAM UAV		✓		
2012	Finale Emilia Earthquake (Italy)	NIFTi			✓	
2013	Typhoon Haiyan (Philippines)	unknown			✓	
2013	Lushan Earthquake (China)	HW18 (Ewatt HoverWings)	✓	✓		
2013	Boulder Colorado floods (USA)	Falcon Fixed		✓		
2014	SR350 Mudslides Response (USA)	DJI Phantom		✓		
		AirRobot 100		✓		
		Precision Hawk		✓		
2014	SR350 Mudslides Recovery (USA)	AirRobot 180				✓
		Precision Hawk				✓
2014	Balkans flooding (Serbia, Bosnia-Herzegovina)	ICARUS custom		✓		✓
2014	Collbran landside (USA)	Falcon Fixed	✓	✓		
		Falcon Hover	✓	✓		
2014	Yunnan China Earthquake (China)	Parrot AR Type 2		✓		

A=Search, B=Reconnaissance and mapping, C=structural inspection, and D=estimation of debris.

[2] In the United States, Federal Aviation Administration (FAA) requires UAVs to be operated under a ceiling of 400ft which will severely limit the effective range of utilizing drones for disaster relief operation (Federal Aviation, 2016)