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A framework for assessing the resilience of a disaster debris management system

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ABSTRACT

Disaster debris management plays a critical role in expediting the disaster recovery process. This study aims to present a framework for effective disaster debris management for a resilient community. The framework consists of a Geographical Information System (GIS) and system dynamics to assess debris removal performance.

GIS was used to conduct a land suitability analysis for a temporary debris management site and system dynamics were applied to evaluate the debris removal performance in different scenarios.

This systemic approach and quantitative analysis enable a decision maker to gain insights into the inter-relationship between critical infrastructure and resources, the effectiveness of temporary debris management sites, and the debris removal performance. Also, a debris management team would have benefits from the framework by being able to (1) understand dynamic behaviors of debris removal operation, (2) evaluate the existing debris management plan, and (3) set up multiple strategies for optimal debris removal operations under different disaster-impact scenarios.

1. Introduction

Recent research shows that the world is experiencing more extreme natural hazards such as hurricanes, floods, earthquakes, and tsunamis [1]. The experiences with recent disaster recovery efforts have highlighted the need for additional guidance, structure, and support to improve the response to disaster recovery challenges.

Disasters generate an exceptionally large amount of debris, causing considerable processing and disposal challenges [2]. In the past, a primary objective was to transport the debris generated by disasters from an original site to its final destination as soon as possible. Consequently, the debris generated was simply buried or burned [3]. Historically, the volume of debris has been about five to ten times the annual solid waste generation in a community [4,5]. This huge amount of debris causes delays in the debris removal operation and other emergency responses. It results in the delay of the entire disaster recovery process.

For example, the 13 million cubic yards (CY) of debris generated in the 2010 Haiti earthquake hampered emergency response and recovery projects [6]. Debris cleanup was also delayed by damaged infrastructure and insufficient resources. After several months, the destruction continued to disrupt the lives of many Haitians. Cholera outbreaks began in October 2010 and killed at least 7000 Haitians. It was recorded as the worst epidemic among the epidemics in recent history [7]. While the Haitian government identified debris removal as one of

the top priorities, only 3–10% of the total debris generated had been removed after 12 months [8]. Lack of infrastructure and insufficient resources also hampered the disaster recovery in Haiti.

A framework for effective debris management is crucial to building community resilience.

There is a need for a framework to assess debris removal system and performance under the interrelationship of critical infrastructure and resources. Therefore, this study presents a framework for developing an effective disaster debris management for local governments and emergency agencies. The specific objectives are to:

- Establish the interrelationship between critical infrastructure (CIs) and the waste management system.
- Develop a temporary debris management site selection model.
- Develop a system dynamic model to understand the complex behavior of the debris removal system and identify unexpected bottlenecks from a system viewpoint (i.e., TDMS impacts, shortages of required resources, and infrastructure capacity during debris removal operations).
- Support disaster debris managers with multiple debris removal operational strategies.

The remainder of this study is organized as follows. Section 2 discusses disaster debris management and the results of the literature review. Section 3 describes the suggested framework and methodology applied in this

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study. Section 4 discusses results from tested scenarios. Finally, Sections 5 and 6 conclude the study and present future research directions.

2. Literature review

2.1. Debris removal

A debris removal operation has two phases: response and recovery [9]. In the response phase, the main objective is cleaning up the debris on emergency access routes immediately after a disaster. In the recovery phase, debris on the public right-of-way is removed. According to the national disaster recovery framework by FEMA, debris removal activities are in phases 2 and 3 [2].

- Phase 1: Pre-Disaster Preparedness.
- Phase 2: Post-Disaster Short Term (days to weeks)
 - o Debris: clear primary transportation routes.
- Phase 3: Post-Disaster Intermediate Term (weeks to months)
 - o Debris: Initiate debris removal on curbside.
- Phase 4: Post-Disaster Long Term (months to years).

It was identified that much of the literature categorized debris removal in the recovery phase and there were a few studies considering the debris removal as a prerequisite for emergency responses such as emergency rescue, medical care and evacuation [10]. They investigated debris removal operations in the emergency phase and suggested a resource routing model to clean up debris on roadsides in order to increase access of emergency relief suppliers to disaster-affected regions.

Several studies investigated debris removal in the recovery phase, e.g., resource (vehicle) routing and management to improve debris removal performance. Brooks et al. [11–13] presented a model for dynamic allocation of debris removal trucks in closed queueing networks using queueing theory to improve debris removal performance. Brooks and Mendonca [12] studied the optimal hauling trucks mix from two perspectives (efficiency and equity). A spreadsheet-based decision support tool was developed and illustrated the applicability and effectiveness of the tool with a disaster scenario based on Hurricane Andrew [14–16]. While the literature suggested multiple methods to optimize either a component of the debris management system or the entire debris management system, it is limited in its understanding of the dynamic behaviors of a debris management system under the inter-relationship with CIs. System dynamics is a well-established method for studying and managing complex systems and many solid waste management systems have been examined by this method [17–22].

2.2. Temporary debris management site

A temporary debris management site (TDMS) is sometimes called a temporary staging site, temporary debris management area, temporary debris storage and processing facility, temporary debris storage and reduction site, or a temporary disaster waste management site [23–27]. A TDMS is a designed buffer to sort, recycle, and dispose of the debris generated. To process one million cubic yards of debris (754,555 m³) 100 acres of land (0.4 km²) is required [9]. Several agencies have emphasized the importance of TDMS for effective debris management [28–30]. However, unsuitable TDMS locations in areas near playgrounds, swamps, and rice paddies have been cited as potentially damaging to the environment and affecting the livelihood of people in a community [31,32]. It also can attract vermin such as rodents and other pests, produce noise and odors at levels deemed unacceptable by residents, or place a large burden on normal traffic patterns [9,33]. To prevent these negative effects, US EPA (U.S. Environmental Protection Agency) and UNEP (United Nation Environment Programme) provided the following suggestions for a TDMS [29,30]:

- Sufficient in size with appropriate topography and soil type.
- Appropriate distances from potable water wells, rivers, lakes, and streams.
- Not in a floodplain or wetland.
- Controls in the TDMS to mitigate stormwater runoff, erosion, fires, and dust.
- Free from power lines and pipelines.
- Limited access to only specific areas open to the public such as areas to drop off debris.
- Located close to the impacted area but far enough away from residences, infrastructure, and businesses that could be affected by site operations.
- Preferably located on public land because approval for this use is easier to obtain, but it could also be located on private lands.

Identifying potential TDMS locations is considered as land use suitability assessment. Kim et al. [34] conducted spatial analysis to determine a TDMS location within certain environmental constraints. Grzeda et al. [26] identified potential TDMSs by using binomial cluster analysis and GIS. Cheng and Thompson [27] reviewed 50 recently published articles and summarized the criteria of land suitability assessment in three areas (using environmental, social-cultural, and economic-engineering criteria). They used Boolean logic and GIS to determine suitable locations for TDMSs. These studies are limited to considering environmental regulations to install a TDMS excluding the technical perspective to expedite debris removal performance. Many studies in the literature have referred to the fact that either double handling of debris generated or acquiring lands for TDMSs could result in higher debris removal operation costs [9,23,35,36]. Thus, it is critical to evaluate the impacts of TDMS location and capacity on debris removal performance.

2.3. Critical infrastructure

Tierney and Bruneau [37] emphasized that critical infrastructures, including transportation and utility lifeline systems, are essential to enhance resilience in a community in terms of four determinants: *robustness, redundancy, resourcefulness, and rapidity*. Guerrero et al. [38] studied various factors which impact the solid waste management system for each activity (see Table 1). They identified the essential infrastructure needed, such as transportation systems, technologies, and facilities for treatment, recycling, and disposal. Required resources were identified as hauling vehicles, incinerators, and chipping and grinding equipment [35] as well as proper knowledge of treatment, disposal, and recycling of waste [38].

Deshmukh and Hastak [46,47] suggested a framework for expediting community post-disaster recovery through capacity building resulting from

Table 1
Factors influencing waste management systems.

Activity	Factors
Collection, Transfer, and Transport	Poor route/improper bin collection [39] Infrastructure/vehicle for waste collection [40] Organization of the informal sector [41] Quality of roads [42] Transportation facility available [42]
Treatment	Knowledge of treatment systems by authorities [43] Suitable infrastructure [42] Local knowledge of waste management issues [42]
Disposal	Supply of containers and distances [44] Priced disposal [44]
Recycling	Organization of informal sector [41] Collection of recyclables supported by companies [45] Efficiency collection system [42]

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