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An Optimization-Based Decision-Support Tool for Post-Disaster Debris Operations

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Debris generated by disasters can hinder relief efforts and result in devastating economic, environmental and health problems. In this paper, we present a decision-support tool employing analytical models to assist disaster and waste management officials with decisions regarding collection, transportation, reduction, recycling, and disposal of debris. The tool enables optimizing and balancing the financial and environmental costs, duration of the collection and disposal operations, landfill usage, and the amount of recycled materials. In addition to post-disaster operational decisions, the tool can also support the challenging task of developing strategic plans for disaster preparedness. We illustrate the applicability and effectiveness of the tool with a disaster scenario based on Hurricane Andrew.

Keywords: debris management, disaster management, humanitarian logistics, decision-support.

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1. Introduction

An important post-disaster logistics activity is managing the resulting debris, which is defined as any kind of waste generated by a disaster. Types of debris include building materials (e.g., concrete, bricks, and wood), vegetation (e.g., fallen trees and plantation), household waste (e.g., furniture and white goods), hazardous waste (e.g., industrial chemicals), cars, rubbles of road infrastructure, and sediments. The timely management of post-disaster debris has important consequences. In the short term, it enables response activities such as relief transportation, search-and-rescue, and evacuation. In the long term, it prevents adverse effects on human health and the environment due to factors such as decaying chemicals and water pollution.

Debris management is a costly and complicated process. For example, Hurricane Katrina in 2005 resulted in more than 100 million cubic yards of debris, and debris management costs exceeded USD 4 billion, accounting for more than a quarter of the total cost associated with disaster response and recovery (UNEP, 2012). The 2011 cascading disasters in Japan generated more than 25 million tons of debris, with a substantial amount mixed and displaced due to the tsunami, hampering the removal efforts as the composition of the debris required substantial amount of separation (UNEP, 2012). In the Fukushima area, radioactive debris contents posed difficulties for local authorities, who were still undecided on how to carry out collection and disposal three months after the disaster "because there were no official guidelines on how to handle it" (Japan Times, 2011). The lack of space for debris disposal also results in challenging issues, as exemplified by the cascading disasters in Japan and the 2010 Haiti earthquake.

Given their high cost and complexity, debris management operations can significantly benefit from quantitative models and decision-support tools. Motivated by the lack of such models and tools in the literature and practice, particularly of those addressing the decisions in the longer term where the aim is to recover from the effects of the disaster, this paper presents a mathematical model for debris management operations and a user-friendly decision-support tool that implements this model. The model balances multiple objectives such as financial costs, environmental effects, duration of the collection and disposal operations, and recycled debris amount. The tool can be used in the pre-disaster stage to prepare strategic debris management plans and study what-if scenarios, as well as in the post-disaster stage for operational decisions.

The timeline of a disaster can be decomposed into three stages: pre-disaster, response and recovery (FEMA, 2007). Before the disaster hits, each local community considers potential disaster scenarios and corresponding forecasts of debris amounts and compositions, and plans workforce and equipment requirements as well as potential debris management facilities such as debris processing sites, recycling plants, and disposal areas. In the immediate aftermath of a disaster, debris amounts and compositions are estimated and the workforce and equipment requirements are assessed. During this stage, debris is *cleared* off the roads to facilitate response activities such as search-and-rescue and relief transportation. The disaster recovery stage involves *debris collection*, i.e., debris is transported from road and curb sides to temporary processing sites, where it may go through certain processes such as sorting, separation, grinding, incineration, wood chipping, and concrete crushing. After being processed, debris components may be disposed of in landfills, recycled, reused, or sold.

This paper focuses on debris collection and disposal activities, and addresses the following decisions: location of debris processing sites, selection of specific processes and respective capacity levels to install at each processing site, transportation of debris between facilities, and debris amounts and types to recycle or dispose at landfills. In general, these complex decisions are made and documented by local communities and carried out using both local resources and contractors.

As is the case with most problems in disaster logistics, multiple stakeholders (e.g., local governments, aid agencies, contractors) with potentially different objectives are involved during debris collection and disposal operations. For example, local governments may want to complete debris collection as quickly as possible to minimize negative effects on the community. Private contractors may prioritize a cost-efficient process, while environmental agencies may push for minimizing environmental impacts and/or maximizing recycled debris amounts. Multiple objectives result in critical trade-offs. For example, separating debris in the disaster area versus at a processing site may increase the duration of the operations but enhance recycling opportunities. Similarly, open burning to reduce debris volume speeds up the disposal process, but has adverse environmental effects. The model we present considers multiple objectives, enabling the users of the decision-support tool to analyze the trade-offs and evaluate the impact of their decisions.

Debris management operations can be considered as an emergency management and humanitarian logistics activity (see Altay and Green (2006), Apte (2009), Çelik et al. (2012), and Özdamar and Ertem (2015) for recent reviews in this area). The literature on disaster debris management mostly focuses on the documentation of past experiences and their qualitative analysis, e.g., after the Japanese earthquake and tsunami in 2011 (UNEP, 2012), and Hurricane Katrina (Moe, 2010). Brandon et al. (2011) retrospectively analyze the debris collection efforts by the US Army Corps of Engineers (USACE). Karunasena et al. (2009) present a case study based on post-disaster waste management practices in Sri Lanka. Debris management guidelines prepared by institutions such as the US Federal Emergency Management Agency (FEMA, 2007) and the US Environmental Protection Agency (EPA, 2008) provide operational recommendations and document past experiences. Many local communities have developed debris management plans in line with these recommendations. A comprehensive review article by Brown et al. (2011) presents previous experiences and guidelines on planning, waste composition and treatment, social aspects, and environmental consequences. Brown and Milke (2016) further study the effectiveness of different recycling strategies for post-disaster debris based on the experience from specific disasters, rather than the use of quantitative models or decision support tools. Other qualitative studies on disaster debris management include Reinhart and McCreanor (1999), McEntire (2006), and Ekici et al. (2009).

Despite the abundance of debris management guidelines, quantitative support on how to carry out debris collection and disposal activities is lacking in the literature, which we aim to address in this paper. Further, even though there has recently been an increasing interest in the Operations Research and Management Science literature in developing quantitative models for the clearance stage (e.g., Aksu and Özdamar (2014), Çelik et al. (2015), Sahin et al. (2016)), the recovery stage has not received the same attention.

An important aspect of the quantitative models developed to address problems faced by practitioners of humanitarian logistics is the applicability of these models in practice. In general, it is highly unlikely that a practitioner in the field has the technical knowledge to implement mathematical optimization models. This paper aims to address this issue bridging theory and practice by means of a user-friendly decision support tool that can be readily implemented with minimal requirements for technical knowledge and technological infrastructure on the user end.

Our work is among the few in the literature in terms of using an analytical approach to debris collection and disposal operations. Similar to Fetter and Rakes (2012), we address decisions about the locations of processing sites, the selection of processes to make available at each site, and debris flows. However, our model also includes decisions of whether or not to sort during collection, the selection of processing capacities (a decision involving fixed costs with a direct impact on the total duration of the operations), and the possibility of separating debris before applying other processes, allowing for a more precise and comprehensive analysis and operational support. As in Hu and Sheu (2013), we consider the temporal aspects of the problem, but with a different emphasis. Hu and Sheu (2013) model processing capacities as constant and fixed, focusing on debris flow details. In contrast, a fundamental feature of our model is the selection of processing capacities and the times at which they will become available and the impact of these decisions on the duration of debris removal operations. Finally, our work differs from the previously mentioned papers on debris clearance by focusing on collection and disposal activities instead.

The main contributions of this paper are two-fold: (i) an innovative mathematical model that captures critical decisions and objectives in post-disaster debris collection and disposal operations, and (ii) a user-friendly decision-support tool that aids in pre- and post-disaster decisions related to debris operations and the analysis of trade-offs among different objectives.

The remainder of the paper is organized as follows. Section 2 discusses the mathematical model developed and its data requirements. Section 3 describes the decision-support tool, whereas Section 4 presents a case study based on Hurricane Andrew. Finally, Section 5 concludes the paper and presents future research directions.

2. Modeling approach

We develop a mathematical model for managing debris collection and disposal operations. In this section, we present our modeling assumptions, input parameters, decisions, and objectives, as well as a discussion on the availability and quality of the data required by this model.

2.1. Modeling assumptions

During the post-disaster timeline, cleared debris will go through several different procedures, see Figure 1. Immediately after the disaster (time period $b = 0$) only collection takes place. Then, a first batch of sites/capacities become available (time period $b = 1$) for processing and while debris is being moved to disposal sites collection may also continue. Then (time period $b = 2$) a second batch of processing capacities may become available, and a combination of processing (e.g., separation, crushing, grinding, etc.), collection, recycling and disposal at landfills can take place as in the previous period.

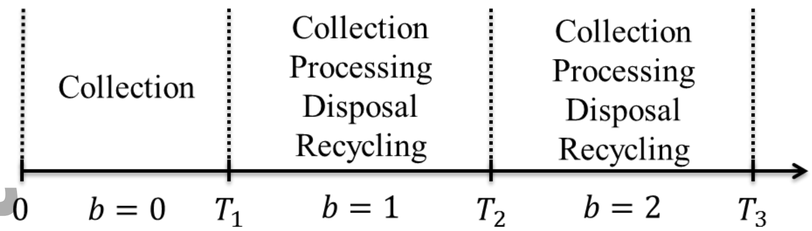

Figure 1 – Time periods used in the mathematical model

Multiple processing steps can be applied within each time period, as well as disposal or recycling. For the sake of simplicity and motivated by real-world applications, on a given unit of debris we assume that at most two processes are applied, which could be performed at the same site or at different processing sites.

We combine multiple debris sources (e.g., road segments, residential, commercial, and industrial blocks) into *debris zones* and treat each zone as an aggregate debris source. The debris amounts and compositions at each zone can be estimated initially or during pre-planning using forecasting tools such as Hazus by FEMA (2015) in the US, and are input to the model.

We assume that potential debris processing sites are determined prior to the disaster. In practice, these sites are often listed in local debris management plans (see FEMA, 2007).

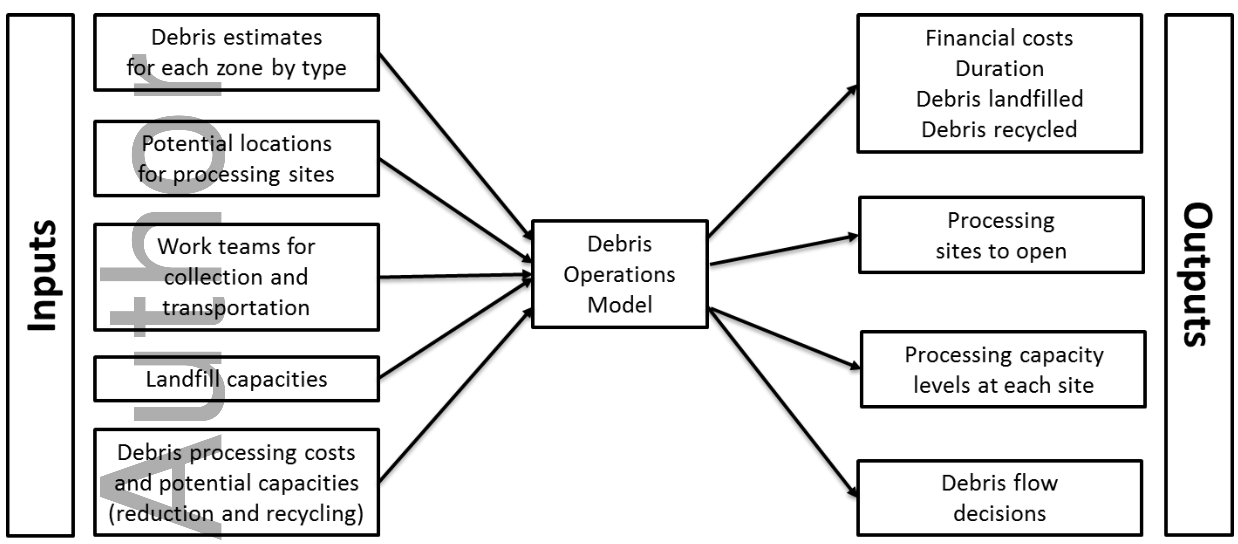

Figure 2 – Main inputs and outputs of the model

2.2. Inputs, decisions, and objectives of the model

The mathematical formulation of the model we propose is given in the Appendix. Here, we discuss the main inputs, decisions, and objectives, which are summarized in Figure 2. The amount and composition of debris in each zone as well as potential debris processing site locations are inputs to the model. Each debris type can go through a subset of the available processes. For example, mixed brick-wood type debris can only go through separation, whereas wood type debris can be ground, mulched, or incinerated. After each process, the composition and/or type of debris may change. For example, after separation, 5 tons of mixed brick-wood type debris may be decomposed into 3 tons of brick, 1 ton of wood, and 1 ton of waste. The available processes for each debris type and the conversion rates are among the model inputs.

Another input of the model is a set of potential collection methods, each of which has a predetermined collection rate (days per metric ton), cost, and transformation rate. For example, one method may separate debris during collection, but may be slower than another method that quickly collects debris in a mixed form.

The model also takes as input the processes and corresponding potential capacity levels, space requirements, and setup times for each potential processing site. For example, the concrete crushing process may be installed at capacity levels of 0, 500, or 1,000 tons/day, corresponding to 0, 1 and 2 machines, respectively. Installing concrete crushing at a capacity level of 500 tons/day may require 10,000 square feet of space and a setup time of one month (for our case study, capacity and space requirements are adapted from Alibaba Group, 2015).

The remaining main inputs to the model include the collection rates (in tons/hour) of debris collection teams, transportation times, landfill capacities, fixed costs of opening processing sites and installing the processes, unit costs of debris collection, processing, and disposal (per ton), unit revenue from sold debris (per ton), and transportation costs (per mile-ton).

The main decisions considered are: i) processing sites to open, ii) processes to employ at each opened processing site, iii) capacity to make available for the processes selected at each opened processing site, iv) collection methods to use at each debris zone, v) processes debris will go through, and vi) which landfills to use and how much.

In making these decisions, the model aims to balance the objectives of (i) financial costs, (ii) environmental effects, (iii) duration until collection and final disposal are completed, (iv) landfill utilization, and (v) revenue from recycled debris. These can be incorporated into the objective function with different weights/priorities, or included among the constraints with corresponding bounds. The problem can be solved multiple times by varying the weights and bounds to study trade-offs.

The solution has to adhere to the following constraints: i) all debris must be collected from the debris zones and ultimately either disposed of or recycled, ii) processes can be employed only at opened processing sites and after the setup time for capacity installation, iii) the number of opened processing sites cannot exceed a predetermined limit, and iv) available space at opened processing sites cannot be exceeded.

For our case study instances (see Section 5) the decision-support tool (see Section 3) employing the above discussed model and using open-source optimization software finds close-to-optimal solutions within a few minutes.

2.3. Data Requirements

As can be inferred from Section 2.2, the successful implementation of the model proposed in this paper depends on the availability and accuracy of a number of data categories. The required input data can be categorized into five groups (see Table A2 in the Appendix for details): (i) per-unit revenue from recycled debris, depending on its composition; fixed, variable, and environmental costs of transportation, processing, and disposal, (ii) capacities in terms of total process time and space in each existing/potential facility, (iii) per-weight time required for debris collection, transportation, and processing, depending on its composition, iv) how each process transforms a given debris composition into a different one, and (v) initial debris volumes and composition in each debris generating zone.

Among the five groups of data mentioned, the first four can be estimated, determined or calibrated by local governments or emergency management agencies before the disaster hits. In particular, existing debris management guidelines can support their determination. For example, FEMA (2007) outlines how costs can be calculated, the characteristics of different debris collection and processing methods, and the design of debris processing sites. Thus, the most critical data inputs of the model presented above are the resulting debris amounts after the disaster hits, which depend not only on the impact of the disaster itself, but also on the number and types of buildings as well as the demographic and geographic properties of the disaster area. Given this, we will outline in what follows various pre- and post-disaster estimation methods for debris amounts.

As a first step during pre-disaster debris management operations, FEMA requires each local community to generate potential disaster scenarios and estimate the resulting debris amounts (FEMA, 2007). In order to guide the estimation process, FEMA (2010) provides a debris estimation field guide, along with easy-to-apply methods to estimate the debris amounts. A similar guideline, specific to the debris generated by hurricanes, has been proposed by USACE (2010), with an estimated accuracy of within ±30% of the actual debris amounts.

A more sophisticated debris estimation tool is HAZUS-MH (Scawthorn et al., 2006), provided free for download by FEMA (2015). The tool uses geographic and demographic data of the potential disaster location, along with state-of-the art structural analysis methods to estimate the economic and physical damage, including the resulting debris composition and amounts, under a given disaster scenario. The resulting debris amounts, which are estimated at the census tract, county, or state level, can be displayed on a map using Geographic Information Systems (GIS) software. HAZUS-MH generally provides accurate estimates for US-based disaster scenarios. For example, a validation study has observed that the debris estimations of the tool for Hurricane Ike resulted in an error of only 4.6% (Ding and Spinks, 2013). The HAZUS-MH methodology has also been validated on non-US-based disaster scenarios with satisfactory results (e.g., Ploeger et al. (2010) for Ottawa, Canada, and Levi et al. (2015) for Israel). Due to the proven accuracy of the tool, we use HAZUS-MH to estimate the debris amounts in the case study provided in Section 5.

In addition to these tools, with the recent technological advancements, various different sources of data collection have been employed to gather disaster damage and debris information. An example is the light detection and ranging (LiDAR) technology, which has been used to estimate the debris resulting from Hurricane Katrina, where the estimates were made available within a week of the dissipation (Hansen et al., 2007) and in the aftermath of Hurricane Sandy (Xian et al., 2015, and Hatzikyriakou et al., 2016). Finally, with the increasing employment of data sharing mechanisms (e.g., GOV, 2016) and Big Data approaches for disaster response (e.g., NSF, 2014), post disaster situational data is expected to become increasingly available, making it easier for contractors and policy makers to successfully use quantitative models and decision support tools for debris management.

3. The decision-support tool

There are important challenges in implementing the mathematical model described in Section 2: (i) the potential users of the model (e.g., local communities or private contractors) are unlikely to be familiar with mathematical optimization, (ii) the results should be visually accessible, and iii) the model may need to be repeatedly run under different settings (e.g., for different disaster scenarios or objectives). To overcome these challenges, a user-friendly decision-support tool is needed. For this end, the optimization model proposed is embedded into a spreadsheet-based decision-support tool. The tool requires a PC with 64 bit Microsoft Windows, Microsoft Office Excel version 2003 or later, and internet connection. It utilizes the open source optimization package GLPK (GLPK, 2015) to solve the model, which eliminates the need for proprietary optimization software, not generally available for the potential users of the model. Google Maps API Web Services (Google, 2015) are used to display maps for visualizing inputs and solutions.

The tool contains four groups of worksheets: (i) "Control panels", where different procedures such as generating input files, creating and solving the model, and displaying outputs can be executed, (ii) spreadsheets for inputting data, (iii) tables for model outputs, and (iv) maps where some of the inputs and outputs can be visualized. Details of the tool are provided in Section EC.1 of the Electronic Companion. The most up to date version of the tool and its documentation can be downloaded from DOT (2015).

The tool can be useful in the pre and post-disaster stages, and under different types of disasters (e.g. earthquakes, hurricanes, and floods). In the pre-disaster stage the tool can support the evaluation of locations for new landfills or potential processing sites. The tool can also be run under different potential disaster scenarios to evaluate: (i) the extent at which local versus external contractors should be employed for collection and transportation, and (ii) the impact of pre versus post-disaster installation of certain processes.

In the post-disaster stage the tool can aid disaster responders and solid waste officials in making the various operational decisions discussed in Section 2. Contractors or other entities responsible for the debris management of large affected areas can also utilize the tool for operational support.

4. Case study: Hurricane Andrew

Hurricane Andrew was a Category 5 hurricane that mainly affected the Florida and Louisiana coastline in the summer of 1992 and generated the most disaster-related debris in the United States until Hurricane Katrina in 2006 (National Hurricane Center, 2015). The reason behind the selection of this specific disaster stems from Florida being the US state that is hit most frequently by major hurricanes (National Hurricane Center, 2016), and Hurricane Andrew being the most devastating hurricane in Florida within the last hundred years.

The specific area we consider for analysis is Miami-Dade County, where the volume of debris constituted more than 75% of the post-disaster debris generated by Hurricane Andrew in Florida. To estimate the amount of debris in each census tract under the current demographical setting, the hazard estimation tool Hazus was used (FEMA, 2015). In total, slightly more than 4 million metric tons of debris is estimated, of which 93.7% is brick and wood-based, 4.9% is concrete-based, and 1.4% is vegetative. We divided the region into a "grid" of 22 zones of equal area. The geographical centers of these zones are given in Figure 3. The debris in each census tract was then assigned to the closest zone.

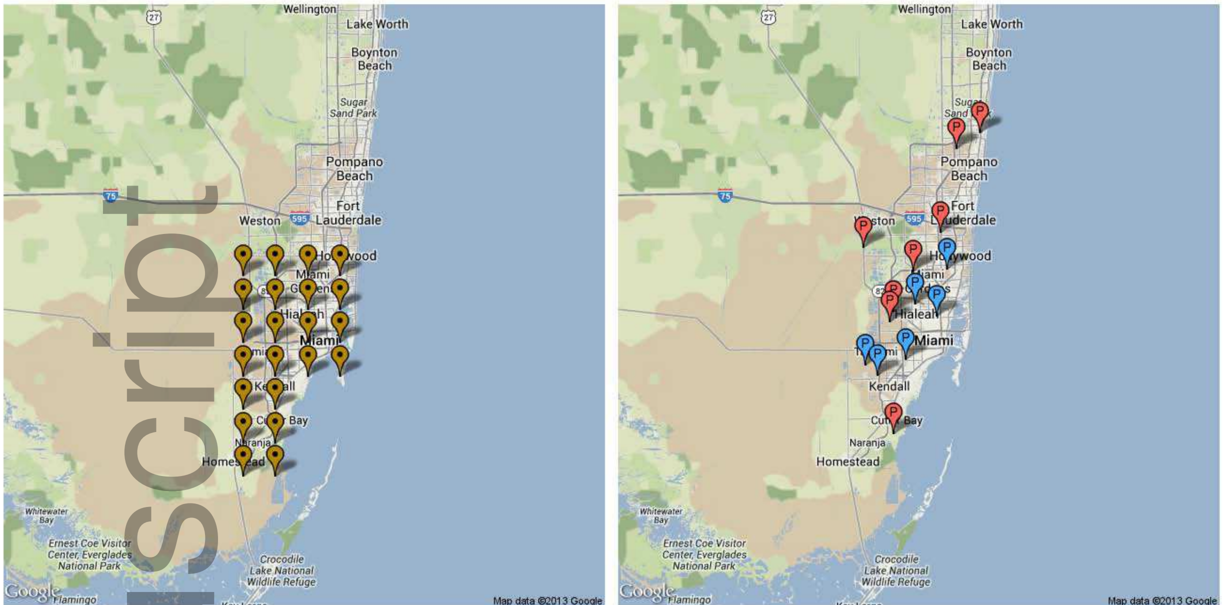

Figure 3 - Debris source locations (left), and potential site locations (right)

There are 14 potential locations considered for opening processing sites (see Figure 3). Eight of these locations are existing landfills and six are either parks or large empty areas that could be used as temporary processing sites in the disaster response and recovery stages. Each landfill has a disposal capacity as well as a processing rate. There is a fixed cost incurred for installing processes at each potential site. These rates and costs are adapted from Atlantic County Utilities Authority (2011) and Alibaba Group (2015), respectively.

Four processes are considered: separation, concrete crushing, grinding, and compaction. Since the disaster area is highly urbanized, open burning is not considered as a candidate process. At each potential site, each process can be installed in one out of three different capacity levels, with corresponding fixed costs and processing rates (see Section EC.2 of the Electronic Companion). Upon collection, each debris type (brick-wood, concrete, vegetative) can be landfilled, separated into its components (brick, wood, concrete, vegetative, and waste), or further processed (brick and wood can be ground, concrete can be crushed, and waste can be compacted). Figure 4 illustrates these debris types. Ground or crushed debris can be sold for revenue. Disposed debris incurs a cost of $6 per metric ton (Atlantic County Utilities Authority, 2011; scaled down to account for a post-disaster scenario).

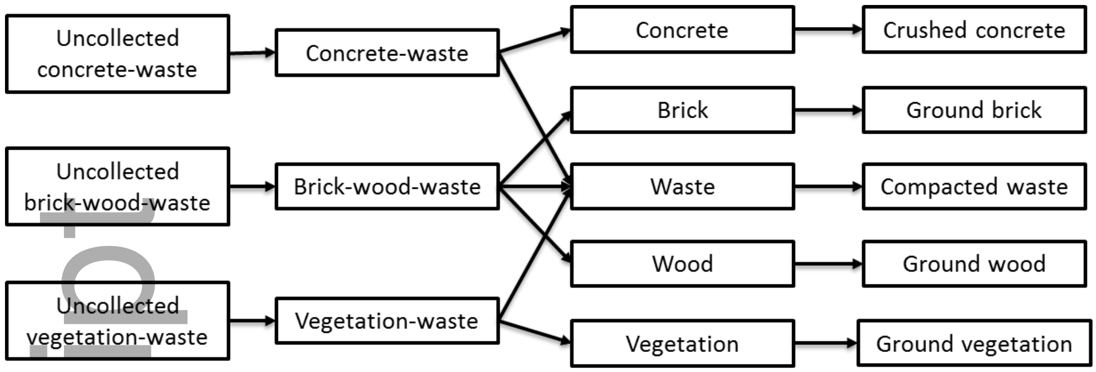

Figure 4 – Debris types considered in the case study

We assume that the processes are installed after the disaster hits and it takes two months to complete the installation of any given process (1-2 weeks to determine the needs and order the machinery, 2-6 weeks for transportation lead time, and an additional week for setup; adapted from Alibaba Group, 2015).

There are two rate levels at which debris can be collected. Collection without sorting is fast (100 metric tons per team per workday) and low cost ($10 per metric ton), while collection with sorting takes longer (66.67 metric tons per team per workday) and is more expensive ($15 per metric ton), but involves certain degree of separation (for example, concrete-waste can be partially transformed into separated concrete and waste). The collection rates and unit costs presented here have been estimated from FEMA (2007).

Transportation cost is assumed to be $0.30 per cubic yard per mile. There are 500 work teams, each of which can transport 30 cubic yards in each trip, and can cover 300 miles per workday (based on USACE, 2002, which reports a peak of 2,000 trucks per day; this figure is varied to assess its sensitivity in Section 4.2). Since the valuable materials obtained from processing debris can be sold, we define net cost as the difference between the financial cost of the operations and the revenue from sold debris.

Aside from the work teams hired for collection and transportation, external contractors can be hired (at a higher cost) to take debris from processing sites to recycling facilities and/or landfills away from Miami-Dade County.

For each setting we consider in this section, we solve the mathematical model with the objective of net cost minimization, for different disposal time limits.

4.1. Base case analysis

Table 1 presents the results for the base case when minimizing net cost under different disposal time limits. A longer disposal time allows flexibility for processing, lowers the cost spent on external contractors, and lowers net cost, but there are diminishing returns. For example, the (average per month) reduction in net cost when disposal time increases from 3 to 6 months is 4.39 million USD, but when disposal time increases from 12 to 24 months it is 1.97 million USD. When disposal time is limited to 3 months, approximately 57% of the total cost is due to external contractors. This is because *the completion of the disposal operations without substantial involvement of external contractors is not possible when the target disposal time is "short"* (note that the processes take two months to be installed). As the target disposal time increases, the external contractor costs dramatically decrease, since the expenditure in fixed costs for increased processing capacities can be justified.

Table 1 - Base case results when minimizing net cost with different upper bounds on disposal time. All costs are in million USD.

Target disposal time (months)	3	6	12	24
Net cost	169.00	155.84	133.65	110.05
Fixed costs	3.20	9.05	10.89	7.72
Collection costs	43.98	49.84	56.71	53.54
Transportation costs	18.75	26.79	37.88	30.49
Processing costs	0.61	6.57	20.40	29.09
Disposal costs	6.57	8.88	8.98	7.78
External contractor costs	97.11	61.49	15.93	3.05
Revenue from sold debris	1.21	6.78	17.14	21.61
Debris landfilled (million metric tons)	1.10 (27%)	1.48 (37%)	1.50 (37%)	1.30 (32%)
Debris picked up by external contractors (million metric tons)	2.77 (69%)	1.71 (43%)	0.44 (11%)	0.08 (2%)
Debris sold (million metric tons)	0.15 (4%)	0.83 (21%)	2.08 (52%)	2.63 (65%)
Collection duration (months)	3.00	3.45	3.91	3.64

Number of processing sites opened	7	12	12	9

When the target disposal time increases, collection, transportation, and disposal costs increase (while external contractor costs decrease) up to a time limit (12 months in our case study), and then start decreasing. This is mainly due to the fact that *increasing the target disposal time decreases the dependency on the more expensive external contractors and leads to opening more processing sites*. When the target disposal time exceeds a threshold (i.e., when external contractors are no longer needed), debris can be collected and processed in fewer sites with more convenient locations. *Under a tight time constraint, opened sites are the ones that are closest to the locations with the highest amount of debris* (see Figure 3). When more time is allowed, the savings from less dependence on external contractors lead to the convenience of opening more sites at more remote locations. Processing more debris increases processing costs, but this is compensated by the reduction in other costs and the increased revenue from recycled materials.

Table 2 - Capacities (in metric tons per day) of each process at each opened site under the base case with disposal time limits of 6 and 24 months

	6 months				**24 months**			
Site	**Separation**	**Concrete Crushing**	**Grinding**	**Compaction**	**Separation**	**Concrete Crushing**	**Grinding**	**Compaction**
A	500		1,000		500	100	500	500
B					1,000			500
C		100		1,000			500	
D		100	500	500				
E			500		500			
F			1,500					
G		100	500	500	1,000			500
H		100		1,500	500		500	500
I	500		500		500	100	500	
J	500		1,000				1,500	
K		100	500					
L	1,000		500		500		500	
Total	2,500	500	6,500	3,500	4,500	200	4,000	2,000

Table 2 shows the processing capacities installed at each of the opened sites for the solutions with disposal time limits of 6 and 24 months to better analyze the effect of increasing the disposal time limit. The total capacities for these two cases are 12,900 and 10,500 metric tons per day, respectively. *When the target disposal time is 6 months, the total amount of processed debris is close to 1.5 million metric tons, and the total processing capacity is higher for concrete crushing, grinding, and compaction, whereas when the target disposal time is 24 months capacity is higher for separation and the amount of processed debris increases to more than 6.5 million tons.* The latter is due to the fact that separated debris is further processed and sold when there is sufficient time.

An important feature of the decision-support tool is the visualization of model outputs. Figure 5 shows the opened separation sites for disposal time limits of 6 and 24 months. The total separation capacity is 2,500 and 4,500 tons per workday, respectively, and the total amount of debris separated is 0.304 and 2.677 million metric tons, respectively.

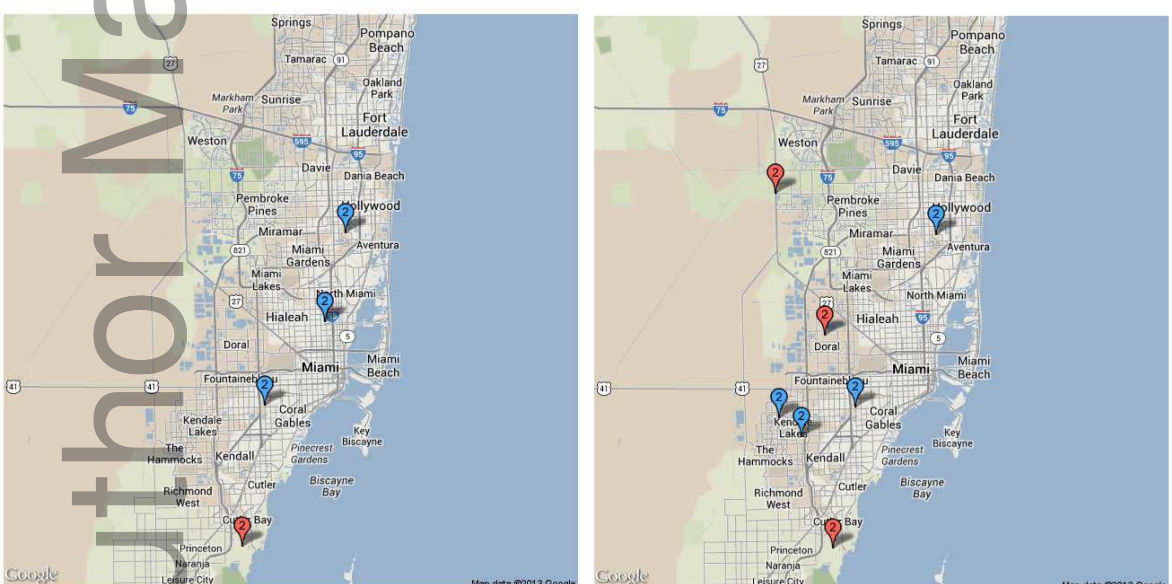

Figure 5 – Locations where the separation process has been installed in the solutions for the base case, when disposal time is 6 months (left) and 24 months (right).

4.2. Effect of the number of work teams

We analyze the effect of the number of work teams available for collection and transportation. If there are 750 work teams available compared to the 500 teams in the base case, we observe that collection time can be reduced by roughly 30%, but without significant improvement in net cost (under any given disposal time limit). Hence, *the number of work teams should be selected considering the target disposal time.* More work teams will reduce collection time, but if there is not enough processing capacity, disposal time can still be long due to processing bottlenecks.

4.3. Effect of external contractor costs

To analyze the robustness of the solutions against external contractor costs, we increase these costs by 25%, 50%, and 100% of that of the base case. As shown in Figure 6, when the target disposal time exceeds 12 months, net cost is very close in all cases, as *under sufficiently long planning horizons the dependence on external contractors decreases*, due to the fact that the fixed costs of opening processing sites and installing processes is compensated by the cost savings from not using external contractors. However, *when the target disposal time is short, external contractor costs significantly affect net cost.* When the external contractor cost rate increases by 100% over the base case, net cost increases by 57% and 33% for target disposal times of 3 and 6 months, respectively. Hence, the impact of external contractor costs on net cost depends strongly on the target disposal time.

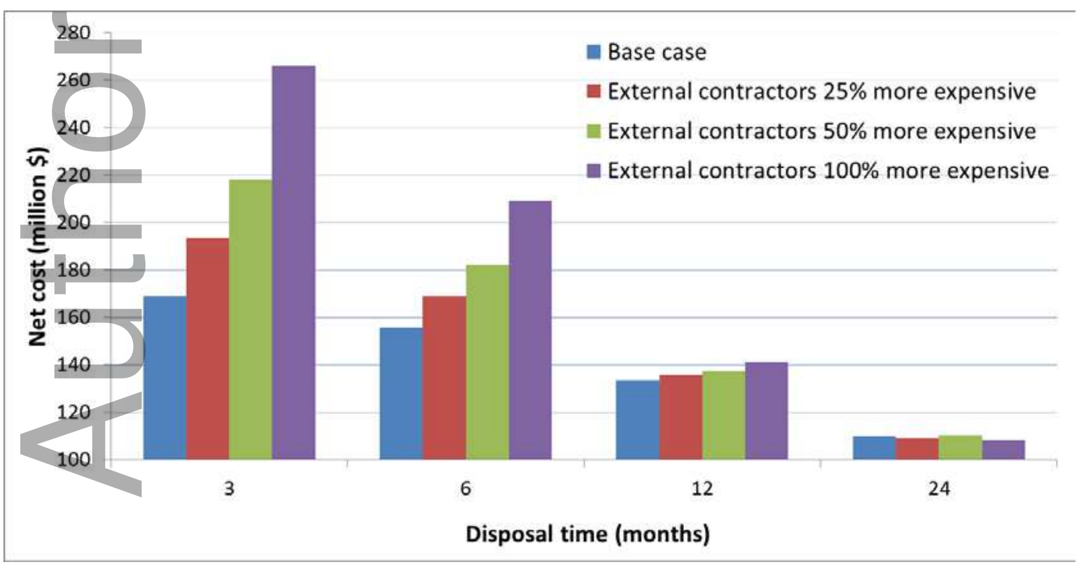

Figure 6 - Net cost variations when the disposal time limit and the cost of external contractors are varied

When external contractors are more expensive, the number of opened sites increases (for a 50% increase in contractor costs, the number of opened sites increases from 7 to 11 when the disposal time limit is 3 months and from 12 to 14 when the limit is 6 months). This, in turn, increases the amount of debris processed and recycled locally. However, *when the target disposal time is short, opening more sites is not beneficial* as there is not enough time for processing to generate revenue from sold processed debris.

4.4. Effect of landfill space allocated for post-disaster debris disposal

The tool can be helpful for decision-makers in the pre-disaster stage to analyze what portion of existing landfill capacities should be used for post-disaster debris, to balance the long term benefit of this capacity for typical waste management operations and the short term benefit for post-disaster operations. Such analysis is especially important for urban or other settings where landfill capacity is limited, e.g., as in the case of the 2010 Haiti earthquake or the 2011 cascading disasters in Japan.

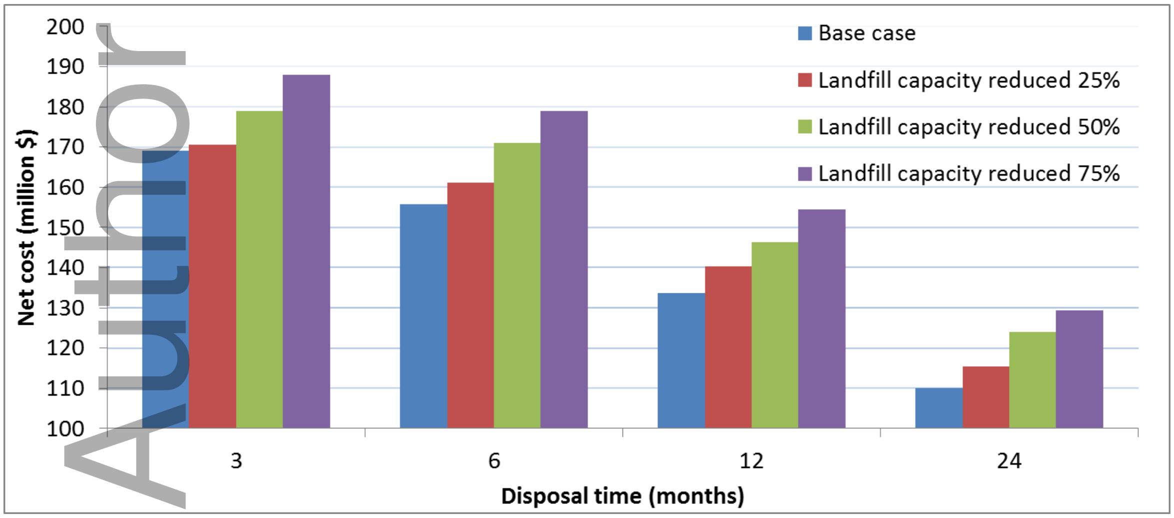

Figure 7 - Net cost variations when the disposal time limit and the landfill capacities are varied

The impact of varying landfill capacities on net cost is shown in Figure 7. When the target disposal time is low, net cost for the base case is almost the same as when landfill capacity is reduced by 25%. This is mainly because in both cases, less than 75% of the landfill capacity is used, and hence, the resulting plans are almost identical. For higher disposal time limits, each 25% reduction in landfill capacity results approximately in a $5 million increase in net cost. **Error! Not a valid bookmark self-reference.** breaks down the resulting costs when landfill capacity is reduced by 75%. While transportation and disposal costs may be lower, due to less debris being moved to landfills, these savings are offset by the higher external contractor costs.

Table 3 - Transportation, disposal, and external contractor costs for the base case and the case with landfill capacity reduced by 75%, for different disposal time limits

	Base case				**Landfill capacity reduced by 75%**			
Disposal time (months)	3	6	12	24	3	6	12	24
Transportation cost (million $)	18.7	26.8	37.9	30.5	11.9	17.4	24.3	22.3
Disposal cost (million $)	6.6	8.9	9.0	7.8	2.0	2.3	2.3	2.2
Cost of external contractors (million $)	97.1	61.5	15.9	3.0	128.7	99.5	56.1	36.2

4.5. Impact of incinerator availability

Another useful pre-disaster application of the tool is to evaluate the possibility of installing incineration capacity at existing landfills under potential disaster debris scenarios. In our case study, in addition to the base case (no incineration available), we consider two cases where six incinerators become available (i) immediately (due to pre-disaster installation), and (ii) 6 months later (i.e., installation begins after the disaster strikes). For each of these cases Figure 8 shows cost decomposition (fixed, collection, transportation, processing, disposal, and external contractor costs) under various disposal time limits.

When the target disposal time is 3 or 6 months, the base case and the case where incinerators become available after 6 months are identical. *When the target disposal time is 12 or 24 months, the investment in incinerators results in significant cost savings* (of around $25 million in our case study). For 12 months, the savings are mostly due to less reliance on external contractors. For 24 months, the majority of the savings are due to reduced transportation and disposal costs. Fixed costs are also slightly reduced, since incineration availability increases processing capacity at landfills, and thereby decreases the need for more processing sites. Processing costs are slightly increased due to the use of incineration.

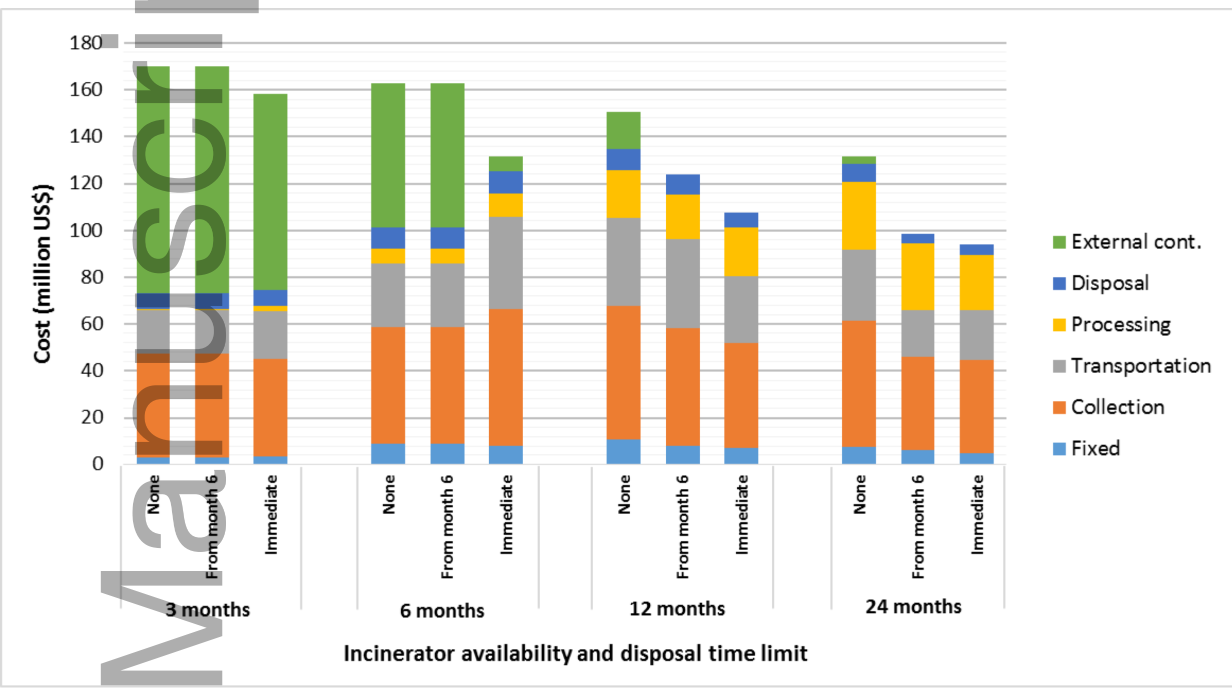

Figure 8 – Cost breakdown under different disposal time limits for the case with no incinerators, incinerators available at month 6 after the disaster, and incinerators available from the onset of the disaster

If the incinerators are already installed when the disaster strikes, additional cost savings are observed. When the target disposal time is 3 months, most of the savings are due to the reduction in external contractor costs. For 12 months, the savings are mainly due to less disposal and more efficient transportation. For 24 months, no significant savings are obtained over the case where incinerators become available after 6 months, since there is sufficient time to carry out the activities in a cost-effective way under both cases. The most significant savings are obtained when the target disposal time is 6 months. In this case, the time horizon is long enough to provide significant savings over external contractors. Hence, *the benefit of incinerator* *availability depends on the target disposal time, and in our case study, is especially beneficial when the target disposal time is neither too short nor too long.*

4.6. Robustness to debris estimation errors

Given that debris estimation methods are not exact, as discussed in Section 2.3, we illustrate here a simple procedure based on the tool developed to study the robustness of the solutions obtained under debris estimation errors.

Let us first consider the flexibility of the different decisions addressed by the model. Suppose that at some point of the debris collection and disposal processes, after a portion of the debris has been collected, the operational plan is to be redesigned given new and more accurate estimates for the remaining uncollected debris amounts. At this point, decisions corresponding to collection, transportation, processing, recycling, and disposal are flexible, and can be immediately updated, whereas modifying the opened processing sites or installed processing capacities is much slower. Based on this observation, we will illustrate how the quality of a given set of site/capacity decisions (that is, opened processing sites and installed processing capacities) can be assessed under debris estimation errors.

Consider the site/capacity decisions obtained in the base case described in Section 4.2, under a target disposal time of 6 months. We study the robustness of this site/capacity solution under debris over- and under-estimations by constraining these decision variables to stay fixed, while re-optimizing the remaining decision variables for cases where debris amounts are modified by -20%, -10%, 10%, and 20% with respect to the amounts considered in the base case, for all debris types and locations. Then, for each case we observe the performance obtained by the base case site/capacity solution and compare it to the performance obtained when site/capacity decisions are allowed to be optimized (that is, when they are not fixed, as if a perfect estimation was available). Table 4 breaks down the most relevant costs obtained for each of these cases.

If we compare the net cost obtained under debris estimation errors against the case with perfect debris information, we obtain a relative difference of 1.01%, 0.49%, 0.53%, and 1.51%, under the -20%, -10%, 10%, and 20% debris variation cases, respectively. Further, from Table 4 we can observe that *when debris is over-estimated the net cost increase is due to an excess of* *processing capacities, incurring high fixed costs, whereas when debris is under-estimated the net cost increase is explained by insufficient processing capacities, requiring a high employment of expensive external contractors.*

Table 4 – Percent change in the net, fixed, processing, and external contractor costs (in million US$) under debris estimation errors, compared to the perfect information case, for various debris variation cases

Debris estimate variation	-20%	-10%	10%	20%
Net cost	1.02%	0.49%	0.53%	1.51%
Fixed costs	19.87%	2.84%	-2.69%	-12.81%
Processing costs	18.59%	-0.75%	-5.48%	-14.23%
External cont. costs	-6.73%	2.24%	1.52%	12.19%

5. Conclusions

Debris collection and disposal operations are among the most complicated, time consuming, and costliest activities in the disaster response and recovery stages. Existing literature on post-disaster debris management mostly focuses on policy-related issues such as assigning responsibilities and listing administrative procedures. Motivated by the lack of quantitative models and decision support tools for debris management operations, we have proposed a mathematical model that optimizes the localization of processing sites, selection of processing capacities, and debris flow decisions encompassing collection, transportation and disposal, with the goal of balancing conflicting objectives such as cost and duration of the operations. To the best of our knowledge, the proposed model is the first to consider all of these aspects.

The limited availability of user-friendly tools that allow decision-makers to use mathematical models for decision aid creates a significant gap between theory and practice. We have developed a spreadsheet-based decision-support tool that runs our proposed model based on user inputs and allows simple output visualization. To solve the problem, the tool uses open source optimization software, avoiding the need for expensive commercial solvers. The tool can be used by local disaster management authorities to conduct what-if analysis in the pre-disaster stage and as an operational tool in the response or recovery stages.

Our case study on Hurricane Andrew shows that the tool is able to capture various tradeoffs. We summarize the insights obtained for this case study as follows:

- The overall costs are significantly affected by the dependence on external contractors, which plays an important role when there is a short time limit for disposal.
- When the target disposal time is short, processes such as concrete crushing, grinding, and compaction are more widely employed, whereas with longer target disposal times separation is used more, since this process is critical for extended recycling.
- The number of work teams to be employed for collection and transportation needs to be in line with the target disposal time.
- Increasing the available landfill space for post-disaster debris disposal results in significant cost and time savings.
- Installing incinerators after (before) the onset of the disaster is beneficial if the target disposal time is long (neither too short nor too long).
- Under-estimating (over-estimating) debris amounts can lead to high external contractor costs (fixed costs).

While these results are specific to the case study discussed in the paper and the specific input data used, they provide a means to shed light into and exemplify how the proposed model and decision support tool can be used by decision makers to draw policy-based insights of similar nature.

Debris management decisions are complex, as many interrelated factors are at play, with outcomes that are difficult to understand based only on intuition and previously reported experiences. In this context, the tool helps decision-makers evaluate the consequences and trade-offs of alternative operational decisions and preparedness strategies.

Decisions for debris management in various stages of the disaster life cycle are often considered independently. Therefore, there is a need for developing holistic models and tools to address problems in all disaster management stages. The tool we have developed will serve as an example of innovative and practical solutions in this context while bridging the gap between methodology and practice.

Appendix: Mathematical formulation of the problem

In Tables A1 through A4, we present the index sets, parameters, decision variables, and auxiliary variables used in the mathematical formulation of the problem, respectively.

Table A1 – Index sets used in the mathematical formulation of the problem

Index Sets	
B	time periods
I	debris types
I^C	debris types in I that need to be collected before transportation
I^T	debris types in I that have been collected and can be transported
I^{NR}	debris types in I^T that cannot be sold
J	all debris zones and existing/potential landfill/processing site locations
J^D	debris zone locations
J^P	existing and potential landfill or processing site locations
K	available processes ($k = 1$ represents storage without processing)
L	available processing capacity levels
P	processing phases
Q	collection methods

Table A2 – Parameters used in the mathematical formulation of the problem

Parameters	
a_i	density (ton per cy) of debris type $i \in I$
AP_{ikp}	1, if process $k \in K$ is applicable for debris type $i \in I$ at phase $p \in P$; 0, otherwise
$\hat{b}_{kl}$	time period at which process $k \in K$ is made available at capacity level $l \in L$
B_j^{DIS}	total disposal capacity (cy) in existing/potential site $j \in J^P$
c_j^S	fixed cost of opening a processing site at site $j \in J^P$
c_{jkl}^{FP}	fixed cost of making process $k \in K$ available at site $j \in J^P$ at capacity $l \in L$
c_{ijq}^{COL}	fixed cost of collecting debris type $i \in I$ at location $j \in J^D$ with collection method $q \in Q$
$c_{ijj'}^{TR}$	cost per weight (\$/ton) of transporting debris type $i \in I$ from location $j \in J$ to $j' \in J$
c_{ik}^{PR}	cost per weight (\$/ton) of applying process $k \in K$ on debris type $i \in I$
c_{ij}^{DIS}	cost per weight (\$/ton) of disposing of debris type $i \in I$ at location $j \in J^P$
$c_{ijj'}^{TE}$	environmental cost (\$/ton) of transporting debris type $i \in I$ from location $j \in J$ to $j' \in J$

c_{ik}^{EP}	environmental cost ($/ton) of processing debris type $i \in I$ with process $k \in K$
c_{ij}^{ED}	environmental cost ($/ton) of disposing of debris type $i \in I$ at location $j \in J^P$
K_j^S	spatial capacity (sq. ft.) available at processing site at location $j \in J^P$
K_{kl}^{PR}	spatial capacity (sq. ft.) used by process $k \in K$ if available at processing capacity $l \in L$
m_{ij}	initial volume (ton) of debris type $i \in I$ at location $j \in J^D$
M^θ	upper bound for objective θ, $\theta \in \{FC, CT, DT, DL, EC\}$
m^{DR}	lower bound for the revenue obtained from recycled/reused debris ($)
r_{ij}^{REV}	revenue per weight ($/ton) from selling debris type $i \in I$ at location $j \in J^P$
TID	total initial debris of all types in all locations
T_b	duration (in days) from the beginning of the horizon to the start of time period $b \in B$
$\underline{x}, \overline{x}$	minimum and maximum number of processing sites that can be installed
$\underline{y}_k, \overline{y}_k$	minimum and maximum number of sites where process $k \in K$ can be installed
$\gamma_{i'ik}^{PR}$	transformation rate from debris type $i' \in I$ to $i \in I$ when applying process $k \in K$
$\gamma_{i'iq}^{C}$	transformation rate from debris type $i' \in I$ to $i \in I$ with collection method $q \in Q$
τ_{ijq}^{COL}	time per weight (days/ton) taken when collecting debris type $i \in I^C$ at location $j \in J^D$ with collection method $q \in Q$
$\tau_{ijj'}^{TR}$	time per weight (days/ton) taken when transporting debris type $i \in I^T$ from location $j \in J$ to location $j' \in J$
τ_{ikl}^{PR}	time per weight (days/ton) taken when processing debris type $i \in I$ with process $k \in K$ for capacity level $l \in L$
ρ^θ	weight of objective θ, $\theta \in \{FC, CT, DT, DL, EC, DR\}$

Table A3 – Decision variables used in the mathematical formulation of the problem

Decision variables	
$x_j \in \{0,1\}$	1, if a processing site is opened at location $j \in J^P$; 0, otherwise
$y_{jkl} \in \{0,1\}$	1, if process $k \in K$ is made available at location $j \in J^P$ with processing capacity $l \in L$; 0, otherwise
φ_{ijq}	amount (in ton) of debris type $i \in I^C$ at location $j \in J^D$ collected with method $q \in Q$
$\theta_{ijj'}^0$	amount (in ton) of debris type $i \in I^T$ transported from location $j \in J^D$ to location $j' \in J^P$ immediately after collection
$\theta_{ijj'bp}$	amount (in ton) of debris type $i \in I^T$ transported from location $j \in J^P$ to location $j' \in J^P$ in time period $b \in B$ and processing phase $p \in P$
π_{ijklbp}	amount (in ton) of debris type $i \in I^T$ processed at location $j \in J^P$ with process $k \in K$ under

	capacity level $l \in L$, in time period $b \in B$ and processing phase $p \in P$
λ_{ij}	amount (in ton) of debris type $i \in I^T$ sold at location $j \in J^P$
μ_{ij}	amount (in ton) of debris type $i \in I^T$ disposed at location $j \in J^P$

Table A4 - Auxiliary variables used in the mathematical formulation of the problem

Auxiliary variables	
FC	total financial cost (in \$)
CT	total duration of collection (in days)
DT	total disposal time (in days)
DL	total space used in landfills by disposed debris (in cy)
EC	total environmental costs (\$)
DR	total revenue obtained from sold debris (in \$)

Based on the notation in Tables A1-A4 we formulate the problem as follows:

Minimize $\rho^{FC}\,\mathrm{FC} + \rho^{CT}\,\mathrm{CT} + \rho^{DT}\,\mathrm{DT} + \rho^{DL}\,\mathrm{DL} + \rho^{EC}\,\mathrm{EC} - \rho^{DR}\,\mathrm{DR}$

subject to

$$FC = \sum_{j\in J^P} c_j^S x_j + \sum_{j\in J^P}\sum_{k\in K}\sum_{l\in L} c_{jkl}^{FP} y_{jkl} + \sum_{i\in I^C}\sum_{j\in J^D}\sum_{q\in Q} c_{ijq}^{COL}\varphi_{ijq} + \sum_{i\in I^T}\sum_{j\in J^D}\sum_{j'\in J^P} c_{ijj'}^{TR}\theta_{ijj'}^0 + \sum_{i\in I^T}\sum_{j\in J^P}\sum_{j'\in J^P}\sum_{b\in B}\sum_{p\in P} c_{ijj'}^{TR}\theta_{ijj'bp} + \sum_{i\in I^T}\sum_{j\in J^P}\sum_{k\in K}\sum_{l\in L}\sum_{b\in B}\sum_{p\in P} c_{ik}^{PR}\pi_{ijklbp} + \sum_{i\in I^T}\sum_{j\in J^P} c_{ij}^{DIS}\mu_{ij} \tag{1}$$

$$\mathrm{CT} = \sum_{i\in I^C}\sum_{j\in J^D}\sum_{q\in Q}\tau_{ijq}^{COL}\varphi_{ijq} + \sum_{i\in I^T}\sum_{j\in J}\sum_{j'\in J}\tau_{ijj'}^{TR}\theta_{ijj'}^0 \tag{2}$$

$$\mathrm{DT} \geq T_b\, y_{jkl} + \sum_{i \in I^T} \sum_{p \in P} \tau_{ikl}^{PR} \pi_{ijklbp} \qquad \forall j \in J^P, k \in K, l \in L, b \geq \hat{b}_{kl} \tag{3}$$

$$\mathrm{DT} \geq \sum_{i \in I^C} \sum_{j \in J^D} \sum_{q \in Q} \tau_{ijq}^{COL} \varphi_{ijq} + \sum_{i \in I^T} \sum_{j \in J} \sum_{j' \in J} \sum_{b \in B} \sum_{p \in P} \tau_{ijj'}^{TR} \theta_{ijj'bp} \tag{4}$$

$$\mathrm{DL} = \sum_{i \in I^T} \sum_{j \in J^P} \frac{\mu_{ij}}{a_i} \tag{5}$$

$$\mathrm{EC} = \sum_{i \in I^T} \sum_{j \in J^D} \sum_{j \in J^P} c_{ijj'}^{TE} \theta_{ijj'}^{0} + \sum_{i \in I^T} \sum_{j \in J^P} \sum_{j' \in J^P} \sum_{b \in B} \sum_{p \in P} c_{ijj'}^{TE} \theta_{ijj'bp} + \sum_{i \in I^T} \sum_{j \in J^P} \sum_{k \in K} \sum_{l \in L} \sum_{b \in B} \sum_{p \in P} c_{ik}^{PE} \pi_{ijklbp} + \sum_{i \in I^T} \sum_{j \in J^P} c_{ij}^{DE} \mu_{ij} \tag{6}$$

$$\mathrm{DR} = \sum_{i \in I^T} \sum_{j \in J^P} r_{ij}^{REV} \lambda_{ij} \tag{7}$$

$$\underline{x} \leq \sum_{j \in J^P} x_j \leq \bar{x} \tag{8}$$

$$\underline{y}_k \leq \sum_{j \in J^P} \sum_{l \in L} y_{jkl} \leq \bar{y}_k \qquad \forall k \in K \tag{9}$$

$$\sum_{l \in L} y_{jkl} \leq x_j \qquad \forall j \in J^P, k \in K - \{1\} \tag{10}$$

$$\sum_{k \in K} \sum_{l \in L} K_{kl}^{PR}\, y_{jkl} \leq K_j^S\, x_j \qquad \forall j \in J^P \tag{11}$$

$$\pi_{ijklbp} \leq \mathrm{AP_{ikp}}\, TID\, y_{jkl} \qquad \forall b \in B, i \in I^T, j \in J^P, k \in K, l \in L, p \in \mathrm{P} \tag{12}$$

$$\pi_{ijklbp} = 0 \qquad \forall b \in B, i \in I^T, j \in J^P, k \in K, l \in L, p \in \mathrm{P}\colon \hat{b}_{kl} > b \tag{13}$$

$$\sum_{i\in I^T}\sum_{p\in P}\tau_{ikl}^{PR}\pi_{ijklbp} \leq T_{b+1} - T_b \qquad \forall b\in\{1,\dots,B-1\}, j\in J^P, k\in K, l\in L \qquad (14)$$

$$\lambda_{ij} \leq \text{TID}\, x_j \qquad \forall i\in I^T, j\in J^P \qquad (15)$$

$$\sum_{i\in I^T}\frac{\mu_{ij}}{a_i} \leq B_j^{DIS} \qquad \forall j\in J^P \qquad (16)$$

$$m_{ij} = \sum_{q\in Q}\varphi_{ijq} \qquad \forall i\in I^C, j\in J^D \qquad (17)$$

$$\sum_{i'\in I^C}\sum_{q\in Q}\gamma_{i'iq}^{C}\varphi_{i'jq} = \sum_{j'\in J^P}\theta_{ijj'}^{0} \qquad \forall i\in I^T, j\in J^D \qquad (18)$$

$$\sum_{j'\in J^D}\theta_{ij'j}^{0} = \sum_{k\in K}\sum_{l\in L}\pi_{ijkl11} \qquad \forall i\in I^T, j\in J^P \qquad (19)$$

$$\sum_{i'\in I^T}\sum_{k\in K}\sum_{l\in L}\gamma_{i'ik}^{P}\pi_{i'jklbp} = \sum_{j'\in J^P}\theta_{ijj'bp} \qquad \forall b\in B, i\in I^T, j\in J^P, p\in P \qquad (20)$$

$$\sum_{j'\in J^P}\theta_{ij'jbp} = \sum_{k\in K}\sum_{l\in L}\pi_{ijklb,p+1} \qquad \forall b\in B, i\in I^T, j\in J^P, p\in\{1,\dots,P-1\} \qquad (21)$$

$$\sum_{j'\in J^P}\theta_{ij'jbP} = \sum_{k\in K}\sum_{l\in L}\pi_{ijkl,b+1,1} \qquad \forall b\in\{1,\dots,B-1\}, i\in I^T, j\in J^P \qquad (22)$$

$$\sum_{j'\in J^P}\theta_{ij'jBP} = \lambda_{ij} + \mu_{ij} \qquad \forall i\in I^T, j\in J^P \qquad (23)$$

$$\lambda_{ij} = 0 \qquad \forall i\in I^{NR}, j\in J^P \qquad (24)$$

$$\mathrm{FC} \leq M^{FC}$$
$$\mathrm{CT} \leq M^{CT} \quad (25)$$
$$DT \leq M^{DT}$$
$$\mathrm{DL} \leq M^{DL}$$
$$EC \leq M^{EC}$$
$$DR \geq m^{DR}$$

$$x_j, y_{jkl} \in \{0,1\} \qquad \forall j,k,l \quad (26)$$

$$\varphi_{ijq}, \theta^0_{ij'j}, \theta_{ijj'bp}, \pi_{ijklbp}, \lambda_{ij}, \mu_{ij} \geq 0 \qquad \forall b,i,j,j',k,l,p. \quad (27)$$

The objective is to minimize a weighted sum of financial costs, collection time, disposal time, debris landfilled, environmental costs, and revenue from recycled debris. Constraints (1)-(7) define these objectives. In particular, constraints (3) state that disposal time must be bounded below by the time it takes to make each process available, determined as the starting time of the last time period in which it is used, plus the processing duration within that time period. Based on constraints (3) and (4), disposal time is the maximum between processing time at each opened site, and collection time added with post-collection transportation time (assuming that the same resources used for collection are used for site-to-site transportation). Constraints (8) enforce bounds for the number of processing sites to make available. Constraints (9) enforce bounds for the number of sites where each process can be made available. Constraints (10) state that processes can be made available at sites only if they are opened, and that only one capacity level can be selected for each process at each site, except for $k = 1$, that corresponds to no processing. Constraints (11) enforce spatial capacities of opened sites. Constraints (12) ensure that processes are applied in their corresponding phases according to their respective orders (for example, first separation then grinding) and to the corresponding debris types (for example, wood grinders cannot crush concrete), and only where the respective processes have been made available. Constraints (13) state that processing in any time period can only occur if the process was made available before the start of that time period. Constraints (14) limit the debris processed in each time period according to its duration. Constraints (15) state that debris can only be sold at opened processing sites. Constraints (16) enforce landfill capacities. Constraints (17) ensure that all debris is collected. Constraints (18) and (19) state that all collected debris is transported to processing sites or landfills. Constraints (20) and (21) determine debris flow balance within each time period, so that debris is processed in phase 1, then transported, then processed in phase 2, and so on. Constraints (22) determine debris flow balance between time periods, so that all debris transported at the last phase of each time period is processed in phase 1 of the next time period. Constraints (23) ensure that all debris transported in the last phase of the last time period is either sold or disposed. Constraints (24) state that debris types that cannot be sold are not sold. Constraints (25) enforce bounds for the objectives. Constraints (26) and (27) represent the binary or nonnegative nature of the respective variables. A preliminary version of the model has appeared in Ergun et al. (2015).

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