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A decision-support tool for post-disaster debris operations
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Abstract
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 to assist disaster and waste management officials with the collection, transportation, reduction, recycling, and disposal of debris. The tool enables optimizing and balancing the financial and environmental costs, duration of the removal operations, landfill usage, and the amount of recycled materials generated. It can support post-disaster operational decisions as well as the challenging task of developing strategic plans for disaster preparedness.

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1. Introduction
An important but often overlooked aspect among the post-disaster logistics activities is managing the resulting debris, which is defined as any kind of waste generated by the disaster. Types of debris include building materials such as concrete, bricks, and wood, vegetation such as fallen trees, limbs, and plantation; household waste such as furniture and white goods; hazardous waste such as industrial chemicals; cars, rubbles of road infrastructure, sediments, and so on. Timely removal of debris has important consequences in two different ways: In the short run, it enables the maintenance of disaster response activities such as relief transportation, search-and-rescue, and

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evacuation. In the long term, it prevents the adverse effects on human health and the environment due to factors such as decaying chemicals and pollution of water resources.

Debris management is a long, costly, and complicated process; therefore efficient and effective debris management operations could be significantly aided by quantitative models and decision-support tools that allow easy-to-use access to these models. Motivated by the lack of such models and tools in the literature, this paper presents a mathematical model for debris management operations in the disaster recovery stage and a decision-support tool that implements this model to provide a user-friendly application. The mathematical model balances multiple objectives such as financial costs, environmental effects, duration of the operations, and recycled debris amount. The tool can be used both in the pre-disaster stage to prepare strategic debris management plans and make what-if analyses, as well as in the post-disaster stage to determine decisions at an operational level.

Following large-scale disasters, managing the resulting debris takes a large toll on the infrastructure, economy, and human resources of the affected region. For example, the total cost of debris management activities following Hurricane Katrina in 2005, a disaster that resulted in more than 100 million cubic yards of debris, is estimated to have exceeded USD 4 billion, accounting for more than a quarter of the total cost associated with disaster response and recovery [21]. The management of post-disaster debris following the March 2011 cascading disasters in Japan was exacerbated by the fact that a substantial amount of debris was moved from its original place due to the tsunami, which also mixed different types of debris together, further complicating the removal of more than 25 million tons of debris [21]. In the Fukushima area, radioactive debris contents posed difficulties for local authorities, who were still undecided on how to carry out the removal three months after the disaster because there were no official guidelines on how to handle it [21]. The lack of space to dispose of the debris also results in challenging issues, as exemplified by the cascading disasters in Japan and the 2010 Haiti earthquake.

Adapted from FEMA [10], Figure 1 shows the debris management events throughout the timeline of a disaster. Before the disaster hits, each local community is required to determine a number of potential disaster scenarios, which in turn determine the forecasts for potential debris amounts and compositions. Based on these forecasts, workforce and equipment requirements are planned and potential debris management facilities such as debris processing sites, recycling plants, and disposal areas are determined. In the immediate aftermath of a disaster, based on the initial assessment of the disaster area, 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, where the 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. Once these processes are complete, all or parts of the processed debris may be disposed of in landfills, whereas parts of it may be processed further to be recycled and either reused or sold.
Our work in this paper encompasses the activities in the disaster recovery stage. In particular, we address the following decisions: location of debris processing facilities, selection of specific processes and respective capacity levels to install at each facility, transportation of different types of debris between facilities, and the quantities of debris to recycle or dispose of at facilities or landfills. In general, these decisions are made and documented by local communities and carried out using both local resources and possibly local or larger-scale contractors. Hence, it is of utmost importance that any quantitative decision support be provided in a user-friendly way, eliminating the need for the users to be familiar with mathematical optimization models and the solution procedures involved. This motivates the development of a decision-support tool, such as the one presented in this paper, which serves as a user interface during these activities.

As is the case with most problems in disaster logistics, the existence of multiple stakeholders (e.g., local governments, aid agencies, contractors, etc.) during the debris removal stage involves multiple objectives to take into account. For example, local governments may want to complete the debris removal as quickly as possible to minimize negative effects on the local community. Private contractors, on the other hand, may prioritize a cost-efficient process over other objectives, while environmental agencies may push for minimizing the effect on the environment and/or maximizing the amount of debris that is recycled. The aforementioned decisions impose a number of trade-offs to be resolved for these objectives. As an example, the decision of whether to separate part of the recyclable material in the disaster area (as opposed to separating later in the processing facility) may increase the duration of the operations, but may provide a better opportunity for increasing the amount of debris recycled. Similarly, incineration to reduce the amount of debris may speed up the disposal process, but may have adverse effects on the environment. Considering these multiple objectives and the inherent trade-offs, we aim to provide the users a way to visualize and resolve these trade-offs using our model and decision-support tool.

Debris management falls into the area of humanitarian logistics; for which comprehensive reviews are presented by Altay and Green [2], Apte [3], and Çelik et al. [6]. The literature on disaster debris management mostly focuses on the documentation of past experiences and their qualitative analysis. The United Nations Environment Program documents the Japanese experience after the earthquake and tsunami in 2011 [21]. Brandon et al. [4] make a retrospective analysis of the debris removal efforts by the US Army Corps of Engineers [22], and Moe [19] analyzes policies and political aspects of the debris removal process after Hurricane Katrina. Karunasena et al. [17] present a case study based on post-disaster waste management practices in Sri Lanka.

There are debris management guidelines prepared by institutions such as FEMA [7] and EPA [9], providing general operational recommendations. Many local communities have developed debris management plans in line with these recommendations. A comprehensive review article by Brown et al. [5] presents previous experiences and guidelines on planning, waste composition and treatment, social aspects, and environmental consequences. Other important qualitative studies summarizing several aspects of disaster debris management include Reinhart and McCleanor [20], McEntire [18], and Ekici et al. [8]. Despite the abundance of guidelines, there is lack of quantitative guidance on how to carry out the debris removal activities, which we aim to address in this paper.

In terms of analytical work, Fetter and Rakes [13] present a model that addresses the decisions on location of processing sites, process availability, and assignment of debris from different regions to sites and processes. Hu and Sheu [16] model the debris flow as a linear program, assuming given processing sites and capacities. Their study emphasizes the transportation, recycling and storage of debris throughout the disaster recovery stage, and highlights the psychological costs involved for the affected population. The decisions addressed in our work are similar to those in Fetter and Rakes [13], namely, the location of processing sites, the selection of processes to make available at each site, and debris flow. 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 [16], we also consider the temporal aspects of the problem, but with a different emphasis. Hu and Sheu [16] model processing capacities as constant and fixed, focusing on the details of the debris flow. 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.
The main contributions of this paper are two-fold: (i) we present a mathematical model for debris removal that aims to extensively capture the decisions and multitude of objectives in the problem in the recovery stage, and (ii) we develop a user-friendly decision-support tool that, given the inputs of the disaster scenario, automates the optimization process, provides the results to the user in a visual way, and aids in presenting and resolving the trade-offs among the objectives.

The remainder of this paper is organized as follows. Section 2 discusses the mathematical model addressing debris removal decisions. In Section 3, we describe the decision-support tool. Finally, we summarize our contributions and point to possible future research directions in Section 4.

2. Modelling approach

We develop a mathematical model to aid in decision-making for managing debris collection and disposal operations. In this section, we present an outline of our modeling approach by first describing our modeling assumptions, followed by a discussion of the input parameters, main decisions, and objectives of the model.

2.1. Modeling assumptions

Our first assumptions are related to the timeline of events throughout the debris removal operations. For this purpose, we define a time horizon that starts when the disaster strikes. In order to take into account the lead time from the start of the time horizon until a batch of respective processes can be made available, we define different time periods, during which debris can go through several different procedures. See Figure 2. The time period indexed by \( b = 0 \) starts at time 0, and in this time period only collection can occur. Then, time period indexed by \( b = 1 \) starts at time \( T_1 \), which corresponds to the time in which a first batch of processing capacities become available, which can be applied in this time period, and collection is also allowed to continue if required. Then, time period indexed by \( b = 2 \) starts at time \( T_2 \), which corresponds to the time in which a second batch of processing capacities become available, which can be applied in this time period, as well as those capacities made available before, and collection is also allowed to continue if needed. This goes on with as many time periods as required.

In processing time periods (\( b \geq 1 \)), debris collected from each area can either go through processes (e.g., separation, crushing, grinding, etc.), disposed of at a landfill, or recycled. Multiple processing steps can be applied within each time period on a given unit of debris, as well as disposal or recycling. For the sake of simplicity and motivated by real-life applications, we allow at most two processes to be applied on a given unit of debris, which could be performed in the same facility, or in a different processing facility. In each time period, debris units can be transported between processing phases.

Accounting for every single debris source in the disaster area (road segments, residential, commercial, and industrial blocks) is not only practically intractable for our model, but it also generally results in inaccurate debris estimates. Consequently, we combine these sources into multiple debris zones and treat each zone as an aggregate debris source. The debris amounts and compositions in each zone are assumed to be known (such estimations can be obtained using software such as Hazus by FEMA [12] in the US.

We also assume that the potential locations for processing sites are determined prior to the disaster. As also reflected by Figure 1, potential debris processing site locations are determined prior to the disaster and have to be listed in the local debris management plans.
2.2. Inputs, decisions, and objectives of the model

The mathematical model we propose in this paper is presented formally and explained in detail in Appendix A. Here, we discuss the main inputs, decisions, and objectives of the model, which are summarized in Figure 3.

As stated before, the amounts and compositions of debris in each zone as well as potential debris processing site locations constitute 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. As an 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. Similar rates apply for recycling, which is an available operation only for certain types of debris. The available processes for each debris type and conversion rates are among the model inputs.

Another input of the model is the 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.

In addition to the set of potential locations, the model also takes potential sets of processes for each potential facility as inputs. Each process requires a discrete set of potential capacity levels and space corresponding to each capacity level. For example, the concrete crushing process may be installed at capacity levels 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. In addition, installing a process at a given capacity level may incur a setup time during which the respective process cannot be used. For instance, installing concrete crushing at a capacity level of 500 tons/day may require a setup time of one month (for our case study, these capacity and space requirements are adapted from Alibaba Group [1]).

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

The main decisions considered are:
- Which potential processing sites to open,
• Which processes to employ at each opened processing site,
• What capacity to use for the processes selected to be employed at each opened processing site,
• Collection methods to use at each debris zone,
• Which processes debris will go through,
• Whether to dispose of/recycle each type of processed debris at each opened processing site.

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 either be incorporated into the objective function with different weights/priorities, or can be included among the constraints by assigning a maximum/minimum bound. It can then be solved multiple times by varying the weights and bounds until a desired solution is obtained (e.g., increasing the total time allowed for disposal to reduce the desired level of landfill utilization).

The resulting solution from the model has to adhere to the following set of main constraints:
• All debris must be collected from the debris zones and all collected debris must be ultimately either disposed of or recycled,
• Processes can be employed only at opened processing sites and after a certain lead time for installing the selected processing capacities,
• The number of opened processing sites cannot exceed a predetermined limit,
• Space capacities at opened processing sites cannot be exceeded.

For our case study instances, which are omitted from this conference paper due to space limits, the decision-support tool described in the next Section can find a close-to-optimal solution of the model within a few minutes using open-source optimization software.

3. The decision-support tool

There are two important challenges in implementing the mathematical model in the preceding section: (i) the users of the model (e.g., local communities, private contractors) are generally not familiar with how the model should be implemented, and (ii) the results of the model should be made as visually understandable as possible and the model may need to be re-run under different settings (for example, different disaster scenarios or objectives). To overcome these two challenges, a user-friendly decision-support tool is helpful. For this end, the optimization model described in the previous section and Appendix A is embedded into a user friendly 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 employs the open source optimization package GLPK [14] to solve the model, which eliminates the need for proprietary optimization software, not generally available for the potential users of our model. Google Maps Image APIs [15] are used to display maps for visualizing the inputs and solutions.

The tool contains four groups of worksheets: (i) “Control panels”, where different procedures such as generating the input files, creating and solving the model, and displaying the outputs can be executed, (ii) spreadsheets for inputting data, (iii) tables for model outputs, and (iv) maps where some of these outputs can be visualized. Details of the tool are provided in Appendix B. The most up to date version of the tool and its documentation can be downloaded from DOT [7].

The tool can be used both in preparedness and post-disaster stages of the disaster life cycle, and under different disaster types, such as earthquakes, hurricanes, and floods, for which debris amounts can be estimated using analytical models or available software such as Hazus in the US [12].

In the preparedness stage, when deciding on the location or size of a landfill or processing site, the tool can be run for several potential disaster scenarios to evaluate a set of alternatives, including what-if analysis for understanding (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. Recently, FEMA [11] has documented Emergency Support Functions, which provide a structure for coordinating federal support for incidents. Debris removal falls into the categories of transportation and search-and-rescue. By providing what-if
analysis under various scenarios, the tool could also be useful for federal agencies such as FEMA to provide coordination among the stakeholders of debris removal operations.

Another important use of the tool is in the post-disaster stage, where it can aid disaster responders and solid waste officials in making various decisions discussed in Section 2. The tool can also be useful for contractors or entities responsible for the debris management of large affected areas, in particular with decisions related to the transportation of debris to processing centers and/or landfills.

4. Conclusions

We have considered the debris removal problem, one of the most complicated, time consuming, and costliest activities in the response and recovery stages of a disaster. Based on a review of the relevant literature, we have observed that the studies on post-disaster debris management mostly focus 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 selection of processing site, processing capacities, and debris flow decisions incorporating collection, transportation and disposal, with the goal of balancing cost and duration of the debris removal operations.

While some attention has been given to modeling to address disaster response decisions, the lack of available user-friendly tools that incorporate these models for decision aid creates a significant gap between theory and practice. We have developed an Excel-based decision-support tool that runs our proposed model based on user inputs and presents the results in a visual way. To solve the model, the tool uses open source optimization software, avoiding the need for expensive commercial solvers. The decision-support tool can be used by local disaster management authorities to conduct what-if analysis in the preparedness stage and as an operational tool in the recovery stage.

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 complicated context, the tool developed enables understanding the consequences and trade-offs at stake when selecting operational and preparedness strategies.

To increase the usability of the tool, we are in contact with local communities and contractors in Georgia and Florida. Possible improvements of the tool include automation of the data input process and enhancements in the visualization of the output.

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

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Appendix A. Mathematical formulation of the problem

Indices

- $b$: time period
- $i, i'$: debris type
- $j, j'$: locations of debris zones, potential processing sites, landfills
- $k$: process
- $l$: processing capacity level
- $q$: collection method
- $p$: processing phase
Sets

- \{1, ..., B\}: set of time periods
- \{C, ..., T\}: set of debris types that must be collected before transporting
- \{R, ..., T\}: set of debris types that have been collected and can be transported
- \{NR\}: set of debris types that cannot be sold, \{NR\} \subset \{T\}
- \mathbf{I} = \{C, \ldots, T\} \cup \{R, \ldots, T\}: set of debris types
- \mathcal{J}^D: set of locations where debris is originally located
- \mathcal{J}^P: set of locations where processing sites can be located or landfills are located
- \mathcal{J} = \{D, \ldots, P\}: set of locations
- \mathcal{K}: set of processes, \(k = 1\) represents no processing (or “only storage”)
- \mathcal{L}: set of processing capacity levels
- \mathcal{Q}: set of collection methods
- \{1, ..., P\}: set of phases that determine the order in which processes are applied

Parameters

- \(a_i\): density of debris type \(i\) (ton per cy).
- \(\text{ApplicableProcess}(i, k, p)\): 1 if process \(k\) is applicable for debris type \(i\) at phase \(p\)
- \(\hat{b}_l\): time period on which process \(k\) at capacity level \(l\) is made available
- \(d_j^\text{disposat}\): total disposal capacity at location \(j\) (cy)
- \(c_{\text{site}}\): fixed cost of opening (and later closing) a processing site at location \(j \in \mathcal{P}\)
- \(c_{\text{fixedProcess}}\): fixed cost of making process \(k\) available at location \(j \in \mathcal{P}\) at capacity level \(l\) ($)
- \(c_{\text{collection}}\): cost of collecting debris type \(i\) at location \(j \in \mathcal{J}^D\) with collection method \(q\) ($ per ton)
- \(c_{\text{transport}}\): cost of transporting debris type \(i\) from location \(j\) to location \(j'\) ($ per ton)
- \(c_{\text{process}}\): cost of processing debris type \(i\) with process \(k\) ($ per ton)
- \(c_{\text{disposat}}\): cost of disposing debris type \(i\) at location \(j\) ($ per ton)
- \(c_{\text{transportEnv}}\): environmental cost of transporting debris type \(i\) from location \(j\) to location \(j'\) ($ per ton)
- \(c_{\text{processEnv}}\): environmental cost of processing debris type \(i\) with process \(k\) ($ per ton)
- \(c_{\text{disposEnv}}\): environmental cost of disposing debris type \(i\) at location \(j\) ($ per ton)
- \(K_{\text{site}}\): spatial capacity available at processing site at location \(j\) if opened (sq ft)
- \(K_{\text{Process}}\): spatial capacity used by process \(k\) when making it available at capacity level \(l\) (sq ft)
- \(m_{ij}\): initial volume of debris type \(i\) at location \(j\) (ton)
- \(M^\theta\): upper bound for criteria \(\theta\) (\(\theta \in \{FC, CT, DT, DL, EC\}\), FC: financial costs ($), \(CT\): collection duration (days), \(DT\): disposal time (days), \(DL\): space used in landfills by disposed debris (cy), \(EC\): environmental costs ($))
- \(m_{DR}\): lower bound for the revenue obtained from recycled/reused debris ($)
- \(r_{ij}\): revenue from selling debris type \(i\) at location \(j\) ($ per ton)
- \(\text{TotalInitialDebris}\): the sum of \(m_{ij}\) for all \(i, j\)
- \(T_b\): duration from the beginning of the horizon until the start of time period \(b\) (days)
- \(X, Y\): minimum and maximum number of processing sites that can be installed
- \(y_{k, K}\): minimum and maximum number of sites where process \(k\) can be installed
- \(\gamma_{vik}\): proportion of debris type \(i\) obtained when applying process \(k\) to debris type \(i'\)
• \( y_{ij}^{c} \): proportion of debris type \( i \) obtained when collecting debris type \( i' \) with collection method \( q \)
• \( \tau_{ij}^{\text{collection}} \): time taken when collecting debris type \( i \in I^{c} \) at location \( j \in J^{p} \) with collection method \( q \) (days per ton)
• \( \tau_{ij}^{\text{transport}} \): time taken when transporting debris type \( i \in I^{t} \) from location \( j \) to location \( j' \) (days per ton)
• \( \tau_{ijkl}^{\text{process}} \): time taken when processing debris type \( i \) with process \( k \) for capacity level \( l \) (days per ton)
• \( \rho^{\theta} \): weight of criteria \( \theta \) in the objective function. (\( m \in \{ FC, CT, DT, DL, EC, DR \} \), \( FC \): financial costs, \( CT \): collection duration, \( DT \): disposal time, \( DL \): space used in landfills by disposed debris, \( EC \): environmental costs, \( DR \): revenue obtained from sold debris.)

**Decision variables**

• \( x_{j} \): binary variable that takes the value 1 if a processing site is opened at location \( j \in J^{p} \) and 0 if not
• \( y_{ijkl} \): binary variable that takes the value 1 if process \( k \) is made available at location \( j \in J^{p} \) with processing capacity \( l \) and 0 if not
• \( \varphi_{ij} \): amount of debris type \( i \in I^{c} \) at location \( j \in J^{p} \) collected with method \( q \) (ton)
• \( \theta_{ij}^{0} \): amount of debris type \( i \in I^{t} \) transported from location \( j \in J^{p} \) to location \( j' \in J^{p} \) right after collection (ton)
• \( \theta_{ijb} \): amount of debris type \( i \in I^{t} \) transported from location \( j \in J^{p} \) to location \( j' \in J^{p} \) in time period \( b \) and processing phase \( p \) (ton)
• \( \pi_{ijklb} \): amount of debris type \( i \in I^{t} \) processed at location \( j \in J^{p} \) with process \( k \) under capacity level \( l \), in time period \( b \) and processing phase \( p \) (ton)
• \( \lambda_{ij} \): amount of debris type \( i \in I^{t} \) sold at location \( j \in J^{p} \) (ton)
• \( \mu_{ij} \): amount of debris type \( i \in I^{t} \) disposed at location \( j \in J^{p} \) (ton)

**Auxiliary variables**

• FinancialCost: represents financial costs ($)  
• CollectionTime: represents the duration of the collection phase (days)  
• DisposalTime: represents an approximation of the time until all debris has been disposed (days)  
• DebrisLandfilled: represents the amount of space used in landfills by disposed debris (cy)  
• EnvironmentalCost: represents total penalty costs for activities with environmental impact ($)  
• DebrisRevenue: represents the revenue obtained from sold debris ($)  

Based on the above notation we formulate the post-disaster debris management problem as stated below.

Minimize \( \rho^{FC} \text{ FinancialCost} + \rho^{CT} \text{ CollectionTime} + \rho^{DT} \text{ DisposalTime} \)

\( + \rho^{DL} \text{ DebrisLandfilled} + \rho^{EC} \text{ EnvironmentalCost} - \rho^{DR} \text{ DebrisRevenue} \)

Subject to

\[
\text{FinancialCost} = \sum_{j \in J^{p}} c_{j}^{\text{site}} x_{j} + \sum_{j \in J^{p}} \sum_{k \in K} \sum_{l \in L} c_{ijkl}^{\text{FixedProcess}} y_{ijkl}
\]
\[ \text{CollectionTime} = \sum_{i \in I} \sum_{j \in p} c_{ij} \sum_{q \in Q} \phi_{ijq} + \sum_{i \in I} \sum_{j \in p} c_{ij} \sum_{j' \in j} \Theta_{ijj'}^{\text{transport}} + \sum_{i \in I} \sum_{j \in p} \sum_{k \in K} \sum_{l \in L} \sum_{p \in P} \pi_{ijklp} \mu_{ij} \]

\[ \text{DisposalTime} \geq T_b \gamma_{klt} + \sum_{i \in I} \sum_{j \in p} \sum_{l \in L} \gamma_{jlt} \pi_{ijklp} \quad \forall j \in j^p, k \in K, l \in L, b \in \{b_{klt}, \ldots, B\} \]

\[ \text{DisposalTime} \geq \sum_{i \in I} \sum_{j \in p} \sum_{q \in Q} \phi_{ijq} + \sum_{i \in I} \sum_{j \in p} \sum_{j' \in j} \Theta_{ijj'}^{\text{transport}} \pi_{ijklbp} \]

\[ \text{DebrisLandfilled} = \sum_{i \in I} \sum_{j \in p} \mu_{ij} / a_t \]

\[ \text{EnvironmentalCost} = \sum_{i \in I} \sum_{j \in p} \sum_{j' \in j} \phi_{ijj'} \Theta_{ijj'}^{\text{transportEnv}} + \sum_{i \in I} \sum_{j \in p} \sum_{j' \in j} \sum_{j'' \in j'} \Theta_{ijj''}^{\text{transportEnv}} \pi_{ijklbp} \]

\[ \text{DebrisRevenue} = \sum_{i \in I} \sum_{j \in p} \pi_{ijj}^p \eta_{ijj} \]

\[ \bar{x} \leq \sum_{j \in j^p} x_j \leq \bar{x} \]

\[ \bar{y}_k \leq \sum_{j \in j^p} \sum_{l \in L} y_{jlt} \leq \bar{y}_k^p \quad \forall k \in K \]

\[ \sum_{l \in L} y_{jlt} \leq x_j \quad \forall j \in j^p, k \in K - \{1\} \]

\[ \sum_{k \in K} \sum_{l \in L} \sum_{p \in P} \pi_{ijklp} \eta_{ijklp} \leq K_{ij} \leq K_{ij}^p \]

\[ \pi_{ijklbp} \leq \text{ApplicableProcess}(i, k, p) \cdot \text{TotalInitialDebris} \cdot y_{jlt} \]

\[ \forall b \in \{1, \ldots, B\}, i \in I^T, j \in j^p, k \in K, l \in L, p \in \{1, \ldots, P\} \]

\[ \pi_{ijklbp} = 0 \quad \forall b \in \{1, \ldots, B\}, i \in I^T, j \in j^p, k \in K, l \in L, p \in \{1, \ldots, P\}; b_{klt} > b \]

\[ \sum_{i \in I^T} \sum_{j \in j^p} \sum_{l \in L} \pi_{ijklbp} \leq T_{b+1} - T_b \quad \forall b \in \{1, \ldots, B - 1\}, j \in j^p, k \in K, l \in L \]

\[ \lambda_{ij} \leq \text{TotalInitialDebris} \cdot x_j \quad \forall i \in I^T, j \in j^p \]
The objective of the problem is to minimize a weighted sum of financial costs, collection time, approximated disposal time, debris landfilled, penalty costs for activities with environmental impact, and revenue from recycled debris. (1)-(7) define these objectives. In particular, (3) states that disposal time must be lower bounded by the time taken by each process made available, determined as the starting time of the last time period in which it is used, plus the processing duration within that time period. (8) enforces boundaries for the number of processing sites to make available. (9) enforces boundaries for the number of sites where each process can be made available. (10) states 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. (11) enforces the spatial capacities of opened sites. (12) ensures that processes are applied in their corresponding phases according to the order in which they are applied (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. (13) states that processing in any time period can only occur if the process was made available before the start of the time period. (14) limits the amount processed in each time period according to its duration. (15) states that debris can only be sold at opened processing sites. (16) enforces landfill capacities. (17) ensures that all debris is collected. (18) and (19) state that all collected debris is transported to processing sites or landfills. (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. (22) determines debris flow balance between time period, so that all debris transported at the last phase of each time period is processed in phase 1 of the next time period. (23) ensures that all debris transported in the last phase of the last time period is either sold or disposed. (24) states that debris types that cannot be sold are not sold. (25) enforces bounds for the objectives. (26)-(27) enforce the binary or nonnegative nature of the variables, respectively.
Some observations on the formulation follow. Collection time parameters ($t_{ij}^{collection}$) can be calculated as the inverse of the total debris removal rate available (in metric tons per day), where this rate can be calculated as the number of work teams multiplied by the debris removal rate of each work team. Transportation time parameters ($t_{ij}^{Transport}$) can be calculated as the time (in days) of transportation between the respective locations divided by the total transportation capacity available (in metric tons), where this last capacity can be calculated as the number of work teams multiplied by the transportation capacity of each work team. Disposal time is approximated as the maximum of processing time at each opened site, and collection time plus post-collection transportation time, assuming that the same resources used for collection are used for site-to-site transportation.

Appendix B. Additional description of the decision-support tool

As the first step, the user inputs data in the respective worksheets. Next, the optimization process is carried out through macros to solve the model, and write the outputs into corresponding worksheets. By repeating this process with different parameters for the problem, the trade-offs between various objectives (for example, between net costs and disposal time) can be analyzed. Further, different disaster scenarios can be studied using different copies of the Excel file where the tool has been implemented. The application of the tool is depicted in Figure B1.

Figures B2-B4 present screenshots of the tool. Figure B2 presents the tool’s main control panel. Figure B3 shows the worksheet where the data input steps are outlined and some support buttons that are available for this purpose. Figure B4 shows the worksheet where debris type characteristics are inputted. In this worksheet, each row represents a different debris type, where parameters such as density and disposal costs are specified. All other inputs (locations, processes, etc.), are inputted using analogous worksheets. After all data inputs are present, the model can be run using a button in the worksheet shown in Figure B2.

Figure B1. Flow chart depicting the application of the tool

Figure B2. Screenshot of main worksheet in the tool
Figure B3. Screenshot of the “DataCenter” worksheet

Figure B4. Screenshot of the worksheet where debris types are specified
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