Evaluating the Impact of Equipment Selection on Debris Removal and Dependent Lifeline Infrastructure Recovery

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ABSTRACT

Debris removal is a critical activity in the aftermath of natural disasters such as earthquakes and tsunamis to enable community and lifeline network recovery. This activity is hampered by logistical bottlenecks including the non-availability of equipment and inadequate capacity of temporary debris management sites (TDMS). This paper enables analysis of debris removal and lifeline repair operations quantifying recovery times for informed decision-making about equipment allocation and TDMS selection before the disaster. The developed framework was applied to the case study of a Cascadia Subduction Zone event for the coastal town of Astoria in Oregon. The proposed framework enables decision-makers with an objective means of evaluating decision alternatives both before and after disasters to analyze and improve their community's capability of handling disaster debris. Furthermore, this framework will serve as a platform upon which interdependencies between transportation network and debris removal operations will be analyzed in the future.

INTRODUCTION

The treatment of the debris generated after a disaster is performed in two phases – debris clearance in the short term to provide access to critical facilities and for search and rescue efforts; and debris removal from affected communities in the long term, to enable rebuilding and recovery. Brown et al. (2011) notes that disaster-generated debris typically exceeds 15 times the *annual* solid waste generated in a community and can thus overwhelm local waste management agencies. Indeed, estimates of debris generated after the 2011 Tohoku earthquake and tsunami in Japan resulted in a 100 years' worth of debris generated for the prefecture of Sendai (Ford 2011). Furthermore, FEMA (2007) determined that up to 27% of disaster recovery costs are spent on debris operations. Finally, it must be noted that debris can clog up transportation networks and thus block access to affected areas after a disaster, thus slowing down recovery and repair operations. Therefore, it is imperative to consider the debris clearance and removal operations when considering recovery and resilience of communities after disasters. Slow debris removal can contribute to social inequality and unrest as observed after Hurricane Katrina (Yepsen 2008), and can also lead to illegal dumping that adds to the problem of cleaning up (Jackson 2008) and the uncleared debris can serve as a psychological reminder of the disaster (Brown and Milke

2009). Finally, uncleared debris can cause public health and environmental concerns by causing stagnant water pools that create vector breeding grounds (Watson et al. 2007) and by leeching hazardous waste into environmentally sensitive areas (Brown and Milke 2009).

The presence of debris can also affect the functioning of other infrastructure systems such as transportation and water networks and thus create interdependencies between debris, lifeline systems, and recovery operations. For example, roadways will need to be cleared of debris to ensure access for first responders in the short term, as well as to ensure the thoroughfare of trucks and construction equipment in the longer term for debris removal. These statements emphasize the importance and need to plan for disaster debris

Despite the critical importance of debris removal operations, emergency managers lack a set of tools that provide holistic measures for analyzing debris clearance operations. This research therefore seeks to provide such a tool to link decision variables with operation productivity, which will enable emergency managers to make informed decisions regarding pre-disaster staging of equipment and temporary debris management site (TDMS) selection in order to meet their resilience targets.

The framework presented in this paper is demonstrated for the city of Astoria in Oregon, which is vulnerable to a near-field tsunami caused by a Cascadia Subduction Zone (CSZ) earthquake. The CSZ is a 600-mile fault that runs from northern California in the United States up to British Columbia in Canada, as shown in Figure 1. Emergency management agencies in Oregon are currently preparing for a 9 magnitude CSZ event that could cause widespread losses to in terms of society, economy, and infrastructure, among many other sectors for affect communities. Such an event would generate approximately 10 million tons of debris in Oregon, (OSSPAC 2013), roughly 13 times larger than the *annual* solid waste generated by the entire state. Thus, the developed analysis framework is applied to a case study of the CSZ event for the city of Astoria.

Figure 1. Location of Astoria and the Cascadia Subduction Zone.

LITERATURE REVIEW

While federal, state, and local emergency management agencies do have post-disaster debris management plans, these are usually in the form of generalized procedural guidelines that do not provide quantifiable methods for decision making (Derrible et al. 2019). Therefore, researchers have attempted to provide mathematical and optimization models to select decision-alternatives that result typically in lowest time or cost of removal operations. For example, Kim et al. (2014) and Habib and Sarkar (2017) used analytical tools (simulation and analytical network process-based, respectively) to identify and select temporary debris management sites (TDMS) by considering factors such as time, cost, and availability of resources without consideration of the social or environmental impacts. Fetter and Rakes (2011) and Lorca et al. (2015) considered the additional aspect of sustainable material recycling and other environmental effects, respectively, to provide a more holistic TDMS location identification methodology for disaster debris. Hu and Sheu (2013) considered the conflicting aspects of operation logistics, environmental protection, and psychological cost of waiting time for debris removal, which does broaden the consideration of operations impact. However, the limitation with this method is in the lack of consideration of the diversity of affected population and lack of community engagement efforts to identify inequities in residents' adaptive capacity to respond to debris accumulation and its impacts.

Previous approaches to forecast, predict, and quantify the effect of various debris removal plans are limited to identifying solutions for the most efficient operation and some consideration of its environmental effects, but typically make several assumptions regarding the operations that are performed by not considering available resources and spatial and equipment availability constraints. This framework addresses this issue by utilizing geospatial analysis to obtain realistic locations for TDMS based on local constraints. Furthermore, the interdependencies between resources and their availability is modeled explicitly for various types of debris disposal strategies using discrete event simulation. The simulation-based approach proposed herein will thus provide stakeholders with a realistic view of how the debris removal operations would be conducted for their communities. In this project, simulations will virtually recreate the real-world operations to enable experimentation and thus obtain insights about logistics involved by quantifying performance metrics such as time and cost.

METHODOLOGY

The methodology used in this research involves the development of a framework that enables the analysis and optimization of the debris removal operation. The framework utilizes HAZUS-MH for debris estimation, ArcGIS for identifying feasible TDMS, and jStrobe for discrete event simulation. Figure 2 represents an overview of the research framework.

As shown in Figure 2, the primary steps in the proposed methodology are contained in the dashed boxes and include (1) obtaining debris quantity and spread using HAZUS, (2) obtaining potential TDMS locations using GIS, and (3) using DES to obtain performance measures for recovery operations. The red arrows represent the data flow between the debris quantity, road network, and discrete event simulation represents future work that will be built upon the current framework to analyze interdependencies between debris spread and road network, and its effect on recovery time. The results of applying this methodology to Astoria for a 9.0 magnitude near-field Cascadia event is provided along with the description of the methodological steps for illustrative purposes.

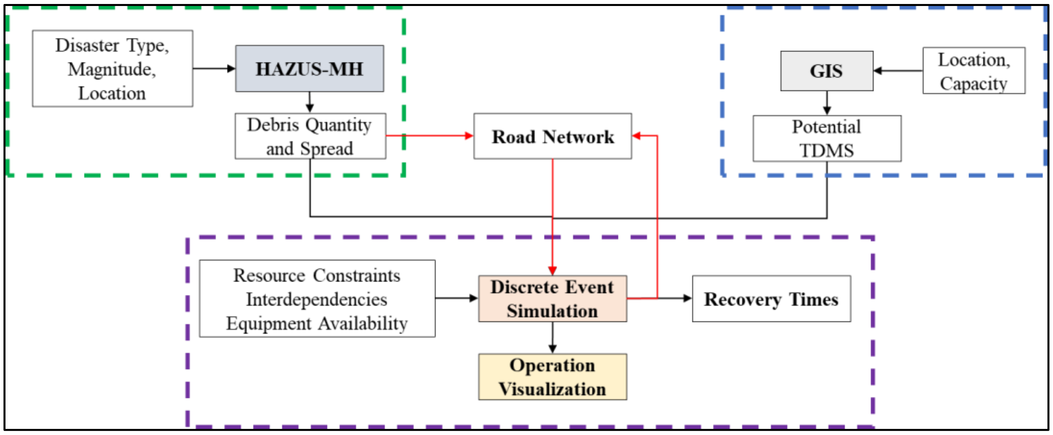

Figure 2. Data flow for creating simulation models.

Estimating Debris Spread. The HAZUS-MH software, developed by FEMA, is used to estimate the potential losses caused by various natural disasters such as earthquakes, tsunami, floods, and hurricanes. Potential loss metrics include physical damage, economic loss, and social impacts. Physical damage includes damages caused to buildings, essential facilities, and infrastructure. Economic loss consists of lost employment, business interruptions, repair, and the cost of rebuilding. Social impacts include the estimation of displaced household and shelter requirements (FEMA, 2018). A critical estimate that is used in this research is the debris generated, which is included in the physical damage. The user first selects a study region, which could be a census tract, state, or country, along with specification of the disaster type. The user also enters information to further describe the hazard scenario, which for an earthquake/ tsunami, includes epicenter location, fault depth, and earthquake magnitude. The results are provided in terms of quantity (in tons) and spread of debris. Figure 3 shows the spread of debris generated for Astoria.

Figure 3. Debris spread for Astoria.

Identify Suitable TDMS Locations. FEMA (2008) and EPA (2007) provide guidelines for the selection of TDMS sites including the following: preference for public over private lands; consideration of parks, fields, and vacant lots; sufficient capacity and accessibility for heavy vehicles; located away from schools , hospitals, and environmentally sensitive areas. The model builder feature of ArcGIS was used to create a buffer zone around the sensitive area mentioned previously and highlight a list of potential candidates for TDMS sites. An example of such a buffering for Astoria is shown in the Case Study section. Local emergency managers could then select a suitable TDMS from among the areas that are not constrained. Figure 4 shows the results of performing a geospatial analysis to identify preferable areas for locating TDMS. The green circles represent feasible locations while the black and red circles represent TDMS sites that are located in sensitive areas.

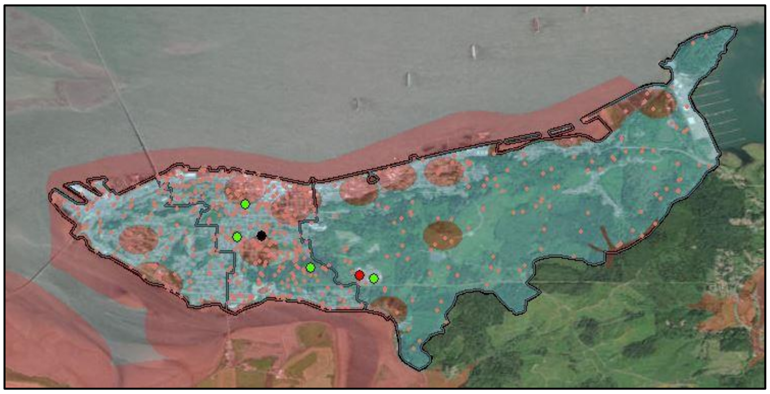

Figure 4. Potential TDMS locations for Astoria.

Obtain Performance Measures of Operation. The performance measure of interest for the debris removal operation will be estimated using discrete event simulation (DES). DES is a method where a real-world process is modeled as a series of discrete activities and is particularly suitable for operations that have significant uncertainty in their activity durations and materials involved, complex activity startup conditions, and resource interdependencies (Martinez 2010). Thus, the uncertain nature of post-disaster scenarios coupled with the need for planning operations that need to consider local spatial and resource constraints and interdependencies make DES ideal for modeling post-disaster debris operations. DES has been previously used to analyze heavy equipment operations such as asphalt paving (Mostafavi et al. 2012; Louis 2010), earthmoving (Shitole et al. 2019, Louis and Dunston 2018), and offsite building construction (Abiri et al. 2019). We will analyze debris operations using the jStrobe simulation software developed by the (Louis and Dunston 2016) based on the STROBOSCOPE simulation language (Martinez 1996). DES models are developed for the activities that occur on a temporary debris management site, which is provided in the layout by FEMA. From the model, insights regarding the logistics, time, cost, and resources of the process can be determined, which can be used to optimize the debris removal operation. Figure 5 shows a portion of the DES model for removing, sorting, and disposing of vegetative debris from the site in Astoria. The details of modeling elements that are not visible in the figure can be ignored for this discussion. The circles in the model represent queues where resources wait while idle, and the rectangles represent activities that can be performed when the required resources become available. Thus, the operation model takes into account equipment availability, resource constraints, and interdependency between them in calculating the time required to complete the debris removal operation. Furthermore, information from HAZUS and the TDMS locations will affect the duration of the entire operation as they will determine the amount of debris to be moved, and the travel duration for moving the truckloads of debris, respectively.

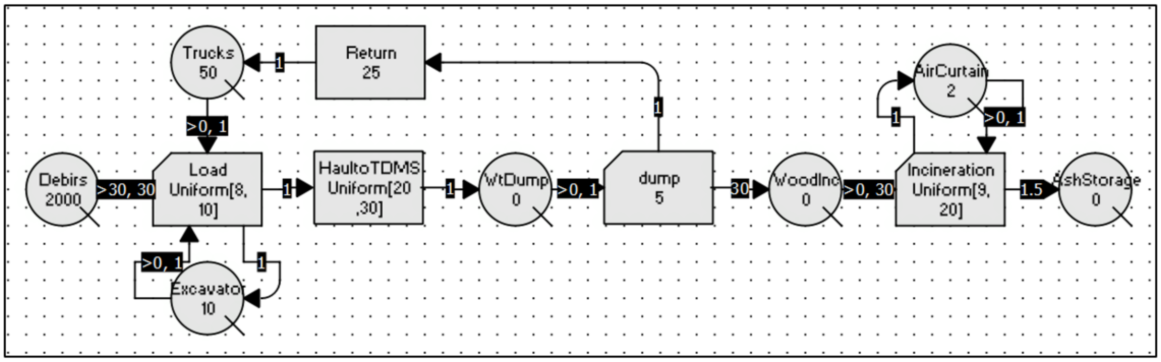

Figure 5. DES model for vegetative debris.

Analyzing Interdependencies Between Road Network and Debris Spread on Recovery Time. One aspect of the methodology that is not completed yet, but planned for in the future, is to expand the GIS analysis capabilities to provide the DES model with updated travel times based on the presence of debris on the roadway network. This can block off certain sections of roadway and thus increase travel times and thereby reduce recovery times. Future work will include the consideration of traffic volumes upon the travel times of truck trips to transport debris from roadways to TDMS locations and thereby capture their effect on recovery times.

PRELIMINARY RESULTS

The proposed framework was used to simulate multiple disaster scenarios for Astoria and sensitivity analysis was performed by varying the amount of equipment available for different disaster scenarios. The objective for decision making here is to determine the bottlenecks in the operation based on the equipment available. In Figures 6 and 7, the various equipment used for removing vegetative debris are indicated as follows: 'E' represents excavators, 'T' represents trucks and 'R' represents recycling equipment.

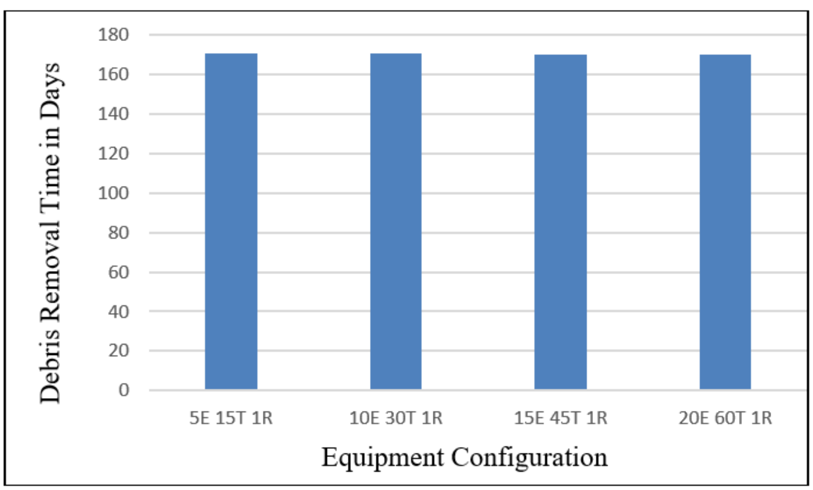

Figure 6. Recovery times with increasing truck-excavator fleets, but only 1 recycling equipment.

In Figure 6, when the number of trucks and excavators are increased, there is no decrease in operations time, thereby indicating the recycling equipment is the bottleneck of the operation. Thus, the model created can enable decisionmakers to determine effect of changing equipment configurations and their effect on recovery time. In Figure 7, there is a corresponding increasing in recycling equipment and there is a considerable difference in recovery times now.

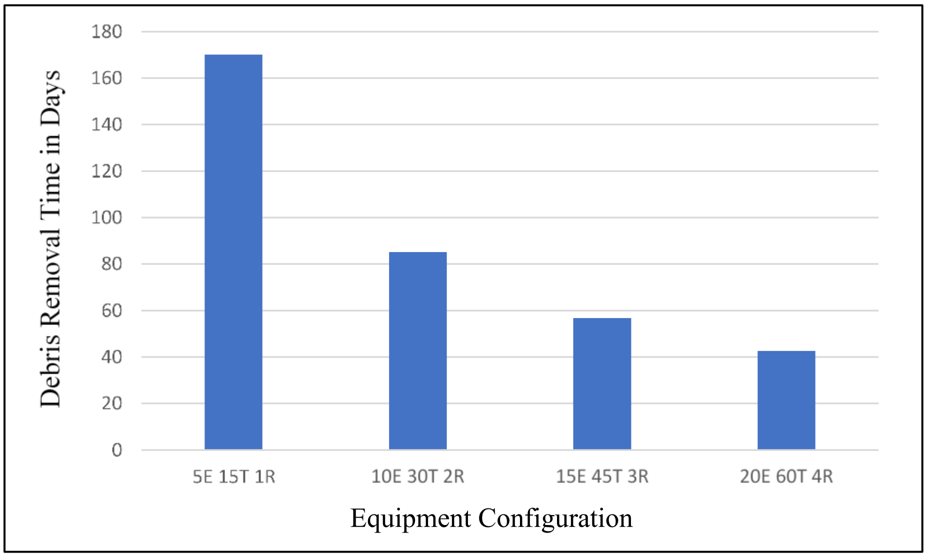

Figure 7. Recovery times with increasing truck-excavator fleets, but only corresponding increase in recycling equipment.

The presented example showcases some of the operational analysis capabilities that can be applied for debris clearance operations in terms of equipment interdependencies and bottlenecks.

CONCLUSIONS

This paper presents a novel methodology for debris operations analysis by integrating HAZUS-MH for debris estimation, ArcGIS for finding the feasible areas for locating a temporary debris management site, and jStrobe for developing discrete event simulation models of the debris removal process. This framework is meant to serve as a platform for further analysis of interdependencies between debris, roadway networks, and clearance operations in the future.

Towards this end, a case study approach using the city of Astoria in Oregon was selected and analysis. Debris was first estimated in the event of a Cascadia Subduction earthquake using HAZUS. Next, geospatial analysis was performed using ArcGIS by utilizing model builder to automate the process of finding feasible areas for TDMS in Astoria. Further, the duration required to travel between a TDMS and the debris pickup point and also the duration required to travel between a TDMS and final disposal site is calculated. The debris capacity of the TDMS are also determined. Finally, a DES model of the of the debris removal operation to identify bottlenecks in the process along with quantifying the debris removal time. This objective is achieved by developing models for construction and demolition debris and vegetative debris using jStrobe. The bottlenecks in the process of debris removal are identified. Along with this, the equipment fleet configuration required and the time required for debris removal in Astoria are determined for construction and demolition debris and vegetative debris.

The research contributes to the existing body of practice and knowledge by developing a framework that utilizes discrete event simulation to analyze the debris removal operation. Different types of debris can also considered for the analysis. The discrete event simulation helps to determine the bottlenecks in the process of debris removal and also the time required for the debris removal is obtained. Equipment configuration of trucks and excavators required for the debris removal process is additionally obtained. These models in combination with the data from government entities can help plan for the disaster debris before disaster. The effect of logistical decision variables on the debris removal identified here can be used by emergency managers to help in deciding the equipment required for the debris removal process. Different equipment configurations can be tested with the help of modeling to determine the optimum amount of resources required for the operation. The research provides a framework on how HAZUS-MH and ArcGIS can be used in the analysis process and how data obtained from these softwares can be used in the discrete event simulation models developed. While the specific example provided in this paper focused on debris removal operations, the same analysis could be applied towards other post-disaster operations such as the repair of lifeline networks.

Research Limitations and Future Work. The quantity of debris generated after the Cascadia subduction earthquake includes the debris generated due to the earthquake only. Combined effects of tsunami and earthquake are not explored in this research. The combined effects can be studied in future and also other types of debris can also be considered in the analysis. Using ArcGIS feasible areas were found based on a few constraints. Additional constraints with respect to accessibility, environmental quality check, etc. were not used in the geospatial analysis process. Further, the temporary debris management sites identified must be verified with the respective site owner and required permissions from government agencies must be obtained before considering them to be used as temporary debris management sites. Automation of the TDMS search process may be an area of future work, wherein, the geospatial analysis directly points at a potential site instead of a feasible area.

Even though the DES models developed accounts for uncertainty through the use of probabilistic durations for activity durations and by enabling probabilistic routing of resources, assumptions are made to model the process. These assumptions may be reasonable for modeling purposes but is not sufficient for practical situations. Actual data from government agencies will help in refining the assumptions.

The models developed for the specific debris must be validated by government agencies before using them in the real world. Data and input from government agencies will make the model more realistic and thus the numbers from the model can be used by emergency managers to plan for debris in their respective counties. Interdependencies between the temporary debris management site and infrastructure restoration, contracts required for debris removal operation, and recycling needs are areas where work can be done in the future. Demographic and socio-economic data could be integrated into the analysis by ensuring an equitable location of TDMS sites and ensuring that routes taken by debris removal trucks do not affect disadvantaged populations disproportionately, without unduly burdening the goals of recovery operations.

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