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An evolutionary multi-objective optimization approach to disaster waste management: A case study of Istanbul, Turkey

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ABSTRACT

Disasters can lead to a high risk of casualties and structural damages. Destructive disasters, such as earthquakes, may cause a great amount of disaster waste to be controlled. Reusing and recycling materials in the debris can decrease the need for re-construction resources. These reusable or recyclable materials can be processed in temporary storage sites like the ones suggested by the United Nations and the United States Federal Emergency Management Agency guidelines on disaster waste management. The objective of this paper is to build a framework for determining the locations of temporary storage facilities, and includes planning for the collection and transportation of disaster waste in order to manage it in an environmentally sustainable way. In this study, a multi-objective optimization model is developed and solved with an evolutionary elitist multi-objective optimization algorithm (NSGA-II). As a city prone to high earthquake damage, Istanbul has been selected for the illustration of the proposed framework. The objectives of the model are cost minimization and minimization of risk from hazardous waste exposure. The study integrates disaster loss estimation methods with post-disaster waste management.

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1. Introduction

Recycling and reuse are both very important in terms of sustainability. When the environmental and economic dimensions of sustainability are considered, recycling and reuse of waste pose a particularly major contribution as they decrease the need for raw materials and the amount of untreated waste disposal. One of the major sources of waste is a disaster and historical data shows that the frequency and the damage caused by disasters are increasing (Brown, Milke, & Seville, 2011). Waste from a disaster may include recyclable, reusable and hazardous materials. Because of the risks found in debris composition, separation and treatment of materials is a serious issue. Disaster waste can block relief efforts unless their removal is planned properly (Brown et al., 2011). Nonetheless, the composition of waste is also an opportunity in terms of environmental and economical sustainability and researchers indicate that the increasing number and intensity of natural disasters increases the necessity of efficient and low impact recovery (Brown et al., 2011). Therefore, disaster waste (DW) related studies should focus on designing environmentally sustainable DW management systems (Milke, 2011).

There are different ways to approach disaster waste management (DWM). The most common way is collecting all the debris and transporting it to dumpsites for final disposal without any treatment. However, uncontrolled disposal of waste is environmentally and economically harmful. Another way of treating waste is by transporting the collected waste to a temporary storage and recycling facility and separating the reusable, recyclable, and hazardous materials from the debris before landfill disposal. Hence, the landfill disposal of un-treated reusable, recyclable, and hazardous wastes could be minimized (Söder & Müller, 2011).

Separating hazardous materials from disaster waste is an important part of this process which must be carried out with extreme care. This statement is especially true because of asbestos and similar hazardous and harmful materials likely to be found in the composition of DW. The concept of temporary storage facilities is therefore crucial when treating these hazardous materials, so as to decrease the risk to health (Söder & Müller, 2011).

Separated materials, other than hazardous materials, can immediately become reusable for new construction which may be important for immediate reconstruction activities after a disaster, or they can be recycled for immediate or future use in reconstruction. This second approach to waste treatment is obviously more appropriate, considering the environmental and economic dimensions of sustainability.

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Moreover, a special needs research session on disaster waste management (DWM) during the 2010 Intercontinental Landfill Research Symposium in Japan indicated that one of the three main future research areas was emergency temporary storage. Since emergency response circumstances can cause poor storage area planning for disaster waste, there is a need for research on planning the temporary storage for keeping, separating, and recycling DW (Milke, 2011).

Planning for temporary storage sites is part of disaster operations which represent the entire set of activities performed before, during, and after a disaster in order to reduce its consequences (Altay & Green, 2006). Traditionally; there are four stages of disaster operations management: mitigation, preparedness, response, and recovery (Galindo & Batta, 2013). Response and preparedness are the most widely studied area of disaster management. However, as is also mentioned by Altay and Green (2006) as well as by Galindo and Batta (2013) that there is still a lack of research in the recovery or post-disaster stage. This issue has also been emphasized in previous reviews such as the work of Simpson and Hancock (2009) and Lorca, Çelik, Ergun, and Keskinocak (2015). Therefore, the main implication of this study is to contribute to post-disaster stage planning.

In order to provide the above mentioned contribution, a framework is proposed for determining the locations of temporary storage facilities and related allocations of waste source points to these facilities. The objectives considered are how to decrease the cost and number of people subjected to the risk of exposure to hazardous waste during treatment operations.

In this study, the proposed framework is applied to the city of Istanbul. As one of the leaders in terms of trade and business in the country and region, Istanbul is the most crowded city in Turkey. As Istanbul has faced several destructive earthquakes in its history (the latest in 1999), appropriate pre and post-disaster planning is crucial. This study analyses an earthquake scenario for Istanbul as predicted by authorities (Ansal et al., 2003). There are vast numbers of buildings that are estimated to collapse or to be heavily damaged in Istanbul if the expected earthquake occurs. Since the estimated damage to these buildings would generate large amounts of waste that could not be treated or recycled within the current capacities of the facilities, temporary sites for storage and recycling need to be located for proper waste management. In this study, a framework is suggested in order to decide the locations of these facilities and allocation of waste source points to them.

Section 2 provides a background and literature survey of disaster waste management that underlines the lack of research on post-disaster management, while highlighting the importance of using an evolutionary approach for this purpose. This section also gives a survey of the literature on disaster risk assessment and disaster loss estimation. Section 3 gives the framework of the proposed methodology. In Section 4, the methodology is applied to Istanbul as a case study. Finally in Section 5 conclusions and further suggestions are given.

2. Background

Disaster waste management falls into the field of humanitarian logistics (Lorca et al., 2015). Previous studies on DWM have documented the efforts of DW removal efforts with a qualitative analysis or they have presented guidelines prepared by several institutions, such as the Federal Emergency Management Agency of United States (FEMA, 2010) and the United Nations (Söder & Müller, 2011). There is still a lack of quantitative studies for guiding the debris removal process during the recovery stage (Lorca et al., 2015).

When it comes to the analytical background of the field, three studies should be mentioned. One of them is the work of Fetter and Rakes (2012). They presented a decision model for locating temporary sites for recycling and storage of disaster waste, with incentives for these operations. Our model is similar to their work in terms of decisions on site location and allocations of sources to these places. However, their objectives were financial and they used a single objective model, despite the multi-objective nature of the problem caused by the conflicting objectives. Another study was done by Hu and Sheu (2013). They introduced three objectives; cost minimization, risk penalty minimization, and psychological cost minimization. They used a multi-objective model for formulating the problem. Like them, cost minimization and risk minimization of exposure to hazardous debris during temporary storage are the two objectives of our model. But, differing from our study, they normalized the objectives and minimized the weighted sum. Their approach required defining the weights but these preferences may affect the efficiency of the solution. The third study worth mentioning was done by Lorca et al. (2015). Their model has many commonalities with the work of Fetter and Rakes (2012) and Hu and Sheu (2013). Our model also holds some similarities to their model, such as location decision for temporary sites and the assignment of debris to them. However, Lorca et al. (2015) used weighted criteria in the objective function like Hu and Sheu (2013). As such, our study is unlike any of the previous research in the literature, as we use an elitist evolutionary multi-objective optimization technique (NSGA-II) in order to solve the DWM problem.

Traditionally, most multi-objective optimization problems are solved by converting multiple objectives into a single objective. Another commonly used approach is converting part of the objectives into constraints. The disadvantage of using such conversions is that they generate a single solution per calculation. To this point, Pareto optimality cannot be guaranteed. In order to map all frontier sets, calculations should be repeated numerous times which decreases the computational performance (Liu, Gao, & Wang, 2015) and elitist evolutionary optimization, especially the NSGA-II, is widely used to overcome this issue. NSGA-II can handle large-sized problems with high computational efficiency and a solid elite preserving mechanism (Liu et al., 2015). NSGA-II was proposed by Deb, Samir, Amrit, and Meyarivan (2002) and the algorithm is one of the most efficient multi-objective evolutionary algorithms (Deb, 2011). The most important advantages of NSGA-II can be listed as follows; (1) it is an algorithm with low complexity and (2) it avoids the difficulty of setting shared parameters (Huang, Buckley, & Kechadi, 2010). Comparing solutions with traditional methods, NSGA-II produces a Pareto optimal set of solutions instead of a single one. This solution set is generated by comparing the fitness of individual solutions via an elitist procedure (Ak et al., 2013).

In addition, classic methods are appropriate for addressing problems which are convex and operate with a single objective function. Classic methods may even reach global optimum for non-convex problems in some cases. Nevertheless, these methods are insufficient to reach Pareto-optimal solution sets (Köhn, 2011). Since multi-objective problems are usually NP-Hard, most of the time, it is impossible to find a Pareto-optimal set for these methods; moreover, NP-Hard problems are usually solved using heuristic approaches. When integer programming (IP) problems are considered, those problems usually have a non-convex solution space and obtaining a Pareto-optimal set for these kinds of discrete problems using classical multi-objective methods can be impossible (Keskin, 2009). In the light of these considerations, the elitist evolutionary multi-objective optimization method (NSGA-II) was decided to be used in this study.

The implementation of the proposed framework requires an estimation of the amount of the debris generated by a disaster. In order to present the link and the gap between estimation and post-disaster planning studies, disaster risk assessment and disaster loss estimation related studies were reviewed.

2.1. Disaster risk assessment and loss estimation

There is a need for risk assessment of natural and man-made disasters. Data concerning past events is limited, and most of the studies rely on probabilistic risk analysis based on past event data. Studies on

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