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Using GIS and optimization to manage construction and demolition waste: The case of abandoned quarries in Lebanon

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ABSTRACT

Increased stress on raw material and limited landfill space due to increasing rates of urbanization have encouraged efforts to divert Construction and Demolition Waste (C&DW) away from landfills toward sorting, recycling, and reusing. While these efforts have been successful in some countries (e.g., Germany, Netherlands), developing countries tend to suffer from illegal and haphazard dumping of C&DW. This study presents an optimization based decision support tool to select a cost and environmentally effective set of abandoned quarries to serve as C&DW landfills and processing facilities. The tool is composed of a GIS model and a mixed integer linear program that accounts for the complete waste management chain. A case study in Lebanon served as a testbed for the tool: A multi-criteria analysis was first used in GIS to evaluate the environmental suitability of candidate quarries based on five thematic groups: socio-economic, topography, geology, hydrology and infrastructure. The most suitable quarries were then inputted to the optimization model. Two out of 148 abandoned quarries in Mount Lebanon were deemed suitable for rehabilitation under the objectives set yielding a profit of 125 million US dollars over a 20 year span. Future challenges include enhancing the model by incorporating time and accounting for more recycling technologies.

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1. Introduction

The construction industry generates massive amounts of rubble with a diverse composition across the multiple stages of construction from shoring to finishing. The bulky volume of construction waste, coupled with shortages in landfill space, have encouraged researchers and practitioners to think of alternative, sustainable solutions such as reuse and recycling. High Construction and Demolition Waste (C&DW) recycling capabilities permitting reuse rates in excess of 80% have been achieved in Germany, Denmark and the Netherlands (Euro-stat and Union Européenne, 2015; Morata and Sandoval, 2012). Developing countries, however, still lag behind in C&DW recycling and reuse (Duan et al., 2019). Among the barriers to sorting and processing C&DW is the fact that buildings have long life spans and multiple owners with different attitudes towards recycling. Beyond the building itself, the absence of processing facilities with adequate capacities and established recycling technologies can pose a barrier. The market for recycled aggregates is also under-developed in many countries (Huang et al., 2018). Finally, legal and economic incentives and appropriate monitoring are rare and thus severely obstruct the efficient management of C&DW (Silva et al., 2017). In fact, a contractor's behavior in C&DW management is driven by the economic viability of the process first and the presence of a governmental supervision second (Wu et al., 2017).

The main objective of this study is to provide an economically viable and environmentally friendly decision support tool for the management of C&DW especially in developing countries. This tool is structured around rehabilitating quarries into processing facilities, an appealing approach that reduces public objection resulting from the "not in my back yard" syndrome.

While quarries provide an initial set of potential sorting and recycling locations, further considerations are needed to guarantee a cost effective and environmentally efficient system of recycling facilities. Previous studies implemented either Geographic Information Systems (GIS) models or mathematical models to solve the problem of facility location selection. However, these models either did not account for the complete value chain or they resulted in areas in which further site-specific analysis was required. Such studies often focused on limiting the environmental effects due to emissions while neglecting the influence of land characteristics on the siting of the facilities. In contrast, the present work combines both geospatial and mathematical modeling

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methods to obtain a unique set of processing sites with the least public and governmental objection possible.

The geospatial portion of this strategy uses an automated multi-criteria analysis to select from a set of quarries the ones that can be rehabilitated into material recovery facilities and landfills. The inputs of the model and the measures adopted can be easily modified to reflect conditions in any locale. The aim is to minimize environmental damage according to shareholders' preferences and any existing regulations. The mathematical modeling portion of this work is an optimization-based model that delineates the set of quarries suitable for use when considering the full supply chain of recycled aggregates. The objective of the mathematical model is to maximize profits across the lifespan of the facilities. As a result, the model output is an estimate of the total profit or total loss of the proposed waste management system. Evidently, the accuracy of the results is dependent on the accuracy of the input provided to the model.

The following section elaborates on previous methods used to locate processing facilities. Next, the decision support tool – the primary contribution of this work – is introduced. The application of the tool to the case of Lebanon is presented and the results summarized. Finally, recommendations to enhance the performance of the decision support tool are discussed.

2. Background

The process of C&DW management begins with the estimation of material streams, continues with the allocation of these streams to appropriate sorting and recycling facilities, and concludes with recycled aggregates being sold for new construction via appropriate market channels (Martinez et al., 2010). The literature includes a host of methods to estimate quantities of C&DW depending on the availability of data (Malia et al., 2013; Srour et al., 2013; Bakshan et al., 2015). Malia et al. (2013), for example, estimated a waste generation rate of 17.8–40.1 kg per m^2 of built-up area for new construction and a rate of 401–840 kg per m^2 of built-up area for the demolition of residential and non-residential developments. The quantification of C&DW serves as input to various parameters such as location and size of landfills and processing facilities.

Several studies provide decision-making tools to evaluate adequate locations for processing facilities. GIS are among the techniques adopted for this purpose. The selection of C&DW processing and landfilling sites requires diverse expertise in social and environmental fields, such as engineering, hydro-geology, topography, land use, sociology, and economics (Tamraz et al., 2012). GIS is a well-known technique adopted for this purpose. It has emerged as a major tool for land use suitability analysis. GIS can correlate and analyze spatially referenced data to enable decision makers to analyze trends, evaluate project outcomes and plan for long-term goals and policy targets (Malczewski, 2004).

Robinson and Kapo (2004) used GIS data to extract a set of regional features of processing facilities and used them to determine new suitable locations. The regional features related to the transportation networks, population density, among other factors. In contrast, Ding et al. (2018) identified, through a literature review, 16 factors affecting the location of C&DW landfills. These factors can be divided into three categories: environmental, social and economic. The authors then combined an analytic hierarchy process with an entropy method to evaluate the respective weights of the factors.

In parallel, Madi and Srour (2019) included in their GIS analysis environmental factors such as slope, snow and vegetation indices, green and urban areas among others in order to identify areas to build processing facilities. Paz et al., (2018) used GIS to locate suitable areas for the installation of urban equipment that support integrated C&DW management.

While GIS frameworks are critical in identifying suitable regions for processing C&DW, they ignore the larger supply chain ramifications associated with selecting any one location. To address this issue, other studies (e.g., Bernardo et al., 2016) proposed the use of mixed integer linear programming (MILP) to find optimal network configurations through cost minimization. Hiete et al. (2011) developed a MILP model that takes into account both supply and demand as well as landfilling with four different recycling techniques leading to different products. The environmental impacts considered are emissions, energy demand and resource consumption. In contrast, Galan et al. (2013) did not account for demand due to high difficulties in the estimation of the end user market, however they did include trans-shipment stations and adopted two objective functions to minimize financial and environmental costs. OptiWasteFlow is one of the most recent tools developed. With a complex MILP masked by a friendly graphical interface, this tool optimizes waste flow while accounting for delays, storage nodes and economies of scale (Parriani and Vigo, 2017). This tool, however, fails to account for environmental impacts nor does it assist in siting the processing facilities.

3. Materials and methods

In this study, we marry the results of a GIS based assessment of potential processing sites with a MILP selection of final sites in the context of the full value chain for recycled aggregates. Fig. 1 provides an overview of the complete site identification and selection process.

3.1. GIS assessment of potential sites

The first step in our selection of cost effective C&DW processing facilities is the identification of suitable areas from a geographic perspective. As C&DW has a multi-faceted impact on society, we chose to apply multi-criteria analysis (MCA) in our identification of suitable areas. We began by reviewing the literature, international best practices and previous projects. These reviews led to the selection of five thematic groups: socio-economic, infrastructure, hydrology, topography, and geology. Evidently, when applicable, the siting of processing facilities must also adhere to, and account for, national and local laws and regulations which address environmental, safety and public concerns.

Once identified, the selection criteria need to be integrated into the maps representing the general region of interest. For example, slopes greater than 18 degrees must be excluded from the analysis. However, the areas with slopes ranging from zero to 18 degrees require further sorting as flatter surfaces are more suitable.

Classification is a recognized method for labeling cells within the general region: a cell is either in or not within a class. Nonetheless, even with further categorization refinement, this binary membership remains subject to sharp boundaries resulting from subjective categorization rules. These classification errors, compounded with measurement errors, can largely affect the results obtained and their applications thereafter. In order to minimize these inaccuracies, we used fuzzy logic. In fuzzy logic, the classes are construed as sets: there is an agreement on what the best value is for the membership in a set, for example, the ideal grade to build a facility on. As the values move away from this target, the level of suitability is reduced to a point where it is evident that the value is not a member of the set.

Fuzzification requires the input of two parameters: the midpoint and the spread. The midpoint is a user-defined number to which is assigned a membership of 0.5. This parameter delineates

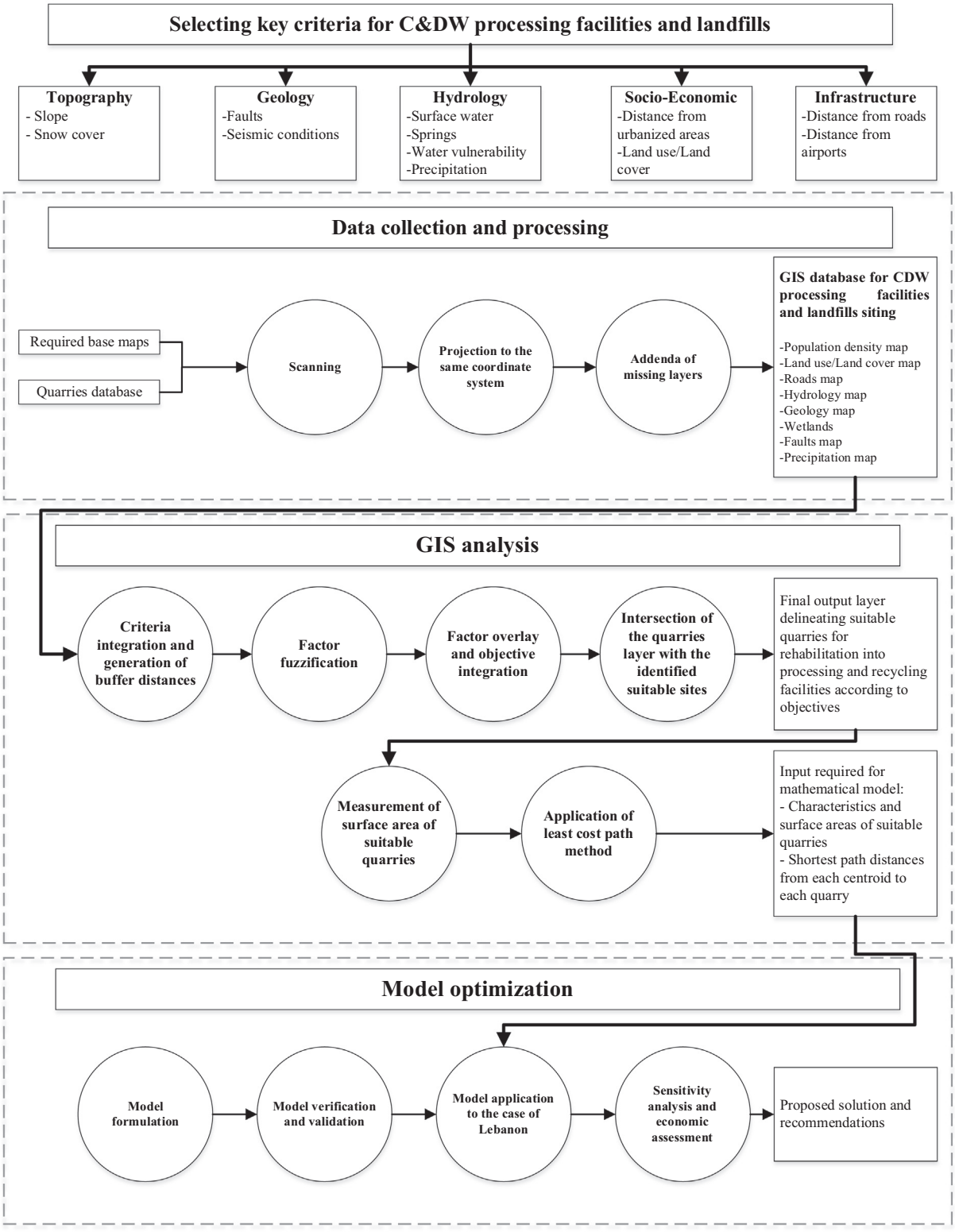

Fig. 1. Steps followed for the development of the decision support tool.

the boundary between suitable and unsuitable options and in consequence, its selection varies with every factor. On the other hand, the spread determines the shape of the transition zone. The spread generally ranges from 1 to 10 with larger values resulting in a steeper distribution from the midpoint, and a decrease in the percent of suitable characteristics.

Several fuzzy membership algorithms exist. This study implements the fuzzy-large and the fuzzy-small functions. The fuzzy-large transformation is considered when the larger input values are more suitable. For example, areas farthest from springs and wetlands are more desirable. As such, values above the midpoint have a higher possibility of membership. The variation of fuzzy

membership with respect to the values corresponds to an increasing S-shaped curve. The fuzzy-small transformation is adopted when the smaller input values are more preferred. For example, flatter slopes are better for constructing landfills. Values below the midpoint, in this case, have a higher possibility of membership and the membership diagram has the shape of a decreasing S-curve.

The last step in the MCA is to overlay the factors to generate a single value of site suitability for each cell. In this work, three overlay strategies are reported: fuzzy and, fuzzy or, and a weighted overlay method. With a "fuzzy and" strategy, the cells hold the minimum value of the sets identified in the region; with a "fuzzy or" strategy, the cells hold the maximum value of the sets identified in the region; and finally, in the weighted method, weights are assigned to each criteria and the value assigned to the cell is the weighted average of the criteria.

Once the factors are overlaid, the cells will hold a numerical value between 0 and 1. Accordingly, we reclassified the cell values into one of the five categories cited in Table 1.

3.2. Optimization model

An adequate waste management approach should account for sorting, processing, and proper disposal of C&DW. As such, a multi-level facility location problem structure is adopted for the developed model. This approach maximizes the profit associated with siting and operating the C&DW processing facilities by simultaneously minimizing the costs associated with all possible flows of sorted, recycled and disposable debris and maximizing the system revenue associated with gate fees and selling to the markets. The model also accounts for existing facilities while identifying the need for new facilities where applicable.

We assume that the locations of the centroids for waste generation along with the projected supply of C&DW and its composition can be identified. We also assume that the aggregate component of the waste stream is of medium-utility/quality and thus, after sorting, requires only grinding to be converted to the recycled product. This assumption serves only to simplify the cost parameters in the model, but has no impact on the structure of the model. Specifically, this assumption allows us to determine the land area and operating cost for the recycling equipment. If one were to assume different waste compositions or recycling strategies, the model would still be able to accommodate those assumptions. We also assume that the potential markets and the projected demand of recycled products are known. Potential markets can include concrete batch plants or large roadway infrastructure construction projects. Finally, as a result of the GIS model, we assume that the suitable candidate sites for C&DW processing are known; the GIS process will also allow us to determine the land area available at each site. Moreover, the shortest distances between the different facilities can be found using the least cost path method in the GIS. We also assume that the processing technologies adopted in the various facilities are known and thus allow for the determination of the capacity per operating module and the corresponding capital and operational costs.

Table 1
Fuzzy overlay values reclassification into levels of suitability.

Range of data	Suitability
[0–0.2]	Low
[0.2–0.4]	Moderate
[0.4–0.6]	Suitable
[0.6–0.8]	Very suitable
[0.8–1]	Extremely suitable

To encapsulate this in a model, we imagine operating over a graph made up of N nodes and E edges. The set N of nodes is comprised of subsets C representing the centroids of waste generating regions, S representing the potential C&DW processing sites, G representing the non-cementitious materials landfill sites, M_1 representing the set of coarse aggregate market centroids and M_2 representing the set of fine aggregate market centroids. The set E of edges includes the edges from the centroids to the potential C&DW processing sites, the edges from the processing sites to the markets, and the edges from the processing sites to the non-cementitious landfills. Edges from processing site to processing site are also included and represent the flow of material from sorting/recycling to cementitious landfilling. This structure is particularly flexible as one can co-locate a waste generation centroid and a potential C&DW processing site – in so doing the edge from the waste generation centroid to the potential C&DW processing site will have a transport cost of zero. Similarly, one may co-locate a C&DW processing site with a market centroid. In short, all nodes in the network, regardless of their type, may be as close or far as the constraints of the operating environment allow.

Any potential site's area may be built with sorting and recycling modules or turned into cementitious landfill space or some combination of both. The recycling modules have operational costs of P_F associated with sorting one ton of C&DW; P_{R1} associated with grinding one ton of C&DW into coarse aggregates; P_{R2} associated with grinding one ton of C&DW into fine aggregates; P_G associated with landfilling one ton of cementitious waste; and P_L associated with landfilling one ton of non-cementitious waste. We further assume that any potential site with recycling or landfilling capabilities will charge a processing fee of ϕ per ton. The revenue gained from selling one ton of recycled coarse aggregates is V_1 and the revenue earned from selling one ton of recycled fine aggregates is V_2. Any non-cementitious waste is ultimately landfilled with a gate fee of Γ per ton.

We assume that the area needed for one module of sorting and recycling is A_F and the area needed for one module of cementitious landfilling is A_L; the capacity that one module of recycling and landfilling can accommodate is U_F and U_L, respectively. The cost of building one module of sorting and recycling at site i in S is b_i while the cost of building one module of cementitious landfilling at site i in S is d_i. Each potential processing location may already have existing sorting and recycling as well as landfilling capabilities in terms of tons which we denote as e_i and l_i, respectively. For each potential processing location, i in S, we can also build additional processing and/or cementitious landfilling capabilities. In this case, we assume a total available area of a_i.

We assume that q_i tons of waste are generated from the current and projected centroids, i in C. Of this waste, we assume that α is the percent suitable for coarse aggregate recycling, β is the percent suitable for fine aggregate recycling, and γ is the percent of C&DW that is non-cementitious material. Despite the overall assumption on the percentage of waste types in the C&DW, we require that all waste coming from the centroids must be sorted in the sorting facilities at the identified processing sites.

Each market for coarse aggregates has a demand of χ_m for m in M_1 and the markets for fine aggregates have demands of ψ_m for each market m in M_2. The transportation costs are encapsulated in the parameter t_{ij} where i and j are both in the set N. This parameter may be interpreted as follows. If i is in C and j is in S, then t_{ij} is the cost of transporting one ton of C&DW from the waste generating centroid i to the processing facility j. If i is in S and j is in S, then it is the cost of transporting one ton of cementitious waste from processing facility i to cementitious landfill j. If i is in S and j is in L, then it is the cost of transporting one ton of non-cementitious waste from the processing facility i to the landfill j. If i is in S and

j is in M_1 or M_2, then it is the cost of transporting one ton of fine or coarse aggregates to market j, respectively.

Given that the premise of this model is to determine the location and operational capacity of each facility needed to handle the C&DW for a specified time period, there is no need to discretize time. For example, the model solves for the optimal way to match supply and demand for recycled C&DW over the entire design period, rather than at each operational time period (e.g. day, month, year).

In this framework, there are three classes of decision variables: y_i denoting the integer number of sorting and recycling modules to open at location i in S; w_i denoting the integer number of cementitious landfilling modules to open at location i in S; and x_{ij} denoting the tons of material going from location i to location j. If location i is in C and j is in S, then x_{ij} represents tons of unsorted C&DW. If location i is in S and j is in S, then x_{ij} represents tons of sorted cementitious waste for landfilling. If location i is in S and j is in M_1 or M_2, then x_{ij} represents tons of recycled coarse and fine aggregates, respectively. Finally, if location i is in S and j is in L, then x_{ij} represents tons of sorted non-cementitious waste.

The objective of the MILP is to maximize the system-wide profits associated with building and operating a set of C&DW processing facilities. We choose to maximize profits as private investments are often the origins of any sustainable initiatives in developing countries where basic regulations for proper waste management are lacking. This represents an extension to the models discussed previously where the sole beneficiaries were the recycled concrete plant owners. The profits in our model are calculated as the difference between system wide revenues and system wide costs. The revenues are a function of the gate fees paid to the processing facilities and the price paid for both the coarse and fine recycled aggregates in the market. The costs are those of building and operating the processing facilities along with transporting the materials from the origin of the waste through the sorting and recycling process to the market or landfills. Using the notation introduced above, Eq. (1) denotes the profit maximizing objective of this model.

$$\begin{aligned} max\Bigg[&\sum_{o\in C}\sum_{i\in S}\varnothing x_{oi}+\sum_{i\in S}\sum_{m\in M_1}V_1x_{im}+\sum_{i\in S}\sum_{m\in M_2}V_2x_{im}\\ &+\sum_{i\in S}\sum_{j\in L}\Gamma x_{ij}-\Big[\sum_{i\in S}b_iy_i+d_iw_i+\sum_{i\in C\cup S}\sum_{j\in S\cup M_1\cup M_2\cup L}t_{ij}x_{ij}\\ &+\sum_{o\in C}\sum_{i\in S}P_Fx_{oi}+\sum_{i\in S}\sum_{m\in M_1}P_{R1}x_{im}+\sum_{i\in F}\sum_{m\in M_2}P_{R2}x_{im}\\ &+\sum_{i\in S}\sum_{j\in S}P_Gx_{ij}+\sum_{i\in S}\sum_{k\in L}P_Lx_{ik}\Bigg] \end{aligned} \tag{1}$$

Environmental costs are accounted for in both the transportation costs and the setting of the operational costs for the landfills. Thus, in an optimal network fewer carbon dioxide particles will be emitted in transport and the landfilling of non-cementitious landfilling will also be avoided as much as possible.

The constraints of this model can be divided into 4 primary categories: facility capacity constraints, flow constraints, market demand constraints, and constraints governing the ratios of the waste streams coming from the centroids.

$$A_Fy_i+A_Lw_i\le a_i,\quad \forall i\in S \tag{2}$$

$$\sum_{o\in C}x_{oi}\le U_Fy_i+e_i,\quad \forall i\in S \tag{3}$$

$$\sum_{i\in S}x_{ij}\le U_Lw_j+l_j,\quad \forall j\in S \tag{4}$$

The constraints represented by Eq. (2) enforce that the total built up area at potential processing site i in S does not exceed the total available area at that site. The constraints represented by Eqs. (3) and (4) ensure that the amount of material handled for sorting and recycling as well as cementitious landfilling, respectively, does not exceed the existing and to be built capacity.

$$\sum_{i\in S}x_{oi}=q_o,\quad \forall o\in C \tag{5}$$

$$\sum_{o\in C}x_{oi}=\sum_{j\in S\cup M_1\cup M_2\cup L}x_{ij},\quad \forall i\in S \tag{6}$$

The constraints represented by Eq. (5) requires that all of the waste available at a centroid leaves the centroid for a processing site. Eq. (6) is a set of constraints ensuring that all of the waste entering a site, leaves the site for cementitious landfilling, one of the two markets (coarse and fine aggregates) or the non-cementitious landfills.

$$\sum_{i\in S}x_{im}\le X_m,\quad \forall m\in M_1 \tag{7}$$

$$\sum_{i\in S}x_{im}\le \psi_m,\quad \forall m\in M_2 \tag{8}$$

The constraints represented by Eqs. (7) and (8) dictate that the market demand cannot be exceeded when sending recycled aggregates to the market. While it might seems strange that this constraint does not enforce meeting all demand, this is due to the fact that there may not be enough waste feedstock in a system to guarantee satisfaction of demand. However, as sending recycled aggregates to the market is the primary source of revenue in the model, demand will be satisfied if at all possible.

$$\sum_{m\in M_1}x_{im}\le\sum_{o\in C}\alpha x_{oi},\quad \forall i\in S \tag{9}$$

$$\sum_{m\in M_2}x_{im}\le\sum_{o\in C}\beta x_{oi},\quad \forall i\in S \tag{10}$$

$$\sum_{k\in L}x_{ik}=\sum_{o\in C}\gamma x_{oi},\quad \forall i\in S \tag{11}$$

The constraints represented by Eqs. (9) and (10) govern the percentage of coarse aggregates and fine aggregates that can come from a processing site, i in S. Similarly, Eq. (11) dictates that of the waste coming from centroid o, a percent γ is non-cementitious waste. The model also requires that x_{ij} is greater than or equal to zero for all edges $\{i, j\}$ in the edge set.

3.3. The case of Lebanon

We applied the decision support tool to two regions in Lebanon, Beirut and Mount Lebanon. The country is divided into 8 governorates: Beirut the capital, North, Mount Lebanon, South, Nabatiyeh along with Bekaa, Akkar and Hermel-Baalback. Beirut and Mount Lebanon combined account for more than half of the country's population.

3.3.1. GIS assessment of sites in Lebanon

In order to implement the GIS model, data in the form of GIS layers are required. The primary data needed to conduct this study came from the National Physical Plan of Lebanon. Prior to any criteria integration, the collected layers of data were extrapolated to the same projection coordinate system (UTM 36 N). The data was then cropped to the area of Lebanon. Any data in vector form were converted to raster cells. Rasters are matrices of identical cells organized in grids, where each cell holds one thematic or continuous value such as elevation, rainfall, type of land cover, etc. A prime advantage for data in raster format is the ability to mathematically

operate on the continuous values of each cell. The latter can be added, subtracted and excluded from any analysis, among other operations. Following the process outlined in Section 3, we integrated the GIS data following a set of factors in order to delineate suitable areas. The factors and associated criteria used to delineate suitable areas for rehabilitation are elaborated in Table 2.

Next, the fuzzy membership tool was applied to all the resulting layers. Table 3 presents the adopted fuzzification function and the parameters selected for each factor. The midpoints were set equal to the required buffer distances when applicable, and to the median of the data in the remaining factors (population density, slope, snow elevation and precipitation rate). The default value of 5 was used for the spread.

Subsequently, in order to overlay the individual raster memberships, the weighted overlay technique was used with equal influence assigned to each factor. In practice, the weights can be adjusted according to regulations or shareholder's preferences.

The results obtained were then reclassified into the five levels of suitability as explained in Table 1 and intersected with a quarries database in order to examine the feasibility of establishing processing facilities at abandoned quarries. After the end of Lebanon's civil war in 1990, mass reconstruction combined with a lack of appropriate regulations and monitoring led to the unregulated expansion of quarrying activities. Between 1989 and 2005, a comparative analysis of satellite imagery show that the number of quarries in Lebanon almost doubled (Darwish et al., 2012). Geology, climate, and proximity to urban expansions were identified as determining factors for the locations of quarries in Lebanon, whose effects were experienced all over the country (El-Fadel et al., 2001). For this reason, this case study focusses on developing potential C&DW processing sites at abandoned quarries. It is important to note, however, that in other locations with space to recycle in situ at new construction sites, closer to the centroids of waste generation, other selection criteria and overlays may be selected without impeding the subsequent mixed integer optimization model.

Table 2
Criteria used in GIS model.

Thematic group	Factor	Criteria
Socio-Economic	Urban areas	Areas with densities exceeding 2000 capita per km^2 are excluded from the analysis
	Land cover	A minimum buffer distance of 1000 m is recommended for agricultural lands and forests
Infrastructure	Roads	A minimum buffer distance of 600 m from main roads is recommended
Hydrology	Water bodies	A minimum buffer distance of 500 m from water bodies and reservoirs is recommended
	Precipitation rate	Areas with a rainfall rate exceeding 1,200 mm per year are excluded from the analysis
Topography	Slope	Areas with slopes exceeding 18 degrees are excluded from the analysis
	Snow Cover	Areas located above Lebanon's snowline (1300 m) are excluded from the analysis
Geology	Seismic Conditions	A minimum buffer distance of 500 m from any major or minor fault is recommended

Table 3
Factor fuzzification for Lebanon.

Factor	Fuzzy membership function	Midpoint	Spread
Population density	Fuzzy small	200	5
Distance from agricultural lands and forests	Fuzzy large	1000	5
Distance from springs, rivers	Fuzzy large	500	5
Precipitation rate	Fuzzy small	600	5
Slope	Fuzzy small	9	5
Snow elevation	Fuzzy small	775	5
Faults	Fuzzy large	500	5

In this study, we used a quarry database available from the Alleviating Barriers for Quarries Rehabilitation in Lebanon (ABQUAR) project where data on 471 quarries was compiled in 2006 following numerous field visits. Information on the quarry owners, the geographic locations (town, region and coordinates), topographic attributes, excavation methods, abandonment dates, proximity to and type of the nearest structure, geological formation (including available faults and directions) along with attributes of and impacts on soil, hydrology and ecology is available in this database. After reviewing the data and projecting it onto a suitable geographic projection system (UTM 36 N), we were left with data on 452 quarries including 148 in Mount Lebanon. The candidate quarries to be used as input in the optimization model would ideally intersect with areas with "very" or "extremely" strong suitability.

3.3.2. Optimization model application in Lebanon

The mathematical model requires multiple parameters beyond the locations of the suitable quarries. Estimating the quantities of C&DW is necessary for sizing and locating the processing facilities and landfills. This case study in Lebanon focuses on the projected supply of non-emergency C&DW for the next 20 years. This supply is referred to as steady-state: it includes debris generated from new construction, renovation and demolition activities. New construction includes residential, commercial and mixed used buildings. The waste generated from new construction is estimated by multiplying the projected total built-up area by a waste generation rate in kilograms per m^2. Bakshan et al. (2015) estimated a range of 38–43 kg per m^2 of total built-up area accounting for 10–20% in weight for waste from unaccounted streams such as paint. In order to determine the Total Built-up Area (TBA), datasets from the municipalities and the Order of Engineers and Architects were used. These datasets allowed us to forecast TBA across the twenty year horizon of our model. In terms of the waste streams from renovated buildings, no national statistics are available in Lebanon.

The demolition waste streams were estimated by taking into account the demolition waste generation rate in kilograms per m^2 for the projected built-up areas that receive demolition permits. Srour et al. (2013) estimated a rate of 1.73 tons per m^2 for Beirut between 2009 and 2010 based on a sample of demolished buildings and collected data from the Municipality of Beirut. The average TBA for the sample studied was 2300 m^2. The number of demolition permits given per year between 2007 and 2014 for all of Lebanon were obtained from the Order of Engineers. A forecast is applied to determine a rough estimate of the number of permits between 2018 and 2040. In total, it is estimated that 6652 demolition permits will be issued between 2018 and 2040. For an average demolition waste generation rate of 1.57 ton per m^2 and a TBA of 2300 m^2, the total projected demolition waste amounts to 47.9 million tonnes for all of Lebanon. This amount was divided on the governorates proportionally to their populations. Considering both the new construction and demolition waste streams, a total of 4 million tons of debris was estimated for Beirut along with 17 million tons in Mount Lebanon up to the year 2040 – these values serve as q_o in the optimization model.

Demand estimation is also essential to the optimization model. No data is available on the demand for the recycled aggregate products (coarse aggregates and find aggregates) in Lebanon. Nonetheless, the rate of consumption of concrete, masonry and tiles is comparable to the rate of waste generation during demolition. Hiete et al. (2011) evaluated the demand on quarry products by removing the weight of water and chemical additives and disaggregating each product into its initial components. In total, an esti-

mated demand of 435 million tons of coarse aggregates versus 202 million tons of fine aggregates will be required until 2040. In reality, a fraction of this demand can be satisfied by recycled aggregates. Recycled aggregates are usually of intermediate quality and can thus replace virgin aggregates fully in pavement applications and in non-structural applications such as fabrication of tiles and masonry blocks. These non-structural elements roughly add up to 35% of the projected demand of developments. Thus, the demand for coarse recycled aggregates is approximated at 249 million tonnes (100 million tonnes to be used in developments) versus 70.5 million tonnes for fine recycled aggregates.

In Lebanon, no official data on the location of recycled aggregate markets per governorate and their respective shares exist. Nevertheless, we can assume that the major markets for recycled aggregates are ready-mix concrete batch plants. With the assistance of national contractors, the major concrete batch plants in Mount Lebanon and Beirut were identified as the following: Araco Ready Mix Concrete, Beton Chantier de Liban (BCL), Holcim Ready Mix Concrete, Nakhle & Co. and Zerock. Due to the absence of information related to their market share, equal shares of market demand were assumed. As a result, we assume that every plant can use up to 49.75 million tonnes of coarse recycled aggregates and 14.11 million tonnes of fine recycled aggregates over the course of the next 20 coming years; these parameters serve as χ_m and ψ_m in the model.

The remainder of the parameters were determined from the literature or from the Lebanese market. Table 4 lists the different inputs, their symbols in the optimization model and their corresponding values.

The transport costs, t_{ij}, require multiplication by the distance between location i and j. As such we assumed that waste generation occurs at the centroid of the governorate. Ideally, the analysis would include the major supply centers in every governorate; however, due to the lack of data, we consider only the centroid. This was done by taking a weighted average of the village centroids, taking into account their respective populations.

The distances from the centroids to the different quarries and from the quarries to the markets and landfills were obtained through a least cost path process in GIS whereby the rasterized road layer was used giving international and primary roads a lowest cost of 1 and the secondary and local roads a cost of 3. In contrast, raster cells that do not fall on any road have a cost of ten. These costs per type of road are only representative of the road-level priority desired and are not representative of any monetary unit in actuality. Using the best single option, the shortest distances among the defined network were determined.

At the time of this study, two main landfills were recognized in Lebanon for non-cementitious waste: Costa Brava and Naameh, located in Beirut and Mount Lebanon respectively. The remaining governorates dispose of their waste in different landfills or through haphazard dumping for which no official data exists. The capacity for these landfills was assumed infinite for simplification. Fig. 2 displays the locations of the suitable quarries, the ready-mix plants that serve as our market locations and the landfills considered in the Mount Lebanon and Beirut.

Table 4
Case study optimization model parameters.

Parameter	Symbol	Value	Unit
Revenue from processing facility gate fee	$\varnothing$	15.00	$/tonne
Revenue from recycled coarse aggregates	V_1	3.63	$/tonne
Revenue from recycled fine aggregates	V_2	6.71	$/tonne
Revenue from non-cementitious waste landfill gate fee	Γ	16.00	$/tonne
Cost of building one module of recycling	b_i	2,103,480	$/module
Cost of building one module of cementitious waste landfill	d_i	9,678,409	$/module
Cost of transport	t_{ij}	0.10	$/tonne per km
Operational cost for sorting	P_F	2.88	$/tonne
Operational cost for recycling into CA	P_{R1}	1.15	$/tonne
Operational cost for recycling into FA	P_{R2}	1.73	$/tonne
Cementitious waste landfill operational cost	P_L	21.00	$/tonne
Non-cementitious waste landfill operational cost	P_G	21.00	$/tonne
Required area to build one recycling module	A_F	10.00	m^2 (000 s)
Required area to build one inert landfill unit	A_L	84.00	m^2 (000 s)
Capacity of one recycling module	U_F	4.48	tonnes (000 s)
Capacity of one landfill module	U_L	691.00	tonnes (000 s)
Percent debris recyclable into CA	α	41.00	%
Percent debris recyclable into FA	β	29.00	%
Percent non-cementitious debris	γ	13.00	%

4. Results and discussion

Fig. 3 displays the maps representing the obtained fuzzification of each factor. White raster cells represent cells with no data. Purple raster cells delineate areas with low fuzzy membership in opposition to green rasters which delineate areas with high fuzzy membership. In contrast, black cells have a fuzzy membership of one and are highly suitable for siting landfills or recycling facilities.

Furthermore, Fig. 4 shows the resulting map of suitable areas in Lebanon. Similarly to the color code adopted in Fig. 3, white raster cells represent cells with no data whereas the different shades of purple and green delineate respectively areas with low and high suitability levels.

Only one quarry in the Mount Lebanon governorate with an area smaller than 10,000 m^2 was found to be "very" suitable. In order to broaden the set of available quarries, we also consider "moderately" suitable quarries in the analysis. As a result, seven quarries are considered for the governorate of Mount Lebanon out of 148 abandoned quarries. Since Beirut does not have any candidate quarries, its C&DW will be directed to the most optimal facilities in Mount Lebanon as dictated by the optimization model.

The locations of the seven quarries were subsequently validated by adding a base-map layer of satellite imagery for Lebanon. This revealed that one of the quarries does not show on the satellite imagery and is potentially misplaced. As such, it was eliminated from the analysis; similarly we found that two quarries had areas less than the minimum acceptable area of 10,000 m^2. As a result, four quarries were input to the optimization model as potential processing sites as follows: Quarry 1 with an available area, a_i, of 49,000 m^2; Quarry 2 with an available area of 122,700 m^2; Quarry 3 with an available area of 63,000 m^2; and Quarry 4 with an available area of 12,900 m^2. None of these quarries has existing sorting and recycling or cementitious landfill capabilities currently.

The optimization model was coded in Python and run once across all input parameters using Gurobi Optimization (2018). An optimal solution was reached in 0.04 s after 67 simplex iterations. The results indicate that two recycling modules and five cementitious landfill modules are needed in Quarry 1, while three recycling modules and one cementitious landfill module is needed in Quarry 2. The 4 million tons of waste generated from Beirut go entirely to Quarry 2, while the waste from Mount Lebanon goes to both Quarry 1 (7.36 million tons) and Quarry 2 (9.44 million tons). Quarry 1 in turn sends 3.018 million tons to the coarse aggregate market and 2.134 million tons to the fine aggregate market; Quarry 2 sends 5.510 tons to the coarse aggregate market and 3.898 tons to the fine aggregate market. All recycled aggregates from both quarries go to the BCL ready-mix plant. Both Quarry 1 and Quarry

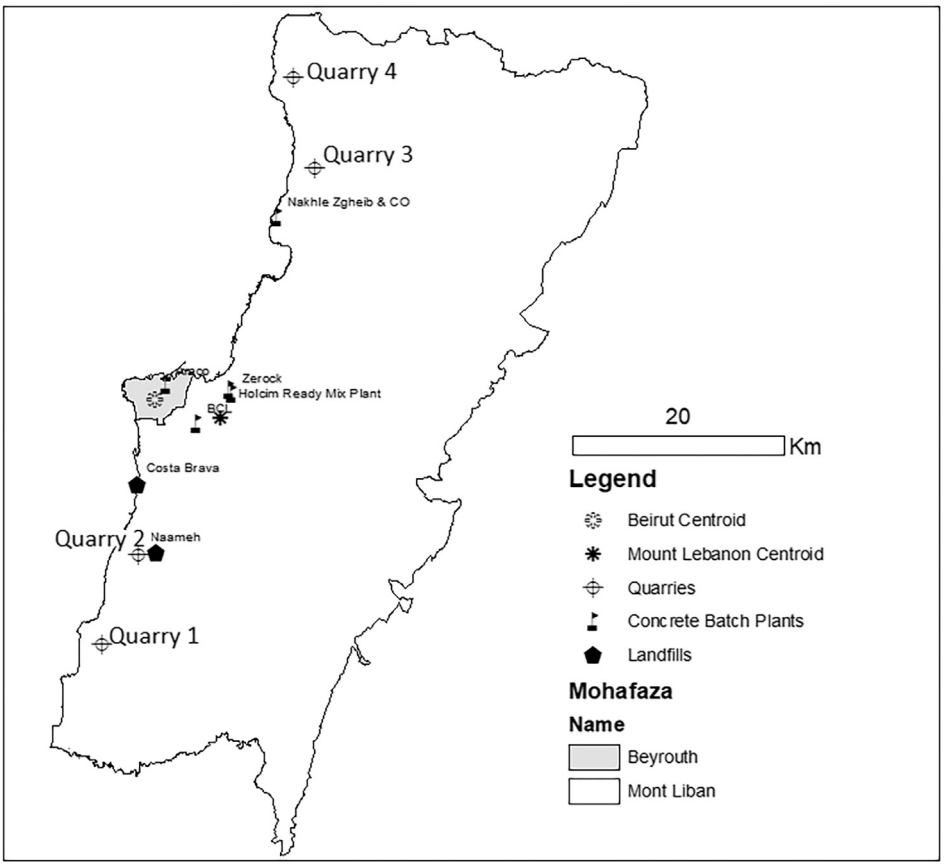

Fig. 2. Quarries, landfills, and concrete batch plants in Mount Lebanon and Beirut.

2 send cementitious waste to the landfill hosted at Quarry 1 on the order of 1.25 million tons and 1.59 million tons, respectively. Quarry 2 also sends cementitious waste to the landfill at Quarry 2 on a smaller scale of 691,000 tons. Combined both quarries send approximately 2.07 million tons to the non-cementitious landfill at Naameh, with Quarry 2 responsible for 1.75 million of those tons. The remainder of the quarries (Quarries 3 and 4) do not warrant rehabilitation at this time.

An important benefit of the combined GIS and optimization model lies in the objective function. The objective function serves to indicate the estimated costs or profits associated with managing C&DW in a specific locale. We see that the structure of our case application yields a gain of approximately 77 million dollars over the span of 20 years. This level of profitability stems from the fact that the supply of aggregates in the C&DW is greater than the demand for recycled aggregates. As such all demand can be served and the revenue of that demand can be gained. If the demand for recycled aggregates were to increase further, then even greater profits would be seen. Furthermore, if we revisit the objective function and focus on the profitability of the facility operators alone, we see that the facilities will be profitable in their own right since the facility operators will not personally bear the cost of transport. In this case-study of Lebanon, we see that the transport costs from the centroids to the facilities, which would normally be borne by the contractor, are on the order of $48 million.

The recycled aggregates were sent completely to the BCL ready-mix plant as it is the closest to the rehabilitated quarries. In real life however, one market may not want to acquire the complete market share of recycled aggregates. Admittedly as a sole supplier of RA to the market, BCL could gain a competitive advantage. On the other hand, RA usage is not currently widespread in Lebanon with poorly defined regulations as a result the revenues may be disappointing. In reality, other batch plants may want a share of this market. In that case, they would have to endure lower profits or increase their prices as they will be receiving the RA at higher costs due to longer hauling distances.

The gains reported here are based on several critical assumptions that warrant further investigation in the context of Lebanon. First, the C&DW is supplied by one centroid in each governorate. Refining the supply centers will alter hauling distances impacting the costs. Second, the supply of C&DW is estimated using a simple extrapolation to the future. This does not account for the country's economic and regulatory status. Accounting for these factors will certainly lead to more accurate cost estimations. Third, all quarries are assumed to be abandoned due to a lack of detailed data and their areas were determined from a satellite imagery using a measuring tool. Hence, measurement errors are inevitable. Finding correct data can alter not only the estimated costs but also the results as a whole. Fourth, recycling and cementitious landfilling module design may vary depending on the siting. For example, the height of one module of cementitious landfill was assumed to be eight meters. In reality, this value can vary depending on the quarries. If this height is exceeded, capacity and hereafter the profits increase.

Recycling facility and landfilling costs were assumed identical regardless of their locations. While this assumption may be valid for the case of Lebanon, the costs may vary by region for the case of other larger countries. Should there be variability in the cost

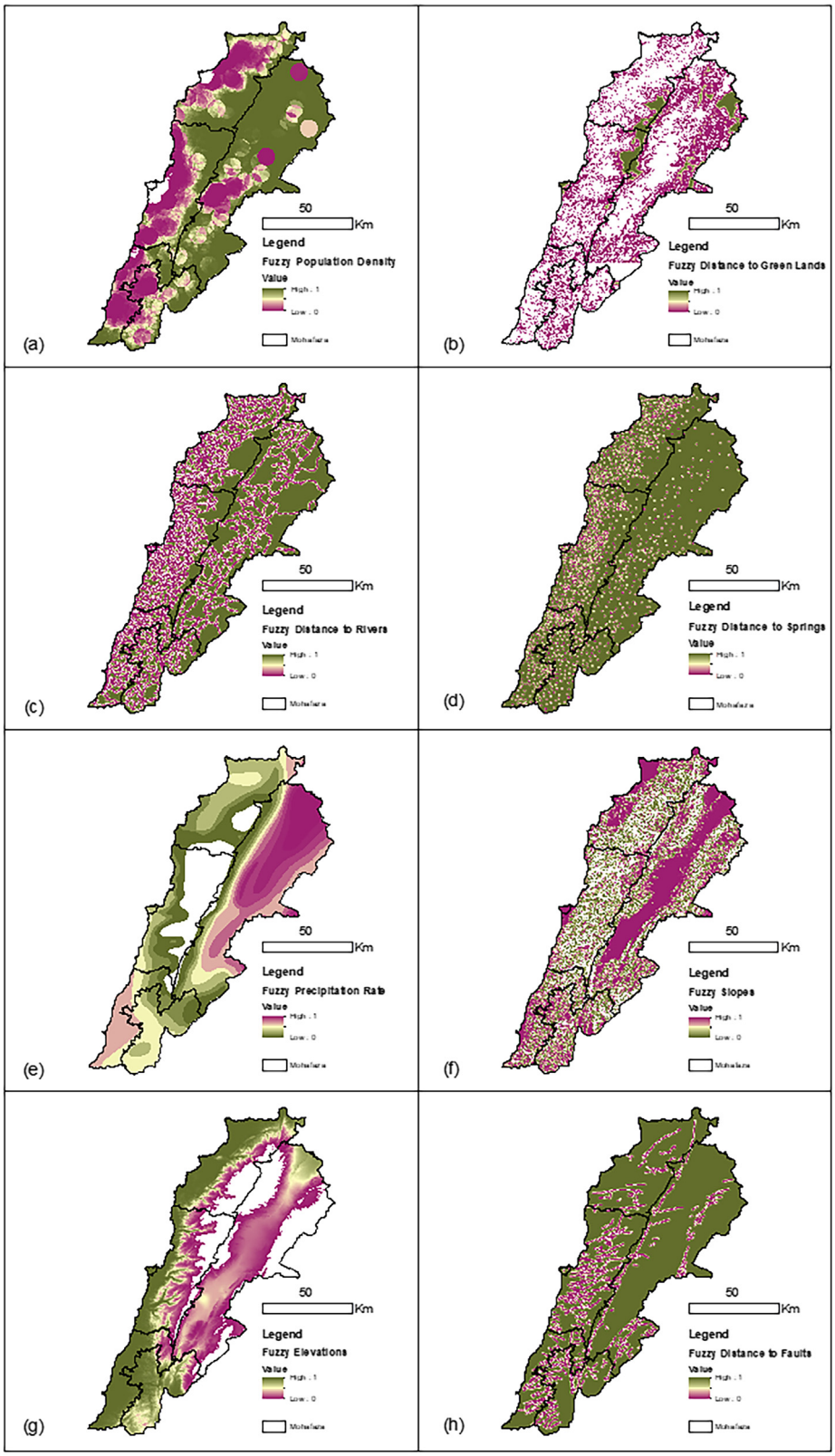

Fig. 3. Fuzzy membership factor properties.

of labor and/or quality of materials, the model parameters P_F, P_{R1} and P_{R2} may be adjusted. In contrast, a change in the capital costs can be reflected in parameters b_i and d_i.

Finally, the markets considered were restricted to ready-mix plants only. In fact, quarries and aggregate suppliers are potential markets as well. The non-cementitious landfills were assumed to have infinite capacity, which is not realistic especially from an environmental standpoint.

Despite these shortcomings in the estimation of our case parameters for Lebanon, we were successful in demonstrating

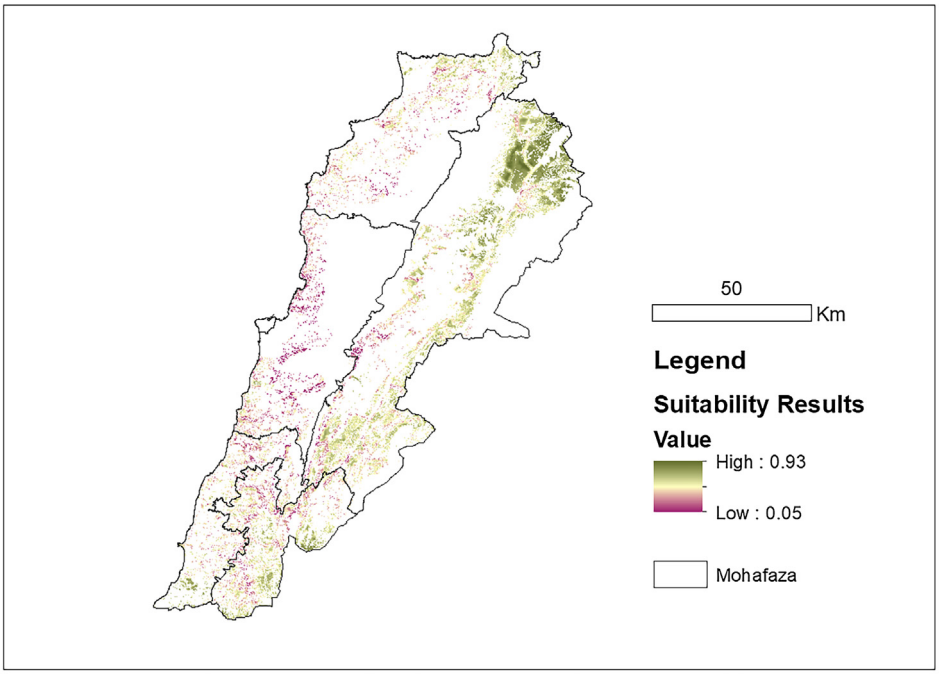

Fig. 4. Factor fuzzification for Lebanon.

the use of the combined GIS and optimization model tool for a real case study.

5. Conclusions

With the increasing rates of urbanization, wars, and natural disasters, waste management can no longer be treated as an option. The consequences could range from destroyed habitats, to degraded lands and a polluted environment. The challenges for a C&DW plan lie in surpassing economic, environmental, legal and organizational barriers. This study combines the extant tools for both siting C&DW processing facilities and optimizing the associated waste streams within one framework. This combined framework was then applied to examine the economic viability of using abandoned quarries for the processing of C&DW.

This work is innovative in the fact that it accounts for the complete waste management chain which is rarely found in the literature. In fact, the model figures the waste supply from the different sources, the different possible products, the various processing methods (recycling and landfilling) as well as the final destination, in this case the markets. More importantly, the model determines the solutions that maximize profits for the whole system while minimizing environmental damage. In addition, the solution can be tailored to stakeholders' preferences and a country's regulations. In fact, a GIS model helped select from the complete list of abandoned quarries, the set that satisfies stringent environmental constraints. Moreover, a MILP coded with Python and solved using Gurobi helped determine how the quarries from that set can be optimally managed and turned to processing facilities and landfills along with the corresponding flows in between. Since the GIS model can be exported to Python, both models were combined into one.

This designed model was then applied to the case of Lebanon, showing a profit across the 20 year span of the two selected quarries. If the model is applied in other locales and indicates that losses will be incurred, then the governing body in that locale will gain insight to the amount of subsidies that might be necessary to encourage recycling. Alternatively, an increase in the prices of the recycled products can be simulated to determine the effect. Furthermore, through simulation, the model can depict the breakeven prices to be charged. Appropriate scenario analysis to drive legislative policy and economic incentives such as reduced taxes will allow recycled aggregates to become a viable product.

Like every modelling work, this model is subject to several assumptions and simplifications imposed by runtime requirements or lack of data. These include the recurrence to modular units to represent the new capacities added, limiting thus the technology considered in the design and forcing a unique type of solution. Moreover, all rubble is assumed processable into intermediate-quality aggregates. However, the quality of the recycled aggregates is highly dependent on several factors such as the source and type of C&DW, as well as the age and condition of the structure. These factors also affect the processing costs, and hence the profitability of the system, which was not accounted for in this study. In addition, only cementitious materials are processed in this model. Other materials such as metals, plastics, organics, etc. are only separated and disposed of. In reality, these are to be recycled and reused as well. Also, the mapping of the C&DW supply origins into centroids considerably reduces the accuracy of the results obtained and excludes the possibility of using mobile plants. Furthermore, the supply and demand over the design period as well as the costs of labor and materials are subject to variations and errors due to surrounding circumstances such as technological breakthrough as well as economical and spatial developments. Last, the accuracy of the results is highly dependent on the accuracy of the data. Nonetheless, these discussed limitations can be addressed in future work.

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