Waste Management Planning Using Stochastic Population-Based Procedures

Julian Scott Yeomans (*)
OMIS Area, Schulich School of Business
York University, 4700 Keele Street
Toronto, ON, M3J 1P3 Canada

(*) Corresponding author

Abstract. When solving waste management (WM) problems, it is often preferable to consider a number of quantifiably good alternatives that provide multiple, disparate viewpoints. This is because solid waste planning generally involves complicated problems that are riddled with incompatible performance objectives and contain inconsistent design requirements that are very difficult to quantify and capture when supporting decision models must be constructed. These potential alternatives need to satisfy the required system performance criteria and yet be maximally different from each other in the decision space. The approach for creating maximally different sets of solutions is referred to as modelling-to-generate-alternatives (MGA). Simulation-optimization approaches have frequently been employed to solve computationally difficult problems containing the significant stochastic uncertainties in waste management. This paper outlines an MGA approach for WM planning that can generate sets of maximally different alternatives for any stochastic, simulation-optimization method that employs a population-based solution procedure. This algorithmic approach is both computationally efficient and simultaneously produces the prescribed number of maximally different solution alternatives in a single computational run of the procedure. The efficacy of this stochastic MGA approach for creating alternatives is demonstrated using a "real world" waste management planning case.

Keywords. Waste management, Population-based algorithms, Metaheuristics, Modelling-to-generate-alternatives, Simulation-Optimization

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1. Introduction

Planners have frequently been confounded by issues related to the processing and management of waste [1][2]. Implementing effective management of waste management (WM) systems has proven to be both notoriously contentious and conflict-laden. Since WM systems generally contain all of the characteristics associated with complex planning situations, waste management problems have provided an ideal backdrop for the testing of an extensive assortment of decision support techniques used for decision-making [3]-[5]. WM decision-making frequently possess inconsistent and incompatible design specifications that can be difficult to formulate into supporting mathematical decision-models [1]-[6]. This situation commonly occurs when final decisions must be constructed based not only upon clearly articulated specifications, but also upon environmental, political and socio-economic objectives that are either fundamentally subjective or not clearly articulated [7]-[10]. Although "optimal" solutions can be determined for the formulated mathematical models, whether these can be considered the best solution to the "real" problem remains somewhat dubious. Moreover, it may not be possible to explicitly convey many of the subjective considerations because there are numerous competing, adversarial stakeholder groups holding diametrically opposed perspectives. Therefore, many of the subjective aspects remain unknown, unquantified and unmodelled in the construction of the corresponding decision models. WM policy formulation can prove even more complicated when the various system components also contain stochastic uncertainties [10]. Consequently, waste management determination proves to be an extremely challenging and complicated enterprise [10][11].

Within WM decision-making, there are routinely many stakeholder groups holding completely incongruent standpoints, essentially dictating that waste managers need to construct decision frameworks that somehow simultaneously reflect numerous irreconcilable points of view. Under such circumstances, it is often more desirable to construct a small number of distinct alternatives that provide dissimilar viewpoints for the particular problem [3][7]. These dissimilar solutions should be close-to-optimal with respect to the specified objective(s), but be maximally different from each other within the decision domain. Numerous approaches collectively referred to as *modelling-to-generate-alternatives* (MGA) have been created to address this multi-solution requirement [6]-[8]. The principal motivation behind MGA is the production of a set of alternatives that are "good" with respect to the specified objective(s), but fundamentally dissimilar from each other in the decision space. Decision-makers then perform a subsequent appraisal of this set of alternatives to determine which option(s) most closely satisfy their specific goals. Consequently, MGA approaches are classified as decision support methods rather than as solution creation processes as assumed in traditional optimization.

Early MGA algorithms employed direct, incremental approaches for constructing their alternatives by iteratively re-running their procedures whenever new solutions needed to be generated [6]-[10]. These iterative approaches replicated the seminal MGA technique of Brill *et al*. [8] where, once the initial mathematical formulation has been optimized, all supplementary alternatives are produced one-at-a-time. Therefore, these approaches all required n+1 iterations of their respective algorithms – firstly to optimize the original problem, then to construct each of the n subsequent alternatives [7][11]-[18].

In this paper, it is demonstrated how a set of maximally different solution alternatives can be generated by extending several earlier MGA approaches to stochastic optimization [12-18]. The stochastic algorithm provides an MGA process that can be performed by *any* population-based solution mechanism. This algorithm advances earlier concurrent procedures [13][15]-[18] by permitting the simultaneous generation of n distinct alternatives in a single computational run. Specifically, to generate n maximally different alternatives, the algorithm runs exactly the same number of times that a function optimization procedure needs to run (i.e. once) irrespective of the value of n [19]-[23]. The objective function is used to produce a maximum distance between the alternatives by ensuring that the alternatives are forced as far apart as possible. Furthermore, the stochastic MGA algorithm employs a novel data structure that permits simultaneous alternatives to be constructed in a very computationally effective way. The use of this data structure enables the above-mentioned solution generalization to all population-based methods. Consequently, this stochastic MGA algorithmic approach proves to be extremely computationally efficient. The efficacy of this method for waste management is demonstrated using a "real world" WM case taken from [24] and [25].

2. Modelling to Generate Alternatives

Mathematical optimization has fixated almost entirely on determining single optimal solutions to single-objective problems or constructing sets of noninferior solutions for multi-objective formulations [2][5][8]. While these approaches may create solutions to the mathematical models, whether these outputs are the best solutions to the "real" problems remains can be debatable [1][2][6][8]. Within most "real world" decision-making environments, there are countless system requirements and objectives that will never be explicitly apparent or included in the model formulation [1][5]. Furthermore, most subjective aspects unavoidably remain unmodelled and unquantified in the decision models constructed. This regularly occurs where final decisions are constructed based not only on modelled objectives, but also on more subjective stakeholder goals and socio-political-economic preferences [7]. Several incongruent modelling dichotomies are discussed in [6][8]-[10].

When unmodelled objectives and unquantified issues exist, non-traditional methods are required for searching the decision region not only for noninferior sets of solutions, but also for alternatives that are evidently *sub-optimal* to the modelled problem. Namely, any search for alternatives to problems known or suspected to contain unmodelled components must concentrate not only on a non-inferior set of solutions, but also necessarily on an explicit exploration of the problem's inferior solution space.

To demonstrate the implications of unmodelled objectives in a decision search, assume that an optimal solution for a maximization problem is $\boldsymbol{X}^*$ with objective value $Z1^*$ [26]. Suppose a second, unquantified, maximization objective $Z2$ exists that represents some "politically acceptable" factor. Assume that the solution, $\boldsymbol{X}^{\boldsymbol{a}}$, belonging to the 2-objective noninferior set, exists that corresponds to a best compromise solution if both objectives could have been simultaneously considered. Although $\boldsymbol{X}^{\boldsymbol{a}}$ would be considered as the best solution to the real problem, in the actual mathematical model it would appear inferior to solution $\boldsymbol{X}^*$, since $Z1^{a} \leq Z1^*$. Therefore, when unquantified components are included in the decision-making process, inferior decisions to the mathematically modelled problem could be optimal to the underlying "real" problem. Thus, when unquantified issues and unmodelled objectives could exist, alternative solution procedures are required to not only explore the decision domain for noninferior solutions to the modelled problem, but also to concurrently search the decision domain for inferior solutions. Population-based algorithms prove to be proficient solution methods for concurrent searches throughout a decision space.

The objective of MGA is to construct a workable set of alternatives that are quantifiably good with respect to the modelled objectives, yet are as different as possible from each other within the solution space. By accomplishing this requirement, the resulting set of alternatives is able to provide truly different perspectives that perform similarly with respect to the known modelled objective(s) yet very differently with respect to various potentially unmodelled aspects. By creating these good-but-different solutions, the decision-makers are able to explore potentially desirable qualities within the alternatives that might be able to satisfy the unmodelled objectives to varying degrees of stakeholder acceptability.

To motivate the MGA process, it is necessary to more formally characterize the mathematical definition of its goals [6][7]. Assume that the optimal solution to an original mathematical model is $\boldsymbol{X}^*$ with corresponding objective value $\boldsymbol{Z}^* = F(\boldsymbol{X}^*)$. The resultant difference model can then be solved to produce an alternative solution, $\boldsymbol{X}$, that is maximally different from $\boldsymbol{X}$*:

$$\text{Maximize} \qquad \Delta(\boldsymbol{X}, \boldsymbol{X^*}) = \min_i |X_i - X_i^*| \tag{1}$$

$$\text{Subject to:} \qquad \boldsymbol{X} \in D \tag{2}$$

$$|F(\boldsymbol{X}) - \boldsymbol{Z^*}| \leq T \tag{3}$$

where Δ represents an appropriate difference function (shown in (1) as an absolute difference) and T is a tolerance target relative to the original optimal objective value $\boldsymbol{Z^*}$. T is a user-specified limit that determines what proportion of the inferior region needs to be explored for acceptable alternatives. This difference function concept can be extended into a difference measure between any *set of alternatives* by replacing $\boldsymbol{X}$* in the objective of the maximal difference model and calculating the overall minimum absolute difference (or some other function) of the pairwise comparisons between corresponding variables in each pair of alternatives – subject to the condition that each alternative is feasible and falls within the specified tolerance constraint.

The population-based MGA procedure to be introduced is designed to generate a pre-determined small number of close-to-optimal, but maximally different alternatives, by adjusting the value of T and solving the corresponding maximal difference problem instance by exploiting the population structure of the algorithm. The survival of solutions depends upon how well the solutions perform with respect to the problem's originally modelled objective(s) and simultaneously by how far away they are from all of the other alternatives generated in the decision space.

3. Simulation-Optimization for Stochastic Optimization

Finding optimal solutions to large stochastic problems proves complicated when numerous system uncertainties must be directly incorporated into the solution procedures [26]-[29]. *Simulation-Optimization* (SO) is a broadly defined family of stochastic solution approaches that combines simulation with an underlying optimization component for optimization [26]. In SO, all unknown objective functions, constraints, and parameters are replaced by simulation models in which the decision variables provide the settings under which simulation is performed.

The general steps of SO can be summarized in the following fashion ([27], [30]). Suppose the mathematical model of the optimization problem contains n decision variables, X_i, represented in the vector $\boldsymbol{X} = [X_1, X_2, \ldots, X_n]$. If the objective function is expressed by F and the feasible region is designated by D, then the mathematical programming problem is to optimize $F(\boldsymbol{X})$ subject to $\boldsymbol{X} \in D$. When stochastic conditions exist, values for the objective and constraints can be determined by simulation. Any solution comparison between two different solutions $\boldsymbol{X1}$ and $\boldsymbol{X2}$ requires the evaluation of some statistic of F modelled with $\boldsymbol{X1}$ compared to the same statistic modelled with $\boldsymbol{X2}$ [26][31]. These statistics are calculated by simulation, in which each $\boldsymbol{X}$ provides the decision variable settings employed in the simulation. While simulation provides a means for comparing results, it does not provide the mechanism for determining optimal solutions to problems. Hence, simulation cannot be used independently for stochastic optimization.

Since all measures of system performance in SO are stochastic, every potential solution, $\boldsymbol{X}$, must be calculated through simulation. Because simulation is computationally intensive, an optimization algorithm is employed to guide the search for solutions through the problem's feasible domain in as few simulation runs as possible [28][31]. As stochastic system problems frequently contain numerous potential solutions, the quality of the final solution could be highly variable unless an extensive search has been performed throughout the entire feasible region. A stochastic SO approach contains two alternating computational phases; (i) an "evolutionary" module directed by some optimization (frequently a metaheuristic) method and (ii) a simulation module [32]. Because of the stochastic components, all performance measures are necessarily statistics calculated from the responses generated in the simulation module. The quality of each solution is found by having its performance criterion, *F*, evaluated in the simulation module. After simulating each candidate solution, their respective objective values are returned to the evolutionary module to be utilized in the creation of ensuing candidate solutions. Thus, the evolutionary module aims to advance the system toward improved solutions in subsequent generations and ensures that the solution search does not become trapped in some local optima. After generating new candidate solutions in the evolutionary module, the new solution set is returned to the simulation module for comparative evaluation. This alternating, two-phase search process terminates when an appropriately stable system state (i.e. an optimal solution) has been attained. The optimal solution produced by the procedure is the single best solution found throughout the course of the entire search process [32].

Population-based algorithms are conducive to SO searches because the complete set of candidate solutions maintained in their populations permit searches to be undertaken throughout multiple sections of the feasible region, concurrently. For population-based optimization methods, the evolutionary phase evaluates the entire current population of solutions during each generation of the search and evolves from a current population to a subsequent one. A primary characteristic of population-based procedures is that better solutions in a current population possess a greater likelihood for survival and progression into the subsequent population.

It has been shown that SO can be used as a very computationally intensive, stochastic MGA technique [31][33]. However, because of the very long computational runs, several approaches to accelerate the search times and solution quality of SO have been examined subsequently [30]. The next section provides an MGA algorithm that incorporates stochastic uncertainty using SO to much more efficiently generate sets of maximally different solution alternatives.

4. Population-based Simulation-Optimization MGA Algorithm

In this section, a data structure is employed that enables an MGA solution approach via any population-based algorithm [34]-[36]. Suppose that it is desired to produce *P* alternatives that each possess *n* decision variables and that the population algorithm is to possess *K* solutions in total. That is, each solution contains one possible set of *P* maximally different alternatives. Let $\boldsymbol{Y}_k$, $k = 1,\ldots, K$, represent the k^{th} solution which consists of one complete set of *P* different alternatives. Specifically, if $\boldsymbol{X}_{kp}$ corresponds to the p^{th} alternative, $p = 1,\ldots, P$, of solution *k*, $k = 1,\ldots, K$, then $\boldsymbol{Y}_k$ can be represented as

$$\boldsymbol{Y}_k = [\boldsymbol{X}_{k1}, \boldsymbol{X}_{k2},\ldots, \boldsymbol{X}_{kP}]\ . \qquad (4)$$

If X_{kjq}, $q = 1,\ldots, n$, is the q^{th} variable in the j^{th} alternative of solution k, then

$$\boldsymbol{X}_{kj} = (X_{kj1}, X_{kj2},\ldots, X_{kjn})\ . \qquad (5)$$

Consequently, an entire population, $\boldsymbol{Y}$, consisting of *K* different sets of *P* alternatives can be written in vectorized form as,

$$\boldsymbol{Y'} = [\boldsymbol{Y}_1, \boldsymbol{Y}_2,\ldots, \boldsymbol{Y}_K]\ . \qquad (6)$$

The following population-based MGA method produces a pre-determined number of close-to-optimal, but maximally different alternatives, by modifying the value of the bound T in the maximal difference model and using any population-based method to solve the corresponding, maximal difference problem. The MGA algorithm that follows constructs a pre-determined number of maximally different, near-optimal alternatives, by modifying the bound value T in the maximal difference model and using any population-based technique to solve the corresponding maximal difference problem. Each solution in the population comprises one set of p different alternatives. By exploiting the co-evolutionary aspects of the algorithm, the algorithm evolves each solution toward sets of dissimilar local optima within the solution domain. In this processing, each solution alternative mutually experiences the search steps of the algorithm. Solution survival depends upon both how well the solutions perform with respect to the modelled objective(s) and by how far apart they are from every other alternative in the decision space.

A straightforward process for generating alternatives solves the maximum difference model iteratively by incrementally updating the target T whenever a new alternative needs to be produced and then re-solving the resulting model [34]. This iterative approach parallels the seminal Hop, Skip, and Jump (HSJ) MGA algorithm [8] in which the alternatives are created one-by-one through an incremental adjustment of the target constraint. While this approach is straightforward, it entails a repetitive execution of the optimization algorithm [7][12][13]. To improve upon the stepwise HSJ approach, a concurrent MGA technique was subsequently designed based upon co-evolution [13][15][17]. In a co-evolutionary approach, pre-specified stratified subpopulation ranges within an algorithm's overall population are established that collectively evolve the search toward the specified number of maximally different alternatives. Each desired solution alternative is represented by each respective subpopulation and each subpopulation undergoes the common processing operations of the procedure. The survival of solutions in each subpopulation depends simultaneously upon how well the solutions perform with respect to the modelled objective(s) and by how far away they are from all of the other alternatives. Consequently, the evolution of solutions in each subpopulation toward local optima is directly influenced by those solutions contained in all of the other subpopulations, which forces the concurrent co-evolution of each subpopulation towards good but maximally distant regions within the decision space according to the maximal difference model [7]. Co-evolution is also much more efficient than a sequential HSJ-style approach in that it exploits the inherent population-based searches to concurrently generate the entire set of maximally different solutions using only a single population [12][17].

While concurrent approaches can exploit population-based algorithms, co-evolution can only occur within each of the stratified subpopulations. Consequently, the maximal differences between solutions in different subpopulations can only be based upon aggregate subpopulation measures. Conversely, in the following simultaneous MGA algorithm, each solution in the population contains exactly one entire set of alternatives and the maximal difference is calculated only for that particular solution (i.e. the specific alternative set contained within that solution in the population). Hence, by the evolutionary nature of the population-based search procedure, in the subsequent approach, the maximal difference is simultaneously calculated for the specific set of alternatives considered within each specific solution – and the need for concurrent subpopulation aggregation measures is avoided.

Using the data structure terminology, the steps for the population-based MGA algorithm are as follows [14][19]-[23][34]-[38]. It should be readily apparent that the stratification approach employed by this method can be easily modified for any population-based algorithm.

Initialization Step. Solve the original optimization problem to find its optimal solution, $\boldsymbol{X^*}$.

Based upon the objective value $F(\boldsymbol{X^*})$, establish P target values. P represents the desired number of maximally different alternatives to be generated within prescribed target deviations from the $\boldsymbol{X^*}$. Note: The value for P has to have been set *a priori* by the decision-maker.

Without loss of generality, it is possible to forego this step and to use the algorithm to find $\boldsymbol{X^*}$ as part of its solution processing in the subsequent steps. However, this significantly increases the number of iterations of the computational procedure and the initial stages of the processing become devoted to finding $\boldsymbol{X^*}$ while the other elements of each population solution are retained as essentially "computational overhead".

Step 1. Create an initial population of size K where each solution contains P equally-sized partitions. The partition size corresponds to the number of decision variables in the original optimization problem. $\boldsymbol{X_{kp}}$ represents the p^{th} alternative, $p = 1,\ldots,P$, in solution $\boldsymbol{Y_k}$, $k = 1,\ldots,K$.

Step 2. In each of the K solutions, evaluate each $\boldsymbol{X_{kp}}$, $p = 1,\ldots,P$, using the simulation module with respect to the modelled objective. Alternatives meeting their target constraint and all other problem constraints are designated as *feasible*, while all other alternatives are designated as *infeasible*. A solution can only be designated as feasible if all of the alternatives contained within it are feasible.

Step 3. Apply an appropriate elitism operator to each solution to rank order the best individuals in the population. The best solution is the feasible solution containing the most distant set of alternatives in the decision space (the distance measures are defined in Step 5).

Note: Because the best solution to date is always retained in the population throughout each iteration, at least one solution will always be feasible. A feasible solution for the first step can always consists of P repetitions of $\boldsymbol{X^*}$.

Step 4. Stop the algorithm if the termination criteria (such as maximum number of iterations or some measure of solution convergence) are met. Otherwise, proceed to Step 5.

Step 5. For each solution $\boldsymbol{Y}_k$, $k = 1,\ldots, K$, calculate D^1_k which represents the Max-Sum distance measure determined between all of the alternatives contained within the solution.

As an illustrative example for calculating a distance measure, compute

$$D^1_k = \Delta^1(\boldsymbol{X}_{ka}, \boldsymbol{X}_{kb}) = \operatorname*{Min}_{a,b,q} |X_{kaq} - X_{kbq}|, \quad a = 1,\ldots,P,\ b = 1,\ldots,P,\ q = 1,\ldots,n, \qquad (7)$$

D^1_k denotes the minimum absolute deviation between all of the alternatives contained within solution k. Alternatively, the distance function could be calculated using some other appropriately defined measure.

Step 6. This step orders the specific solutions by those solutions which contain the set of alternatives which are most distant from each other. The goal of maximal difference is to force alternatives to be as far apart as possible in the decision space from the alternatives of each of the partitions within each solution.

Let $D_k = G(D^1_k)$ represent the objective for solution k. Rank the solutions according to the distance measure D_k objective – appropriately adjusted to incorporate any constraint violation penalties for infeasible solutions.

Step 7. Apply applicable algorithmic "change operations" to each solution within the population and return to Step 2.

5. Waste Management Case Study

As indicated throughout the previous sections, WM decision-makers faced with situations containing numerous uncertainties often prefer to select from a set of “near best” alternatives that differ significantly from each other in terms of the system structures characterized by their decision variables. The efficacy of the stochastic, population-based MGA procedure will be illustrated using the WM case of Hamilton-Wentworth taken from [24] and [25]. While this section briefly summarizes the case, more explicit details, data, and descriptions can be found in [24].

Located at the Western-most edge of Lake Ontario, the Municipality of Hamilton-Wentworth covers an area of 1,100 square kilometers and includes six towns and cities; Hamilton, Dundas, Ancaster, Flamborough, Stoney Creek, and Glanbrook. The Municipality is considered the industrial centre of Canada, although it simultaneously incorporates diverse areas of not only heavy industrial production, but also densely populated urban space, regions of significant suburban development, and large proportions of rural/agricultural environments. Prior to the study of Yeomans *et al*. [24], the municipality had not been able to effectively incorporate inherent uncertainties into their planning processes and, therefore, had not performed effective systematic planning for the flow of wastes within the region. The WM system within the region is a very complicated process which is affected by economic, technical, environmental, legislational and political factors.

The WM system within Hamilton-Wentworth needs to satisfy the waste disposal requirements of its half-million residents who, collectively, produce more than 300,000 tons of waste per year, with a budget of $22 million. The region had constructed a system to manage these wastes composed of: a waste-to-energy incinerator referred to as the Solid Waste Reduction Unit (or SWARU); a 550 acre landfill site at Glanbrook; three waste transfer stations located in Dundas (DTS), in East Hamilton at Kenora (KTS), and on Hamilton Mountain (MTS); a household recycling program contracted to and operated by the Third Sector Employment Enterprises; a household/hazardous waste depot, and; a backyard composting program.

The three transfer stations have been strategically located to receive wastes from the disparate municipal (and individual) sources and to subsequently transfer them to the waste management facilities for final disposal; either to SWARU for incineration or to Glanbrook for landfilling. Wastes received at the transfer stations are compacted into large trucks prior to being hauled to the landfill site. These transfer stations provide many advantages in waste transportation and management; these include reducing traffic going to and from the landfill, providing an effective control mechanism for dumping at the landfill, offering an inspection area where wastes can be viewed and unacceptable materials removed, and contributing to a reduction of waste volume because of the compaction process. The SWARU incinerator burns up to 450 tons of waste per day and, by doing so, generates about 14 million kilowatt hours of electricity per year which can be either used within the plant itself or sold to the provincial electrical utility. SWARU also produces a residual waste ash which must subsequently be transported to the landfill for disposal.

Within this WM system, decisions have to be made regarding whether waste materials should be recycled, landfilled or incinerated and additional determinations have to be made as to which specific facilities would process the discarded materials. Included within these decisions is a determination of which one of the multiple possible pathways that the waste would flow through in reaching the facilities. Conversely, specific pathways selected for waste material flows determine which facilities process the waste. It was possible to subdivide the various waste streams with each resulting substream sent to a different facility. Since cost differences from operating the facilities at different capacity levels produced economies of scale, decisions have to be made to determine how much waste should be sent along each flow pathway to each facility. Therefore, any single WM policy option is composed of a combination of many decisions regarding which facilities received waste material and what quantities of waste are sent to each facility. All of these decisions are compounded by overriding system uncertainties. The complete mathematical model used for WM planning appears subsequently. This mathematical formulation was used not only to examine the existing municipal WM system, but also to prepare the municipality for several potentially enforced future changes to its operating conditions.

Yeomans *et al*. [24] examined three likely future scenarios, with each scenario involving potential incinerator operations. Scenario 1 considered the existing WM system and corresponded to a *status quo* case. Scenario 2 examined what would occur should the incinerator operate at its upper design capacity; corresponding to a situation in which the municipality would landfill as little waste as possible. Scenario 3 permitted the incinerator to operate anywhere in its design capacity range; from being closed completely to operating up to its maximum capacity.

In the complete mathematical model for WM planning in Hamilton-Wentworth [24], any uncertain parameter A is represented by $\vec{A}$. In the model, the various districts from which waste originates will be identified using subscript i; where i = 1, 2,…, 17 denotes the originating district. The transfer stations will be denoted by subscript j, in which j = 1, 2, 3 represents the number assigned to each transfer station, where DTS = 1, KTS = 2, and MTS = 3. Subscript k, k = 1, 2, 3, identifies the specific waste management facility, with Landfill = 1, SWARU = 2, and Third Sector = 3. The decision variables for the problem will be designated by x_{ij}, y_{jk} and z_{ik} where x_{ij} represents the proportion of solid waste sent from district i to transfer station j; y_{jk} corresponds to the proportion of waste sent from transfer station j to waste management facility k, and z_{ik} corresponds to the proportion of waste sent from district i to waste management facility k. For notational brevity, and also to reflect the fact that no district is permitted to deliver their waste directly to the landfill, define $z_{i1} = 0$, for i = 1, 2,…, 17.

The cost for transporting one ton of waste from district i to transfer station j is denoted by $\vec{t}x_{ij}$, that from transfer station j to waste management facility k is represented by $\vec{t}y_{jk}$, and that from district i to waste management facility k is $\vec{t}z_{ik}$. The per ton cost for processing waste at transfer station j is $\vec{\delta}_j$ and that at waste management facility k is $\vec{\rho}_k$. Two of the waste management facilities can produce revenues from processing wastes. The revenue generated per ton of waste is $\vec{r}_2$ at SWARU and $\vec{r}_3$ at the Third Sector recycling facility. The minimum and maximum processing capacities at transfer station j are $\vec{K}_j$ and $\vec{M}_j$, respectively. Similarly, the minimum and maximum capacities at waste management facility k are $\vec{L}_k$ and $\vec{N}_k$, respectively. The quantity of waste, in tons, generated by district i is $\vec{W}_i$, and the proportion of this waste that is recyclable is $\vec{a}_i$. The proportion of recyclable waste flowing into transfer station j is $\vec{R}W_j$. The proportion of residue (residual wastes such as the incinerated ash at SWARU) generated by waste management facility j is $\vec{Q}_j$, where $\vec{Q}_1$ = 0 by definition. This waste residue must be shipped to the landfill for final disposal.

Formulating any single WM policy corresponds to finding a decision variable solution satisfying constraints (9) through (38), with cost determined by objective (8) [24].

$$\text{Minimize Cost} = \sum_{p=1}^{5} T_p + \sum_{q=1}^{6} P_q - \sum_{r=2}^{3} R_r \tag{8}$$

Subject to:

$$T_1 = \sum_{i=1}^{17} \sum_{j=1}^{3} \overleftrightarrow{tx}_{ij}\, x_{ij}\, \overleftrightarrow{W}_i \tag{9}$$

$$T_2 = \sum_{i=1}^{17} \sum_{k=1}^{3} \overleftrightarrow{tz}_{ik}\, z_{ik}\, \overleftrightarrow{W}_i \tag{10}$$

$$T_3 = \sum_{i=1}^{17} \sum_{j=1}^{3} \sum_{k=1}^{3} \overleftrightarrow{ty}_{jk}\, y_{jk}\, x_{ij}\, \overleftrightarrow{W}_i \tag{11}$$

$$T_4 = (\overleftrightarrow{tsl})\, \overleftrightarrow{Q}_2 \sum_{i=1}^{17} \overleftrightarrow{W}_i [\, z_{i2} + \sum_{j=1}^{3} y_{j2}\, x_{ij}\,] \tag{12}$$

$$T_5 = (\overleftrightarrow{ttl})\, \overleftrightarrow{Q}_3 \sum_{i=1}^{17} \overleftrightarrow{W}_i [\, z_{i3} + \sum_{j=1}^{3} y_{j3}\, x_{ij}\,] \tag{13}$$

$$P_1 = \overleftrightarrow{\rho}_1 \sum_{i=1}^{17} \overleftrightarrow{W}_i \sum_{k=1}^{3} [\, \overleftrightarrow{Q}_k\, z_{ik} + \sum_{j=1}^{3} x_{ij}\, y_{jk}\,] \tag{14}$$

$$P_2 = \overleftrightarrow{\rho}_2 \sum_{i=1}^{17} \overleftrightarrow{W}_i [\, z_{i2} + \sum_{j=1}^{3} x_{ij}\, y_{j2}\,] \tag{15}$$

$$P_3 = \overleftrightarrow{\rho}_3 \sum_{i=1}^{17} \overleftrightarrow{W}_i [\, z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3}\,] \tag{16}$$

$$P_4 = \overleftrightarrow{\delta}_1 \sum_{i=1}^{17} x_{i1}\, \overleftrightarrow{W}_i \tag{17}$$

$$P_5 = \overleftrightarrow{\delta}_2 \sum_{i=1}^{17} \overleftrightarrow{W}_i [\, x_{i2} + \overleftrightarrow{Q}_3 \{\, z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3} \}] \tag{18}$$

$$P_6 = \overleftrightarrow{\delta}_3 \sum_{i=1}^{17} x_{i3}\, \overleftrightarrow{W}_i \tag{19}$$

$$R_2 = \overleftrightarrow{r}_2 \sum_{i=1}^{17} \overleftrightarrow{W}_i [\, z_{i2} + \sum_{j=1}^{3} x_{ij}\, y_{j2}\,] \tag{20}$$

$$R_3 = \overleftrightarrow{r}_3 \sum_{i=1}^{17} \overleftrightarrow{W}_i [\, z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3}\,] \tag{21}$$

$$\sum_{i=1}^{17} x_{i1}\, \overleftrightarrow{W}_i \le \overleftrightarrow{M}_1 \tag{22}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i [x_{i2} + \overleftrightarrow{Q}_3 \{z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3}\}] \le \overleftrightarrow{M}_2 \tag{23}$$

$$\sum_{i=1}^{17} x_{i3} \overleftrightarrow{W}_i \le \overleftrightarrow{M}_3 \tag{24}$$

$$\sum_{i=1}^{17} x_{i1} \overleftrightarrow{W}_i \ge \overleftrightarrow{K}_1 \tag{25}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i [x_{i2} + \overleftrightarrow{Q}_3 \{z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3}\}] \ge \overleftrightarrow{K}_2 \tag{26}$$

$$\sum_{i=1}^{17} x_{i3} \overleftrightarrow{W}_i \ge \overleftrightarrow{K}_3 \tag{27}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i \sum_{k=1}^{3} [\overleftrightarrow{Q}_k\, z_{ik} + \sum_{j=1}^{3} x_{ij}\, y_{jk}] \le \overleftrightarrow{N}_1 \tag{28}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i [z_{i2} + \sum_{j=1}^{3} x_{ij}\, y_{j2}] \le \overleftrightarrow{N}_2 \tag{29}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i [z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3}] \le \overleftrightarrow{N}_3 \tag{30}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i [z_{i2} + \sum_{j=1}^{3} x_{ij}\, y_{j2}] \ge \overleftrightarrow{L}_2 \tag{31}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i [z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3}] \ge \overleftrightarrow{L}_3 \tag{32}$$

$$\sum_{j=1}^{3} x_{ij} + \sum_{k=1}^{3} z_{ik} = 1 \qquad i = 1,2,\ldots,17 \tag{33}$$

$$\sum_{j=1}^{3} x_{ij}\, \overleftrightarrow{R}W_j + z_{i3} \le \overleftrightarrow{a}_i \qquad i = 1,2,\ldots,17 \tag{34}$$

$$\sum_{k=1}^{3} y_{jk} = 1 \qquad j = 1,2,3 \tag{35}$$

$$\sum_{i=1}^{17} \overleftrightarrow{W}_i [x_{i2} + \overleftrightarrow{Q}_3 \{z_{i3} + \sum_{j=1}^{3} x_{ij}\, y_{j3}\}] = \sum_{i=1}^{17} \sum_{k=1}^{3} x_{i2} \overleftrightarrow{W}_i\, y_{2k} \tag{36}$$

$$\sum_{i=1}^{17} x_{ij} \overleftrightarrow{W}_i\, y_{j3} = \overleftrightarrow{R}W_j \sum_{i=1}^{17} x_{ij} \overleftrightarrow{W}_i \qquad j = 1,2,3 \tag{37}$$

$$x_{ij} \ge 0,\ y_{jk} \ge 0,\ z_{ik} \ge 0 \qquad i = 1,2,\ldots,17,\ j = 1,2,3,\ k = 1,2,3 \tag{38}$$

In the objective function (8), the total transportation costs for wastes generated are provided by equations (9) to (13). Equation (9) calculates the transportation costs for waste flows from the districts (i.e. the cities and towns) to the transfer stations, while equation (10) provides the costs for transporting the waste from the districts directly to the waste management facilities. The total cost for transporting waste from the transfer facilities to the waste management facilities is determined in equation (11). The transportation costs for residue disposal created at SWARU and the Third Sector are given by equations (12) and (13), respectively. The total processing costs for the transfer stations and waste management facilities are expressed in (14) through (19). Here, P_k represents the processing costs at waste management facility *k*, *k* = 1,2,3, and $P_{(j+3)}$ represents the processing costs at transfer station *j*, *j* = 1,2,3. The processing cost, P_1, in (14) indicates that the landfill receives wastes from both SWARU and the Third Sector in addition to the waste sent from the transfer stations. The relationship specifying the processing costs at KTS, P_5 in (18), is more complicated than for DTS and MTS, since KTS must also process the Third Sector's unrecyclable residue (this waste processing pattern can also be observed in equations (23) and (26)) and this residue may have been sent there directly from the districts or from the other transfer stations. The revenue generated by SWARU, R_2, and by the Third Sector, R_3, are determined by expressions (20) and (21). All of these cost and revenue elements are amalgamated into objective function (8).

Upper and lower capacity limits placed upon the transfer stations DTS, KTS and MTS, are provided by constraints (22) through (27), while capacity limits established for the landfill, SWARU and the Third Sector are given by (28) to (32). The waste processing relationship for the landfill is more complicated than for the other waste management facilities, since the landfill receives residue from both SWARU and the Third Sector. Furthermore, while there is no lower operating requirement placed upon the use of the landfill, both SWARU and the Third Sector require minimum levels of activity in order for their ongoing operations to remain economically viable. Mass balance constraints must also be included to ensure that all generated waste is disposed and that the amount of waste flowing into a transfer facility matches the amount flowing out of it. Constraint (33) ensures the disposal of all waste produced by each district. Recyclable waste disposal is established by constraint (34). In (34), it is recognized that not all recyclable waste produced at a district is initially sent to the Third Sector recycling facility (i.e. some recyclable waste may initially be discarded as "regular" garbage) and that some, but not all, recyclable waste received at a transfer station is subsequently sent for recycling. The expression in (35) ensures that all waste received by each transfer station must be sent to a waste management facility. Equation (36) provides the mass balance constraint for the wastes entering and leaving KTS (which handles more complicated waste patterns than the other two transfer stations). Constraint (37) describes the mass balance requirement for recyclable wastes received by the transfer stations that are then forwarded to the Third Sector. Finally, (38) establishes non-negativity requirements for the decision variables. Hence, any specific WM policy formulated for Hamilton-Wentworth would require the determination of a decision variable solution that satisfies constraints (9) to (38) and would be evaluated by its resulting cost found using objective (8).

Yeomans *et al*. [24] ran SO for a 24-hour period to determine best solutions for each scenario. For the existing system (Scenario 1), a solution that would never cost more than $20.6 million was constructed. For Scenarios 2 and 3, Yeomans *et al*. [24] produced optimal solutions costing $22.1 million and $18.7 million, respectively. In all of these scenarios, SO was used exclusively as a function optimizer with the goal being to produce only single best solutions.

As noted, WM planners faced with difficult and controversial selections generally prefer to choose from a set of near-optimal alternatives that differ significantly from each other in terms of the system structures characterized by their decision variables [37]. In order to create these alternative planning options for the three WM system scenarios, it would be possible to place extra target constraints into the original model which would force the generation of solutions that were different from their respective, initial optimal solutions. Suppose for example that four additional planning alternative options were created through the inclusion of a technical constraint on the objective function that increased the total system cost of the original model from 2.5% up to 10% in increments of 2.5%. By adding these incremental target constraints to the original SO model and sequentially resolving the problem 4 more times for each scenario (i.e. another 12 additional computational runs of the SO procedure), it would be possible to create a specific number of alternative policies for WM planning [37][38].

However, to improve upon the process of running fifteen separate instances of the computationally intensive SO algorithm to generate these solutions, the population-based MGA procedure described in the previous section was run only once, thereby producing the 15 alternatives shown in Table 1. Each column of the table shows the overall system costs for the 5 maximally different options generated for each of the three scenarios. Given the performance bounds established for the objective in each problem instance, the decision-makers can feel reassured by the stated performance for each of these options while also being aware that the perspectives provided by the set of dissimilar decision variable structures are as different from each other as is feasibly possible. Hence, if there are stakeholders with incompatible standpoints holding diametrically opposing viewpoints, the policy-makers can perform an assessment of these different options without being myopically constrained by a single overriding perspective based solely upon the objective value.

Annual WM Costs	**Scenario 1**	**Scenario 2**	**Scenario 3**
Best Solution Found	20.61	22.10	18.71
Best Solution Within 2.5%	20.99	22.88	18.89
Best Solution Within 5.0%	21.31	23.01	19.47
Best Solution Within 7.5%	22.28	23.62	19.92
Best Solution Within 10%	22.65	24.17	20.66

Table 1 Annual WM Costs ($ Millions) for 5 Maximally Different Alternatives for Scenario1, Scenario 2 and Scenario 3

Although a mathematically optimal solution may not provide the best approach to the real problem, it can be shown that the MGA procedure does indeed produce very good solution values for the originally modelled problem, itself. Table 2 clearly highlights how the “Best Solution Found” by the MGA procedure for each scenario are each identical to the ones found by function optimization alone in [24]. This implies that the MGA approach can essentially be used for direct optimization of a problem in conjunction with its alternative generation tasks.

	Scenario 1	Scenario 2	Scenario 3
Yeomans *et al*. (2003) using SO	20.6	22.1	18.7
Best Solution Found using MGA	20.6	22.1	18.7

Table 2 Best Annual WM Costs ($ millions) for (i) Existing System (Scenario 1), (ii) Incinerator at Maximum Capacity (Scenario 2), and (iii) Incinerator at Any Level (Scenario 3)

The computational example highlights several important aspects with respect to the MGA approach: (i) Population-based algorithms can be effectively employed as the underlying solution search procedure for SO routines; (ii) Population-based solution searches can simultaneously generate more good alternatives than planners would be able to create using other MGA approaches; (iii) By the design of the MGA algorithm, the alternatives generated are good for planning purposes since all of their structures are guaranteed to be as mutually and maximally different from each other as possible; (iv) The approach is very computationally efficient since it need be run only once to generate its entire set of multiple, good solution alternatives (i.e. to generate *n* maximally different solution alternatives, the MGA algorithm would run exactly the same number of times that the SO would need to be run for function optimization purposes alone – namely once – irrespective of the value of *n*); and, (v) The best overall solutions produced by the MGA procedure will be identical to the best overall solutions that would be produced for function optimization purposes alone.

6. Conclusions

Waste management problems contain multidimensional performance specifications which inevitably include incongruent performance objectives and unquantifiable modelling features. These problems also often possess incompatible design specifications which are impossible to completely formulate into the supporting decision models. Consequently, there are unmodelled problem components, generally not apparent during model construction, that can significantly influence the acceptability of any model's solutions. These competing and ambiguous components force WM decision-makers to incorporate many conflicting requirements into their decision process prior to the final solution determination. Consequently, waste management decision-makers generally prefer to select from a set of distinct planning perspectives.

This paper has employed a computationally efficient population-based stochastic MGA procedure for WM planning. This MGA approach establishes how population-based algorithms can simultaneously construct entire sets of near-optimal, maximally different alternatives by exploiting the evolving solution characteristics in population-based solution algorithms. In an MGA role, the employed objective can efficiently generate the requisite set of dissimilar alternatives, with each generated solution suggesting an entirely different perspective to the problem. Since population-based algorithms can be extended to an eclectic variety of problem settings, the practicality of this stochastic MGA method can be used on a diverse spectrum of "real world" applications. These extensions will be considered in future studies.

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