

## **Abstract**

CHETAN, SRIGIRIRAJU, KISHAN. Noninferior Surface Tracing Evolutionary Algorithm (NSTEA) for Multi Objective Optimization (Under the direction of Dr. S. Ranjithan.)

Evolutionary algorithms are becoming increasingly valuable in solving large-scale, realistic engineering problems. Most of these problems deal with sufficiently complex issues that typically conflict with each other, thus requiring multi objective (MO) analyses to assist in identifying compromise solutions. The focus of this paper is to develop and test a new multi objective evolutionary algorithm (MOEA). The new procedure, Noninferior Surface Tracing Evolutionary Algorithm (NSTEA), builds upon two fundamental concepts that are established in the mathematical programming literature for MO analysis. Implicit implementation of Pareto optimality and beneficial seeding of initial population are instrumental in the improved performance. NSTEA was evaluated by solving a suite of test problems reported in the MOEA literature. Performance with respect to accuracy, coverage, and spread of noninferior solutions generated by NSTEA is evaluated and compared with those of solutions generated by four other MOEAs that are widely accepted. Also, in some cases, comparisons are made with noninferior sets generated using mathematical programming techniques. Overall, NSTEA performs relatively better than the other MOEAs when tested on these problems. Application and performance evaluation of NSTEA in solving a real-world MO engineering optimization problem was also conducted. In comparison to published mathematical programming-based noninferior solutions, the NSTEA solutions performed

well. In summary, this paper contributes to the MOEA literature by presenting NSTEA as a good alternative evolutionary algorithm-based multi objective method that is relatively simple to implement and to incorporate into existing implementations of evolutionary algorithm-based optimization procedures.

**Noninferior Surface Tracing Evolutionary Algorithm  
(NSTEA) for Multi Objective Optimization**

**by**

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## **Biography**

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## 1 Introduction

Most real world engineering decision making problems, especially those that involve public sector issues, require consideration of a multitude of conflicting design objectives. Although many of these objectives can be represented sufficiently well to allow quantitative analysis, incorporating them into a decision making process requires multiobjective (MO) modeling and optimization. Unlike single objective problems for which the optimal solutions are sought, the multiobjective problems require the consideration of noninferior tradeoffs among competing objectives to help identify best compromise solutions. This information is potentially useful to decision makers in eliminating inferior solutions from consideration, facilitating an efficient search for solutions that really matter with respect to the defined objectives. Generation of tradeoff information in the form of a noninferior, or Pareto optimal set, of solutions within a region of interest in the objective space is the main goal of multiobjective analysis.

An array of multiobjective evolutionary algorithms (MOEAs) has been reported since the early eighties. Detailed summaries of the state-of-the-art in MOEA were discussed recently by Coello (1999a) and Van Veldhuizen and Lamont (2000), and are also represented in the special issue of *Evolutionary Computation* (Vol. 8, No. 2, Summer 2000) on multi criterion optimization (also see Coello (1999b) for an archive of bibliography). Within standard mathematical programming frameworks, the constraint method and weighting method are two commonly used techniques for generating noninferior sets (Cohon, 1978). In the constraint method, one objective is optimized while constraining the others to target levels to identify a noninferior solution. Alternatively, an aggregate objective function, defined as a linearly weighted sum of all objective functions, is optimized in the weighting method.

The underlying Pareto-optimality concepts of these MO methods are general, and can be applied within any evolutionary algorithm (EA) framework as well as within mathematical programming techniques for optimization. Solving a number of independent single objective optimization models to obtain a set of noninferior solutions, however, renders these MO methods less attractive if each model solution is computationally intensive to obtain. This issue is addressed in some mathematical programming approaches (e.g., linear programming, nonlinear programming, integer programming) by seeding a search for a new noninferior solution with a previously generated adjacent noninferior solution. The first noninferior solution can be the optimal solution for any one of the objectives. Any efficiency gain is predicated on the notion that for some class of problems noninferior solutions adjacent in the decision space map to adjacent points in the objective space.

This paper describes the development of the Noninferior Surface Tracing Evolutionary Algorithm (NSTEA), which explicitly uses this adjacency mapping property to its advantage within an MOEA framework. The underlying simple concepts in NSTEA allow it to be adapted easily into existing implementations of evolutionary algorithms for single objective optimization, as well as to eliminate the computational need for iterative sorting and pair-wise comparison that are required when determining Pareto optimality. Starting with a general representation of a standard MO problem, brief descriptions of a four commonly accepted MOEAs that are used for performance comparison in this paper are provided in the next section. The details of NSTEA are then described, followed by a performance comparison of NSTEA and the other MOEAs in solving a suite of published test problems. Where possible, the noninferior solutions are also compared to those obtained via mathematical programming techniques. An application of

NSTEA to a real world problem in environmental management is also presented. Finally, concluding remarks are made with a brief discussion of NSTEA's strengths and weaknesses.

## 2 Background

### 2.1 A standard multiobjective optimization problem

A multiobjective problem consisting of  $k$  objectives and  $m$  constraints defined as functions of decision variable set  $\mathbf{x}$  can be represented, without loss of generality, as follows:

$$\text{Maximize } \mathbf{Z}(\mathbf{x}) = \{Z_l(\mathbf{x}): l=1,2, \dots, k\} \quad (1)$$

$$\text{S.T. } g_i(\mathbf{x}) \leq 0 \quad \forall i = 1,2,\dots,m \quad (2)$$

$$\mathbf{x} \in \mathbf{X} \quad (3)$$

where  $\mathbf{x} = \{x_j : j = 1,2,\dots,n\}$  represents the decision vector,  $x_j$  is the  $j^{\text{th}}$  decision variable,  $\mathbf{X}$  represents the decision space,  $g_i(\mathbf{x})$  is the  $i^{\text{th}}$  constraint,  $\mathbf{Z}(\mathbf{x})$  is the multiobjective vector, and  $Z_l(\mathbf{x})$  is the  $l^{\text{th}}$  objective function.

### 2.2 Noninferiority

Noninferiority (which is also referred as nondominance or Pareto optimality) of a multiobjective solution is formally defined as follows (Cohon, 1978): a feasible solution to a multiobjective problem is non-inferior if there exists no other feasible solution that will yield an improvement in one objective without causing a degradation in at least one other objective.

More rigorous definitions of this and related MO terminology are given by Van Veldhuizen and Lamont (2000) and Zitzler et al. (2000). Based on the definitions by Van Veldhuizen and Lamont (2000) and notations used in Equations 1-3, the following are defined:

**Pareto Dominance:** A multiobjective vector  $\mathbf{u} = (u_1, u_2, \dots, u_k)$  is said to dominate  $\mathbf{v} = (v_1, v_2, \dots, v_k)$  (denoted by  $\mathbf{u} \succeq \mathbf{v}$ ) if and only if  $\mathbf{u}$  is partially more than  $\mathbf{v}$ , i.e.,  $\forall i \in \{1, 2, \dots, k\}, u_i \geq v_i \wedge \exists i \in \{1, 2, \dots, k\} : u_i > v_i$ .

**Pareto Optimality:** A solution  $\mathbf{x} \in \mathbf{X}$  is said to be Pareto optimal with respect to  $\mathbf{X}$  if and only if there exists no  $\mathbf{x}' \in \mathbf{X}$  for which  $\mathbf{v} = \mathbf{Z}(\mathbf{x}')$  dominates  $\mathbf{u} = \mathbf{Z}(\mathbf{x})$ .

**Pareto Optimal Set:** For a given multiobjective problem  $\mathbf{Z}(\mathbf{x})$ , the Pareto optimal set  $\mathbf{P}^*$  is a set consisting of Pareto optimal solutions.  $\mathbf{P}^*$  is a subset of all the possible solutions in  $\mathbf{X}$ .

Mathematically,  $\mathbf{P}^*$  is defined as follows:

$$\mathbf{P}^* := \{ \mathbf{x} \in \mathbf{X} \mid \neg \exists \mathbf{x}' \in \mathbf{X} : \mathbf{Z}(\mathbf{x}') \succeq \mathbf{Z}(\mathbf{x}) \} \quad (4)$$

**Pareto Front:** The Pareto front,  $\mathbf{PF}^*$  is the set that contains the evaluated objective vectors of  $\mathbf{P}^*$ .

Mathematically  $\mathbf{PF}^*$  is defined as:

$$\mathbf{PF}^* := \{ \mathbf{u} = \mathbf{Z}(\mathbf{x}) \mid \mathbf{x} \in \mathbf{P}^* \} \quad (5)$$

### 2.3 Evolutionary algorithms for multiobjective optimization

Since the pioneering work by Schaffer (1984, 1985) in the area of EAs for MO optimization, development of MOEAs has taken multiple directions. Detailed surveys of these techniques are catalogued by Fonesca and Fleming (1993, 1995), Horn (1997), Coello (1999a, 1999b), and Van Veldhuizen and Lamont (2000). Many different bases (such as differences in fitness and selection implementations) for higher level classification of MOEAs are used in these

surveys. For example, Schaffer's (1985) vector evaluated genetic algorithm (VEGA) uses a special single-objective-based preferential selection procedure, the method by Hajela and Lin (1992) uses an aggregated fitness function, and the methods by Horn et al. (1994), Srinivas and Deb (1994), Zitzler and Thiele (1999), and Knowles and Corne (2000) use Pareto-based selection procedures to determine the noninferior set. In addition, these techniques can be categorized by special operators, such as niching and sharing (e.g., Horn et al., 1994; Menczer et al., 2000), restrictive mating (e.g., Loughlin and Ranjithan, 1997), and elitism (e.g., Knowles and Corne, 2000; Zitzler and Thiele, 1999). An EA-based approach presented more recently by Loughlin et al. (2000a) addresses problems with conflicting objectives where some may not be easily quantified or modeled. A wide range of applications (e.g., Hajela and Lin, 1992; Ritzel et al., 1994; Cieniawski et al., 1995; Jimenez and Cadenas, 1995; Harrell and Ranjithan, 1997; Coello et al., 1998; Coello and Christiansen, 2000; Loughlin et al., 2000b; Obayashi et al., 2000) of MOEAs in solving realistic MO engineering problems have also been reported. All existing MOEAs are not described in this paper, but brief discussions are provided below for selected MOEAs that are used to compare the performance of NSTEA proposed in this paper.

### **2.3.1 Vector Evaluated Genetic Algorithm (VEGA)**

VEGA (Schaffer, 1985) was the first reported MOEA that exploited the population within an EA to consider multiple objectives and to search for nondominated solutions simultaneously. For a problem with  $k$  objectives,  $k$  subpopulations of size  $N/k$  are considered, where  $N$  is the population size. Beside the standard crossover and mutation operators, VEGA applies a selection operator preferentially to each subpopulation based on one of the objectives. These subpopulations are then shuffled together at end of each iteration to obtain a new population. Shuffling and merging all subpopulations corresponds to averaging the normalized

fitness components associated with each of the objectives. The linear combination of the objectives implicitly performed over many generations by VEGA can be attributed to the speciation phenomenon. This tends to split the population into species, each specializing with respect to one of the objectives. As a result, VEGA provides a poor coverage of the noninferior set.

### **2.3.2 Niche Pareto Genetic Algorithm (NPGA)**

Horn et al., (1994) proposed NPGA that uses Pareto optimality as a basis for the selection operator. Individuals undergo a tournament selection in which the Pareto dominance of the individuals is used as the criterion for determining the winner. Instead of limiting the tournament comparison to two individuals, a comparison set consisting of a specific number ( $t_{dom}$ ) of individuals is picked at random from the population at the beginning of each selection process. Two individuals are selected at random from the population for determining a winner. Both individuals are compared with the individuals in the comparison set to check for dominance. If one of them is non-dominated and the other is dominated, then the non-dominated individual is selected. If both of them are dominated or non-dominated then a niche count is calculated for each individual and the individual with lower niche count is selected. By ensuring the selection of non-dominated individuals, convergence towards the noninferior set is ensured. By selecting the individual with the lower niche count, diversity is maintained in the population. NPGA has been shown to be successful in obtaining good convergence to the noninferior set as well as maintaining good coverage. The performance of NPGA is heavily dependent, however, on the selection of the sharing factor and size of the tournament ( $t_{dom}$ ).

### **2.3.3 Non-dominated Sorting Genetic Algorithm (NSGA)**

The NSGA (Srinivas and Deb, 1994) is based on several layers of classifications of the individuals. NSGA varies from a simple genetic algorithm only in the way the selection operator is used. The crossover and mutation operators remain unchanged. Before selection, the population is ranked on the basis of nondomination, classifying all nondominated individuals into one category with a dummy fitness value. To maintain diversity in the population, these classified individuals undergo sharing based on their dummy fitness values. This group is then ignored and the next layer of nondominated individuals is classified similarly, assigning a lower fitness value. This layering process continues until the whole population is classified. Thereafter a stochastic remainder roulette-wheel selection is used to select the next generation of individuals, resulting in more copies of individuals that are relatively more dominant. This facilitates search for nondominated regions and consequent convergence to the noninferior set. A tangential pressure applied in the objective space by the sharing procedure helps enhance coverage of the noninferior set. NSGA is shown to obtain a good coverage of the noninferior set, but is sensitive to the sharing factor.

### **2.3.4 Strength Pareto Evolutionary Algorithm (SPEA)**

Zitzler and Thiele (1999) presented SPEA, an elitist MOEA based on Pareto optimality concepts. SPEA maintains an external population of noninferior solution by storing at every generation all Pareto optimal solutions. Along with the current population, this external population undergoes all genetic operations. A fitness value is determined for each individual in the combined population. The fitness value of each individual in the combined population is determined based on the number of solutions it dominates. All Pareto optimal solutions in the

combined population are assigned a fitness value based on the number of solutions they dominate. A relatively higher fitness value is assigned to an individual that dominates more solutions in the combined population, while a relatively lower fitness value is associated with a solution dominated by more solutions in the combined population. Care is taken to assign no non-dominated solution a fitness value worse than the most dominated solution. This methodology of fitness assignment ensures that the search is directed towards the noninferior set while simultaneously maintaining diversity.

### **3 NSTEA - Noninferior Surface Tracing Evolutionary Algorithm**

The most successful among the existing MOEAs with respect to identifying the noninferior set with sufficient coverage use, in general, a Pareto-based approach. Each step for checking Pareto optimality requires sorting and pair-wise comparison of at least a subset of the population, thus increasing the computational needs. This is avoided in the new MOEA technique NSTEA that is presented in this paper. Building upon the concepts of the mathematical programming-based weighting approach (Cohon, 1978) for generating the noninferior set, NSTEA achieves Pareto optimality in an implicit manner by applying fitness pressure that encourages the population at each intermediate step to move towards a noninferior solution. Similar to an objective aggregation approach, a linearly weighted function of all objective functions is used to evaluate fitness at each intermediate step to enforce Pareto optimality of a solution. Normalized objective function values are used to maintain generality. Through repeated execution of this intermediate step with varying weight vectors, NSTEA attempts to identify the noninferior set. A linearly weighted fitness function,  $Z_{ag}$ , is computed as follows:

$$Z_{ag} = \sum_{l=1}^k w_l \bar{Z}_l \quad (6)$$

where,  $\mathbf{w} = \{w_l : l=1,2,\dots,k\}$  is the weight vector,  $w_l$  is the  $l^{th}$  weight and  $\bar{Z}_l$  is the  $l^{th}$  normalized objective function value. The weight  $w_l$  is a fractional number such that

$$\sum_{l=1}^k w_l = 1 \quad (7)$$

A straightforward implementation of an algorithm that repeats this intermediate step with varying  $\mathbf{w}$  would be similar to iterative execution of a single objective EA, which is not necessarily computationally efficient. Instead, NSTEA exploits the basic concept that for some classes of problems, adjacent solutions in the decision space map to adjacent points in the objective space. Its implication is that these decision vectors ( $\mathbf{x}$ s) (that map to adjacent noninferior points in the objective space) have solution features (i.e., values of  $x_j$ s) that are only marginally different. This enables the beneficial use of the final population corresponding to the current noninferior solution to seed the search of an adjacent noninferior solution. The new search of course would have an updated weight vector  $\mathbf{w}$  to represent an adjacent noninferior point in the objective space. When the new selection pressure manifesting from the updated weight vector is applied on the previous population, the population quickly migrates to an adjacent noninferior solution. A systematic update of the weight vector thus enables an efficient mechanism for incrementally tracing the noninferior set. This incremental population migration approach significantly reduces the computational burden compared to that required when solving each single objective EA as independent search problems.

Using a two objective problem as an illustration, let the current weight vector  $\mathbf{w}$  be  $\{w_1, w_2\}$ ; without loss of generality, we assume  $w_1 + w_2 = 1$ . The updated weight vector corresponding to the search for an adjacent noninferior solution would then be  $\{w_1+\mathbf{D}, w_2-\mathbf{D}\}$ , where the

magnitude of  $\mathbf{D}$  determines the minimum interval between adjacent noninferior solutions. For example, smaller values of  $\mathbf{D}$  would result in a finer coverage (or better distribution) of the noninferior set, but would require execution of more intermediate steps, each of which requiring the solution of a single objective EA. At the beginning of the algorithm, the population is converged to an extreme point in the noninferior set by optimizing for one of the objectives. In the above example, this is achieved by solving the optimization problem corresponding to  $w_1=1$  and  $w_2=0$  (or alternately  $w_1=0$  and  $w_2=1$ ). Once the population has converged to this solution according to some stopping criterion, the best solution is stored. Then the weight vector is incremented adaptively to  $w_1 \leftarrow w_1 - \mathbf{D}$  and  $w_2 \leftarrow w_2 + \mathbf{D}$ , and the current population is continually subjected to all the genetic operators where the fitness evaluation is now based on the updated weight vector. To introduce higher population diversity at the beginning of each search, the mutation operator is applied in an adaptive manner during each intermediate step, starting with a higher rate and gradually reducing it (e.g., exponential decay) with generations within each step. Thus, at the beginning of each intermediate step the higher mutation rate perturbs the converged population around the previous noninferior point, introducing diversity for the new search.

This iterative process is terminated when the weight vector corresponds to optimization of the other objective, i.e., when  $w_1=0$  and  $w_2=1$  (or alternatively  $w_1=1$  and  $w_2=0$ ). Two convergence criteria are implemented to determine when to change the weight vector and initiate the search for the next noninferior solution. One of the criteria is to check if the number of generations, *generation*, exceeds a maximum value, *maxGenerations*. The other criterion is to track the improvement in the best solution corresponding to a weight vector; convergence is assumed when the best solution does not improve within a certain number ( $N$ ) of successive

generations. If either of the above two criteria is satisfied then the weight vector is updated. The key steps of NSTEA are shown as a flowchart in Figure 1.

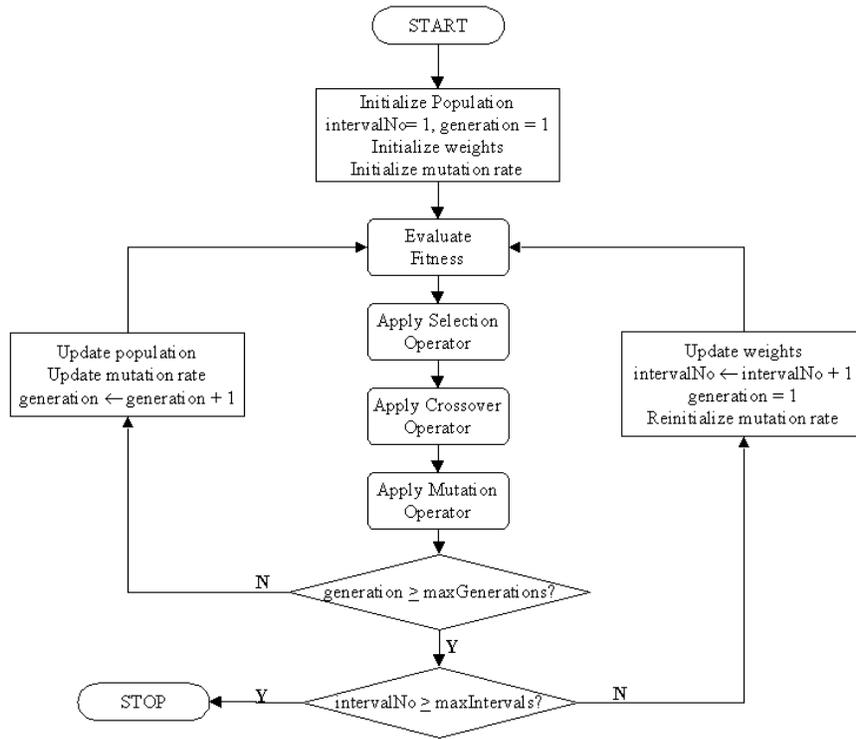


Figure 1: Flowchart for NSTEA - Noninferior Surface Tracing Evolutionary Algorithm.

\* The two convergence criteria are: 1)  $generation \geq maxGenerations$ , and 2) no improvement in N successive generations

Unlike most other MOEAs, NSTEA does not attempt to let the population converge to the noninferior set simultaneously. Instead, at each intermediate step, a point in the noninferior set is identified through a search conducted by the whole population, and the final noninferior set is generated by storing all noninferior solutions found at the intermediate steps. Analogous to the weighting method, the use of an aggregate fitness function implicitly ensures Pareto optimality.

The coverage of the noninferior set is achieved explicitly by traversing the noninferior surface through incremental and systematic updates of the weight vector.

#### **4 Testing and evaluation of NSTEA**

NSTEA was applied to a set of test problems of varied difficulty and characteristics. The first application uses Schaffer's F2 problem (Schaffer, 1985), which is an unconstrained, nonlinear problem. This is included since most other MOEA methods have been tested against it, providing a common basis for comparison. The second application uses a constrained, nonlinear optimization problem (Winston, 1993). Although this problem has not been used for testing of other MOEA methods, it offers a relatively challenging constrained problem that is easily implemented. A noninferior set obtained by solving this problem using a gradient-based nonlinear programming algorithm (Generalized Reduced Gradient-GRG2 algorithm (Lasdon et al., 1978; Fylstra et al., 1998) hosted by Microsoft Excel 97 Solver) is used to evaluate the performance of NSTEA. While the first two applications represent problems in a continuous search space, the third application, which uses the extended 0/1 multiobjective knapsack problem (Zitzler and Thiele, 1999), represent a problem in a combinatorial search space. This problem is a constrained, binary problem. Performance comparisons of several MOEAs in solving this problem are presented by Zitzler and Thiele (1999), and are used here to compare the performance of NSTEA. In addition, a noninferior set was generated using a mathematical programming-based weighting method for the extended 0/1 knapsack problem, which was solved using a binary programming solver (CPLEX<sup>®</sup> Version 4.0).

Several performance criteria are used to evaluate NSTEA and to compare it with other approaches: 1) *accuracy*, i.e., how close are the generated noninferior solutions to the best

available prediction; 2) *coverage*, i.e., how many different noninferior solutions are generated and how well are they distributed; and 3) *spread*, i.e., what is the maximum range of the noninferior surface covered by the generated solutions. Currently reported as well as newly defined quantitative measures are used in comparing NSTEA with other MOEAs. The robustness of NSTEA in solving problems with different characteristics (e.g., real vs. binary variables, constrained vs. unconstrained, continuous vs. combinatorial) is examined, in some limited manner, by applying it to a variety of problems. To evaluate the robustness of NSTEA in generating the noninferior set and providing good coverage, random trials were performed where the problems were solved repeatedly for different random seeds. A representative solution is used in the discussion below

## 4.1 Schaffer's F2 problem

### 4.1.1 Description

The F2 problem is defined as follows:

$$\text{Minimize} \quad Z_1 = x^2 \quad (8)$$

$$\text{Minimize} \quad Z_2 = (x - 2)^2 \quad (9)$$

The range for the decision variable  $x$  is  $[-5,7]$ . The Pareto optimal solutions constitute all  $x$  values varying from 0 to 2. The solution  $x = 0$  is optimum with respect to  $Z_1$  while the solution  $x = 2$  is optimum with respect to  $Z_2$ . That is, objective functions  $Z_1$  and  $Z_2$  are in conflict in the range  $[0,2]$ .

### 4.1.2 Results

The F2 problem was solved using NSTEA with algorithm-specific parameters as shown in Table 1. Results are compared in Figure 2 where the exact solution (obtained analytically using Equations 8 and 9) for this problem is also shown.

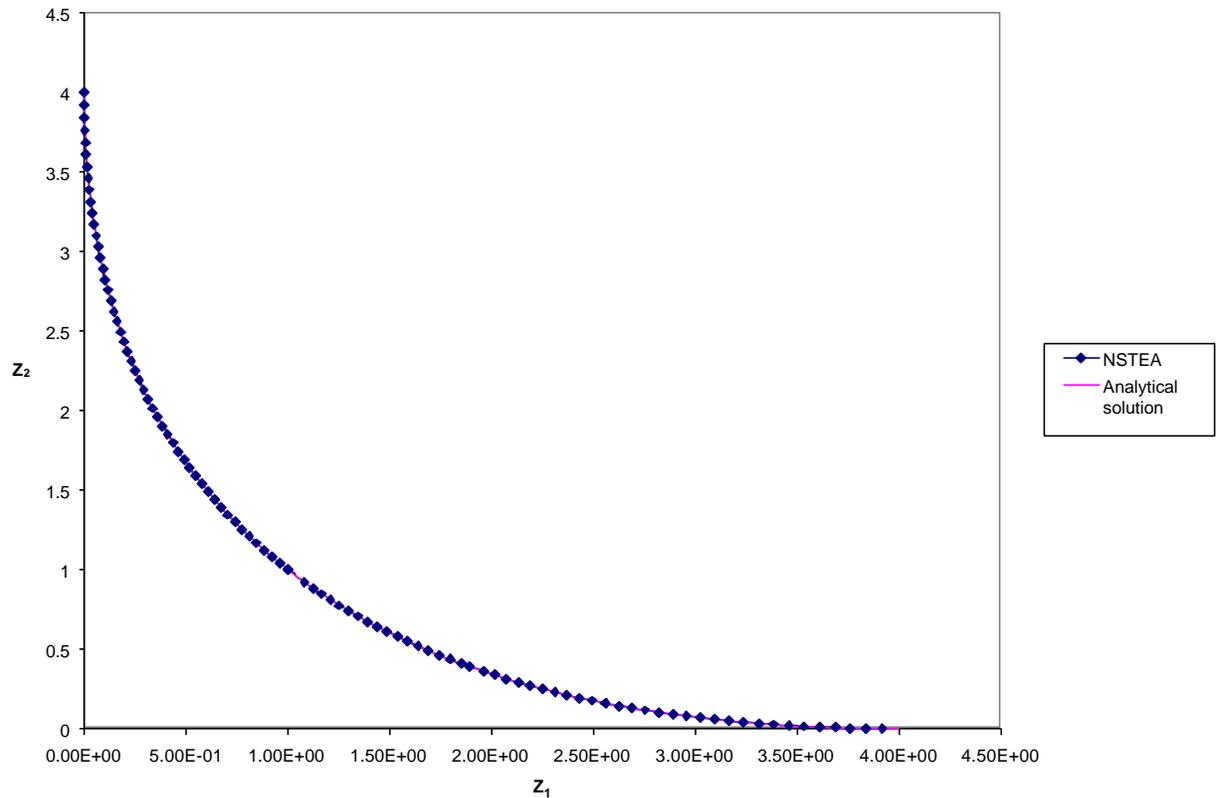


Figure 2: The true noninferior tradeoff curve and the noninferior set determined by NSTEA for Schaffer's F2 problem.

Although this is a relatively simple problem, the results indicate that NSTEA is very accurate in generating the noninferior set for this problem. Also, it provides good coverage by generating a good distribution of noninferior solutions, and provides a full spread.

Table 1: NSTEA parameters and settings for solving the test problems

| Problem  | Decision variable type | NSTEA Parameters |                 |                              |                |                      |
|----------|------------------------|------------------|-----------------|------------------------------|----------------|----------------------|
|          |                        | No. of intervals | Population size | Encoding                     | Crossover type | No. of random trials |
| F2       | Real                   | 100              | 100             | Binary, 32 bits per variable | Uniform        | 5                    |
| Winston  | Real                   | 100              | 100             | Binary, 32 bits per variable | Uniform        | 5                    |
| Knapsack | Binary                 | 100              | 100             | Binary, 1 bit per variable   | Uniform        | 5                    |

## 4.2 Winston problem

### 4.2.1 Description

This problem, adapted from Winston (1993), is a constrained, two objective, nonlinear problem with two real-valued decision variables. This is a resource allocation problem in which television advertising resources must be distributed between two target audiences. The goal is to maximize the exposure of the advertisements to both male and female viewers. Given a limited total advertising budget, the choice is between placing advertisements during football games and soap operas, each costing different amount. This problem is mathematically stated as follows:

$$\text{Maximize the number of men, } Z_1 = 20\sqrt{F} + 4\sqrt{S} \quad (10)$$

$$\text{Maximize the number of women } Z_2 = 4\sqrt{F} + 15\sqrt{S} \quad (11)$$

$$\text{Subject to the budget constraint: } 100F + 60S \leq 1000 \quad (12)$$

where  $F$  and  $S$  (such that  $F \geq 0$  and  $S \geq 0$ ) are the number of one-minute advertisements placed during football games and soap operas, respectively.

### 4.2.2 Results

The Winston problem was solved using NSTEA with parameter settings as shown in Table 1. For comparative purposes, a noninferior set was obtained using the constraint method for this problem. A series of single objective constrained nonlinear programming models were solved using the nonlinear programming (NLP) solver (Generalized Reduced Gradient-GRG2 algorithm (Lasdon et al., 1978; Fylstra et al., 1998) hosted by Microsoft Excel 97 Solver). The resulting noninferior solutions are shown in Figure 3.

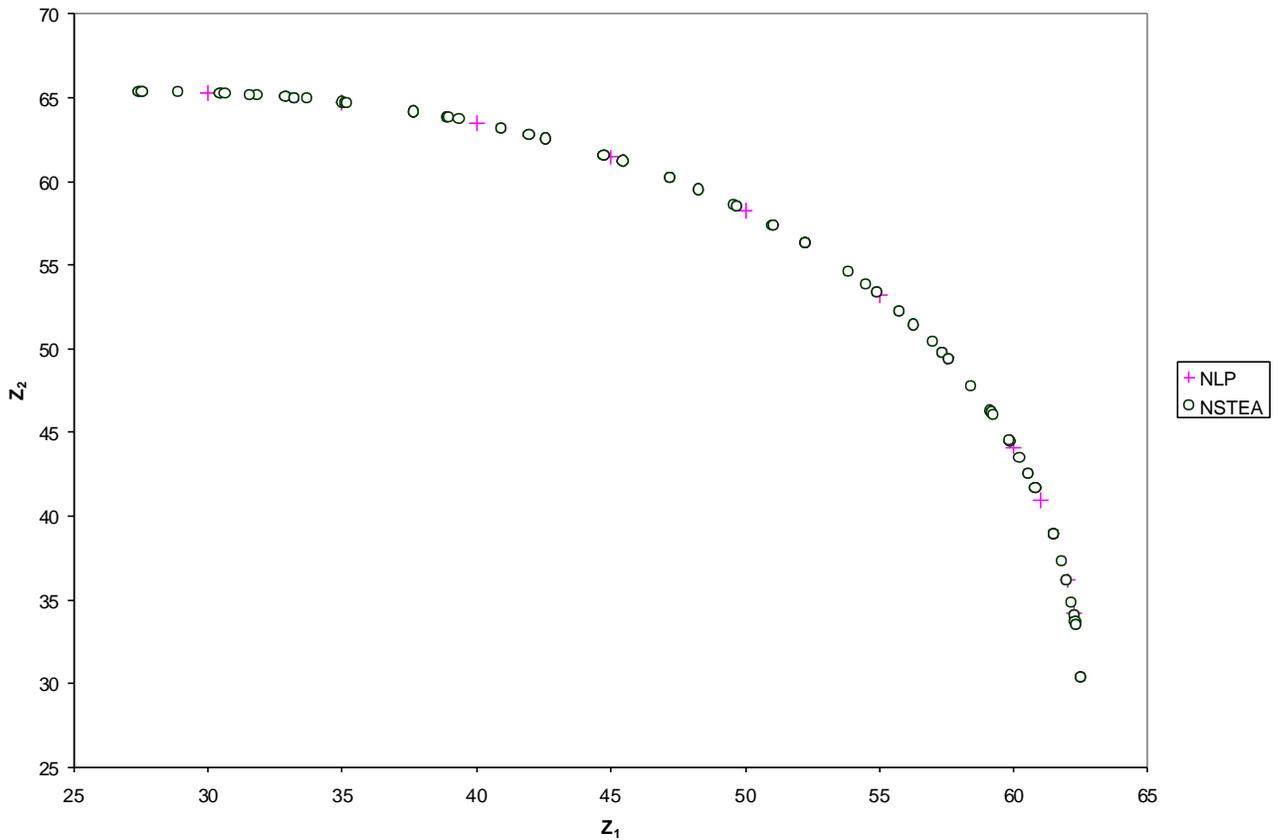


Figure 3: The noninferior solution obtained using NSTEA and an NLP solution approach for the Winston problem.

Noninferior solutions generated by NSTEA are accurate (in comparison with the noninferior solutions generated using the NLP approach) and cover the noninferior surface evenly. Also, the generated solutions spread the entire range of the noninferior set.

### 4.3 Extended 0/1 multiobjective knapsack problem

#### 4.3.1 Description

Zitzler and Thiele (1999) used in their work a knapsack problem that extends the traditional single objective knapsack problem by incorporating two knapsacks that can be filled by items selected from a larger collection of items. Similar to the traditional knapsack problem, each knapsack has a limited weight capacity with different payoff when each item is included in it. The goal is to allocate a limited set of items to maximize the payoff in each knapsack without violating its weight capacity constraint. This multiobjective problem is defined mathematically as follows:

$$\text{Maximize} \quad Z_l(\mathbf{x}) = \sum_{j=1}^n p_{l,j} x_j \quad \forall l = 1, 2, \dots, k \quad (13)$$

$$\text{Subject to} \quad \sum_{j=1}^n w_{l,j} x_j \leq c_l \quad \forall l = 1, 2, \dots, k \quad (14)$$

In the formulation,  $Z_l(\mathbf{x})$  is the total profit associated with knapsack  $l$ ,  $p_{l,j}$  = profit of placing item  $j$  in knapsack  $l$ ,  $w_{l,j}$  = weight of item  $j$  when placed in knapsack  $l$ ,  $c_l$  = capacity of knapsack  $l$ ,  $\mathbf{x} = (x_1, x_2, \dots, x_n) \in \{0, 1\}^n$  such that  $x_j = 1$  if selected and  $= 0$  otherwise,  $n$  is the number of available items and  $k$  is the number of knapsacks.

This binary MO problem was solved for the cases with two knapsacks (i.e.  $k = 2$ ) and 250 and 500 items. The results reported here correspond to  $n = 500$  and  $k = 2$ . The data for the problems solved were adapted from Zitzler and Thiele (1999).

#### **4.3.2 Results**

The extended knapsack problem was solved by NSTEA for the parameter setting shown in Table 1. In addition, the noninferior set was generated using the constraint method for this problem by modeling it as a binary linear programming (BLP) model. This was solved using the binary linear programming solver, CPLEX<sup>®</sup>. In Figure 4, these results are shown along with the results reported by Zitzler and Thiele (1999) for the following MOEAs: VEGA, NPGA, NSGA, and SPEA.

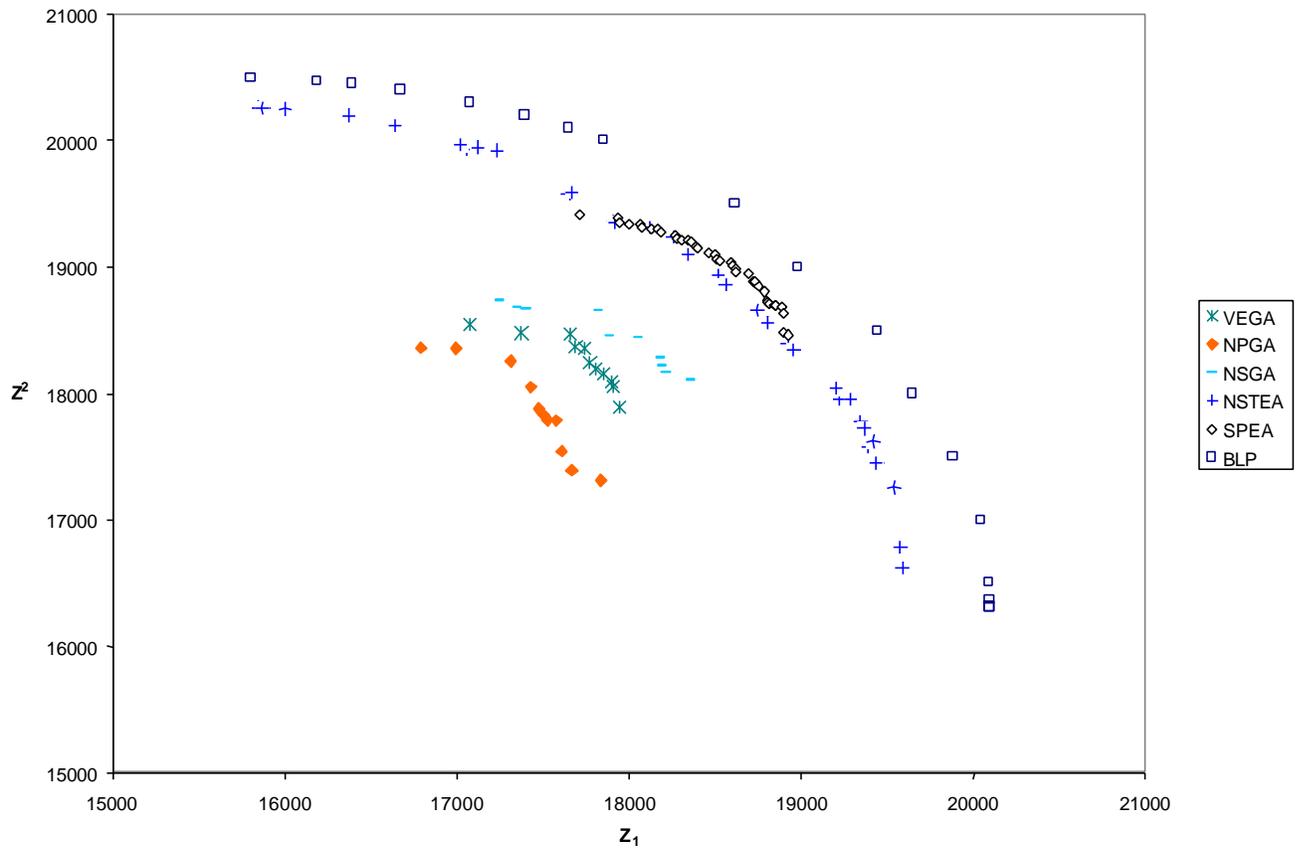


Figure 4: A comparison of noninferior sets obtained using NSTEA, VEGA, NPGA, NSGA, SPEA, and mathematical programming approach (BLP) for the extended 0/1 multiobjective knapsack problem.

To examine the consistency of NSTEA in solving this problem, five trials with different random seeds were conducted. The results are summarized in Figure 5. NSTEA appears to be insensitive to the random seed, indicating robust behavior.

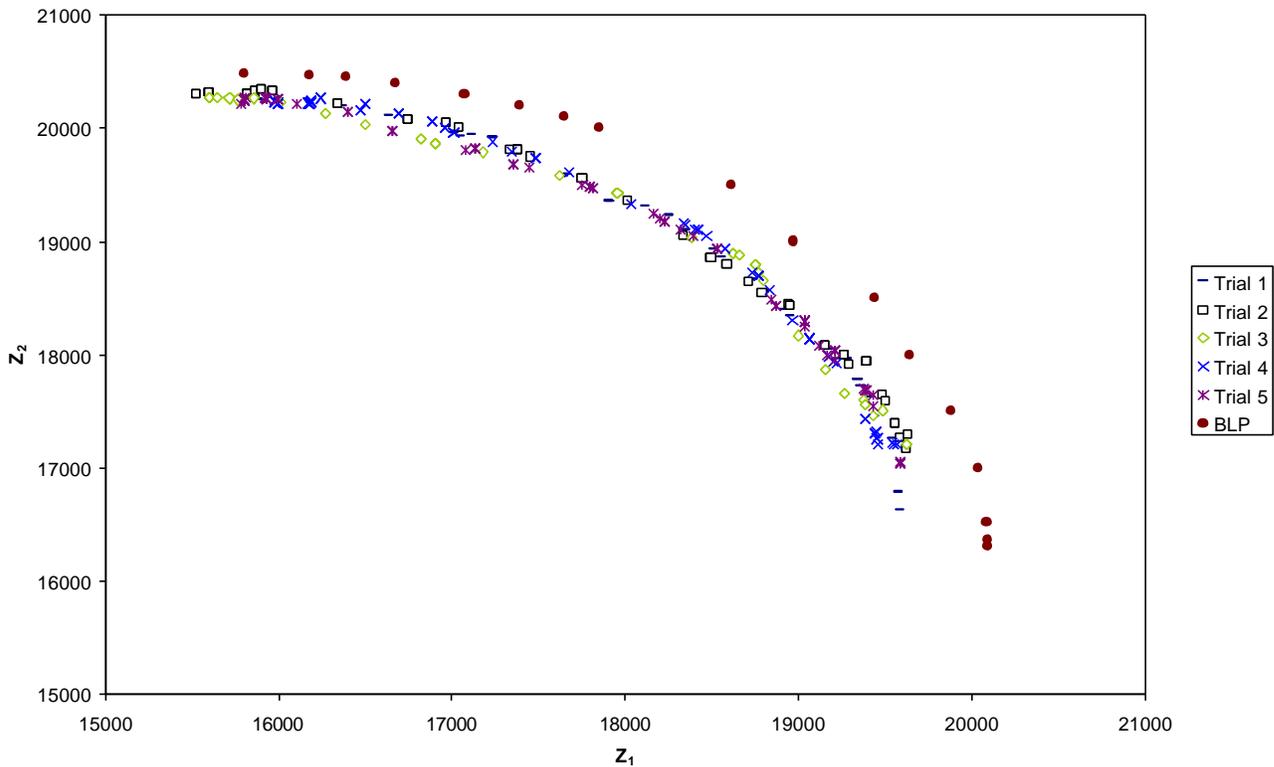


Figure 5: A comparison of noninferior sets obtained using NSTEA for five random trials and BLP (binary linear programming) method for the extended 0/1 multiobjective knapsack problem.

Accuracy of the noninferior solutions generated by NSTEA should be compared with respect to the best available noninferior set, as well as with the best estimate obtained by the other MOEAs. The mathematical programming-based estimate of the noninferior set, the best available for this problem, is included in Figure 4 to make the first evaluation. Compared to this, the accuracy of noninferior solutions generated by NSTEA and the other MOEAs is relatively

poor. The combinatorial nature of the search can be attributed to the weak performance by all EAs. Accuracy of NSTEA in comparison to other MOEA results, however, is very good. Some noninferior solutions obtained by SPEA, the best performing MOEA according to Zitzler and Thiele (1999), appear to dominate some solutions generated by NSTEA. The spread or range covered by the NSTEA generated solutions, however, is far superior to that attained by all other MOEAs. Further, NSTEA is able to provide good coverage by identifying noninferior solutions that are almost evenly distributed throughout the full range.

#### **4.3.3 Performance metrics and comparison of MOEAs**

To compare the performance of NSTEA with that of other MOEAs, the following quantitative measures are used.

##### *Accuracy*

The  $S$  factor used by Zitzler and Thiele (1999) to represent the size of noninferior space covered is used to characterize and compare accuracy. In addition, the approach used by Knowles and Corne (2000), which is based on the method proposed by Fonseca and Fleming (1995), is used to characterize the degree to which a noninferior set outperforms another. The same numbers of radial sampling lines used in computing this metric by Knowles and Corne (2000) are used in the comparisons presented here. An either-or criterion is used to determine if the noninferior set obtained by an MOEA dominates that obtained by another MOEA; the closeness of the two points of intersection are not differentiated statistically.

##### *Spread*

Spread is quantified for each objective as the fraction of the maximum possible range of that objective in the noninferior region covered by a noninferior set. A larger value of this metric

indicates better spread. As shown in Figure 6, let points A and B refer to the two extreme points, i.e., the single objective optimal solutions for objective 1 and 2, respectively, for a two objective case. The maximum range covered by the noninferior set  $C \in \{C_h : h=1, 2, \dots, q\}$  is  $(Z_1^{Cq} - Z_1^{C1})$  and  $(Z_2^{C1} - Z_2^{Cq})$  in  $Z_1$  and  $Z_2$  objective space, respectively. Therefore, the spread metrics in objective space 1 and 2 are defined as  $(Z_1^{Cq} - Z_1^{C1}) / (Z_1^B - Z_1^A)$  and  $(Z_2^{C1} - Z_2^{Cq}) / (Z_2^A - Z_2^B)$ , respectively.

### *Coverage*

A quantitative measure computed based on the maximum gap in coverage is defined to represent the distribution of the noninferior solutions generated by an MOEA. The Euclidean distance between adjacent noninferior points in the objective space is used to indicate the gap. A smaller value of this metric indicates better distribution of solutions in the noninferior set. This metric is defined separately as  $V1$  and  $V2$  to characterize the coverage within the range of noninferior region defined by 1) the extreme points, and 2) the solutions generated by the MOEA, respectively. Using the illustrations shown in Figure 6,  $V1$  is defined as  $Max \{d_h : h=0, 1, \dots, q\}$ , and  $V2$  is defined as  $Max \{d_h : h=1, 2, \dots, q-1\}$ .

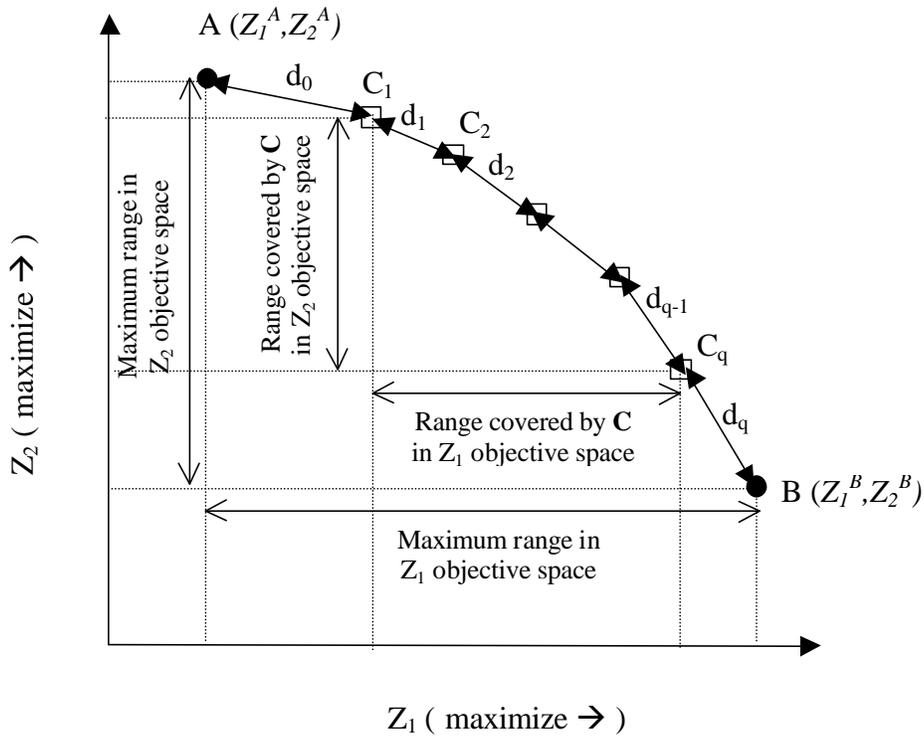


Figure 6: An example two-objective noninferior tradeoff to illustrate the computation of: 1) *Spread* metric, and 2) *Coverage* metric.

A summary of these metrics are compared in Tables 2a-2d for the noninferior solutions generated by all MOEAs shown in Figure 4. These results indicate that overall NSTEA performs better than NPGA, NSGA, SPEA, and VEGA with respect to finding nondominated solutions with a good distribution in the noninferior region. This conclusion is specific to the 0/1 extended multiobjective knapsack problem, and similar performance comparisons for other problems are needed to make more general conclusions. Although NSTEA provides the best distribution of solutions in the entire noninferior range (based on  $V1$  metric), SPEA provides a better distribution (based on  $V2$  metric) within the narrower noninferior range represented by its solutions.

Table 2a: *Accuracy* comparison, based on the *S* factor (Zitzler and Thiele, 1999), of noninferior sets generated by different MOEAs for the extended 0/1 multiobjective knapsack problem. A larger value indicates better performance; the best is shown in bold.

| <b>MOEA Method</b> | <b>S Factor</b> |
|--------------------|-----------------|
| SPEA               | 0.89            |
| NSGA               | 0.79            |
| NPGA               | 0.83            |
| VEGA               | 0.81            |
| NSTEA              | <b>0.95</b>     |

Table 2b: *Accuracy* comparison, based on the metric defined by Knowles and Corne (2000), of NSTEA with different MOEAs for the extended 0/1 multiobjective knapsack problem.

| <b>The MOEAs Compared (MOEA<sub>1</sub> vs. MOEA<sub>2</sub>)</b> | <b>(P<sub>1</sub>, P<sub>2</sub>): (Percentage number of times MOEA<sub>1</sub> outperforms MOEA<sub>2</sub>, Percentage number of times MOEA<sub>2</sub> outperforms MOEA<sub>2</sub>)</b> |            |             |
|---|---|------------|-------------|
|   | <b>Number of Sampling Lines</b>   |            |             |
|   | <b>108</b>  | <b>507</b> | <b>1083</b> |

|                  |             |             |             |
|------------------|-------------|-------------|-------------|
| (NSTEA vs. SPEA) | (96.3, 3.7) | (95.9, 4.1) | (95.9, 4.1) |
| (NSTEA vs. NSGA) | (100, 0)    | (100, 0)    | (100, 0)    |
| (NSTEA vs. NPGA) | (100, 0)    | (100, 0)    | (100, 0)    |
| (NSTEA vs. VEGA) | (100, 0)    | (100, 0)    | (100, 0)    |

Table 2c: Comparison of *Spread* of noninferior sets generated by different MOEAs for the extended 0/1 multiobjective knapsack problem. A larger value indicates better performance; the best is shown in bold.

| MOEA  | Spread Metric            |                          |
|-------|--------------------------|--------------------------|
|       | in $Z_1$ objective space | in $Z_2$ objective space |
| SPEA  | 0.28                     | 0.23                     |
| NPGA  | 0.24                     | 0.25                     |
| NSGA  | 0.26                     | 0.15                     |
| VEGA  | 0.20                     | 0.16                     |
| NSTEA | <b>0.87</b>              | <b>0.88</b>              |

Table 2d: Comparison of *Coverage* of noninferior sets generated by different MOEAs for the extended 0/1 multiobjective knapsack problem. A smaller value indicates better performance; the best is shown in bold.

| MOEA  | Coverage Metric  |  |
|-------|--|--|
|       | <i>V1</i> (includes the extreme points for each objective) | <i>V2</i> (excludes the extreme points for each objective) |
| SPEA  | 0.118  | <b>0.011</b>   |
| NPGA  | 0.122  | 0.016  |
| NSGA  | 0.121  | 0.021  |
| VEGA  | 0.130  | 0.015  |
| NSTEA | <b>0.028</b>   | 0.027  |

#### 4.3.4 A computational comparison

A major premise underlying the new technique was the adjacency mapping between decision space and objective space. By using the population that has converged around a noninferior solution to seed the initial population for search for an adjacent noninferior solution, it was assumed that the number of evaluations to convergence in subsequent searches would be significantly reduced. To verify this premise, the search for each noninferior solution was conducted without seeding the initial population. This is analogous to running NSTEA without

seeding at each intermediate step. These runs were repeated for five random trials. The numbers of function evaluations required by NSTEA with and without seeding are compared in Table 3.

Table 3: A computational comparison, for five random trials, in terms of number of function evaluations needed by NSTEA with and without population seeding to solve the extended 0/1 multiobjective knapsack problem.

| Random Trial No. | No. of function evaluations   |                                  |
|------------------|-------------------------------|----------------------------------|
|                  | NSTEA with population seeding | NSTEA without population seeding |
| 1                | 211,800                       | 445,600                          |
| 2                | 201,700                       | 421,100                          |
| 3                | 206,200                       | 440,200                          |
| 4                | 205,400                       | 450,900                          |
| 5                | 204,700                       | 440,400                          |

Two main observations can be made: 1) the number of function evaluations needed by NSTEA is significantly smaller (over 50% less than the case when no seeding was applied); and 2) similar computational improvement is observable in all random trials. These results confirm the benefit of the primary concept of adjacency mapping that is used in constructing the algorithmic steps in NSTEA. Also, NSTEA is sufficiently robust, and the computational needs are consistent as well as independent of the random trials.

## **5 Application of NSTEA to a realistic engineering problem– The Delaware estuary management problem**

To evaluate the applicability of NSTEA in generating noninferior solutions for a realistic multiobjective optimization problem, a case study that was reported in the literature and had all necessary input information was identified. Brill (1972) reported a relatively large-scale real world multiobjective analysis for a water quality management problem in the Delaware estuary. This was build upon an extensive chemical-physical simulation model (Thomann, 1963) to describe the water quality and earlier pollution discharge management models (e.g., Smith and Morris, 1969). A stretch of 84 miles of the Delaware estuary was studied. This stretch was bordered by a large metropolitan and industrial complex, including one of the largest oil refining and chemical areas in the United States. The primary water quality parameter of interest was dissolved oxygen (DO) in the water. The critically low level of DO was attributed to the discharge of wastewater, which had high levels of biochemical oxygen demand (BOD).

The management model described by Brill (1972) is represented as a linear mathematical programming (LP) model. Although an LP-based model was used in that analysis, the structure of the management model would become more complex (e.g., nonlinear and binary programming) when nonlinear cost functions and nonlinear physical-chemical processes are incorporated in the analysis, calling for evolutionary algorithm-based solution approaches. This LP-based management model considered 44 major BOD dischargers and their impact on DO in 30 discrete reaches (each approximately 10,000 - 20,000 ft long). The main goal of this management model was to identify good BOD control strategies (i.e., which discharger should control its BOD release and by how much) to meet a specified DO standard. Like most environmental management problems, the design criteria were in conflict, and compromise

solutions were sought to assist in the decision making process. The MO analysis focused on consideration of two conflicting objectives: minimizing cost of BOD control, and maximizing equity with respect to levels of treatment among the different dischargers. In general, the least cost discharge control strategy tends to be inequitable since the most cost-effective treatment options are preferentially selected during optimization, resulting in inequities due to different treatment levels by the dischargers. Alternatively, the most equitable strategy, i.e., uniform treatment, where all dischargers treat at the same rate is typically not cost effective because of various factors that differ among dischargers, including economies of scale effects, location effects and other differences among dischargers. Therefore, consideration of noninferior tradeoff between these conflicting objectives was needed. Different equity measures were studied by Brill et al. (1976), and the particular management model that is compared in this paper is as follows:

$$\text{Minimize } Z_1 = (e_{\max} - e_{\min}) \quad (\text{equity measure}) \quad (15)$$

$$\text{Minimize } Z_2 = \sum_{j=1}^N \sum_{k=1}^{K_j} C_{j,k} \cdot f_{j,k} \quad (\text{cost}) \quad (16)$$

$$\sum_{j=1}^n A_{i,j} \cdot \sum_{k=1}^{K_j} f_{j,k} \geq B_i \quad i = 1, 2, \dots, M \quad (17)$$

$$f_{j,k} \leq U_{j,k} \quad \begin{array}{l} j = 1, 2, \dots, N \\ k = 1, 2, \dots, k_j \end{array} \quad (18)$$

$$(1/FT_j) \cdot \sum_{k=1}^{K_j} f_{j,k} \geq 0.35 \quad j \in E \quad (19)$$

$$e_j - (1/FT_j) \cdot \sum_{k=1}^{K_j} f_{j,k} = D_j \quad j = 1, 2, \dots, N \quad (20)$$

$$e_j - e_{\max} \leq 0 \quad j \in J_q \quad (21)$$

$$e_j - e_{\min} \geq 0 \quad j = 1, 2, \dots, N \quad (22)$$

$$f_{j,k} \geq 0 \quad \begin{array}{l} j = 1, 2, \dots, N \\ k = 1, 2, \dots, K_j \end{array} \quad (23)$$

$$e_j \geq 0 \quad j = 1, 2, \dots, N \quad (24)$$

$$\begin{array}{l} e_{\max} \geq 0 \\ e_{\min} \geq 0 \end{array} \quad (25)$$

where,  $N$  is the number of dischargers,  $J = \{1, 2, \dots, j, \dots, N\}$  is the set of the indices of the dischargers,  $f_{j,k}$  is the  $k^{th}$  piecewise waste reduction variable for discharger  $j$ ,  $C_{j,k}$  is the unit cost for  $f_{j,k}$ ,  $K_j$  is the number of waste reduction variables for discharger  $j$ ,  $A_{i,j}$  is the impact coefficient representing the improvement in water quality resulting from a unit waste reduction by discharger  $j$ ,  $D_j$  is the initial efficiency for discharger  $j$ ,  $B_i$  is the water quality improvement required for section  $i$ ,  $M$  is the number of sections with water quality improvement goals,  $U_{j,k}$  is the upper bound for  $f_{j,k}$ ,  $FT_j$  is the total waste production for discharger  $j$ ,  $E$  is the set of all dischargers that need primary treatment,  $e_{\max}$  is the maximum efficiency among dischargers that increase efficiency,  $e_j$  is the efficiency in discharger  $j$ ,  $e_{\min}$  is the minimum efficiency among all dischargers, and  $J_q$  is the set of dischargers that increase efficiencies.

Brill et al. (1972) solved the above management model using the constraint method (Cohon, 1978) via linear programming (LP). The same problem was also solved using NSTEA. This problem had 44 decision variables represented as real-valued strings, and a population size of 100 was used. The number of intervals was set to 100. The noninferior solutions that were reported in Brill (1972) are used as the basis for evaluation and comparison of the performance of NSTEA. The resulting noninferior sets are shown in Figure 7.

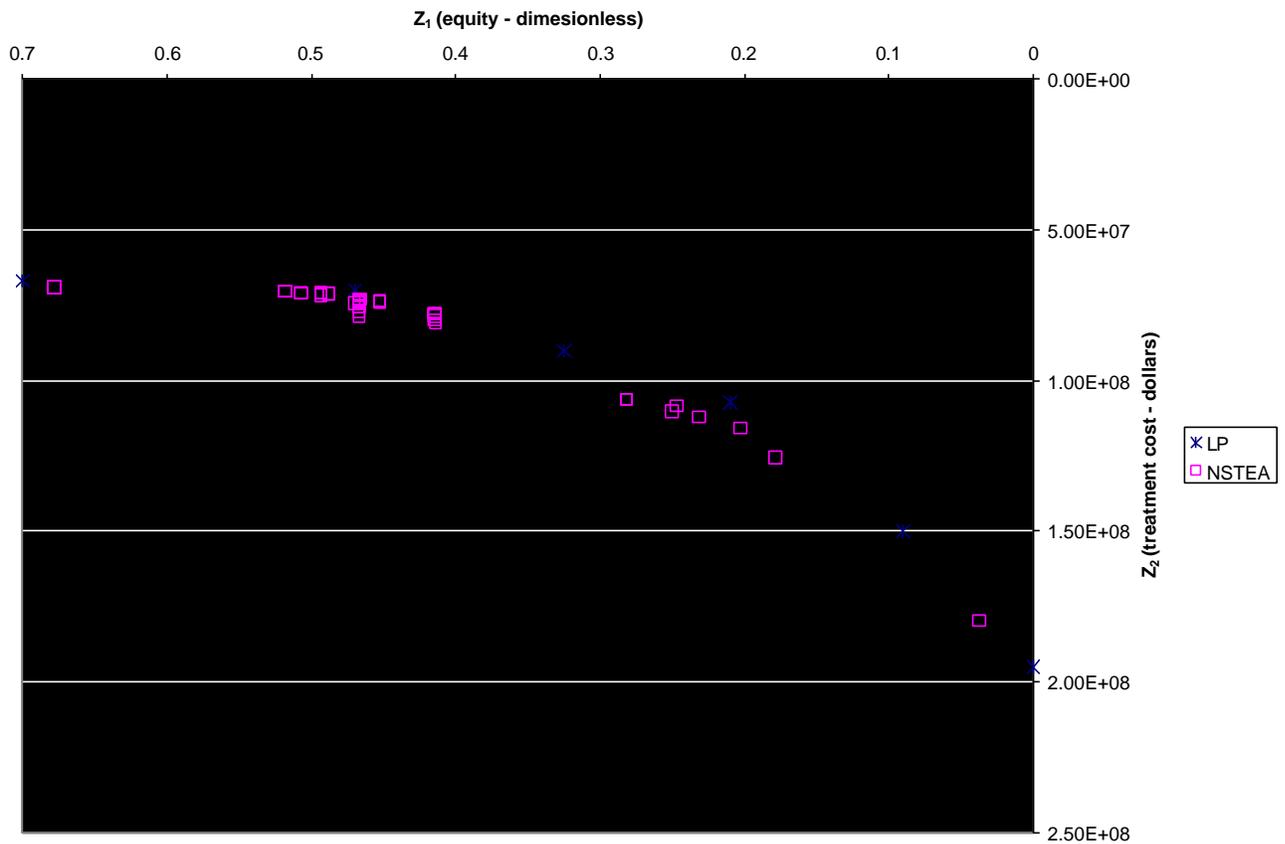


Figure 7: Comparison of noninferior solutions obtained using NSTEA and LP (linear programming) for the Delaware Estuary management problem.

The noninferior solutions generated by NSTEA provide a good coverage as well as spread well across the noninferior set. The accuracy of these solutions is good in most sections

of the noninferior set, except in the middle where some NSTEA solutions are slightly inferior. It must be noted that the linear programming-based noninferior solutions are globally optimal and therefore represent the best noninferior tradeoff for this problem.

## **6 Summary and Conclusions**

This paper presents a new MOEA, Noninferior Surface Tracing Evolutionary Algorithm (NSTEA) for solving multiobjective optimization problems. NSTEA is founded upon two simple, but powerful concepts: 1) optimization of an aggregate function of all objective functions finds a noninferior, or Pareto optimal, solution; and 2) for some classes of problems, noninferior solutions adjacent in objective space map to adjacent decision vectors with only marginal differences in the decision space. The attractive features of NSTEA include: easily adaptable for use with existing implementation of evolutionary algorithms for an optimization problem since no new operators are needed; and relatively less compute intensive since Pareto optimality is ensured in an implicit manner, and therefore expensive sorting and pair-wise comparison operations that are typically required by other Pareto-based MOEAs are eliminated.

To evaluate the applicability of NSTEA to different MO problems, it was applied to a set of standard test problems (reported in recent MOEA literature) with differing characteristics and of varying levels of difficulty. Test problems covered continuous as well as combinatorial search, unconstrained as well as constrained optimization, real as well as binary variables, and as few as one variable to as high as 500 variables. This evaluation included performance comparisons with other MOEAs and where available, with mathematical programming-based noninferior solutions. Accuracy, coverage, and spread of the noninferior solutions were used to compare the performance. To evaluate the consistency of NSTEA in generating the noninferior set, several random trials were performed when solving each problem. Overall, NSTEA

performed well with respect to these criteria for all problems tested. The spread and coverage of noninferior solutions obtained using NSTEA were always better than those demonstrated by other MOEAs. With respect to accuracy, NSTEA did well in almost all cases, except for the extended 0/1 multiobjective knapsack problem for which SPEA did better for a few noninferior solutions.

NSTEA was also applied to a real-world problem that required a multiobjective analysis of two conflicting, environmental management objectives. This problem, which is well documented and reported in the literature, looked at environmental management strategies for meeting water quality standards in the Delaware estuary while minimizing the cost of environmental pollution control as well as minimizing the differences in control levels among the polluters, i.e., maximizing the equity. Results reported by other researchers included noninferior sets with respect to the cost and equity objectives. These solutions are globally optimal since a linear programming approach was used to solve the MO model. In a comparison of noninferior solutions obtained using NSTEA with the reported results, NSTEA performed well in providing good coverage and spread, and the solutions were sufficiently accurate compared to the global optimal solutions.

Some known limitations of NSTEA include the following. The computational efficiency gain obtained in NSTEA is premised on the existence of similarities in noninferior solutions that correspond to adjacent points in the objective space. For problems where this may not hold true strongly, the search implemented by NSTEA becomes analogous to solving a number of independent single objective optimization problems, and therefore, may not realize any significant computational gain. As the underlying search mechanism for a Pareto optimal solution uses an incrementally varying aggregate function, the amount of each weight increment

would dictate the number of noninferior solutions found. If this increment is relatively large, it is possible to miss some of the noninferior solutions, thus affecting the coverage. As a result, NSTEA with relatively large weight increments will likely miss noninferior solutions that lie within any linear segment of the noninferior tradeoff. For a problem with more than two objectives, incrementally updating the weight vector to obtain an adjacent point is not necessarily as straightforward as is for the two-objective cases presented here. More investigation is needed to evaluate this issue when applying NSTEA to higher dimensional problems.

The computational performance of NSTEA and other MOEAs needs to be studied further. Using the number of functions evaluations as a measure was useful in comparing the computational needs for NSTEA and a single objective-based MO analysis. This measure alone is not sufficient to compare the computational gain, if any, that may be realized by NSTEA over the other MOEAs that use explicit Pareto optimality checks. As this is dependent on the algorithmic steps beyond just function evaluation, timing studies based on equivalent implementations of each algorithm are required. Future investigations will examine this issue.

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