

# Scalarizing Functions in Decomposition-Based Multiobjective Evolutionary Algorithms

Shouyong Jiang, Shengxiang Yang, *Senior Member, IEEE*, Yong Wang, *Member, IEEE*, and Xiaobin Liu

**Abstract**—Decomposition-based multiobjective evolutionary algorithms (MOEAs) have received increasing research interests due to their high performance for solving multiobjective optimization problems. However, scalarizing functions (SFs), which play a crucial role in balancing diversity and convergence in these kinds of algorithms, have not been fully investigated. This paper is mainly devoted to presenting two new SFs and analyzing their effect in decomposition-based MOEAs. Additionally, we come up with an efficient framework for decomposition-based MOEAs based on the proposed SFs and some new strategies. Extensive experimental studies have demonstrated the effectiveness of the proposed SFs and algorithm.

**Index Terms**—Decomposition, evolutionary algorithm, multiobjective optimization, scalarizing function (SF).

## I. INTRODUCTION

MULTIOBJECTIVE evolutionary algorithms (MOEAs) [6] have been shown to be well-suited for multiobjective optimization problems (MOPs) as they can approximate the Pareto-optimal front (PF) with a population in a single run. After decades of development, a number of MOEAs have emerged in the field of evolutionary multiobjective optimization (EMO). According to their selection techniques, these MOEAs can be generally grouped into three different classes.

- 1) Pareto dominance-based methods, such as the nondominated sorting genetic algorithm II [5] and strength Pareto evolutionary algorithm 2 [51].

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- 2) Indicator-based methods, such as the indicator-based evolutionary algorithm [50].
- 3) Decomposition-based methods, such as the multiple single-objective Pareto sampling [13], cellular multiobjective genetic algorithm [30], and MOEA based on decomposition (MOEA/D) [46].

Decomposition-based MOEAs are a popular class of metaheuristics for EMO. They decompose an MOP into a number of subproblems<sup>1</sup> and simultaneously solve them in a collaborative manner. MOEA/D [46] is a representative of this class of metaheuristics. MOEA/D decomposes an MOP by scalarizing functions (SF) (or termed decomposition approaches in some studies [46]) into a set of subproblems, each of which is associated with a search direction (or weight vector) and assigned a candidate solution. In every generation, parents from a mating pool are selected to generate an offspring solution for each subproblem. Then, the offspring replaces certain existing solutions if it achieves better scalarizing values. So far, there have been a number of contributions to the improvement of MOEA/D, with regard to the following aspects.

- 1) *Weight Vectors*: The quality (particularly uniformity and coverage) of approximations depends largely on the chosen weight vectors. In the original MOEA/D, the simplex lattice design [4] was used to construct weight vectors. However, it was later found that this method cannot ensure the uniformity of the obtained solutions on the PF [32], and other methods, such as uniform design [38], weight transformation [32], and two-layered design [8], [25], were therefore introduced to reduce this drawback. It is noteworthy that the specification of weight vectors depends largely on PF shapes, and inappropriate weight vectors can lead to poor performance of decomposition-based approaches [17], [19].
- 2) *Scalarizing Functions*: SFs play a fundamental role in MOEA/D and its variants. They can significantly affect the search ability of the evolving population and the quality of the resulting approximations. It has been suggested that adaptive SFs are beneficial to balance diversity and convergence at different search stages [16], [39]. Some existing SFs have been adapted to improve the quality of solutions [9], [20], [34], [35], [40].
- 3) *Mating Selection*: In MOEA/D, each subproblem requires a mating range where parents are selected

<sup>1</sup>Note that subproblems can be not only single-objective optimization problems [46] but also multiobjective ones [28].

to mate. As a result, mating selection has an important impact on population diversity and convergence. Originally, MOEA/D used subproblems' neighborhood as the mating range [46]. Later, Li and Zhang [26] studied the influence of the mating range and showed the benefit of using the whole population with a low probability. In [20], niching techniques were employed to determine the mating range. The size of the mating range or neighborhood has been investigated in a number of studies [14], [48].

- 4) *Genetic Operators*: MOEA/D needs appropriate genetic operators to generate promising offspring, depending on the difficulty of the problem to be optimized. In [26], two different genetic operators were investigated on complicated problems. In [10], cross entropy was successfully integrated into MOEA/D for continuous optimization. An adaptive variation operator [28] is used to solve hard-to-converge problems. Recently, Li *et al.* [27] combined covariance matrix adaptation evolution strategy [12] and differential evolution (DE) [7] for biased multiobjective optimization. Additionally, adaptive strategies [23] have been developed to automate the selection of proper operators for MOEA/D.
- 5) *Replacement Selection*: When an offspring solution is generated, MOEA/D needs to decide what kinds of old solutions to be replaced by the new solution and how to do the replacement. The original MOEA/D [46] defines a replacement range/neighborhood for each subproblem, and old solutions in this range will be replaced if they are no longer promising. However, it has been found that it is more efficient to induce replacement within the neighborhood of the offspring's most suitable subproblem [41]. Other promising methods include the adoption of effective replacement range [45] and the use of constrained replacement range [40].<sup>2</sup> Instead of considering a proper replacement range, some studies focus on the match between subproblems and solutions, and thus stable matching [25] and inter-relationship [24] based selection strategies are proposed to facilitate replacement. In addition, chain-reaction replacement strategies [36] also help to enhance replacement selection in some sense.
- 6) *Resource Allocation*: In MOEA/D, different subproblems may have different optimization difficulties. Thus, for efficiency, it is desirable to allocate computational resources to subproblems according to their difficulties. Much effort has been made along this direction, resulting in a number of effective resource allocation strategies [2], [47], [49].

Despite plenty of advances, MOEA/D still receives increasing research interests. A particular research direction is concerning SFs, which have not been fully explored yet. In MOEA/D, the weighted sum (WS), weighted Tchebycheff (TCH) and penalty-based boundary

intersection (PBI) are the top three commonly used SFs. These SFs respectively, have their own strengths and drawbacks [39], [43], [45]. In view of the advantages and disadvantages of each SF, Ishibuchi *et al.* [16], [18] proposed to use different SFs adaptively or simultaneously during the search. In [10], a generalized form of SFs was developed to cope with various PF geometries. Sato [35] proposed an inverted PBI method to overcome the poor spread performance of existing SFs in some problems. Modified or advanced SFs have also been developed to facilitate the environmental selection in other algorithms [3], [22], [34], [44].

It is noteworthy that one important property of an SF is the shape or positioning of its contour lines [9], [43]. The contour lines are a set of equal SF values and play a crucial role in guiding the search in scalarizing search algorithms [9]. Derbel *et al.* [9] argued that the dynamics of the search process is rather independent of the SF under consideration and instead mainly influenced by the induced contour lines. Another study [40] showed that imposing proper constraints to the contours of an SF can improve search efficiency. Recently, Wang *et al.* [39] systematically studied the search ability of a family of widely used SFs with different contours, called the  $L_p$  SFs, and have argued that different contours should be used at different search stages.

Generally, desired contours in scalarizing search algorithms can be obtained by: 1) using traditional SFs and modifying their contours by adding constraints [40] or specifying different parameters [39] or 2) designing new and effective SFs. The former method looks intuitive and easy but may not always generate the exact contours one wants. For example, the modified SFs (excluding PBI) in both [39] and [40] cannot produce contour lines that have opening angles [9] smaller than  $\pi/2$ , which may not balance diversity and convergence well during the search. In this paper, the focus is on the latter, and new SFs that can induce adjustable contour lines are presented. The main contributions of this paper are summarized as follows.

- 1) Two new SFs with adjustable contours are proposed and their properties are analyzed.
- 2) On the basis of the new SFs and other new techniques, an efficient MOEA/D framework, called eMOEA/D, is introduced. eMOEA/D uses adaptive SFs to guide the search and a new replacement strategy to efficiently update the population.
- 3) The effectiveness of the new SFs is verified. Extensive algorithm comparisons and discussions are conducted, and experimental studies show that eMOEA/D obtains better performance than the other compared algorithms.

The rest of this paper is organized as follows. Section II describes some background knowledge. Section III presents the proposed SFs and corresponding theoretical analysis, followed by preliminary experiments with regard to their influence in Section IV. Section V presents the efficient MOEA/D framework based on the SFs and some new techniques. Algorithm comparisons are provided in Section VI, followed by extensive discussions in Section VII. Section VIII concludes this paper.

<sup>2</sup>Note that adding constraints to subproblems in [40] is actually equivalent to restricting replacement range.

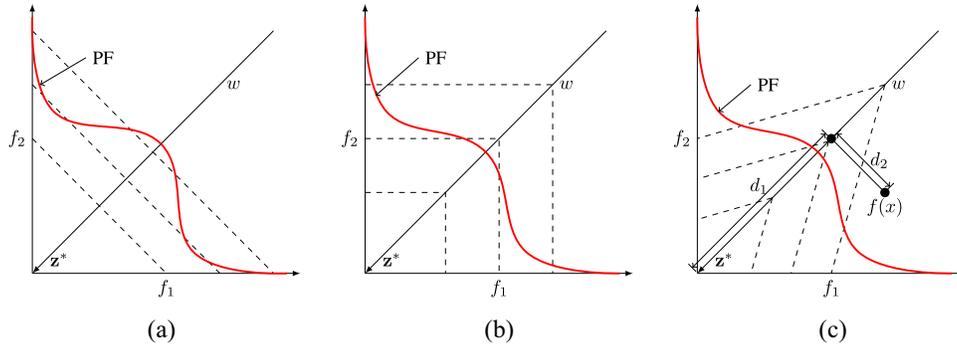


Fig. 1. Illustration of three SFs on weight vector  $w$ , where dashed lines are contour lines.

## II. RELATED WORK

### A. Basic Concepts

An MOP can be mathematically described as follows:

$$\begin{aligned} \min \quad & f(x) = (f_1(x), f_2(x), \dots, f_m(x))^T \\ \text{s.t.} \quad & x \in \Omega_x \end{aligned} \quad (1)$$

where  $\Omega_x \subseteq \mathbb{R}^n$  is the decision space and  $x = (x_1, \dots, x_n)^T$  is a candidate solution.  $f: \Omega_x \mapsto \Omega_f \subseteq \mathbb{R}^m$  contains  $m$  objective functions, and  $\Omega_f$  is the attainable objective space.

*Definition 1:* A solution  $x$  is said to dominate another solution  $y$  if  $x$  is not worse than  $y$  in all objectives and is better than  $y$  in at least one objective. This is denoted as  $x < y$ .

*Definition 2:* A solution  $x^*$  is said to be Pareto optimal if no another solution  $x$  in the decision space satisfies  $x < x^*$ .

*Definition 3:* The Pareto-optimal set (PS) is a set of Pareto-optimal solutions, i.e.,  $\text{PS} = \{x \in \Omega_x | x \text{ is Pareto optimal}\}$ . Correspondingly, the image of PS in the objective space is called the PF, i.e.,  $\text{PF} = \{f(x) \in \Omega_f | x \in \text{PS}\}$ .

*Definition 4:* For a given SF, a solution  $x$  is said to be better than another solution  $y$  if  $x$  obtains a better SF value than  $y$ . This is denoted as  $x <_{\text{SF}} y$ .

*Definition 5:* For a given SF, the improvement region (in the objective space) of a solution  $x$  is denoted as  $\Phi(x) = \{f(\bar{x}) \in \Omega_f | \bar{x} <_{\text{SF}} x\}$ .

### B. Scalarizing Methods in MOEA/D

1) *WS Method:* Assume that  $w = (w_1, \dots, w_m)^T$  is a weight vector where all components are non-negative and should satisfy  $\sum_{i=1}^m w_i = 1$ . The WS method defines the following single-objective problem:

$$\begin{aligned} \min \quad & g^{\text{ws}}(x|w, z^*) = \sum_{i=1}^m (w_i |f_i(x) - z_i^*|) \\ \text{s.t.} \quad & x \in \Omega_x. \end{aligned} \quad (2)$$

If necessary, throughout the paper,  $f_i(x) - z_i^*$  should be replaced by  $(f_i(x) - z_i^*) / (z_i^{\text{nadir}} - z_i^*)$  where  $z_i^*$  and  $z_i^{\text{nadir}}$  are the  $i$ th objective values of ideal point and nadir point found so far [46], respectively. The WS method is illustrated in Fig. 1(a), and it can obtain a set of PF points by different weight vectors. The method can approximate the PF if it is convex, but will miss some PF points if the PF is nonconvex [46].

2) *TCH Method:* The TCH method transforms an MOP into a scalar problem in the following form:

$$\begin{aligned} \min \quad & g^{\text{te}}(x|w, z^*) = \max_{1 \leq i \leq m} \left( \frac{1}{w_i} |f_i(x) - z_i^*| \right) \\ \text{s.t.} \quad & x \in \Omega_x \end{aligned} \quad (3)$$

where  $w_i = 10^{-4}$  is used in this method if  $w_i = 0$ . In (3),  $1/w_i$  instead of  $w_i$  is adopted in order to obtain a set of uniformly distributed solutions from a set of uniformly distributed weight vectors [25]. The TCH method has the advantage in approximating nonconvex PFs compared with the WS method. It has been widely employed as a decomposition approach in MOEA/D variants [20], [25], [26], [40]. This method is shown in Fig. 1(b).

3) *PBI Method:* The PBI method transforms an MOP into a scalar problem as follows:

$$\begin{aligned} \min \quad & g^{\text{pbi}}(x|w, z^*) = d_1 + \theta d_2 \\ \text{s.t.} \quad & x \in \Omega_x \end{aligned} \quad (4)$$

where

$$d_1 = \frac{\|(f(x) - z^*)^T w\|}{\|w\|} \quad (5)$$

$$d_2 = \left\| f(x) - \left( z^* + d_1 \frac{w}{\|w\|} \right) \right\|. \quad (6)$$

In PBI,  $\theta$  is a user-defined penalty factor.  $d_1$  and  $d_2$  are the length of the projection of vector  $(f(x) - z^*)$  on the weight vector  $w$  and the perpendicular distance from  $f(x)$  to  $w$ , respectively. Fig. 1(c) provides a brief illustration of the PBI approach. It is clear that  $\theta$  is a key parameter for balancing convergence (measured by  $d_1$ ) and diversity (measured by  $d_2$ ). Recent studies [15], [35] have shown that, when PBI approximates convex PFs, large diversity is likely to be obtained from minute and large  $\theta$  values, and small  $\theta$  values are beneficial to convergence.

### C. Motivation

SFs (or decomposition approaches) play a fundamental role in the performance of decomposition-based MOEAs. SFs and decomposition-based MOEAs work closely as follows. First, SFs transform an MOP into a number of single-objective optimization problems. Then, decomposition-based

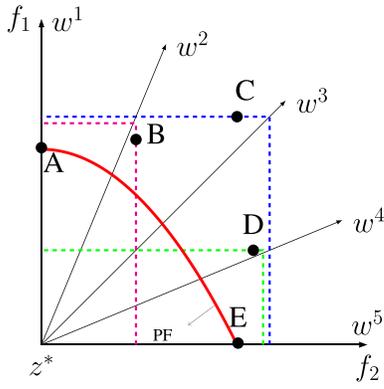


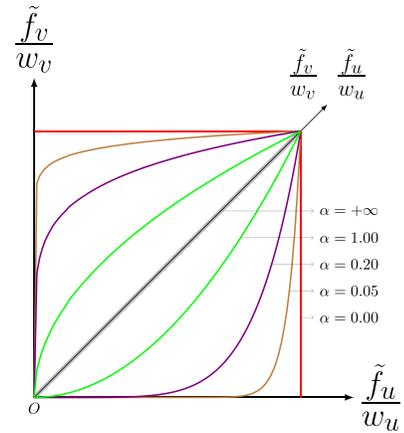
Fig. 2. Illustration of solution distribution in the bi-objective space. Dashed lines are contours of  $L_\infty$  SFs.

MOEAs optimize each subproblem in a collaborative manner. If an inappropriate SF is chosen or the used SF cannot transform MOPs well to subproblems, then decomposition-based MOEAs may fail to approximate the PF.

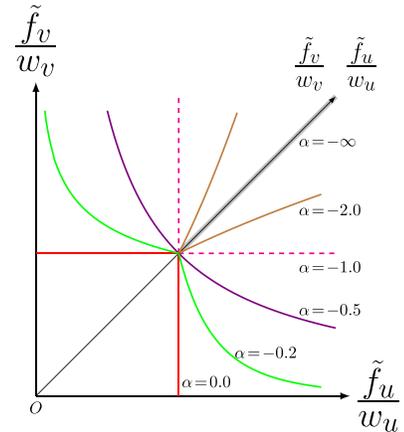
The three SFs mentioned previously, i.e., WS, TCH, and PBI, have been widely used in decomposition-based MOEAs. Despite their great success in solving a variety of MOPs, these SFs have their own limitations. For example, PBI is very sensitive to the search landscape of the objective space and may miss some PF points if the underlying penalty factor is not well-tuned [35], [43].

On the other hand, WS and TCH belong to the family of the  $L_p$  ( $p \geq 1$ ) SFs [39], and they are two extreme cases of this family (WS and TCH correspond to  $L_1$  and  $L_\infty$ , respectively). As pointed out by Wang *et al.* [39], TCH is the best in the  $L_p$  family in terms of diversity maintenance because its contour lines have the smallest opening angle, i.e.,  $\pi/2$ , as shown in Fig. 1(b). However, we argue here that a contour with  $\pi/2$  opening angle is still insufficient to maintain diversity in some cases. Fig. 2 illustrates a situation where the  $L_\infty$  SF fails to maintain diversity. In the figure, three individuals (B, C, and D) are of great importance to diversity, but they will be replaced by two boundary individuals (A and E) because their improvement regions contain A and/or E, i.e.,  $\{A\} \subset \Phi(B)$ ,  $\{A, E\} \subset \Phi(C)$ , and  $\{E\} \subset \Phi(D)$ . This implies that  $L_\infty$  along with its family members lacks the property of maintaining/promoting diversity. It may be of little use and even fails if search environments are very complex and little information is available in advance.

Generally, the above-mentioned drawback with regard to  $L_p$  SFs can be alleviated by the following possible ways. First, constraints can be added to the contour lines of  $L_p$  SFs to reduce opening angles or  $L_p$  SFs work with appropriate replacement strategies to stop abandoning diverse individuals. Second, a new and effective SF with adjustable contours or improvement regions that well control diversity would help MOEA/D yield good performance. Obviously, the second approach is more straightforward and easier to implement because it does not require any modification of the basic framework of MOEA/D. For this reason, it is desirable to devise new SFs for MOEA/D.



(a)



(b)

Fig. 3. Contour lines of MSF with different  $\alpha$  values. (a)  $\alpha \geq 0$ . (b)  $\alpha \leq 0$ .

### III. PROPOSED SCALARIZING FUNCTIONS

In the following, we propose two SFs for MOEA/D.

#### A. Multiplicative Scalarizing Function

The multiplicative SF (MSF) method is defined as follows:

$$g^{\text{msf}}(x|w, z^*) = \frac{\left[ \max_{1 \leq i \leq m} \left( \frac{1}{w_i} |f_i(x) - z_i^*| \right) \right]^{1+\alpha}}{\left[ \min_{1 \leq i \leq m} \left( \frac{1}{w_i} |f_i(x) - z_i^*| \right) \right]^\alpha} \quad (7)$$

where  $w_i$  is set to  $10^{-4}$  if  $w_i$  equals zero, and  $\alpha$  is a control parameter. If the denominator is zero, it is replaced with a minute positive value (e.g.,  $10^{-5}$ ) to keep the division legal. When  $\alpha = 0$ ,  $g^{\text{msf}}(x|w, z^*)$  degenerates to (3). That is, the TCH method is a special case of MSF. MSF is technically able to find all Pareto optimal solutions and this is presented in the supplementary material.

For the convenience of denotation, let  $\tilde{f}_i = f_i - z_i^*$ . We also assume  $u$  and  $v$  ( $1 \leq u, v \leq m$ ) are the indices that maximize and minimize  $\tilde{f}_i/w_i$  ( $1 \leq i \leq m$ ), respectively. Fig. 3 presents contour lines of MSF with different  $\alpha$  values on the  $(\tilde{f}_u/w_u, \tilde{f}_v/w_v)$ -plane. As can be seen from the figure, the size of the improvement region decreases with the increase of  $\alpha$ . Obviously,  $\alpha \geq 0$  is more desired compared with  $\alpha < 0$  because just like the WS method, MSF with  $\alpha < 0$  is unable to

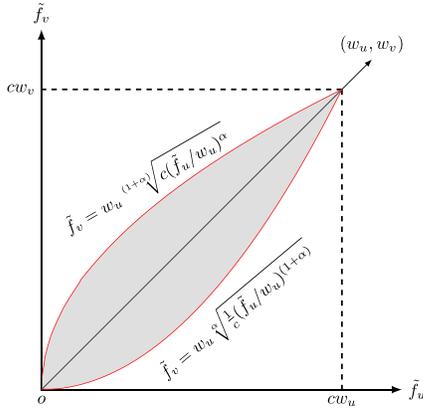


Fig. 4. Improvement region (shaded area) of MSF.

approximate nonconvex PFs and is very likely to lose diversity as mentioned earlier.<sup>3</sup> For this reason, we only consider  $\alpha \geq 0$  in this paper.

*Theorem 1:* On the  $\tilde{f}_u\tilde{f}_v$ -plane, the maximum size of the improvement region enclosed by  $g^{\text{msf}}(x|w, z^*) = c$  ( $c \geq 0$ ), denoted  $\Delta(c)$ , is equal to  $w_u w_v c^2 / (2\alpha + 1)$ .

*Proof:* The improvement region is enclosed by the curve  $g^{\text{msf}}(x|w, z^*) = c$ , as shown in Fig. 4. It is easy to see that  $g^{\text{msf}}(x|w, z^*) = c$  and  $\tilde{f}_u/w_u = \tilde{f}_v/w_v$  have two common points of intersection, i.e.,  $(0, 0)$  and  $(cw_u, cw_v)$ . Next, we calculate the two parts of  $g^{\text{msf}}(x|w, z^*) = c$  below and above  $\tilde{f}_u/w_u = \tilde{f}_v/w_v$ , respectively.

If  $\tilde{f}_u/w_u > \tilde{f}_v/w_v$ , then  $g^{\text{msf}}(x|w, z^*) = (\tilde{f}_u/w_u)^{1+\alpha} / (\tilde{f}_v/w_v)^\alpha = c$ . Thus,  $f_v = w_v \sqrt[1+\alpha]{c (\tilde{f}_u/w_u)^\alpha}$ .

If  $\tilde{f}_u/w_u < \tilde{f}_v/w_v$ , then  $g^{\text{msf}}(x|w, z^*) = (\tilde{f}_v/w_v)^{1+\alpha} / (\tilde{f}_u/w_u)^\alpha = c$ . Thus,  $f_v = w_v \sqrt[1+\alpha]{\frac{1}{c} (\tilde{f}_u/w_u)^{1+\alpha}}$ .

Therefore,  $\Delta(c)$  is equal to the area bounded by the above two function curves. That is

$$\begin{aligned} \Delta(c) &= \int_0^{cw_u} \left( w_v^\alpha \sqrt[1+\alpha]{\frac{1}{c} \left(\frac{\tilde{f}_u}{w_u}\right)^{1+\alpha}} - w_v^{1+\alpha} \sqrt[1+\alpha]{c \left(\frac{\tilde{f}_u}{w_u}\right)^\alpha} \right) d\tilde{f}_u \\ &= \frac{w_u w_v c^2}{2\alpha + 1}. \end{aligned} \quad (8)$$

*Theorem 2:* For  $m$  ( $m \geq 2$ ) objectives, the maximum size of the improvement region enclosed by  $g^{\text{msf}}(x|w, z^*) = c$  ( $c \geq 0$ ), denoted  $\Delta_m(c)$ , is equal to

$$\Delta_m(c) = \begin{cases} \frac{w_1 w_2 c^2}{2\alpha + 1} & \text{if } m = 2 \\ \frac{\left(\frac{c^2 \pi(m-1)}{m}\right)^{\frac{m-1}{2}} \left(\prod_{i=1}^m w_i\right) (m-1)!}{\Gamma\left(\frac{m-1}{2} + 1\right) (m(\alpha+1) \cdots (m\alpha + (m-1)))} & \text{otherwise} \end{cases} \quad (9)$$

where  $\Gamma(\cdot)$  is the gamma function [31].

The proof of Theorem 2 is provided in the supplementary material. It is clear from the theorem that, the size of the improvement region for a predefined weight vector is controlled by  $\alpha$ . When  $\alpha$  is fixed, the improvement region is

<sup>3</sup>However,  $\alpha \leq 0$  may provide fast convergence in the early stage of the search and solve concave MOPs efficiently.

affected by the weight vector values, as shown in Fig. 5. Generally, intermediate weight vectors tend to have larger  $\Delta_m(c)$  values than boundary ones. This is because the product of the elements of an intermediate weight vector is larger than that of a boundary weight vector. This means that subproblems associated with intermediate weight vectors have more opportunities to be updated than those with boundary weight vectors. Thus, to be fair for all the subproblems, it is plausible to penalize intermediate subproblems or compensate boundary subproblems so that all subproblems can have improvement regions with relatively equal sizes.

According to Theorem 2, a straightforward way of balancing subproblems is to vary  $\alpha$  for different subproblems. In this paper, we adjust  $\alpha$  as follows:

$$\alpha = \beta \left\{ m \min_{1 \leq i \leq m} (w_i) \right\} \quad (10)$$

where  $w_i$  is the  $i$ th element of weight vector  $w$ , and  $m$  is the number of objectives.  $0 \leq m \min_{1 \leq i \leq m} (w_i) \leq 1$  always holds under the assumption  $\sum_{i=1}^m w_i = 1$ .  $\beta$  is the underlying control parameter. It is worth mentioning that the improvement region in TCH is nonadjustable as it is constant (i.e.,  $\Delta_2(c) = w_1 w_2 c^2$ ) if both contour line value  $c$  and weight vector  $w$  are predetermined. However, MSF can control each subproblem's improvement region through the adjustment of  $\alpha$  [or  $\beta$  in (10)].

### B. Penalty-Based Scalarizing Function

Inspired by the idea of PBI that controls diversity by penalizing solutions far from a weight vector, we modify the weighted TCH function in the following way:

$$g^{\text{psf}}(x|w, z^*) = \max_{1 \leq i \leq m} \left( \frac{1}{w_i} |f_i(x) - z_i^*| \right) + \alpha d \quad (11)$$

$$d = \frac{\sqrt{\|f(x) - z^*\|^2 \|w\|^2 - \|(f(x) - z^*)^T w\|^2}}{\|w\|} \quad (12)$$

where  $d$  is the perpendicular distance of a solution to the weight vector  $w$ , i.e.,  $d$  is the same as  $d_2$  defined in (6).  $\alpha$  is a penalty value used to control diversity. Fig. 6 illustrates the contour lines of penalty-based SF (PSF) with different  $\alpha$  values. Similar to MSF, the improvement region of PSF varies dramatically with  $\alpha$ , and  $\alpha \geq 0$  is preferable in this paper as diversity is the focus of this paper. Fig. 7 presents the contour lines of PSF for different weight vectors. PSF is technically able to find all Pareto optimal solutions and this is presented in the supplementary material.

Like MSF, the size of the improvement region of PSF also depends largely on  $\alpha$  and the considered weight vector  $w$ . Thus, PSF uses the same adjustment strategy [see (10)] to balance different subproblems.

### C. Remarks

1) *MSF and PSF Versus  $L_p$ :* Let us revisit the problem previously illustrated in Fig. 2, where  $L_\infty$  and other  $L_p$  SFs cannot induce proper contours or improvement regions to avoid diversity loss. We wonder whether the proposed MSF

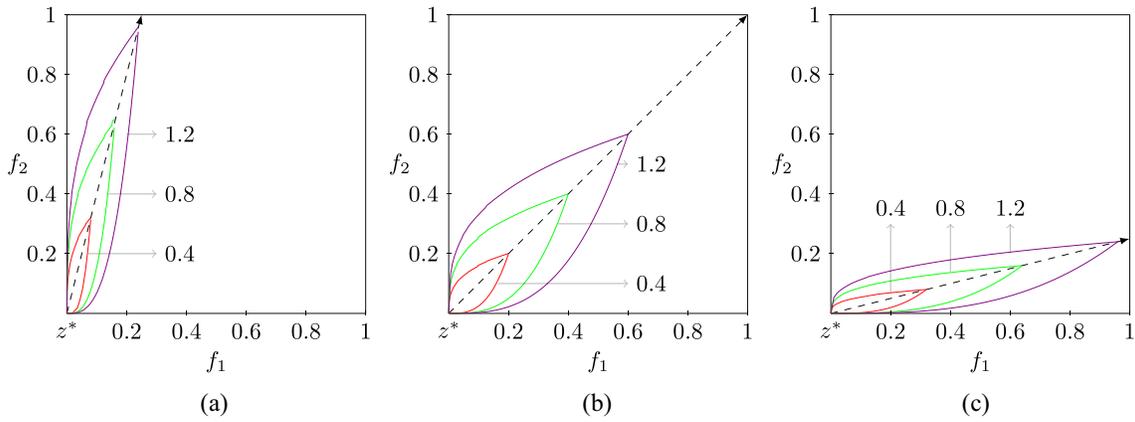


Fig. 5. Contour lines of MSF with  $\alpha = 0.5$  for the contour values 0.4, 0.8, and 1.2. (a)  $w = (0.2, 0.8)^T$ . (b)  $w = (0.5, 0.5)^T$ . (c)  $w = (0.8, 0.2)^T$ .

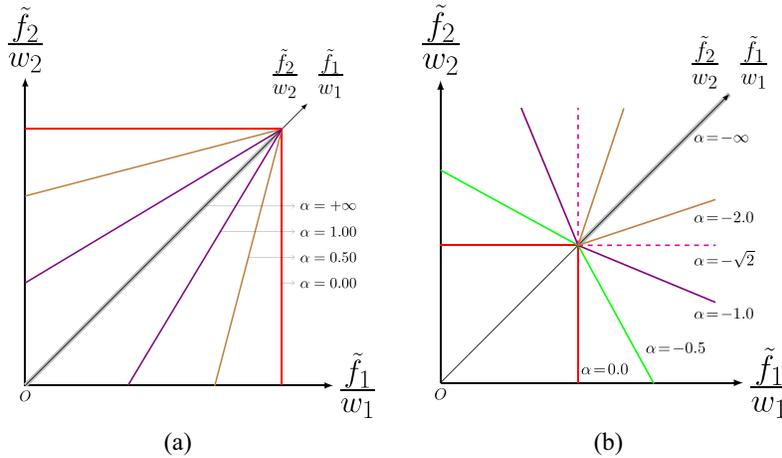


Fig. 6. Contour lines of PSF with different  $\alpha$  values. (a)  $\alpha \geq 0$ . (b)  $\alpha \leq 0$ .

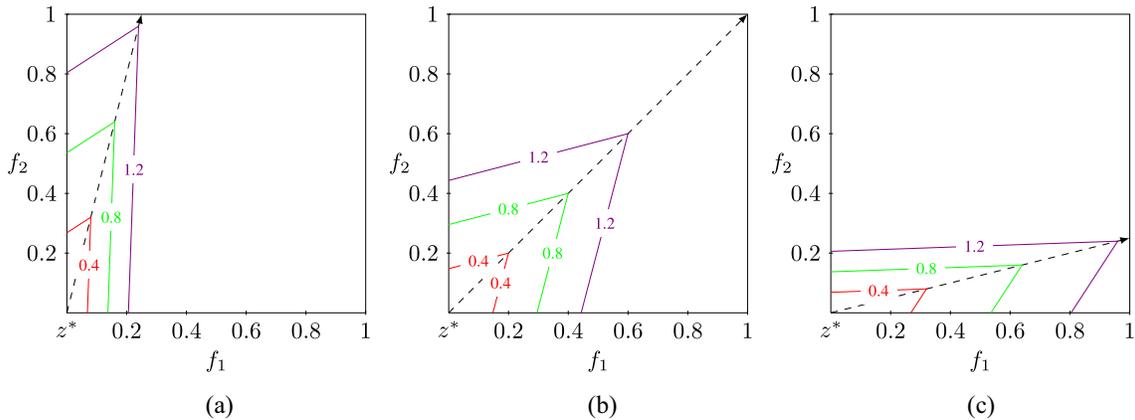


Fig. 7. Contour lines of PSF with  $\alpha = 1.0$  for the contour values 0.4, 0.8, and 1.2. (a)  $w = (0.2, 0.8)^T$ . (b)  $w = (0.5, 0.5)^T$ . (c)  $w = (0.8, 0.2)^T$ .

and PSF can overcome this drawback. Fig. 8 presents the contours of MSF and PSF (both are with  $\alpha = 1$ ) passing through three important points ( $B$ ,  $C$ , and  $D$ ). It is clear that when MSF or PSF is used, all the five points from  $A$  to  $E$  can survive during the replacement because no point resides in the improvement region of another point. Thus, MSF and PSF are effective and promising for diversity maintenance.

2) *MSF Versus PSF*: The improvement region of both methods varies with  $\alpha$ , and both degenerates to TCH when

$\alpha = 0$ . For  $\alpha \geq 0$ , however, the geometries of MSF and PSF are different. The contour lines of MSF are nonlinear whereas those of PSF are polytopes. Thus, boundary points besides the ideal point can be in an improvement region induced by PSF, but this is not the case with MSF. Fig. 9 presents a situation where a boundary point  $X$  will replace an intermediate point  $Y$  associated with the search direction  $w$  if PSF with inappropriate opening angles is used. But, this will not happen to MSF. For this reason, MSF may keep diversity better than

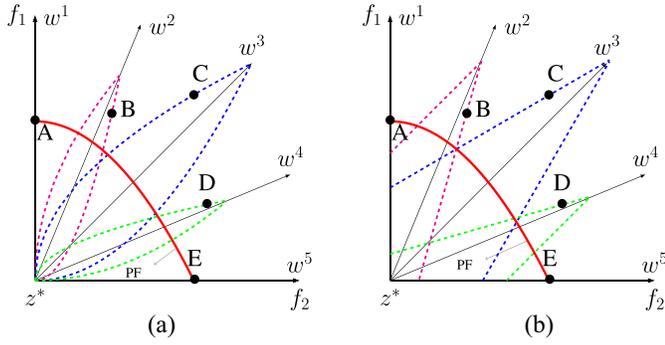


Fig. 8. Illustrations of (a) MSF and (b) PSF for maintaining diversity, where dashed lines are contours.

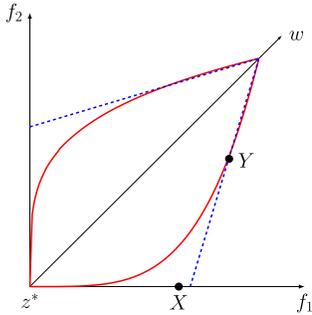


Fig. 9. Illustration where MSF (red solid) and PSF (blue dashed) induce different shapes of contours.

PSF whereas PSF may have advantage in locating boundary solutions.

3) *PSF Versus PBI*: Since PSF borrows the idea of diversity maintenance from PBI, PSF and PBI have similar contour lines, i.e., their contour lines are polytopes. However, they differ much in convergence promotion. Specifically, PBI measures convergence via  $d_1$  values [see Fig. 1(c)]. In complex problems with irregular PF shapes [20],  $d_1$  values vary significantly. In order to balance diversity and convergence, PBI needs to carefully select the penalty factor. Otherwise, PBI is likely to obtain an incomplete approximation of the PF [35]. Unlike PBI, PSF measures convergence via TCH, which can approximate both convex and nonconvex PF geometries. Therefore, PSF may be less sensitive to different PF scenarios compared with PBI.

#### IV. PRELIMINARY EXPERIMENTS

As a starting point, we investigate the effectiveness of the proposed SFs in this section.

##### A. Experimental Settings

As our focus is mainly on the diversity aspect of SFs, test problems used for experimental validation should be able to challenge MOEAs' diversity performance. For this reason, the MOP [28] test suite is selected. This test suite has seven instances, each of which has local attractors on boundary regions of the PF. Thus, MOEAs are very easy to get trapped into these attractors if their diversity is not well maintained. A detailed description of the MOP test suite can be

found in the supplementary material, where two more tri-objective instances, i.e., MOP8 and MOP9, are proposed by considering new characteristics. MOP8 places local attractors in the intermediate regions of its linear PF, whereas MOP9 increases optimization difficulties by placing local attractors only on corner regions (i.e., the intersection of the PF and coordinate axes). These added features are expected to further understanding of MOEAs' search behavior.

The proposed MSF and PSF are integrated into the MOEA/D-DE [26] framework, whose recombination operator is replaced by the adaptive operator [29] due to its reported success on MOP problems [28].

Parameters in MOEA/D-DE were set as follows. The population size  $N$  was 100 and 105 for bi- and tri-objective problems, respectively. The neighborhood size  $T$  was  $T = 0.1N$  and the probability  $\delta$  used to select mating neighborhood was  $\delta = 0.9$ . The maximal allowable number  $n_r$  of solutions to be replaced by a child solution was  $n_r = 2$ . Due to the difficulty of the MOP test suite, the maximum number MaxGen of generations was set to MaxGen = 5000. The total number of independent runs was 31.

Since both MSF and PSF use (10) to assign  $\alpha$  values, we just need to test the influence of different  $\beta$  values in (10). In the experimental study,  $\beta$  was chosen from  $\{0, 0.05, 0.2, 1, 5, 10, 20\}$  for MSF and  $\{0, 1, 5, 10, 20, 100\}$  for PSF.  $\beta = 0$  is a special case where both MSF and PSF degenerate to TCH.

##### B. Performance Indicators

In our experimental studies, we adopt the following widely used performance indicators.

1) *Inverted Generational Distance* [28]: Inverted generational distance (IGD) can provide reliable information on both diversity and convergence of obtained solutions. Let  $P$  be a set of solutions uniformly sampled from the true PF, and  $P^*$  be the approximated solutions in the objective space, the indicator measures the gap between  $P^*$  and  $P$ , calculated as follows:

$$\text{IGD}(P^*, P) = \frac{\sum_{x \in P} d(x, P^*)}{|P|} \quad (13)$$

where  $d(x, P^*)$  is the distance between the member  $x$  of  $P$  and the nearest member of  $P^*$ . For the calculation of IGD,  $P$  is composed of 5000 scattered points which are uniformly sampled from the true PF.

2) *Averaged Hausdorff Distance* ( $\Delta_p$ ) [37]:  $\Delta_p$  is a recently developed indicator that prefers evenly spread solutions along the PF [33] and can somewhat handle the outlier tradeoff [37]. The indicator is calculated as follows:

$$\Delta_p(P^*, P) = \max \left\{ \left( \frac{\sum_{x \in P} d^p(x, P^*)}{|P|} \right)^{\frac{1}{p}}, \left( \frac{\sum_{x \in P^*} d^p(x, P)}{|P^*|} \right)^{\frac{1}{p}} \right\} \quad (14)$$

where  $d(x, P)$  is the distance between the member  $x$  of  $P^*$  and the nearest member of  $P$ . In this paper,  $p = 2$  is used.

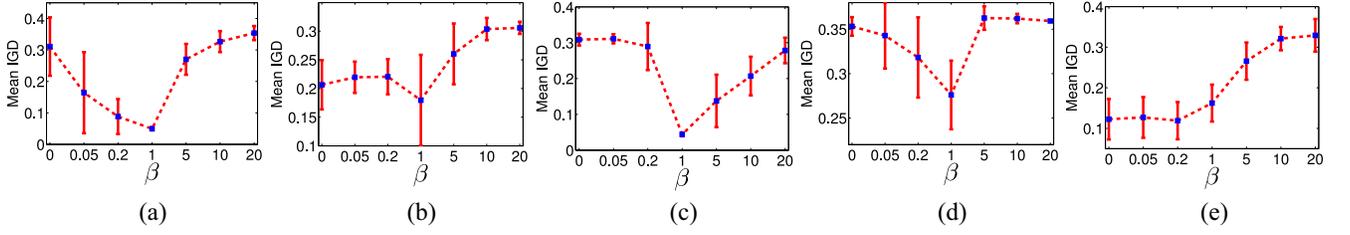


Fig. 10. Mean IGD values obtained by MSF with different  $\beta$  settings. (a) MOP1. (b) MOP2. (c) MOP5. (d) MOP7. (e) MOP8.

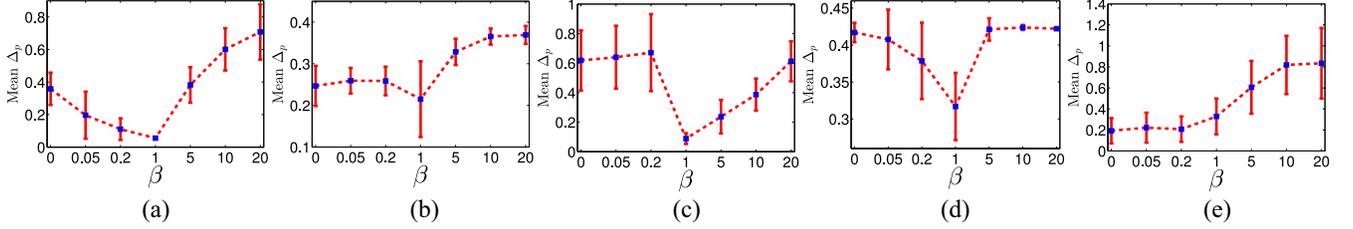


Fig. 11. Mean  $\Delta_p$  values obtained by MSF with different  $\beta$  settings. (a) MOP1. (b) MOP2. (c) MOP5. (d) MOP7. (e) MOP8.

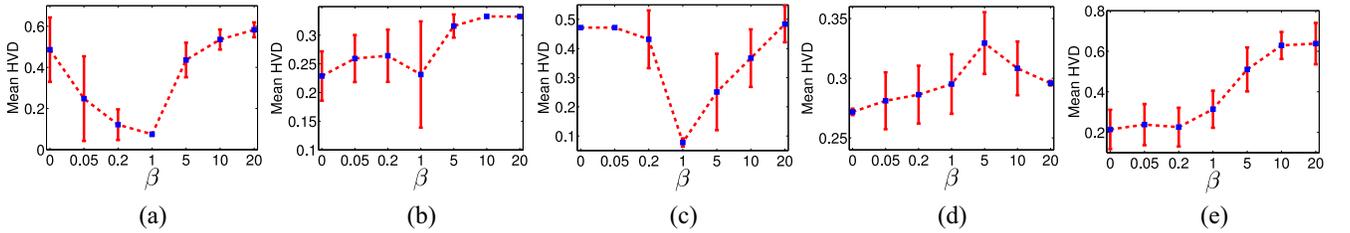


Fig. 12. Mean HVD values obtained by MSF with different  $\beta$  settings. (a) MOP1. (b) MOP2. (c) MOP5. (d) MOP7. (e) MOP8.

3) *Hypervolume Difference*: The hypervolume difference (HVD) [21] measures the gap between the hypervolume of the obtained  $P^*$  and that of the true PF

$$\text{HVD} = \text{HV}(\text{PF}) - \text{HV}(P^*) \quad (15)$$

where  $\text{HV}(S)$  is the hypervolume of a set  $S$ . The reference point for the computation of hypervolume is  $(z_1 + 0.2, z_2 + 0.2, \dots, z_M + 0.2)$ , where  $z_j$  is the maximum value of the  $j$ th objective of the true PF and  $M$  is the number of objectives.  $\text{HV}(\text{PF})$  can be estimated by  $\text{HV}(P)$ , where  $P$  remains the same in the IGD indicator.

### C. Results

Figs. 10–12 show the mean values of three indicators obtained by MSF with different  $\beta$  settings on some selected test problems (the results for all the test problems are presented in the supplementary material), where standard deviation is shown around the mean values. Two observations can be obtained from the figures. First, all the three indicators are roughly consistent when they are used for performance assessment. The only exception occurs on MOP7, where both IGD and  $\Delta_p$  show the performance improves at first and then degrades as  $\beta$  increases from 0 to 20. HVD, however, shows a conflicting performance trend on MOP7. This may be because HVD prefers boundary solutions but does not necessarily favor well-diversified distribution on this particular instance. Second, for the majority of the problems,

the performance is likely to be maximized when  $\beta$  approximately equals one. Meanwhile, it seems that a smaller  $\beta$  value is suitable for MOP8. This implies that, when local attractors reside in the intermediate regions of the PF, restrictions on the diversity aspect of MSF can be relaxed and MSF with a large improvement region is helpful in this situation.

On the other hand, the mean values of the three indicators obtained by PSF with different  $\beta$  settings on some selected test problems are displayed in Figs. 13–15. Similar observations can be obtained from these figures, and PSF works best on most of the problems when  $\beta$  is around 10.

The above results clearly show that both MSF and PSF can help improve decomposition-based MOEAs if the corresponding control parameter is well configured. The experiment indirectly reflects that the popular TCH method (corresponding to the case of  $\beta = 0$  in MSF and PSF) are not always the best choice, and enhancing diversity by nicely controlling improvement regions can lead to a clear performance improvement.

Besides, the mean HVD evolution curves obtained by MSF versus the number of generations are shown in Fig. 16 (those obtained by PSF are included in the supplementary material due to page limit). We can observe that different  $\beta$  values result in distinct performances.  $\beta = 0$  is not the best setting for MSF and PSF on the majority of the test problems in terms of final HVD values.

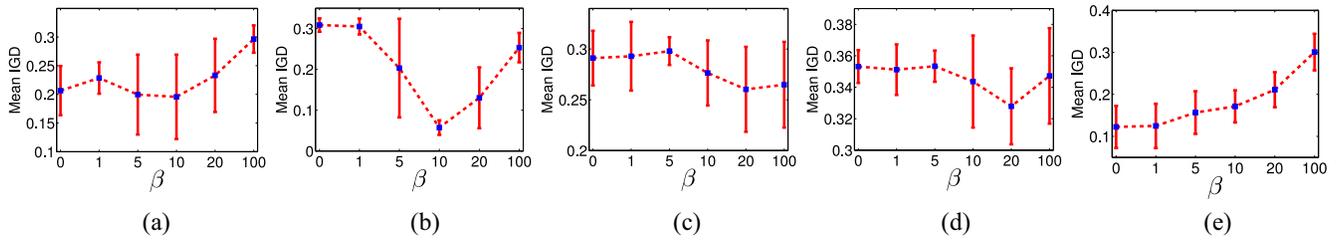


Fig. 13. Mean IGD values obtained by PSF with different  $\beta$  settings. (a) MOP2. (b) MOP5. (c) MOP6. (d) MOP7. (e) MOP8.

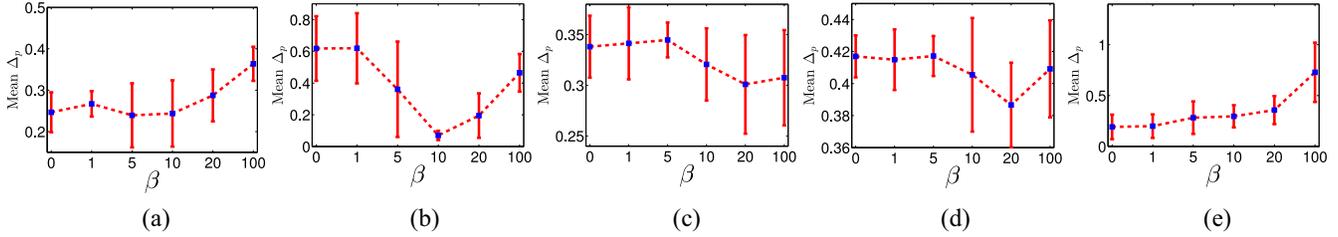


Fig. 14. Mean  $\Delta_p$  values obtained by PSF with different  $\beta$  settings. (a) MOP2. (b) MOP5. (c) MOP6. (d) MOP7. (e) MOP8.

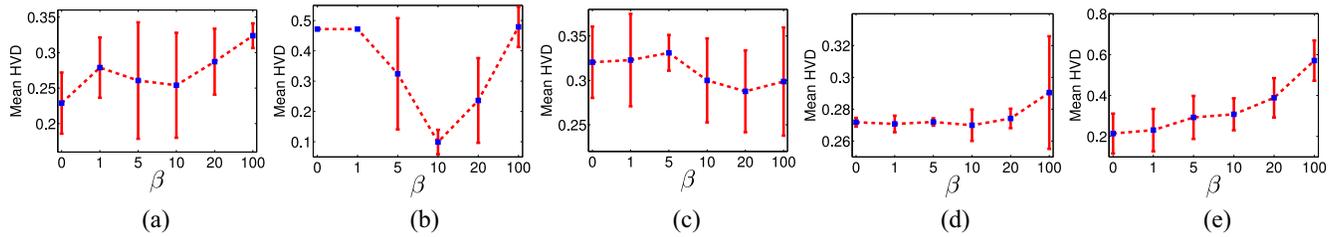


Fig. 15. Mean HVD values obtained by PSF with different  $\beta$  settings. (a) MOP2. (b) MOP5. (c) MOP6. (d) MOP7. (e) MOP8.

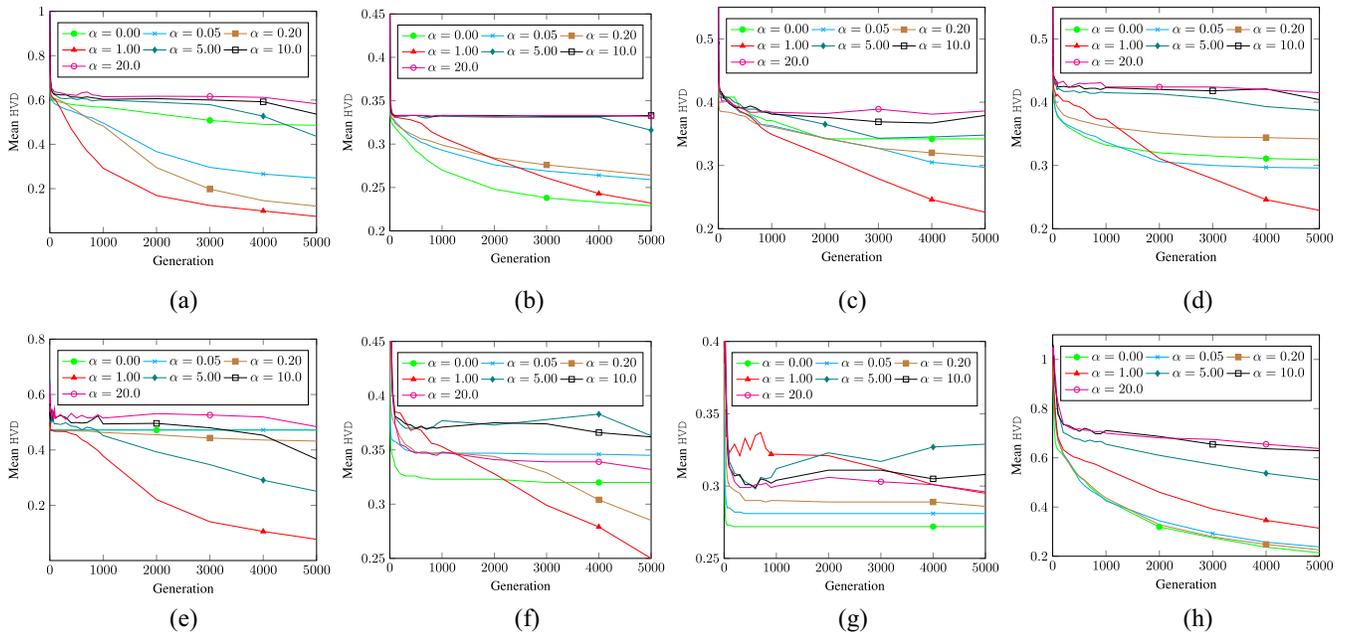


Fig. 16. Evolution curves of the mean HVD indicator obtained by MSF with different  $\beta$  settings. (a) MOP1. (b) MOP3. (c) MOP4. (d) MOP5. (e) MOP6. (f) MOP7. (g) MOP8. (h) MOP9.

$\beta = 1$  and  $\beta = 10$  again help MSF and PSF yield good results, respectively. However, it seems that smaller  $\beta$  values are likely to enable faster convergence, owing to relatively larger improvement regions. These observations suggest

decomposition-based MOEAs may need different  $\beta$  (or the resulting  $\alpha$ ) values at different stages of the search. Therefore, it is plausible to adaptively adjust the value of  $\alpha$  during the search.

**Algorithm 1:** eMOEA/D Framework

---

**Input:** stopping criterion (*MaxGen*), population size ( $N$ ), neighborhood size ( $T$ ), replacement size ( $n_r$ );

**Output:** approximated Pareto-optimal set  $P$ ;

- 1 Generate a uniform spread of  $N$  weight vectors:  $\{w^1, w^2, \dots, w^N\}$  and then compute the  $T$  closest weight vectors to each weight vector by the Euclidean distance. For each  $w^i$ , set  $B(i) = \{i_1, \dots, i_T\}$  where  $w^{i_1}, \dots, w^{i_T}$  are the  $T$  closest weight vectors to  $w^i$ ;
- 2 Generate an initial population  $P = \{x^1, \dots, x^N\}$  by uniformly randomly sampling from the decision space;
- 3 Initialize *ideal* and *nadir* points, i.e.,  $z^*$  and  $z^{nad}$ ;
- 4 Choose a scalarizing function SF for MOEA/D;
- 5  $gen \leftarrow 1$ ;
- 6 **while**  $gen \leq MaxGen$  **do**
- 7 Update  $\alpha$  for the selected SF according to (16);
- 8 **for**  $i \leftarrow 1$  **to**  $N$  **do**
- 9 Randomly select indexes  $r_1$  and  $r_2$  from  $B(i)$ ;
- 10 Apply genetic operators on individuals  $x^{r_1}, x^{r_2}$  to produce a new solution  $y$ ;
- 11 Evaluate the objective vector of  $y$ , and update  $z^*$ ;
- 12 Find the  $T$  most suitable subproblems for  $y$ :  
 $S = \{s_1, s_2, \dots, s_T\}$ ;
- 13  $c \leftarrow 0$ ;
- 14 **for**  $j \leftarrow 0$  **to**  $T$  **do**
- 15 **if**  $y \prec_{SF} x^{s_j}$  **then**
- 16  $x^{s_j} \leftarrow y$  and  $c \leftarrow c + 1$ ;
- 17 **end**
- 18 **if**  $c \geq n_r$  **then**
- 19 **break**;
- 20 **end**
- 21 **end**
- 22 **end**
- 23 Update  $z^{nad}$  using  $P$ ,  $gen \leftarrow gen + 1$ ;
- 24 **end**

---

## V. EMOEA/D: EFFICIENT MOEA/D FRAMEWORK

The proposed MOEA/D variant remains almost the same as its predecessors [26], [46] except a few modifications in scalarizing methods, offspring production and solution replacement. The framework of the algorithm is depicted in Algorithm 1. First, a set of uniformly distributed weight vectors is created, and each weight vector is assigned a neighborhood containing the  $T$  closest weight vectors. Meanwhile, the ideal point ( $z^*$ ) and nadir point ( $z^{nad}$ ) are estimated by the minimum and maximum values of each objective in the population.  $z^*$  and  $z^{nad}$  are then used for objective normalization ( $(f_i(x) - z_i^*) / (z_i^{nadir} - z_i^*)$ ) is adopted in this paper to normalize each objective  $f_i$ ). After that, either MSF or PSF is chosen as a SF beforehand. The  $\alpha$  value of the SF is generationally updated in line 7. For each subproblem  $i$ , mating parents are selected only from  $B(i)$  (see line 9), which is the same as the original MOEA/D [46] but different from another popular variant MOEA/D-DE [26]. In line 10, genetic operators are applied on the selected parents to produce offspring. The offspring is evaluated in terms of the objective vector and is then used to update the ideal

point. From lines 12 to 21, a new solution replacement strategy is introduced, and similar to MOEA/D-DE, we also place a restriction on the number of replacements (see lines 18–20). At the end of every generation, the approximated nadir point is updated by the whole population.

## A. Adaptive Scalarizing Strategy

While the proposed SFs are helpful for maintaining population diversity, it may decrease the convergence performance. A small  $\alpha$  value in both MSF and PSF are beneficial to convergence, but it is very likely to cause the loss of diversity. This is just the case with TCH, which struggles to recover from the loss of diversity for hard problems. Without any information about problem properties *a priori*, it is plausible to emphasize diversity at the early stage of search and then gradually emphasize convergence at the late stage. To this end, we propose an adaptive strategy to adjust the value of  $\alpha$  (line 7 of Algorithm 1). As a result, (10) is rewritten as follows:

$$\alpha = \beta \left(1 - \frac{gen}{MaxGen}\right) \left\{ m \min_{1 \leq i \leq m} (w_i) \right\} \quad (16)$$

where  $gen$  is the current generation number, and  $MaxGen$  is the maximum number of generations. It is clear that, for each subproblem,  $\alpha$  is decreased linearly as the evolution proceeds and becomes zero at the end of search. This means that both MSF and PSF gradually degenerate to TCH, and in this process the improvement region for each subproblem is gradually increased, resulting in steady-state de-emphasis of diversity and speed-up of convergence simultaneously. Note that, any adaptive decreasing strategy (no matter it is linear or nonlinear) can be used as long as it can reduce  $\alpha$  gradually. The linear strategy is adopted here because it is very simple and meets the requirement of reducing  $\alpha$  well.

## B. Reproduction Operation

Reproduction operation (lines 9 and 10 of Algorithm 1) includes mating pool selection and genetic recombination. In many MOEA/D variants [26], [41], a probability parameter  $\delta$  is adopted to select a mating pool from either the neighborhood of solutions or the whole population. The main purpose for this is to increase population diversity. However, this induces the difficulty in tuning such an extra parameter. Since we have introduced advanced SFs that can keep diversity well, we discourage the use of the probability parameter and simply set the mating pool as the neighborhood of solutions.

When mating parents are randomly selected from the mating pool, the next step is to perform genetic operators on the mating parents to generate offspring. In this paper, we use the adaptive DE [29] as our genetic operator. The adaptive DE was also used in [28] and showed good performance for hard problems. The details of this operator are presented in the supplementary material.

## C. Replacement Operation

Replacement operation (lines 12–21 of Algorithm 1) is a key step in many MOEA/D variants. It is related to what and how subproblems can be updated. If a new solution is not suitable for subproblems that are chosen to be updated, then

TABLE I  
BEST, MEDIAN, AND WORST  $\Delta_p$  VALUES OBTAINED BY DIFFERENT ALGORITHMS ON MOP PROBLEMS

| Prob. | MSF*            | PSF*            | TCH                   | ACD                   | AGR                   | DU                    | STM                   | M2M                   |
|-------|-----------------|-----------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| MOP1  | 9.14E-03        | 9.38E-03        | 7.37E-02              | 9.50E-03              | 1.86E-02              | 1.01E-02              | <b>8.65E-03</b>       | 1.46E-02              |
|       | <b>9.46E-03</b> | 9.68E-03        | 3.97E-01 <sup>‡</sup> | 9.77E-03              | 1.99E-02 <sup>‡</sup> | 1.04E-02 <sup>‡</sup> | 9.98E-02 <sup>‡</sup> | 1.60E-02 <sup>‡</sup> |
|       | 9.95E-03        | <b>9.92E-03</b> | 4.11E-01              | 9.95E-03              | 2.63E-02              | 1.17E-02              | 3.96E-01              | 1.75E-02              |
| MOP2  | <b>4.60E-03</b> | 4.63E-03        | 1.89E-01              | 4.62E-03              | 7.65E-03              | 5.47E-03              | 4.72E-03              | 1.18E-02              |
|       | <b>4.67E-03</b> | 4.67E-03        | 2.35E-01 <sup>‡</sup> | 4.67E-03              | 2.26E-02 <sup>‡</sup> | 5.74E-03 <sup>‡</sup> | 7.47E-03 <sup>‡</sup> | 1.36E-02 <sup>‡</sup> |
|       | <b>4.86E-03</b> | 5.58E-03        | 4.12E-01              | 4.87E-03              | 2.02E-01              | 7.60E-03              | 2.76E-01              | 1.22E-01              |
| MOP3  | 5.65E-03        | 5.24E-03        | 4.63E-01              | <b>5.11E-03</b>       | 1.05E-02              | 6.52E-03              | 4.63E-01              | 1.28E-02              |
|       | 6.02E-03        | 6.00E-03        | 4.93E-01 <sup>‡</sup> | <b>5.98E-03</b>       | 3.49E-02 <sup>‡</sup> | 8.37E-03 <sup>‡</sup> | 4.63E-01 <sup>‡</sup> | 1.55E-02 <sup>‡</sup> |
|       | 3.40E-02        | 4.04E-02        | 6.36E-01              | <b>8.77E-03</b>       | 1.41E-01              | 3.76E-02              | 4.76E-01              | 2.87E-02              |
| MOP4  | <b>6.65E-03</b> | 8.43E-03        | 3.04E-01              | 8.28E-03              | 7.08E-03              | 6.72E-03              | 6.60E-03              | 1.28E-02              |
|       | <b>1.31E-02</b> | 1.31E-02        | 3.19E-01 <sup>‡</sup> | 1.33E-02              | 1.45E-02 <sup>‡</sup> | 1.32E-02              | 2.81E-01 <sup>‡</sup> | 1.55E-02 <sup>‡</sup> |
|       | <b>2.52E-02</b> | 2.49E-02        | 3.74E-01              | 2.04E-02              | 9.64E-02              | 1.88E-02              | 2.90E-01              | 2.87E-02              |
| MOP5  | <b>8.58E-03</b> | 9.11E-03        | 2.95E-01              | 1.07E-02              | 1.80E-02              | 1.54E-02              | 2.64E-02              | 1.81E-02              |
|       | 3.11E-02        | <b>1.26E-02</b> | 6.28E-01 <sup>‡</sup> | 1.27E-02 <sup>◊</sup> | 2.32E-02 <sup>‡</sup> | 1.69E-02 <sup>◊</sup> | 1.92E-01 <sup>‡</sup> | 2.65E-02 <sup>‡</sup> |
|       | 1.21E-01        | 4.14E-02        | 1.08E+00              | 1.53E-01              | 4.61E-02              | <b>3.52E-02</b>       | 1.92E-01              | 2.12E-01              |
| MOP6  | <b>4.30E-02</b> | 4.34E-02        | 2.83E-01              | 1.76E-01              | 8.15E-02              | 5.15E-02              | 5.69E-02              | 1.29E-01              |
|       | <b>4.35E-02</b> | 4.40E-02        | 3.59E-01 <sup>‡</sup> | 2.65E-01 <sup>‡</sup> | 1.62E-01 <sup>‡</sup> | 6.10E-02 <sup>‡</sup> | 2.49E-01 <sup>‡</sup> | 1.76E-01 <sup>‡</sup> |
|       | <b>4.69E-02</b> | 4.90E-02        | 3.59E-01              | 5.37E-01              | 2.66E-01              | 1.49E-01              | 2.83E-01              | 1.08E+00              |
| MOP7  | 7.78E-02        | <b>6.78E-02</b> | 3.69E-01              | 3.25E-01              | 2.83E-01              | 8.70E-02              | 3.24E-01              | 1.89E-01              |
|       | 8.30E-02        | <b>7.21E-02</b> | 4.21E-01 <sup>‡</sup> | 3.59E-01 <sup>‡</sup> | 3.59E-01 <sup>‡</sup> | 1.01E-01 <sup>‡</sup> | 3.59E-01 <sup>‡</sup> | 2.46E-01 <sup>‡</sup> |
|       | <b>1.34E-01</b> | 2.55E-01        | 4.21E-01              | 4.21E-01              | 4.21E-01              | 1.84E-01              | 4.21E-01              | 3.80E+00              |
| MOP8  | 4.13E-02        | <b>4.10E-02</b> | 6.22E-02              | 1.73E-01              | 6.21E-02              | 7.01E-02              | 4.54E-02              | 2.29E-01              |
|       | 4.71E-02        | <b>4.58E-02</b> | 1.65E-01 <sup>‡</sup> | 3.00E-01 <sup>‡</sup> | 2.10E-01 <sup>‡</sup> | 7.78E-02 <sup>‡</sup> | 5.40E-02 <sup>‡</sup> | 6.43E-01 <sup>‡</sup> |
|       | <b>7.82E-02</b> | 8.74E-02        | 4.61E-01              | 4.14E-01              | 4.26E-01              | 9.30E-02              | 4.04E-01              | 1.13E+00              |
| MOP9  | <b>7.01E-02</b> | 8.23E-02        | 3.24E-01              | 1.69E-01              | 1.64E-01              | 8.79E-02              | 3.24E-01              | 2.02E-01              |
|       | <b>7.78E-02</b> | 9.17E-02        | 5.11E-01 <sup>‡</sup> | 3.67E-01 <sup>‡</sup> | 2.24E-01 <sup>‡</sup> | 9.25E-02 <sup>‡</sup> | 3.25E-01 <sup>‡</sup> | 3.36E-01 <sup>‡</sup> |
|       | <b>9.30E-02</b> | 2.40E-01        | 7.47E-01              | 9.78E-01              | 3.78E-01              | 2.13E-01              | 4.09E-01              | 1.06E+00              |

<sup>†</sup> and <sup>◊</sup> indicate MSF\* and PSF\* significantly outperform the corresponding algorithm, respectively.

<sup>‡</sup> indicates both MSF\* and PSF\* significantly outperform the corresponding algorithm.

both population diversity and convergence can be negatively affected. To this end, various replacement strategies have been proposed [41], [49]. The main idea behind these strategies is to find the most suitable subproblem for a newly generated individual  $y$  and then conduct replacement within the neighborhood of this subproblem. However, these strategies fail to consider that the individual  $y$  may not be good for the neighboring subproblems of the most suitable subproblem. If the individual does not improve any solution of the neighborhood of the most suitable subproblem but does improve solutions of other subproblems outside the neighborhood, it should enter the population. In other words, the replacement range should be gingerly elaborated. In this paper, the replacement range is composed of the most suitable  $T$  subproblems. It is calculated as follows. First,  $g^{\text{SF}}(y|w^i, z^*)$  is computed for each  $1 \leq i \leq N$ . Second, all the  $g^{\text{SF}}(y|w^i, z^*)$  values are sorted in the ascending order. Then, the subproblems corresponding to the first  $T$  smallest scalarizing values are regarded as the replacement range  $S = \{s_1, s_2, \dots, s_T\}$ , with  $s_1$  being the first most suitable and  $s_T$  being the  $T$ th most suitable (line 12 of Algorithm 1).

The replacement procedure (lines 14–21 of Algorithm 1) is executed on the ordered replacement range  $S = \{s_1, s_2, \dots, s_T\}$  one by one. Like its predecessor [26], the proposed eMOEA/D framework allows at most  $n_r$  solutions to be replaced by a newly generated solution.

## VI. ALGORITHM COMPARISON AND RESULTS

The experiment in this section is designed for two purposes. One is to verify the proposed eMOEA/D. The other

purpose is to deeply analyze the performance of other existing decomposition-based MOEAs in multiobjective optimization.

### A. Compared Algorithms and Parameter Settings

Algorithms for comparison consist of popular peer MOEAs. The MOEAs are MOEA/D with TCH [26], ACD [40], AGR [41], DU [45], STM [25], and M2M [28] schemes. For notational convenience, MSF\* and PSF\* denote the proposed eMOEA/D with MSF and PSF, respectively.

Key parameters in each compared algorithm remain the same as in the referenced papers. The population size, stopping criterion, and other important parameters are kept the same as in Section IV. All the algorithms use the adaptive operator [29] as the recombination operator. The key factor  $\beta$  in MSF\* and PSF\* is set to 1 and 10, respectively, based on the previous experimental study.

### B. Results on MOP Problems

In this section,  $\Delta_p$  and HVD are used as performance indicators since IGD and  $\Delta_p$  have shown consistent performance assessment in the previous experiment. Tables I and II show the best, median, and worst values of  $\Delta_p$  and HVD on nice MOP problems over 31 independent runs, respectively. The best values obtained by one of the ten algorithms are highlighted in bold face. The differences between the approximations are assessed by the Wilcoxon rank-sum test [42] at the 0.05 significance level, with the standard Bonferroni correction [1] to deal with the problem of the higher probability of Type I errors in multiple comparisons. Signs of <sup>†</sup>, <sup>◊</sup>, and <sup>‡</sup> in

TABLE II  
BEST, MEDIAN, AND WORST HVD VALUES OBTAINED BY DIFFERENT ALGORITHMS ON MOP PROBLEMS

| Prob. | MSF*            | PSF*            | TCH                   | ACD                   | AGR                   | DU                    | STM                   | M2M                   |
|-------|-----------------|-----------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| MOP1  | 1.39E-02        | 1.43E-02        | 7.66E-02              | 1.59E-02              | 2.73E-02              | 1.53E-02              | <b>1.32E-02</b>       | 2.48E-02              |
|       | <b>1.43E-02</b> | 1.46E-02        | 5.46E-01 <sup>‡</sup> | 1.61E-02 <sup>‡</sup> | 2.91E-02 <sup>‡</sup> | 1.58E-02 <sup>‡</sup> | 6.80E-02 <sup>‡</sup> | 2.70E-02 <sup>‡</sup> |
|       | 1.50E-02        | <b>1.49E-02</b> | 5.82E-01              | 1.64E-02              | 3.56E-02              | 1.69E-02              | 5.39E-01              | 2.88E-02              |
| MOP2  | <b>6.30E-03</b> | 6.48E-03        | 1.48E-01              | 6.90E-03              | 1.02E-02              | 8.39E-03              | 6.42E-03              | 1.76E-02              |
|       | <b>6.39E-03</b> | 6.55E-03        | 2.22E-01 <sup>‡</sup> | 8.29E-03 <sup>‡</sup> | 1.82E-02 <sup>‡</sup> | 8.64E-03 <sup>‡</sup> | 6.78E-03              | 1.91E-02 <sup>‡</sup> |
|       | <b>6.53E-03</b> | 8.36E-03        | 3.33E-01              | 9.51E-03              | 2.64E-01              | 1.20E-02              | 1.84E-01              | 1.36E-01              |
| MOP3  | <b>6.08E-03</b> | 6.29E-03        | 2.15E-01              | 6.13E-03              | 1.03E-02              | 8.12E-03              | 2.15E-01              | 1.26E-02              |
|       | <b>6.76E-03</b> | 6.80E-03        | 3.48E-01 <sup>‡</sup> | 7.16E-03 <sup>‡</sup> | 1.24E-02 <sup>‡</sup> | 8.69E-03 <sup>‡</sup> | 2.15E-01 <sup>‡</sup> | 1.53E-02 <sup>‡</sup> |
|       | <b>7.94E-03</b> | 1.45E-02        | 4.15E-01              | 1.03E-02              | 1.55E-01              | 3.19E-02              | 2.82E-01              | 1.88E-02              |
| MOP4  | 3.45E-03        | 6.48E-03        | 2.78E-01              | 7.21E-03              | 4.35E-03              | 4.26E-03              | <b>3.06E-03</b>       | 8.72E-03              |
|       | 9.45E-03        | <b>9.57E-03</b> | 3.12E-01 <sup>‡</sup> | 1.33E-02 <sup>‡</sup> | 1.31E-02              | 1.02E-02              | 2.29E-01              | 1.48E-02 <sup>‡</sup> |
|       | 2.10E-02        | <b>1.54E-02</b> | 3.48E-01              | 2.82E-02              | 1.25E-01              | 1.33E-02              | 2.45E-01              | 2.47E-02              |
| MOP5  | <b>1.38E-02</b> | 1.45E-02        | 4.72E-01              | 1.70E-02              | 2.73E-02              | 2.33E-02              | 2.94E-02              | 2.92E-02              |
|       | 1.63E-02        | <b>1.60E-02</b> | 4.72E-01 <sup>‡</sup> | 1.77E-02              | 3.12E-02 <sup>‡</sup> | 2.46E-02 <sup>‡</sup> | 3.13E-01 <sup>‡</sup> | 3.55E-02 <sup>‡</sup> |
|       | 2.09E-02        | <b>1.87E-02</b> | 4.72E-01              | 1.88E-02              | 4.63E-02              | 3.95E-02              | 3.13E-01              | 5.45E-02              |
| MOP6  | <b>5.15E-02</b> | 5.25E-02        | 2.46E-01              | 1.20E-01              | 9.28E-02              | 6.23E-02              | 5.77E-02              | 1.53E-01              |
|       | <b>5.25E-02</b> | 5.31E-02        | 3.47E-01 <sup>‡</sup> | 2.17E-01 <sup>‡</sup> | 2.00E-01 <sup>‡</sup> | 7.66E-02 <sup>‡</sup> | 1.83E-01 <sup>‡</sup> | 1.91E-01 <sup>‡</sup> |
|       | <b>6.32E-02</b> | 6.50E-02        | 3.47E-01              | 3.47E-01              | 2.91E-01              | 1.20E-01              | 2.46E-01              | 2.96E-01              |
| MOP7  | <b>9.58E-02</b> | 1.08E-01        | 2.60E-01              | 1.70E-01              | 1.58E-01              | 9.67E-02              | 1.58E-01              | 1.63E-01              |
|       | <b>1.03E-01</b> | 1.11E-01        | 2.72E-01 <sup>‡</sup> | 2.62E-01 <sup>‡</sup> | 2.65E-01 <sup>‡</sup> | 1.13E-01              | 2.55E-01 <sup>‡</sup> | 2.14E-01 <sup>‡</sup> |
|       | <b>1.60E-01</b> | 2.10E-01        | 2.72E-01              | 2.98E-01              | 2.72E-01              | 1.88E-01              | 2.72E-01              | 1.20E+00              |
| MOP8  | 4.44E-02        | <b>4.38E-02</b> | 8.65E-02              | 6.59E-02              | 6.94E-02              | 9.25E-02              | 5.62E-02              | 2.63E-01              |
|       | 5.81E-02        | <b>5.46E-02</b> | 2.02E-01 <sup>‡</sup> | 1.16E-01 <sup>‡</sup> | 1.01E-01 <sup>‡</sup> | 1.01E-01 <sup>‡</sup> | 6.88E-02 <sup>‡</sup> | 4.29E-01 <sup>‡</sup> |
|       | <b>9.58E-02</b> | 1.09E-01        | 3.81E-01              | 1.54E-01              | 1.52E-01              | 1.71E-01              | 3.15E-01              | 7.30E-01              |
| MOP9  | 9.25E-02        | <b>8.05E-02</b> | 1.59E-01              | 1.32E-01              | 1.04E-01              | 9.71E-02              | 1.58E-01              | 2.05E-01              |
|       | <b>1.01E-01</b> | 1.03E-01        | 6.15E-01 <sup>‡</sup> | 3.96E-01 <sup>‡</sup> | 1.72E-01 <sup>‡</sup> | 1.03E-01 <sup>‡</sup> | 1.59E-01 <sup>‡</sup> | 2.48E-01 <sup>‡</sup> |
|       | <b>1.71E-01</b> | 3.25E-01        | 6.76E-01              | 6.20E-01              | 3.58E-01              | 2.23E-01              | 4.78E-01              | 4.63E-01              |

† and ◊ indicate MSF\* and PSF\* significantly outperform the corresponding algorithm, respectively.

‡ indicates both MSF\* and PSF\* significantly outperform the corresponding algorithm.

the superscript form on median values indicate the significance of the proposed methods.

From the tables, we can obtain the following observations.

- 1) Compared with the predecessor TCH, all the other MOEA/D variants show improvements on the MOP problems in some sense. The improvements are obvious on the five bi-objective problems, as indicated by the  $\Delta_p$  and HVD values. However, on the four tri-objective problems, ACD, AGR, STM, and M2M do not have any advantage over TCH, as their  $\Delta_p$  and HVD values are very similar to those of TCH.
- 2) MSF\* and PSF\* significantly outperform the other algorithms on the majority of cases. On the bi-objective cases, ACD also shows comparable performance in terms of  $\Delta_p$ . However, ACD degrades dramatically and performs worse than most of the algorithms on the tri-objective cases.
- 3) DU, aimed to improve solution replacement by considering distance to weight vectors, works well on most of the test problem, although it is not the best among all the algorithms and degrades slightly for tri-objective problems. Its good performance is probably due to the emphasis on diversity. This indirectly shows improvements on diversity management is beneficial for solving the MOP test suite.
- 4) Apart from dimensionality, other characteristics of the test problems also affect the compared algorithms' performance. Taking MOP6 and MOP8 for example, they have the same PF shape except that the former has local attractors in boundary regions of the PF whereas

the latter has those in intermediate regions. Judging by HVD, boundary attractors are easier than intermediate ones for MSF\*, PSF\*, DU, and M2M, but seem more difficult for STM.

- 5) Additionally, if we compare the algorithms' performance on MOP7 and MOP9, we can see that most of the algorithms degrade when the number of local attractors in boundary regions decreases. This is understandable because the decrease in the number of local attractors reduces the chance of finding boundary solutions on the PF. However, it seems that such features do not influence too much the performance of the proposed methods, as the obtained HVD results vary little.

We can conclude from the above observations that MSF\* and PSF\* are more likely to generate good performance than the other algorithms on the MOP test suite with a wide variety of problem characteristics and optimization difficulties. This might be mainly attributed to good diversity maintenance induced by the new SFs.

Fig. 17 presents evolutionary curves of the mean IGD values obtained by some selected algorithms on two bi-objective and two tri-objective problems. It is clear that MSF\*, PSF\* and ACD are able to reduce the IGD value efficiently for the bi-objective MOP1 and MOP2 as the evolution proceeds. In the case of tri-objective problems like MOP6 and MOP7, only MSF\* and PSF\* manage to decrease the IGD value constantly during the evolution, while the other approaches seem to end up in evolutionary stagnation after 1000 generations of search.

For an inspection of the real performance of these algorithms, we also plot their PF approximations on several

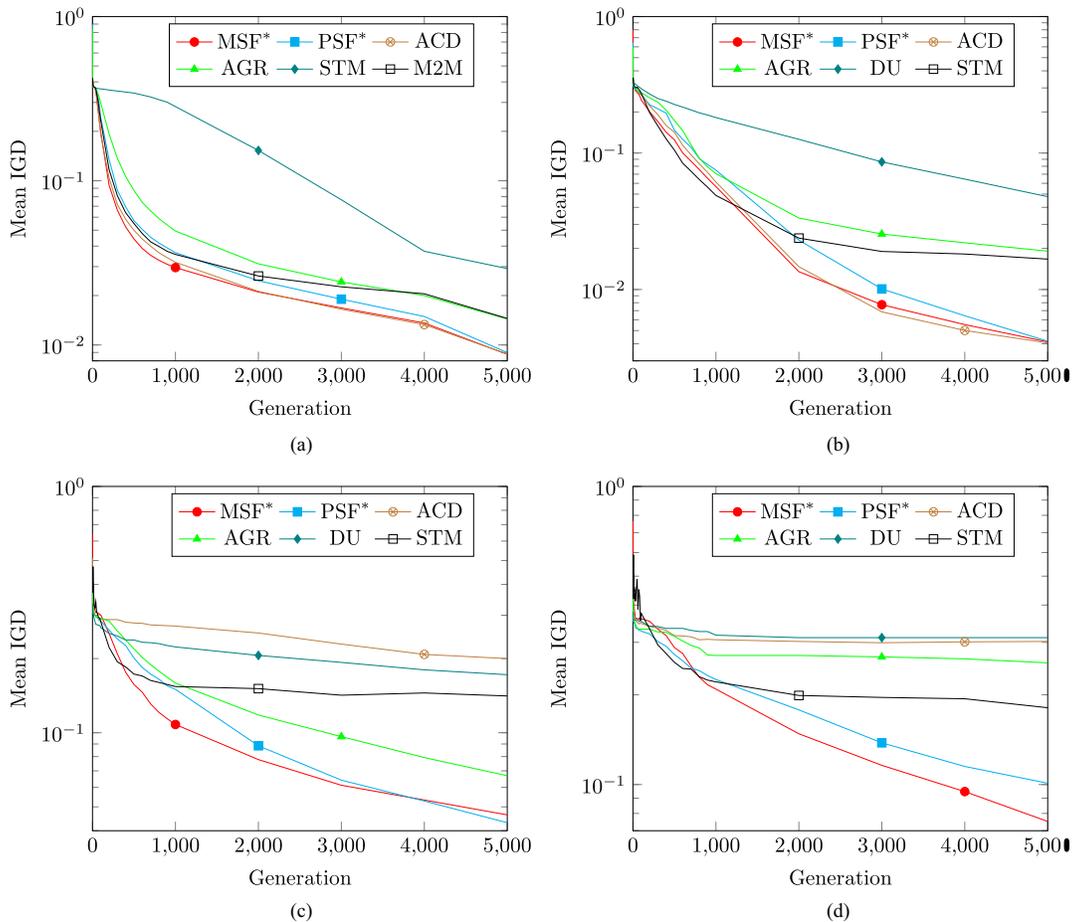


Fig. 17. Evolution curve of the mean IGD indicator obtained by six algorithms on four test problems. (a) MOP1. (b) MOP2. (c) MOP6. (d) MOP7.

selected test problems in the supplementary material. From the plots, we can observe that some algorithms (e.g., ACD, AGR, DU, and M2M) converge slowly and some (e.g., TCH) cannot maintain diversity well. Also, most of them cannot work well on tri-objective problems, particularly on MOP9. Nevertheless, both MSF\* and PSF\* show better performance compared with the other algorithms.

### C. Results on UF and WFG Problems

More test problems are selected from the UF [47] and WFG [11] test suites to verify the effectiveness of the proposed algorithm. The number of variables was 30 and the maximum number of generations was equivalently set to be 3000 in UF problems, according to [25] and [47]. The selected WFG problems were set to have two position-related variables and ten distance-related variables in the case of two objectives, the maximum number of generations is 200.

Table III reports the HVD values obtained by ten algorithms on the selected UF and WFG test problems. It is clear to observe from the table that both MSF\* and PSF\* significantly outperform almost all the other compared algorithms on the UF problems considered in both bi-objective and tri-objective cases (UF4 and UF5 have two objectives whereas UF8 and UF9 have three objectives). There exists little difference between the ten algorithms when solving the three WFG problems as most of them obtain similar HVD values.

Nevertheless, MSF\* and PSF\* again manage to outperform ACD, DU, and M2M on some of these WFG problems.

The experiment here also shows that the proposed eMOEA/D has great advantages over the other algorithms when solving hard-to-converge and diversity-resistant problems like the UF problems. The UF problems are hard to handle because strong nonlinear linkages between decision variables in these problems challenge dramatically EAs' diversity and convergence performance. In this situation, the adaptive scalarizing strategy in eMOEA/D can make a difference and therefore help generate promising performance. In contrast, the WFG problems are less challenging in diversity maintenance compared with the UF problems, so any algorithm with proper (not necessarily advanced) diversity management is able to solve them. Therefore, the proposed eMOEA/D has little advantage but performs comparably to the other algorithms when solving the WFG problems.

## VII. DISCUSSION

### A. Influence of Mating Selection

Many MOEA/D variants are developed based on the predecessor [26], and thus inevitably inherit a parameter  $\delta$  that is the probability of choosing mating parents from the neighborhood of subproblems rather than the whole population.  $\delta$  is of undisputed importance in the predecessor

TABLE III  
BEST, MEDIAN, AND WORST HVD VALUES OBTAINED BY DIFFERENT ALGORITHMS ON UF AND WFG PROBLEMS

| Prob. | MSF*            | PSF*     | TCH                   | ACD                   | AGR                   | DU                    | STM                   | M2M                   |
|-------|-----------------|----------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| UF4   | <b>1.54E-02</b> | 2.89E-02 | 1.72E-02              | 1.01E-01              | 9.23E-02              | 9.50E-02              | 8.83E-02              | 9.68E-02              |
|       | <b>7.14E-02</b> | 8.56E-02 | 8.95E-02 <sup>‡</sup> | 1.07E-01 <sup>‡</sup> | 1.02E-01 <sup>‡</sup> | 1.04E-01 <sup>‡</sup> | 9.46E-02 <sup>‡</sup> | 1.01E-01 <sup>‡</sup> |
|       | <b>1.06E-01</b> | 1.12E-01 | 1.69E-01              | 1.23E-01              | 1.13E-01              | 1.15E-01              | 1.09E-01              | 1.12E-01              |
| UF5   | <b>9.84E-02</b> | 1.11E-01 | 1.06E-01              | 2.92E-01              | 2.69E-01              | 3.33E-01              | 2.55E-01              | 2.70E-01              |
|       | <b>1.12E-01</b> | 1.19E-01 | 1.14E-01              | 4.20E-01 <sup>‡</sup> | 4.04E-01 <sup>‡</sup> | 5.02E-01 <sup>‡</sup> | 3.80E-01 <sup>‡</sup> | 3.35E-01 <sup>‡</sup> |
|       | <b>1.23E-01</b> | 1.34E-01 | 1.28E-01              | 6.73E-01              | 4.75E-01              | 6.87E-01              | 5.75E-01              | 4.65E-01              |
| UF8   | <b>2.31E-02</b> | 2.58E-02 | 4.01E-02              | 2.58E-01              | 2.40E-01              | 3.16E-01              | 2.49E-01              | 7.66E-01              |
|       | <b>3.12E-02</b> | 3.80E-02 | 6.05E-02 <sup>‡</sup> | 4.95E-01 <sup>‡</sup> | 3.56E-01 <sup>‡</sup> | 4.87E-01 <sup>‡</sup> | 4.71E-01              | 8.54E-01 <sup>‡</sup> |
|       | <b>2.26E-01</b> | 2.49E-01 | 4.97E-01              | 5.57E-01              | 5.93E-01              | 5.76E-01              | 5.27E-01              | 1.16E+00              |
| UF9   | 2.56E-01        | 3.51E-01 | <b>1.88E-01</b>       | 6.18E-01              | 5.98E-01              | 6.00E-01              | 4.84E-01              | 8.99E-01              |
|       | 4.76E-01        | 4.91E-01 | <b>2.16E-01</b>       | 6.87E-01 <sup>‡</sup> | 7.14E-01 <sup>‡</sup> | 7.04E-01 <sup>‡</sup> | 6.47E-01 <sup>‡</sup> | 1.07E+00 <sup>‡</sup> |
|       | <b>5.24E-01</b> | 5.55E-01 | 5.87E-01              | 9.71E-01              | 1.14E+00              | 1.06E+00              | 9.90E-01              | 1.51E+00              |
| WFG4  | 2.08E-02        | 2.62E-02 | 3.04E-02              | 2.50E-02              | <b>1.67E-02</b>       | 4.35E-02              | 2.05E-02              | 2.51E-02              |
|       | 3.16E-02        | 3.54E-02 | 3.77E-02              | 3.63E-02 <sup>‡</sup> | 3.05E-02              | 5.43E-02 <sup>‡</sup> | <b>2.86E-02</b>       | 3.27E-02 <sup>‡</sup> |
|       | <b>3.97E-02</b> | 4.43E-02 | 5.62E-02              | 5.42E-02              | 4.32E-02              | 7.36E-02              | 4.79E-02              | 4.68E-02              |
| WFG5  | 5.98E-02        | 5.64E-02 | 6.38E-02              | 6.40E-02              | 5.53E-02              | 6.80E-02              | <b>5.17E-02</b>       | 6.33E-02              |
|       | 6.47E-02        | 6.48E-02 | 6.51E-02 <sup>‡</sup> | 6.46E-02 <sup>‡</sup> | <b>6.41E-02</b>       | 7.49E-02 <sup>‡</sup> | 6.47E-02              | 7.08E-02 <sup>‡</sup> |
|       | 6.48E-02        | 6.50E-02 | 6.62E-02              | 6.55E-02              | <b>6.44E-02</b>       | 9.59E-02              | 6.49E-02              | 7.21E-02              |
| WFG6  | 3.01E-02        | 5.12E-02 | 5.90E-02              | 2.49E-02              | <b>9.11E-03</b>       | 6.99E-02              | 4.46E-02              | 3.17E-02              |
|       | 1.64E-01        | 1.65E-01 | 1.18E-01              | 7.08E-02              | 1.64E-01              | 1.65E-01              | <b>1.58E-01</b>       | 1.71E-01 <sup>‡</sup> |
|       | 1.65E-01        | 1.66E-01 | 1.65E-01              | 1.65E-01              | <b>1.64E-01</b>       | 1.66E-01              | 1.65E-01              | 1.73E-01              |

<sup>†</sup> and <sup>◇</sup> indicate MSF\* and PSF\* significantly outperform the corresponding algorithm, respectively.  
<sup>‡</sup> indicates both MSF\* and PSF\* significantly outperform the corresponding algorithm.

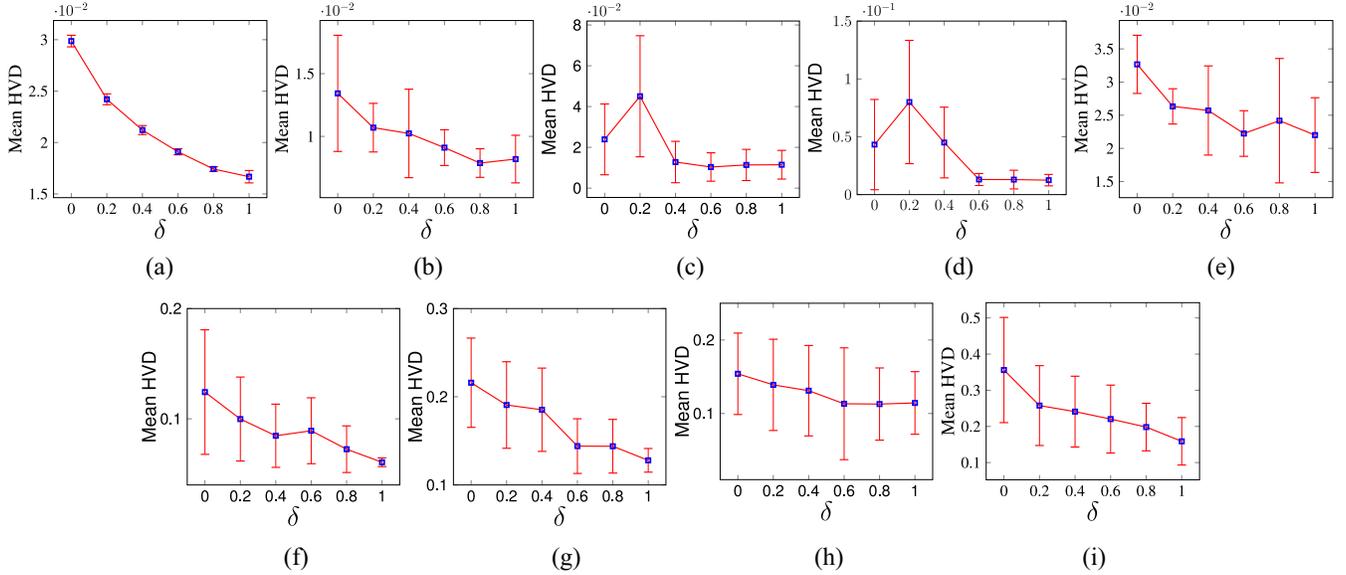


Fig. 18. Mean HVD values obtained by MSF\* with different  $\delta$  settings. (a) MOP1. (b) MOP2. (c) MOP3. (d) MOP4. (e) MOP5. (f) MOP6. (g) MOP7. (h) MOP8. (i) MOP9.

because it helps much to enhance diversity. However, most MOEA/D variants take for granted that the use of  $\delta$  is always beneficial.

Here,  $\delta$  from 0 to 1, with an increment of 0.2, was tested in the framework of MSF\*. Fig. 18 shows the influence of  $\delta$  on the obtained HVD values. It is clear that a large value of  $\delta$  is roughly good for all the problems. This indicates that the higher probability of choosing subproblems' neighborhood as mating range, the better the resulting performance. This is probably because our methods have already soundly considered diversity within SFs, and in this situation using as much neighborhood mating as possible to enhance local search helps the convergence of population. Thus, in our

eMOEA/D we discourage the use of  $\delta$  and simply select only the neighborhood as the mating range.

### B. Influence of Replacement Strategies

It has been shown the performance of decomposition-based MOEAs can be significantly affected by replacement strategies [25], [41]. To achieve efficient population replacements, MOEA/D needs to find an appropriate replacement range. Most often, the replacement range is the neighborhood of the best matched subproblem [25]. In AGR [41], the best matcher is the one that has the minimal SF value, whereas in other MOEA/D variants [49], the best matcher is the one that can

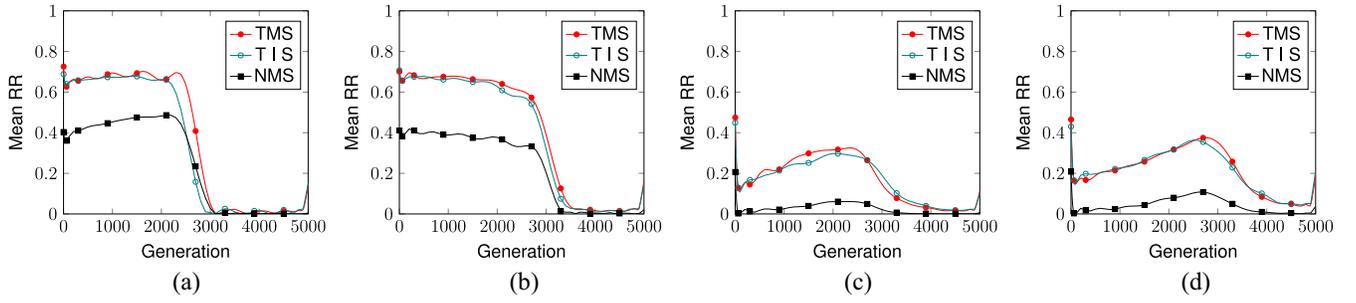


Fig. 19. Evolution curves of the mean RR obtained by different replacement strategies. (a) MOP1. (b) MOP2. (c) MOP6. (d) MOP7.

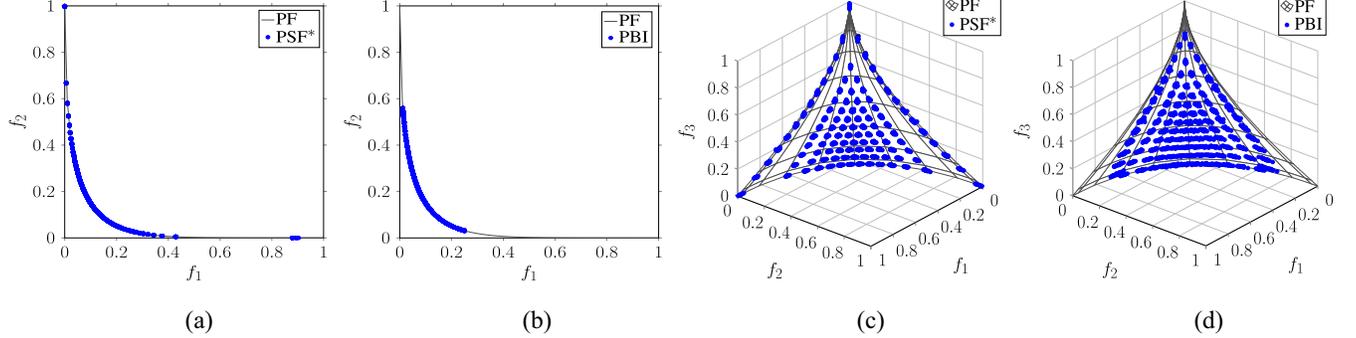


Fig. 20. Whole PF approximations obtained by PSF\* and PBI over 30 runs on two convex problems. (a) PSF\* for F1. (b) PBI for F1. (c) PSF\* for convex DTLZ2. (d) PBI for convex DTLZ2.

be improved most among all the subproblems. However, in our MOEA/D framework, the replacement range consists of the top  $T$  best matchers. In this section, we investigate the influence of different replacement strategies. We compare our replacement strategy (called TMS) with that of AGR (called NMS). To study the influence of the definition of matchers, we also include an replacement strategy whose replacement range is composed of the top  $T$  most improved subproblems, and this strategy is called TIS. To assess the efficiency of replacement strategies, we define the replacement rate (RR) of the population in every generation as

$$RR = \frac{N_T}{Nn_r} \quad (17)$$

where  $N_T$  is the total number of replacements that occur in the considered generation, and as stated before,  $N$  and  $n_r$  are the population size and the maximal allowable number of replacements, respectively. The larger RR, the better the replacement efficiency.

The three above-mentioned strategies have been tested in MSF\* on four selected problems. Fig. 19 plots evolution curves of the mean RR value of 100 independent runs. It can be observed that replacements occur mainly at the early stage of search and the occurrence drops to near zero as the population moves close to the PF. Another observation is that NMS performs worse than TMS and TIS in terms of the RR value, and TMS is better than TIS on the two bi-objective problems but is similar to TIS on the two tri-objective problems. The high RR of TMS helps the population evolve fast. This observation can be also used to partly explain

TABLE IV  
BEST, MEDIUM, AND WORST VALUES OF  $\Delta_p$  AND HVD OBTAINED BY PSF\* AND PBI

| Prob.       | $\Delta_p$      |          | HVD             |          |
|-------------|-----------------|----------|-----------------|----------|
|             | PSF*            | PBI      | PSF*            | PBI      |
| F1          | <b>7.53E-02</b> | 2.93E-01 | <b>4.51E-03</b> | 3.34E-02 |
|             | <b>7.57E-02</b> | 2.93E-01 | <b>4.53E-03</b> | 3.35E-02 |
|             | <b>7.87E-02</b> | 2.93E-01 | <b>4.63E-03</b> | 3.35E-02 |
| Convex DTLZ | <b>4.53E-02</b> | 8.56E-02 | <b>2.12E-02</b> | 2.63E-02 |
|             | <b>4.61E-02</b> | 9.03E-02 | <b>2.17E-02</b> | 2.90E-02 |
|             | <b>4.86E-02</b> | 9.52E-02 | <b>2.28E-02</b> | 3.11E-02 |

why MSF\* and PSF\* perform better than AGR in the previous experiments.

### C. Comparison of PSF and PBI

Since PSF and PBI have similar contour lines, it is interesting to make a comparison between them. Both PSF and PBI use our eMOEA/D framework, and accordingly the comparison objects are actually PSF\* and the proposed eMOEA/D with PBI. They are investigated in two convex problems mentioned in [20]. The convex problems are chosen here because it has been increasingly recognized that irregularly shaped problems (particularly convex ones) influence much the performance of SFs [20], [32], [35], [39]. The penalty factor of PBI was set to 5, according to [46]. Other parameter settings remained the same as in Section VI-B except the maximal number of generations was changed to 500.

The whole approximations of 31 independent runs are plotted in Fig. 20, and the corresponding  $\Delta_p$  and HVD values are shown in Table IV. Both considered indicators and graphical

TABLE V  
BEST, MEDIAN, AND WORST VALUES OF HVD OBTAINED  
BY DIFFERENT SCALARIZING APPROACHES

| Prob. | MSF      | PSF      | WS       | TCH      |
|-------|----------|----------|----------|----------|
| MOP1  | 6.32E-02 | 8.08E-02 | 2.86E-01 | 7.66E-02 |
|       | 7.63E-02 | 2.84E-01 | 3.76E-01 | 5.46E-01 |
|       | 8.62E-02 | 5.79E-01 | 5.45E-01 | 5.82E-01 |
| MOP2  | 3.12E-02 | 6.59E-02 | 3.33E-01 | 1.48E-01 |
|       | 2.53E-01 | 2.51E-01 | 3.33E-01 | 2.22E-01 |
|       | 3.33E-01 | 3.33E-01 | 3.33E-01 | 3.33E-01 |
| MOP5  | 6.38E-02 | 7.15E-02 | 3.13E-01 | 4.72E-01 |
|       | 7.36E-02 | 8.60E-02 | 3.72E-01 | 4.72E-01 |
|       | 1.23E-01 | 2.20E-01 | 4.72E-01 | 4.72E-01 |
| MOP6  | 1.55E-01 | 1.83E-01 | 7.34E-01 | 2.46E-01 |
|       | 2.49E-01 | 3.04E-01 | 8.33E-01 | 3.47E-01 |
|       | 3.25E-01 | 3.49E-01 | 8.33E-01 | 3.47E-01 |

plots clearly illustrate that PSF helps yield better performance than PBI. By inspecting closely the approximations in the figure, we can see that PBI favors intermediate regions of the PF and is very likely to miss boundary solutions in convex problems. This can be explained by the contour lines of PBI where boundary solutions likely need a very large penalty value in the PBI SF [15]. On the other hand, PSF\* has a better coverage than PBI and has the potential to maintain extreme solutions and boundary solutions.

#### D. Further Discussion

1) *Comparison With Other Scalarizing Approaches:* SFs play a fundamental role in decomposition-based EAs. Here, we would like to compare our scalarizing methods with other widely used methods in literature. Specifically, MSF with  $\alpha = 1$  and PSF with  $\alpha = 10$  are compared with the WS approach and the TCH approach (PBI is excluded here because it has shown to be inferior to our methods in Section VII-C). All the approaches are tested within the algorithm framework mentioned in Section IV.

Table V presents the HVD values obtained by these approaches on four MOP problems. It is clear from the table that both MSF and PSF are likely to obtain better HVD values than WS and TCH. The comparison demonstrates the promise of our SFs in helping MOEA/D to achieve high performance, which is a reason for the good performance of MSF\* and PSF\* in algorithm comparison shown in Section VI.

2) *Investigation of Adaptive Strategies and Replacement Strategies:* The proposed eMOEA/D is a combination of several strategies, i.e., new SFs, adaptive tuning of  $\alpha$ , and a new replacement strategy. Although previous experiments have shown that the new SFs are effective and promising in decomposition-based EAs, here we want to investigate deeply the role that different strategies play in the proposed eMOEA/D.

To study each component of the two eMOEA/D instances (i.e., MSF\* and PSF\*), we design the following experiment. MSF with a fixed  $\alpha$  value (i.e.,  $\alpha = 1$  for MSF) is compared against MSF with the proposed adaptive tuning of  $\alpha$  (termed as “MSF+AS”), which in turn is compared against MSF\*. This experimental design is also applied to PSF ( $\alpha = 1$  is used). Through these two steps of comparison, one can easily see

TABLE VI  
BEST, MEDIAN, AND WORST VALUES OF HVD OBTAINED  
BY MSF AND PSF WITH DIFFERENT STRATEGIES

| Prob. | MSF      | MSF+AS   | MSF*     | PSF      | PSF+AS   | PSF*     |
|-------|----------|----------|----------|----------|----------|----------|
| MOP1  | 6.32E-02 | 1.39E-02 | 1.39E-02 | 8.08E-02 | 1.44E-02 | 1.43E-02 |
|       | 7.63E-02 | 1.44E-02 | 1.43E-02 | 2.84E-01 | 1.47E-02 | 1.46E-02 |
|       | 8.62E-02 | 5.55E-02 | 1.50E-02 | 5.79E-01 | 1.69E-02 | 1.49E-02 |
| MOP2  | 3.12E-02 | 6.26E-03 | 6.30E-03 | 6.59E-02 | 6.51E-03 | 6.48E-03 |
|       | 2.53E-01 | 6.43E-03 | 6.39E-03 | 2.51E-01 | 6.84E-03 | 6.55E-03 |
|       | 3.33E-01 | 9.73E-02 | 6.53E-03 | 3.33E-01 | 2.64E-01 | 8.36E-03 |
| MOP6  | 1.55E-01 | 5.46E-02 | 5.15E-02 | 1.83E-01 | 9.60E-02 | 5.25E-02 |
|       | 2.49E-01 | 6.23E-02 | 5.25E-02 | 3.04E-01 | 3.36E-01 | 5.31E-02 |
|       | 3.25E-01 | 1.10E-01 | 6.32E-02 | 3.49E-01 | 3.47E-01 | 6.50E-02 |
| MOP7  | 2.70E-01 | 1.26E-01 | 9.58E-02 | 2.31E-01 | 1.38E-01 | 1.08E-01 |
|       | 2.90E-01 | 1.72E-01 | 1.03E-01 | 2.72E-01 | 2.72E-01 | 1.11E-01 |
|       | 3.78E-01 | 2.32E-01 | 1.60E-01 | 2.75E-01 | 2.72E-01 | 2.10E-01 |

the importance of each strategy in the proposed eMOEA/D algorithm.

Table VI presents the HVD results obtained by MSF and PSF with different strategies on several MOP problems. It can be observed that MSF+AS and PSF+AS obtain better HVD values than MSF and PSF, respectively, implying that the use of adaptive  $\alpha$  values generates better performance than a fixed  $\alpha$  value during the evolution. By comparing MSF+AS with MSF\*, and PSF+AS with PSF\*, we can clearly see that the incorporation of the new replacement strategy tends to reduce the deviation of the HVD values (the difference between the best and worst HVD values becomes smaller), which means the replacement strategy can enhance the stability of our eMOEA/D algorithm.

The experiment shows that the proposed SFs need to work collaboratively with other strategies in order to perform to the best of their ability. This is understandable because the SFs are only a method of transforming a multiobjective problem into scalar subproblems and are unable to generate multiple solutions if there is a lack of effective collaboration when solving different subproblems. The adaptive tuning of  $\alpha$  can control the balance between diversity and convergence by changing improvement regions (it gradually increases the size of improvement regions during the evolution in eMOEA/D) induced by SFs, leading to a high level of diversity at early stages of search and fast convergence at late stages. In contrast, fixed  $\alpha$  values emphasize diversity all the time but may affect convergence performance. Therefore, the use of adaptive tuning of  $\alpha$  is encouraged in our work. On the other hand, the replacement strategy, as demonstrated in Section VII-B, can increase the RR, which means the population evolves fast. Thus, the use of the replacement strategy will further improve the performance of eMOEA/D.

3) *Potential Limitations:* This paper has some potential limitations of which practitioners or interested readers may need to be aware. The first limitation is that a high number of generations, i.e., 5000, are used for the MOP test suite due to its high optimization difficulties. This setting may not be applicable in practice, particularly when limited resources like time and computational investments are available. However, this setting makes sense when good PF approximations are the main focus. A possible way of obtaining good PF approximations with less computational resources when solving problems

like the MOP ones is to use efficient reproduction operators, if any, to shorten the convergence process. Second, the performance of the proposed SFs or eMOEA/D may degrade with the scaling of the number of objectives, as this often happens in decomposition-based methods, and therefore may need other techniques to enhance it in the case of many-objective optimization. Third, it should be acknowledged that decomposition-based methods are less robust than dominance-based ones using SFs, in particular for problems with complex (nonuniform, discrete, degenerated) Pareto fronts.

### VIII. CONCLUSION

Decomposition-based MOEAs are an important class of methods for multiobjective optimization, and have been frequently shown to work well when proper SFs are provided. In this paper, we have proposed two new SFs which can induce controllable contours. By adjusting the size of induced improvement regions, the new SFs can easily manage population diversity. We have studied the influence of the new SFs and have demonstrated that the proposed SFs with proper improvement regions can significantly boost the performance of decomposition-based MOEAs. Additionally, we have introduced an efficient MOEA/D (i.e., eMOEA/D) framework based on the proposed SFs and some new strategies. We have compared eMOEA/D with other recently developed approaches. The experimental results have clearly verified the effectiveness of the eMOEA/D framework.

In this paper, the proposed eMOEA/D uses a very simple adaptive strategy (i.e., linearly decreasing  $\alpha$  in MSF and PSF) to adjust the balance between diversity and convergence at different stages of search. Despite the appealing performance, the adaptive strategy may not be the best choice because different search stages have different (not necessarily linearly decreasing) convergence or diversity requirements. Further investigations in this direction are beneficial. In our future research, it will be also interesting to investigate the performance of the proposed SFs in many-objective optimization.

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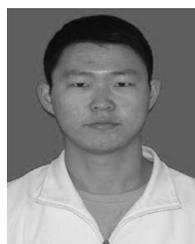
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