論 文

MOEA/D-RAD - Resource Allocation by Diversity

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Summary

MOEA/D decomposes multi-objective problems into single-objective subproblems and solve them in parallel. In standard MOEA/D, all subproblems receive the same computational effort. However, as each subproblem is related to a different area of the objective space, it is expected that some subproblems are more difficult than others. Using Resource Allocation, MOEA/D could spend less effort on easier subproblems and more on harder ones, improving efficiency. In this paper, we address Resource Allocation that uses priority functions. They determine which subproblems should receive more computation resources. We propose the MOEA/D-RAD, a MOEA/D that considers diversity in the decision space as the measure of priority among candidate solutions. We compare MOEA/D-RAD, MOEA/D-DE and MOEA/D-DRA on the bbob-biobj benchmark, composed of 55 functions grouped into 15 groups, based on the function properties. We investigate the performance of these three methods based on hypervolume and proportion of non-dominated solutions in all of these 15 groups. Exploratory experiments show that MOEA/D-RAD obtained the best hypervolume in 24 functions. In particular MOEA/D-RAD obtained a good performance in groups characterized by moderated and weakly-structured groups.These results validate the effectiveness of using diversity in the objective space as priority function in the MOEA/D framework.

1. Introduction

Multi-objective Optimization Problems (MOP) are maximization (or minimization) problems characterized by multiple, conflicting objective functions. It arises in real world applications that require a compromise among multiple objectives. An MOP can be summarized as

$$\text{minimize} f(x) = (f_1(x), ..., f_m(x)), x \in \mathbb{R}^D, \quad (1)$$

where m is the number of objective functions and $\mathbb{R}^m$ is the objective function space. $x \in \mathbb{R}^D = \{x_1, x_2, ..., x_D\}$ is a D-dimensional vector which represents a candidate solution with D variables, $f : \mathbb{R}^D \rightarrow \mathbb{R}^m$ is a vector of objective functions.

These objectives often conflict with each other, as there is usually no solution in $\mathbb{R}^D$ that minimizes all the objectives at the same time. Consequently, the goal of the MOP optimization algorithm is to find the approximate set of solutions that balance the different objectives in an optimal way.

This balance is defined by the concept of "pareto dominance". Given two solutions vectors u, v in $\mathbb{R}^D$, we said that u Pareto-dominates v, denoted by $f(u) \prec f(v)$, if and only if $f_k(u) \leq f_k(v), \forall_k \in \{1, ..., m\}$ and $f(u) \neq f(v)$. Likewise, a solution $x \in \mathbb{R}^D$ is considered Pareto-Optimal if there exists no other solution $y \in \mathbb{R}^D$ such that $f(y) \succ f(x)$, i.e., if x is non-dominated in the feasible decision space. A non-dominated solution exists if no other solution provides a better trade-off in all objectives. Consequently, the set of all Pareto-Optimal solutions is known as the Pareto-Optimal Set (PS), while the image of this set is referred to as the Pareto-optimal Front (PF).

$$PS = \{x \in \mathbb{R}^D | \nexists y \in \mathbb{R}^D : f(y) \succ f(x)\}, \quad (2)$$

$$PF = \{f(x) | x \in PS\}. \quad (3)$$

The Multi-Objective Evolutionary Algorithm Based on Decomposition (MOEA/D) [Zhang 07] is an effective algorithm for solving MOPs. The key idea of the MOEA/D is that the multi-objective optimization problem is decomposed into a set of single objectives subproblems All subproblems are then solved in parallel.

In the original MOEA/D, all subproblems are treated uniformly, in the sense that all of them receive the same computational effort. However, it has been observed that some subproblems are harder than others, and take more effort to converge to an optimal solution [Zhou 16]. Because of this, *Resource Allocation* approaches have been

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proposed to allocate different amount of computational effort to different subproblems, based on an estimation of the relative difficulty of each subproblem [Zhou 16], [Zhang 09], [Kang 18]. The most popular MOEA/D algorithm related to Resource Allocation is the MOEA/D-DRA [Zhang 09]. It uses the Relative Improvement for estimating subproblem difficulty, which calculates how much a subproblem has improved in recent iterations.

Here, we propose a new approach for estimating difficulty and calculating priority in Resource Allocation for MOEA/D. Our approach uses the idea of *diversity* in objective space to calculate the priority of solutions. Our motivation for this choice is that the quality of a MOP solution set is often evaluated by the diversity in the objective space. If we assign higher priority for regions with lower diversity, we are encouraging the algorithm to spend more computational effort in regions that are not yet well explored.

In this paper, we define a priority function based on diversity on the objective space using the MRDL, proposed by Gee [Gee 15]. The MRDL is an online diversity metric based on a geometrical perspective and indicates the loss of diversity related to a solution to the whole population. We understand that this priority function is able to monitor diversity during the execution of the algorithm guiding the search behavior of the algorithm.

We compare the new approach with the MOEA/D-DRA and with the standard MOEA/D (with no Resource Allocation). The results show that a priority function focused on decision space lead to better results on the metric Hypervolume (HV), for some groups of problems.

2. Related Works

2·1 Priority functions

We define priority functions (also called utility functions) as one way of establishing preferences between solutions for Resource Allocation [Chankong 83]. These functions are used to decide how to allocate computational resources among subproblems by monitoring the algorithm search and guiding the distribution over iterations [Cai 15].

Only a few studies have been concerned with Resource Allocation in MOEA/D. We highlight two groups. The first is composed by MOEA/D-GRA [Zhou 16], MOEA/D-DRA [Zhang 09] and in the Two-Level Stable Matching-Based Selection in MOEA/D [Nasir 11]. The other is composed by EAG-MOEA/D [Cai 15] and MOEA/D-CRA [Kang 18].

According to Zhou and Zhang [Zhou 16], MOEA/D-GRA could be seen as an extension of MOEA/D-DRA and MOEA/D-AMS [Chiang 11]. They reason that all these algorithms use a very similar priority function and that MOEA/D-GRA can simulate the behavior of MOEA/D-DRA or MOEA/D-AMS by changing the values of a single parameter.

This priority function is named as the Relative Improvement (R.I.) and defines the priority values of each subproblem $i = 1, ..., N$, as

$$\delta_i = \frac{\text{old function value} - \text{new function value}}{\text{old function value}}. \tag{4}$$

Where new function value is the value at the current iteration (T) and old function value is the value at iteration ($T - \Delta T$).

For MOEA/D-GRA $u_i = \delta_i$, but in MOEA/D-DRA, as well as in the Two-Level Stable Matching-Based Selection in MOEA/D, a second equation is used,

$$u_i = \begin{cases} (0.95 + 0.05 \cdot \frac{\delta_i}{0.001} \cdot u_i), & \text{if } \delta_i > 0.001, \\ 1, & \text{otherwise} \end{cases}$$

The R.I. is based the assumption that if a subproblem has been improved over the last ΔT iteration (*old function value*), it should have a high probability of being improved over the next iterations.

The priority function used EAG-MOEA/D [Cai 15] and MOEA/D-CRA [Kang 18] differ from the ones in the MOEA/D-GRA group. In their case, the framework keeps two populations: one working population, and one external archive. This priority function estimates priorities for a subproblem given the number of solutions from that subproblem that are in the external archive.

Together these studies indicate that it is worth monitoring the algorithm behavior and guiding its search, but it is unclear how the choice of priority functions influence the results. In all Resource Allocation works mentioned above, the choice of priority function was just one of multiple changes applied to the base framework. For example, in Zhang et al. used a 10-tournament selection in MOEA/D-DRA [Zhang 09], while Zhou and Zhang used a new replacement strategy in MOEA/D-GRA [Zhou 16]. Chiang in MOEA/D-AMS proposes an adaptive mating selection mechanism as it dynamically adjusts the mating pools of individuals [Chiang 11]. Finally, both the studies of Cai and Lai in EAG-MOEA/D [Cai 15] and Kang et al. in MOEA/D-CRA [Kang 18] used an archive population.

We focus on improving the performance of the standard MOEA/D by using priority functions, given the recent success of addressing Resource Allocation with priority functions. We believe in the idea that diversity is a critical issue in the search process for any multi-objective algorithm. Therefore, we consider using priority functions to address lack of diversity aiming to make solutions better spread among each other. The proposed priority function focus on how to better spread solutions the Pareto Set (diversity on the decision space). For that, we define the MRDL priority function.

2·2 Diversity Metric

One way to measure diversity is to use metrics that evaluate MOPs solvers. The hypervolume indicator (HV) [Zitzler 98] and the Inverted Generational Distance (IGD) [Zhang 08] are frequently used as metrics to evaluate such solvers. However they include information about both quality of the solutions and diversity in a single metric.

Among the metrics that only measure diversity, there are mainly two groups. The offline group, that calculate the diversity after the execution of the algorithm, while online group, that calculate the diversity during the execution of the algorithm. We are interested in measuring diversity during the execution of the algorithm, therefore we briefly introduce some studies that are part of the online group.

The online group includes: sigma method [Mostaghim 03] (PF lies in the positive objective space); entropy of the solutions by using Parzen window density estimation-[Tan 08] (sensitive to kernel width); and maximum relative diversity loss, MRDL, [Gee 15] (expensive $O(N^2)$, with N being the size of the parent population).

In this work we chose to apply the MRDL as the strategy to measure diversity on the objective space. This is an online diversity metric estimates the diversity loss of a solution to the whole population [Gee 15]. High values indicate the existence of similar solutions or that the offspring solution is close to the convergence direction. The further an objective vector of a solution is from the convergence direction, the more it contributes for the diversity of the approximated the Pareto Front. The MRDL is the maximum value for Relative Diversity Loss (RDL) of each solution.

3. Proposed Method

In this work we propose a variant of the MOEA/D, the MOEA/D with online Resource Allocation by Diversity Metric (MOEA/D-RAD). This algorithm uses the maximum relative diversity loss, MRDL, for determining the values of the priority function.

Algorithm 1 MOEA/D-RAD

```
1: Initialize the weight vectors λ_i, the neighborhood B_i,
   the priority value u_i every subproblem i = 1, ..., N.
2: while Termination criteria do
3:     for 1 to N do
4:         if rand() < u_i then
5:             Generate an offspring y for subproblem i.
6:             Update the population by y.
7:     Evaluate and after ΔT iterations, keep updating u
   by a priority function.
```

MOEA/D-RAD is described in algorithm 1. This basic algorithm is similar to the MOEA/D-DE [Zhang 09] with exception of lines 4 and 7. Line 4 deals with the selection of solutions given their priority function values, while the line 7 deals with the calculation of the priority function values. All other procedures and parameters are the same as in MOEA/D-DE [Li 09]. We highlight that the neighborhood is only calculated in the initialization period.

The selection of priority functions provides an important way to control MOEA/D. They allow ways of designing MOEA/D variants that might focus on desired characteristics, such as diversity, performance contribution, convergence to a specific region of the PF or others. This is possible because different methods can be used as priority functions to create the vector u in algorithm 1.

We initialize the value of the vector $u = 1$, as in MOEA/D-DRA. As in DRA and GRA we have a learning period of ΔT iterations. Here $\Delta T = 20$ as in MOEA/D-GRA [Zhou 16]. A sensitivity analysis should be performed for deciding suitable initial values for u and for ΔT.

It should also be noted that if the priority function values results in less than 3 subproblems being updated in one iteration, we reset the priority vector $u = 1$ and all subproblems will be chosen for offspring reproduction at the that iteration.

3·1 Priority Function - MRDL

To consider diversity on the objective space, we propose a priority function based on the the Maximum Relative Diversity Loss, MRDL [Gee 15].

The diversity on objective space as a priority function is based on the Maximum Relative Diversity Loss, MRDL [Gee 15]. The idea of using MRDL is that by measuring diversity on the objective space, more resources are given to incumbent solutions that have similar objective function values between two consecutive iteractions. Therefore, it

Algorithm 2 MRDL

Input: old MRDL (initial value is 0); Y^t, objective function values from the incumbent solutions; Y^{t-1}, objective function values from the incumbent solutions of the previous iteraction; N, the population size.
for i=1 to N **do**
  find index h where $(Y_h^{t-1} \succeq Y_i^t)$ and $||Y_h^{t-1} - Y_i^t||$ is minimal.
  if If none is found **then**
    MRDL[i] = $-\infty$
  else
    $d.conv = Y_i^t - Y_h^{t-1}$.
    for j=1 to N **do**
      $p\prime = Y_j^{t-1} - Y_h^{t-1}$
      $c\prime = Y_j^t - Y_i^t$
      $proj_{d.conv} * p\prime = \dfrac{sum(conv \cdot p\prime)}{(p\prime \times p\prime)} * p\prime$
      $proj_{d.conv} * c\prime = \dfrac{sum(conv \cdot c\prime)}{(c\prime \times c\prime)} * c\prime$
      $RDL_j = \dfrac{||p\prime - proj_{d.conv}p\prime||}{||c\prime - proj_{d.conv}c\prime||}$
    MRDL[i] = maximum RDL
u = 1 - scale (MRDL - old MRDL) // between 0 and 1
return u, MRDL

is expected that this will lead to a higher exploration of the objective space. Algorithm 2 gives the details on implementation.

The calculation of MRDL depends on the concept of weak dominance [Zitzler 03]. A solution a weakly dominates b if in all objectives $a \geq b$ (note that $a \succeq a$).

Let N be the number of incumbent solutions and the objective values of iteraction t be Y^t and the objectives values of iteraction $t-1$ be Y^{t-1}. For each incumbent solution i, find index $h \in Y^{T-1}$. This index is the index of a parent that weak dominates the solution i. If h is not found (no parent weak dominates the solution) the MRDL value for this solution is set to $-\infty$. Given i and h, for each subproblem, the value of Relative Diversity Loss (RDL) is given by

$$RDL = \frac{||p\prime - proj_{d.conv}p\prime||}{||c\prime - proj_{d.conv}c\prime||}. \tag{5}$$

RDL is a diversity measurement quantity that indicates the amount of diversity loss of an individual solution between two consecutive iterations. High values of RDL imply a reduction of the solution spread, since the further an objective vector of a solution is from the convergence direction, the more it contributes in terms of diversity in the objective space [Gee 15]. The maximum value of RDL is the MRDL of the solution i.

4. Experimental Design

To examine the effects of MOEA/D-RAD we perform a comparative experiment of bbob-biobj benchmark functions. In this experiment, we use the MOEA/D-DE implemented by the MOEADr package [Campelo 18], modified to include Resource Allocation as described in the previous section. We compare three different algorithms MOEA/D-DE and MOEA/D-DRA as well as the proposed MOEA/D-RAD.

4·1 Target Problems

The Black-Box Optimization Bi-Objective Benchmark (bbob-biobj) test functions [Tusar 16] are used as our benchmark problem sets. This test suit is composed of 55 bi-objective functions combined into 15 different groups.

We list below the function groups:

- Group 1: separable - separable;
- Group 2: separable - moderate;
- Group 3: separable - ill-conditioned;
- Group 4: separable - multi-modal;
- Group 5: separable - weakly-structured;
- Group 6: moderate - moderate;
- Group 7: moderate - ill-conditioned;
- Group 8: moderate - multi-modal;
- Group 9: moderate - weakly-structured;
- Group 10: ill-conditioned - ill-conditioned;
- Group 11: ill-conditioned - multi-modal;
- Group 12: ill-conditioned - weakly-structured;
- Group 13: multi-modal - multi-modal;
- Group 14: multi-modal - weakly structured;
- Group 15: weakly-structured - weakly-structured.

Here we give a simple explanation of the groups. A separable function does not show any dependencies between the variables while a multi-modal function have at least two minima. Moderate- and ill-conditioned have a high sensitivity in the contribution of a solution to the objective function value [Hansen 11]. Finally, a weakly-structured function is a function that the general structure is very unclear [Finck 10].

4·2 Experimental Parameters

We use the conventional MOEA/D-DE parameters [Li 09] for each Resource Allocation strategy: update size $nr = 2$, neighborhood size $T = 20$, and the neighborhood search probability $\delta_p = 0.9$. The DE mutation operator value is $phi = 0.5$. The Polynomial mutation operator values are $\eta_m 20$ and $p_m = 0.03333333$. The decomposition function is Simple-Lattice Design (SLD), the scalar aggregation function is Weighted Sum (WS), the update strategy is the Restricted Update Strategy and we performed a simple linear scaling of the objectives to [0, 1].

For every strategy/function pair we perform 21 repetitions with 30000 function evaluations and population size $N = 150$.

4·3 Experimental Evaluation

We compare the results of the different strategies based on their Hypervolume (HV) metric. Higher values of the HV indicate better approximations of the Pareto Front.

For the calculation of HV, the objective function was scaled to the $0, 1$ interval, and the reference point was set to $(1, 1)$. To verify any statistical differences in the results for the different strategies, we use the Pairwise Wilcoxon Rank Sum Tests with confidence interval $\alpha = 0.05$ and with the Hommel adjustment method for multiple comparisons.

5. Results

Figure 1 shows the boxplots of the hypervolume values obtained by the three methods on functions F26, F1 and F32 of bbob-biobj. F26 is an example of a moderate and weakly structured function (group 9), where MOEA/D-RAD performed best. F1 is a separable and separable function (group 1), where MOEA/D-DRA performed best, and F32 is a moderate and multi-modal function (group 8), where MOEA/D-DE performed .

Table 1 gives us a general view of these results over all functions and function groups. In general, MOEA/D-RAD performed better than the other methods (or second best) in terms of hypervolume. This ranking is reinforced by a Pairwise Wilcoxon Rank Test over the entire experiment (Table 2).

However, a post-hoc analysis of these results focusing on the function groups suggests some interesting properties of the three methods. We observe that MOEA/D-RAD was specially successful for function groups that included moderate-conditioned or weakly-structured functions (groups 2, 5, 6, 7, 8, 9, 12 and 15, shaded in Table 1), and performed slightly worse for groups including multi-modal functions (groups 4, 8, 11, 13 and 14). In particular, we find it very interesting that MOEA/D-DE without priority performed better in the multi-modal groups. This post-hoc analysis suggests a follow up experiment to confirm this observations.

5·1 Proportion of Non-dominated Solutions

Another difference that we see among the algorithms is the proportion of non dominated solutions. The results on the Table 1 indicate that MOEA/D-DRA leads to the highest rate of non-dominated solutions in the final solution set, followed by MOEA/D-RAD. In general, both substantially improve this proportion over the results of MOEA/D-DE. It seems that there is no relation between hypervolume performance and the proportion of non-dominated solutions.

5·2 Resource Allocation

Figure 2 and Figure 3 illustrate the amount resource allocated by MOEA/D-DRA and MOEA/D-RAD to each subproblem on problems F26 and F32. MOEA/D-DE is not included since it does not perform resource allocation.

These figures show how the choice of priority function influences the resource allocation. The resource allocation by MOEA/D-DRA is much more adaptive to each problem, while the resource allocation done by MOEA/D-RAD is more conservative and uniform.

However, even though the resource allocation behavior seen in these figures may seem limited, it is clear from Table 1 that it has a deep impact on the performance of the algorithm.

6. Conclusion

In this research, we propose a new algorithm for Resource Allocation in Multi-Objective Optimization, MOEA/D-RAD. The performance of this algorithm is studied on the bbob-biobj. benchmark functions. This algorithm differs from the standard MOEA/D by using Resource Allocation techniques computational effort proportional to each subproblem's difficulty.

MOEA/D-RAD uses a priority function based on a geometrical perspective, MRDL, for Resource Allocation. This algorithm determines the computational resource assigned to each subproblem, based on its contribution to the overall diversity of the population.

We have compared the new approach with the MOEA/D-DE and a variant with dynamic resource allocation strategy, MOEA/D-DRA, and the experimental results suggested our method performs well on many test problems.

MOEA/D-RAD showed a better performance on bbob-biobj, specially in functions that are in the moderate-conditioned and weakly-structured groups. Although MOEA/D-DRA lead to the highest rate of non-dominated solutions in the final solution set, MOEA/D-RAD could be seem as an improvement to the MOEA/D-DE proportion values.

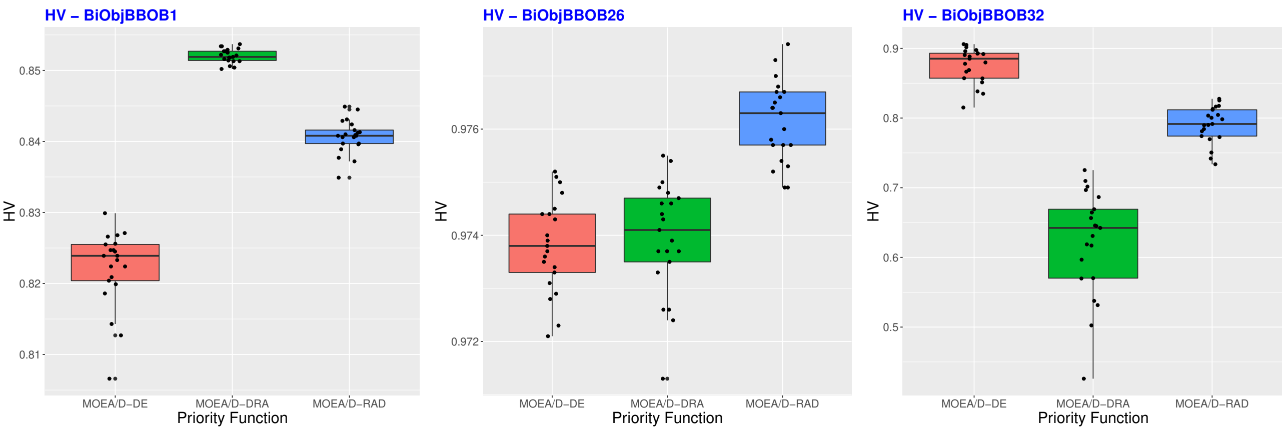

Fig. 1: Box plot of HV values on bbob-biobj-1, bbob-biobj-26 and bbob-biobj-32. (Higher values are better)

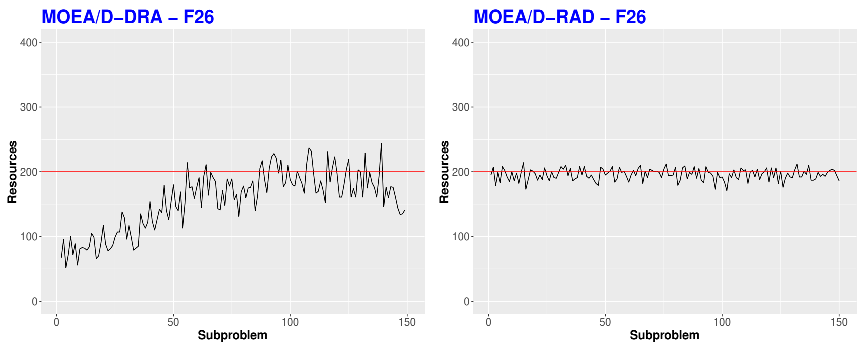

Fig. 2: Resource Allocation by subproblem - The red line indicates the default amount of resource for each problem, i.e., with no priority function.

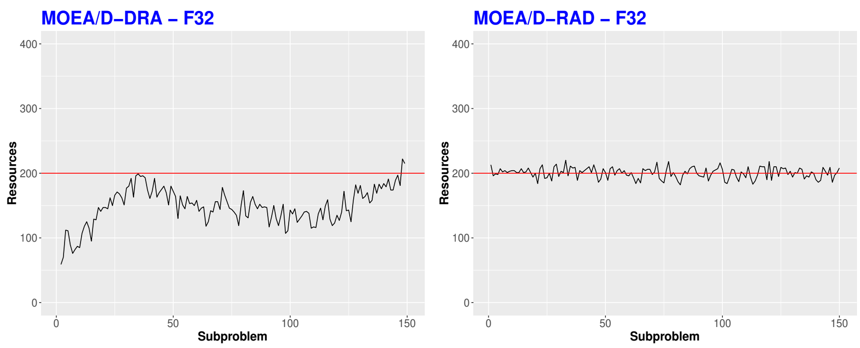

Fig. 3: Resource Allocation by subproblem - The red line indicates the default amount of resource for each problem, i.e., with no priority function.

Since the Resource Allocation distribution of MOEA/D-RAD is not so much different to the one of MOEA/D-DE we understand that this explains why the results in the hypervolume metric of the MOEA/D-RAD tend to be better, but not so much different to the hypervolume values of the MOEA/D-DE. Consequently, we conclude that MOEA/D-RAD does represent a improvement in diversity not only since it improves the hypervolume metrics in many functions but since for *all* functions the proportion of non-dominated solutions is always higher.

Overall, the findings of this work strengthens the idea that Resource Allocation techniques are worth of attention, specially those that focuses on critical issues (such as diversity in the object space). This suggests the choice of priority functions is a critical component of a Resource Allocation system. Our results indicate that MOEA/D-RAD might be a reasonable choices MOP where at least one objective is in one of the following groups: moderate-conditioned; and weakly-structured. It is crucial to explore this further.

In this work, we do not yet consider archive based Resource Allocation and archive based priority functions, such as MOEA/D-CRA [Kang 18]. We will address this issue in a continuation to this study. There are many components and variants of MOEA/D and is interesting to combine the Norm priority function with the them. Then, we

Metric	HV			Proportion of Non-dominated		
Algorithm:	MOEA/D-DE	MOEA/D-RAD	MOEA/D-DRA	MOEA/D-DE	MOEA/D-RAD	MOEA/D-DRA
Group 1 - F1.	0.8239 (0.005)	0.8408 (0.002)	**0.8519 (0.001)**	0.460 (0.07)	0.910 (0.09)	1.000 (0.00)
Group 1 - F2.	0.9480 (0.003)	**0.9572 (0.001)**	0.6435 (0.043)	0.3933 (0.05)	0.800 (0.08)	0.9933 (0.04)
Group 2 - F3.	0.9113 (0.002)	**0.9211 (0.001)**	0.5783 (0.043)	0.4800 (0.06)	0.9133 (0.12)	0.9933 (0.04)
Group 2 - F4.	0.9392 (0.002)	**0.9477 (0.002)**	0.7236 (0.018)	0.4267 (0.06)	0.8267 (0.06)	1.0000 (0.01)
Group 3 - F5.	0.6722 (0.008)	0.6937 (0.006)	**0.7024 (0.003)**	0.4867 (0.07)	0.9067 (0.07)	1.000 (0.01)
Group 3 - F6.	0.8946 (0.003)	0.9092 (0.003)	**0.9146 (0.002)**	0.4533 (0.05)	0.8467 (0.06)	1.000 (0.00)
Group 4 - F7.	0.8313 (0.008)	**0.8350 (0.018)**	0.8173 (0.017)	0.3600 (0.04)	0.8533 (0.09)	0.9933 (0.03)
Group 4 -F8.	**0.8784 (0.016)**	0.8159 (0.032)	0.7500 (0.031)	0.3533 (0.06)	0.8533 (0.11)	1.000 (0.02)
Group 5 - F9.	0.9526 (0.002)	**0.9583 (0.081)**	0.8340 (0.002)	0.4533 (0.08)	0.867 (0.06)	1.000 (0.04)
Group 5 - F10.	0.7780 (0.030)	**0.7882 (0.031)**	0.7484 (0.038)	0.5267 (0.07)	0.8667 (0.07)	1.000 (0.00)
Group 1 - F11.	0.8214 (0.003)	0.8315 (0.001)	**0.8398 (0.000)**	0.6000 (0.06)	0.9200 (0.05)	1.000 (0.00)
Group 2 - F12.	0.9945 (0.001)	**0.9948 (0.001)**	0.9876 (0.005)	0.4533 (0.08)	0.8933 (0.09)	1.000 (0.00)
Group 2 - F13.	0.9890 (0.001)	**0.9907 (0.001)**	0.9855 (0.003)	0.4200 (0.07)	0.8200 (0.11)	1.000 (0.00)
Group 3 - F14.	0.8995 (0.008)	**0.9155 (0.009)**	0.6580 (0.056)	0.48733 (0.05)	0.8800 (0.08)	0.9933 (0.01)
Group 3 - F15.	0.9881 (0.002)	**0.9903 (0.002)**	0.8981 (0.033)	0.3733 (0.06)	0.7333 (0.12)	1.000 (0.02)
Group 4 -F16.	**0.9609 (0.007)**	0.9449 (0.009)	0.8562 (0.037)	0.3533 (0.07)	0.8067 (0.09)	0.9867 (0.05)
Group 4 -F17.	**0.9752 (0.017)**	0.9042 (0.022)	0.7901 (0.053)	0.3000 (0.06)	0.7667 (0.11)	0.9733 (0.13)
Group 5 - F18.	0.9455 (0.001)	**0.9455 (0.001)**	0.8988 (0.015)	0.4733 (0.09)	0.8533 (0.09)	1.0000 (0.00)
Group 5 - F19.	0.9217 (0.025)	**0.9441 (0.057)**	0.6001 (0.182)	0.4800 (0.09)	0.8333 (0.11)	1.000 (0.05)
Group 6 - F20.	0.9857 (0.001)	**0.9869 (0.001)**	0.9868 (0.001)	0.5800 (0.09)	0.9333 (0.05)	1.0000 (0.00)
Group 6 - F21.	0.9719 (0.001)	0.9756 (0.001)	**0.9766 (0.001)**	0.4933 (0.07)	0.9000 (0.09)	1.000 (0.00)
Group 7 - F22.	0.8035 (0.006)	**0.8177 (0.005)**	0.6182 (0.031)	0.5067 (0.08)	0.8800 (0.06)	1.0000 (0.02)
Group 7 - F23.	0.9677 (0.001)	**0.9714 (0.001)**	0.7871 (0.027)	0.4933 (0.05)	0.8800 (0.08)	0.9933 (0.03)
Group 8 - F24.	**0.9674 (0.009)**	0.9408 (0.013)	0.8609 (0.031)	0.3933 (0.06)	0.7800 (0.11)	0.9800 (0.12)
Group 8 - F25.	**0.9699 (0.009)**	0.9349 (0.012)	0.8647 (0.045)	0.3200 (0.05)	0.7600 (0.11)	0.9533 (0.13)
Group 9 - F26.	0.9738 (0.001)	**0.9763 (0.001)**	0.9741 (0.001)	0.5600 (0.09)	0.9467 (0.05)	1.0000 (0.00)
Group 9 - F27.	0.9437 (0.042)	**0.9480 (0.044)**	0.6161 (0.172)	0.5467 (0.08)	0.8933 (0.06)	0.9867 (0.07)
Group 6 - F28.	0.9808 (0.001)	0.9836 (0.001)	**0.9866 (0.001)**	0.4067 (0.06)	0.8333 (0.09)	1.000 (0.00)
Group 7 - F29.	0.7314 (0.016)	**0.8589 (0.008)**	0.8403 (0.009)	0.4600 (0.08)	0.8467 (0.07)	1.000 (0.00)
Group 7 - F30.	0.9687 (0.002)	**0.9738 (0.002)**	0.8009 (0.025	0.4600 (0.06)	0.8000 (0.10)	0.9933 (0.03)
Group 8 - F31.	**0.9255 (0.036)**	0.8529 (0.036)	0.7477 (0.045)	0.3400 (0.07)	0.8000 (0.08)	0.9733 (0.13)
Group 8 - F32.	**0.8852 (0.025)**	0.7915 (0.026)	0.6423 (0.076)	0.3400 (0.06)	0.7933 (0.07)	0.9733 (0.12)
Group 9 - F33.	0.9849 (0.001)	0.9867 (0.000)	**0.9885 (0.031)**	0.4400 (0.05)	0.7867 (0.08)	1.0000 (0.00)
Group 9 - F34.	0.8744 (0.038)	**0.8776 (0.031)**	0.6388 (0.182)	0.5000 (0.11)	0.8400 (0.10)	1.0000 (0.01)
Group 10 - F35.	0.5550 (0.003	0.5831 (0.004)	**0.5956 (0.003)**	0.5067 (0.07)	0.9000 (0.07)	01.000 (0.00)
Group 10 - F36.	0.7872 (0.006)	**0.7983 (0.006)**	0.7872 (0.006)	0.4733 (0.08)	0.8733 (0.09)	0.9933 (0.01)
Group 11 - F37.	0.7367 (0.009)	0.7425 (0.010)	**0.7479 (0.013)**	0.4000 (0.05)	0.8667 (0.08)	1.000 (0.01)
Group 11 - F38.	**0.8619 (0.010)**	0.8550 (0.011)	0.8461 (0.019)	0.3133 (0.05)	0.8667 (0.07)	0.9867 (0.04)
Group 12 - F39.	0.8128 (0.005)	**0.8285 (0.004)**	0.7280 (0.015)	0.5067 (0.08)	0.9000 (0.07)	1.0000 (0.00)
Group 12 - F40.	0.4736 (0.047)	**0.5116 (0.048)**	0.3954 (0.042)	0.6333 (0.08)	0.9467 (0.03)	1.0000 (0.01)
Group 10 - F41.	0.9281 (0.0.003)	0.9368 (0.004)	**0.9480 (0.003)**	0.4133 (0.06)	0.8267 (0.10)	1.0000 (0.00
Group 11 - F42.	**0.9379 (0.010)**	0.9034 (0.021)	0.8975 (0.021)	0.3667 (0.06)	0.8467 (0.08)	0.9933 (0.03)
Group 11 - F43.	**0.8744 (0.026)**	0.7937 (0.031)	0.7410 (0.060)	0.3733 (0.07)	0.7800 (0.10)	0.9533 (0.15
Group 12 - F44.	0.9687 (0.003)	**0.9761 (0.002**	0.9032 (0.011)	0.4067 (0.06)	0.8200 (0.08)	0.9867 (0.04)
Group 12 - F45.	0.8091 (0.043)	0.8223 (0.052)	**0.8557 (0.063)**	0.5200 (0.07)	0.8867 (0.05)	1.0000 (0.01
Group 13 - F46.	**0.8817 (0.012)**	0.8428 (0.023	0.8378 (0.027)	0.2933 (0.06)	0.8467 (0.09)	1.000 (0.03)
Group 13 - F47.	**0.8208 (0.031)**	0.6803 (0.043)	0.5553 (0.071)	0.4000 (0.08)	0.8667 (0.08)	0.9933 (0.04
Group 14 - F48.	**0.9520 (0.0018)**	0.8673 (0.033)	0.7799 (0.044)	0.3400 (0.07)	0.7067 (0.13)	0.9733 (0.17)
Group 14 - F49.	**0.8967 (0.051)**	0.8730 (0.059)	0.8579 (0.068)	0.4533 (0.07)	0.8533 (0.07)	1.000 (0.03
Group 13 - F50.	**0.8794 (0.036)**	0.7626 (0.038)	0.7402 (0.031)	0.3667 (0.07)	0.8600 (0.07)	1.000 (0.01)
Group 14 - F51.	**0.9801 (0.008)**	0.9535 (0.009)	0.9218 (0.017)	0.3467 (0.06)	0.8000 (0.11)	0.9667 (0.20
Group 14 - F52.	**0.8839 (0.060)**	0.8652 (0.069)	0.8414 (0.074)	0.4067 (0.07)	0.8533 (0.10)	1.0000 (0.109)
Group 15 - F53.	0.9927 (0.000)	0.9929 (0.000)	**0.9930 (0.00)**	0.5267 (0.05)	0.8600 (0.06)	1.0000 (0.00
Group 15 - F54.	**0.8950 (0.045)**	0.8717 (0.057)	0.7629 (0.135)	0.5267 (0.08)	0.9000 (0.07)	1.000 (0.02)
Group 15 - F55.	**0.3855 (0.070)**	0.3769 (0.084)	0.3709 (0.111)	0.8867 (0.07)	0.9733 (0.02)	1.000 (0.00

Table 1: On the left side, HV medians and standard deviations, in parenthesis for every function/priority function. The best values found by a priority function are in bold. On the right side, mean of the percentage of the median values and mean of the median values of the standard deviation (in parenthesis) of non-dominated solutions for every function/priority function. Shaded lines show the groups MOEA/D-RAD was specially successfulin terms of hypervolume values.

can further explore the relationship of priority functions based on diversity with others components and variants of the MOEA/D framework. How to define more efficient and effective utility functions for different problems is also

HV	MOEA/D-DRA	MOEA/D-RAD
MOEA/D-RAD	3.1e-08	-
MOEA/D-DE	3.1e-08	3.1e-08

Table 2: Statistical Analysis of the HV results based on the Pairwise Wilcoxon Rank Sum Test. It shows that exists significant difference between the ranks of MOEA/D-RAD, MOEA/D-DRA and MOEA/D-DE.

worth further investigation (such as priority function that also consider constraints) as well as to verify the results of using priority function in other real-world problems.

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