On Fitness Landscape Analysis of Permutation Problems: From Distance Metrics to Mutation Operator Selection

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Abstract

In this paper, we explore the theory and expand upon the practice of fitness landscape analysis for optimization problems over the space of permutations. Many of the computational and analytical tools for fitness landscape analysis, such as fitness distance correlation, require identifying a distance metric for measuring the similarity of different solutions to the problem. We begin with a survey of the available distance metrics for permutations, and then use principal component analysis to classify these metrics. The result of this analysis aligns with existing classifications of permutation problem types produced through less formal means, including the A-permutation, R-permutation, and P-permutation types, which classifies problems by whether absolute position of permutation elements, relative positions of elements, or general precedence of pairs of elements, is the dominant influence over solution fitness. Additionally, the formal analysis identifies subtypes within these problem categories. We see that the classification can assist in identifying appropriate metrics based on optimization problem feature for use in fitness landscape analysis. Using optimization problems of each class, we also demonstrate how the classification scheme can subsequently inform the choice of mutation operator within an evolutionary algorithm. From this, we present a classification of a variety of mutation operators as a counterpart to that of the metrics. Our implementations of the permutation metrics, permutation mutation operators, and associated evolutionary algorithm, are available in a pair of open source Java libraries. All of the code necessary to recreate our analysis and experimental results are also available as open source.

Keywords: fitness landscape analysis, permutation distance, combinatorial optimization, fitness distance correlation, evolutionary algorithms, permutation mutation operators

MSC Classification: 68W50 , 05A05 , 90C27 , 62H20

1 Introduction

Analyses of evolutionary algorithms (EA) and other forms of optimization often employ a fitness landscape (Mitchell, 1998), which is a spatial arrangement of the space of all possible solutions to the problem such that structurally "similar" solutions are located near to each other. To be most relevant to the algorithm under analysis, nearby solutions should correspond with solutions reachable in a small number of applications of the search operators. Thus, an effective fitness landscape analysis requires identifying an appropriate measure of distance for the combination of problem and operators. There exists much work on fitness landscape analysis, including for permutation landscapes (Hernando et al, 2016; Tayarani-N and Prugel-Bennett, 2014; Cicirello, 2014; Cicirello

and Cernera, 2013; Sörensen, 2007; Schiavinotto and Stützle, 2007; Reidys and Stadler, 2002). This current article is an extended version of our prior conference paper on the topic (Cicirello, 2019).

The available fitness landscape analysis tools include fitness distance correlation (FDC) (Jones and Forrest, 1995), Pearson correlation between solution fitness and distance to the nearest optimal solution, as well as search landscape calculus (Cicirello, 2016), which examines the local rate of change of fitness. FDC, search landscape calculus, and other related techniques require distance metrics. The features of a permutation, or other structure, that are important in determining similarity or distance is often problem dependent. For the Traveling Salesperson Problem (TSP), the permutation represents a set of edges between adjacent pairs of cities, and is thus rotationally invariant since rotation doesn't change element adjacency. Permutations can also represent one-to-one mappings between sets, such as in the largest common subgraph problem, where one seeks the largest subgraph of graph G_1 that is isomorphic to a subgraph of G_2. You can represent a mapping by ordering the vertexes of G_1, and using a permutation of the vertexes of G_2, such that vertex i of G_2 in permutation index j corresponds to mapping vertex i of G_2 to vertex j of G_1. In this case, absolute element position is most important to fitness. Campos et al (2005) categorized permutation problems into two types: R-permutation, such as the TSP, where relative positions (i.e., adjacency implies edges) are important; and A-permutation, such as mapping problems, where absolute positions have greatest effect on fitness. Cicirello (2016) previously added a third type, P-permutation, where general element precedences most directly impact fitness (e.g., element w occurs prior to elements x, y, and z, but not necessarily adjacent to any of them). Many scheduling problems are this type (e.g., a job may be delayed if jobs with long process times are anywhere prior to it in the schedule).

We survey permutation distances in Section 2, and then formally identify groups of related permutation metrics using principal component analysis (PCA) in Sections 3 and 4. The first three principal components correspond to the three problem classes defined above; and the next few identify new subtypes. A classification of metrics aligned with the existing classification of problems

Table 1 Summary of distance measure classes

Distance	Runtime	Metric?
edit	$O(n^2)$	yes
exact match	$O(n)$	yes
interchange	$O(n)$	yes
acyclic edge	$O(n)$	pseudo
cyclic edge	$O(n)$	pseudo
r-type	$O(n)$	yes
cyclic r-type	$O(n)$	pseudo
Kendall tau	$O(n \lg n)$	yes
reinsertion	$O(n \lg n)$	yes
deviation (dev)	$O(n)$	yes
normalized dev.	$O(n)$	yes
squared dev.	$O(n)$	yes
Lee	$O(n)$	yes
reversal edit	init: $O(n!n^3)$	yes
	calc: $O(n^2)$	

is a desirable property. For example, if one requires a metric relevant for analyzing the fitness landscape of a problem within a known problem class, then the distance classification can directly lead to the most relevant metrics. In Section 5, we provide a set of fitness landscapes corresponding to the identified classes of permutation metric. For each landscape and metric, we compute FDC as an example application of the classification scheme. We implement the PCA, as well as our FDC examples, using JavaPermutationTools, an open source library of permutation distance metrics (Cicirello, 2018). In Section 6, we apply the classification to choosing a mutation operator for use in an EA, and derive a classification of a wide variety of permutation mutation operators. The experiments use the EA implementation of the open source Chips-n-Salsa library (Cicirello, 2020). The code to replicate the experiments and analysis is also available: https://github.com/cicirello/MONE2022-experiments. We wrap up with a discussion in Section 7.

2 Permutation Distance

Table 1 summarizes the permutation distances used in the analysis, including runtime, and metric status. The n in runtimes and equations is permutation length, $p(i)$ refers to the element at index i in permutation p, $p^{-1}(e)$ refers to the index of element e in p. We use 1-based indexing in equations (index of first position is 1). Subscripts refer to different permutations. Thus, $p_1(i)$ refers to the element in position i of permutation p_1.

Edit distance: The edit distance is the minimum cost of the "edit operations" to transform one structure into another. Levenshtein distance is a string edit distance (Levenshtein, 1966), on binary strings (i.e., of ones and zeros), with edit operations character insertion, removal, and changes. Wagner and Fischer (1974) extended this to non-binary strings, introduced configurable costs to the three edit operations, and provided a dynamic programming algorithm to compute it. Sörensen (2007) suggested treating a permutation as a string, and applying string edit distance. All edit distances are metrics. Our implementation is of Wagner and Fischer's dynamic programming algorithm, including parameters for the costs of the edit operations. Runtime is $O(n^2)$.

Exact match distance: Ronald (1998) extends Hamming distance to non-binary strings, producing exact match distance, an edit distance with element changes as the edit operation. It is widely used (Cicirello, 2014; Cicirello and Cernera, 2013; Sörensen, 2007; Sevaux and Sörensen, 2005), satisfies the metric properties (Ronald, 1998), and computed in $O(n)$ time by counting the number of positions with different elements:

$$\delta(p_1, p_2) = |\{i \in \{1 \ldots n\} \mid p_1(i) \neq p_2(i)\}|.$$

Interchange distance: Interchange distance is an edit distance with one edit operation, element interchanges. It is the minimum number of swaps needed to transform p_1 into p_2; and is computed efficiently ($O(n)$ time) by counting the number of cycles between the permutations (Cicirello and Cernera, 2013). A permutation cycle of length k is transformed into k fixed points with $k-1$ swaps (a fixed point is a cycle of length 1). Let CycleCount(p_1, p_2) be the number of permutation cycles, and define interchange distance as:

$$\delta(p_1, p_2) = n - \text{CycleCount}(p_1, p_2).$$

Cyclic edge distance and acyclic edge distance: Ronald (1997, 1995) defines the cyclic edge and acyclic edge distances for permutations that represent sets of edges. Element adjacency corresponds to undirected edges. Cyclic edge distance considers the permutation to be a cycle, with adjacent endpoints; whereas acyclic edge distance does not. Cyclic edge distance interprets the permutation, $[0, 1, 2, 3]$, as the undirected edges,

$\{(0, 1), (1, 2), (2, 3), (3, 0)\}$, while acyclic edge distance excludes $(3, 0)$ from this set. Both are invariant under a reversal (e.g., $[0, 1, 2, 3]$ is equivalent to $[3, 2, 1, 0]$). The cyclic form is also invariant under rotations. Distance is the number of edges in p_1 that are not in p_2, and is computed in $O(n)$ time. Both are pseudo-metrics (Ronald, 1997) due to reversal invariance, and rotational invariance for the cyclic form. Define acyclic and cyclic edge distances, respectively, as:

$$\delta(p_1, p_2) = |\{i \mid i \in \{1 \ldots n - 1\} \wedge \\ |p_2^{-1}(p_1(i + 1)) - p_2^{-1}(p_1(i))| \neq 1\}|,$$

$$\delta(p_1, p_2) = |\{i \mid i \in \{1 \ldots n\} \wedge x = \\ |p_2^{-1}(p_1((i \bmod n) + 1)) - p_2^{-1}(p_1(i))| \\ \wedge x \neq 1 \wedge x \neq n - 1\}|.$$

R-type and cyclic r-type distances: The r-type distance ("r" for relative) (Campos et al, 2005) is a directed edge version of acyclic edge distance. Cyclic r-type (Cicirello, 2016) is its cyclic counterpart, including an edge between endpoints. Though r-type is a metric, cyclic r-type is a pseudo-metric due to rotational invariance. Runtime for both is $O(n)$, and defined respectively:

$$\delta(p_1, p_2) = |\{i \mid i \in \{1 \ldots n - 1\} \wedge \\ p_2^{-1}(p_1(i + 1)) - p_2^{-1}(p_1(i)) \neq 1\}|,$$

$$\delta(p_1, p_2) = |\{i \mid i \in \{1 \ldots n\} \wedge x = \\ p_2^{-1}(p_1((i \bmod n) + 1)) - p_2^{-1}(p_1(i)) \\ \wedge x \neq 1 \wedge x \neq 1 - n\}|.$$

Kendall tau distance: The metric Kendall tau distance is a variation of Kendall's rank correlation coefficient (Kendall, 1938):

$$\delta(p_1, p_2) = |\{x, y \in p_1 \mid p_1^{-1}(x) > p_1^{-1}(y) \\ \wedge p_2^{-1}(x) < p_2^{-1}(y)\}|.$$

Some divide by $n(n-1)/2$, but most use it as defined above (Fagin et al, 2003; Meilă and Bao, 2010), where it is the minimum number of adjacent swaps to transform p_1 into p_2, an adjacent swap edit distance. Compute in $O(n \lg n)$ time using a mergesort modified to count inversions.

Reinsertion distance: An edit distance with a single atomic edit operation, removal/reinsertion, which removes an element and reinserts

it elsewhere in the permutation, is called reinsertion distance. It is the minimum number of removal/reinsertions to transform p_1 into p_2. Observing that the elements that must be removed and reinserted are exactly the elements that do not lie on the longest common subsequence (Cicirello, 2016), it is computed efficiently in $O(n \lg n)$ time using Hunt and Szymanski (1977)'s algorithm for longest common subsequence. We implement it as:

$$\delta(p_1, p_2) = n - |\text{MaxCommonSubsequence}(p_1, p_2)|.$$

Deviation distance and normalized deviation distance: Deviation distance, a metric, sums the positional deviations of the permutation elements. The positional deviation of an element is the absolute difference of its index in p_1 from its index in p_2. Ronald (1998) originally divided this sum by $n-1$ to normalize an element's contribution to total distance in the interval $[0, 1]$. Many use this form (Sörensen, 2007; Cicirello and Cernera, 2013; Cicirello, 2014), while others (Sevaux and Sörensen, 2005; Campos et al, 2005; Cicirello, 2016) do not divide by $(n-1)$. Runtime of our implementation is $O(n)$. The two forms are:

$$\delta(p_1, p_2) = \tfrac{1}{n-1} \sum_{e \in p_1} |p_1^{-1}(e) - p_2^{-1}(e)|,$$

$$\delta(p_1, p_2) = \sum_{e \in p_1} |p_1^{-1}(e) - p_2^{-1}(e)|.$$

Squared deviation distance: Sevaux and Sörensen (2005) suggest squared deviation distance, based on Spearman's rank correlation coefficient, summing of the squares of the positional deviations of the elements. Prior authors state that squared deviation distance as well as deviation distance require quadratic time (Sevaux and Sörensen, 2005). However, we implement these in $O(n)$ time with two linear passes, one computing the inverse of one permutation, which is then used in the second pass to look up element indexes.

$$\delta(p_1, p_2) = \sum_{e \in p_1} (p_1^{-1}(e) - p_2^{-1}(e))^2.$$

Lee distance: Lee distance originated in coding theory for strings (Lee, 1958). Here we adapt it for permutation distance. Lee distance, a metric, treats the permutation as a cycle, summing

the minimum of the left and right positional deviations. It is computed in $O(n)$ time. Define as:

$$\delta(p_1, p_2) = \sum_{e \in p_1} \min(|p_1^{-1}(e) - p_2^{-1}(e)|, \\ n - |p_1^{-1}(e) - p_2^{-1}(e)|).$$

Reversal edit distance: Reversal edit distance is the minimum number of reversals to transform p_1 into p_2. Computing reversal edit distance is NP-Hard (Caprara, 1997); and Schiavinotto and Stützle (2007) argue that the best available approximations are insufficient for search landscape analysis. We implement it with a breadth-first enumeration to initialize a lookup table mapping each of the $n!$ permutations to its reversal edit distance from a reference permutation. Computing the distance between a given pair of permutations is then a table lookup. This is only feasible for short permutation length. Initialization cost is $O(n!n^3)$ (i.e., breadth-first enumeration of $O(n!)$ permutations, each with $O(n^2)$ neighbors (possible sub-permutation reversals), and a reversal costs $O(n)$). Applications with the need to compute $O(n!)$ distances all from the same reference permutation can do so with an amortized initialization cost of $O(n^3)$ per distance calculation. The table lookup costs $O(n^2)$ (cost to compute mixed radix representation of the permutation).

3 Classifying Distance Metrics

We perform PCA to identify groups of related permutation metrics, using the distance measures from Section 2 except the edit, normalized deviation, and reversal edit distances. Normalized deviation distance is deviation distance scaled, and thus observations made about one apply to both. Edit distance's parameters define a continuum of metrics. Reversal edit distance is too costly, but we later discuss how it fits in our classification.

For all permutations of length $n = 10$, compute distance to a single reference permutation. Using Jacobi iteration, compute the eigenvalues and eigenvectors of the correlation matrix of Table 2. Table 3 lists the eigenvalues of the principal components (PC), the first three of which are greater than 1.0; and the first five PCs combine for more than 90% of the sum. Table 4 shows the eigenvectors for the first five PCs. Correlation between the original distance metrics and each of the first

Table 2 Lower triangle of correlation matrix (columns in same order as rows)

exact match	1.0										
interchange	.766	1.0									
acyclic edge	.019	.070	1.0								
cyclic edge	-.000	.056	.899	1.0							
rtype	.024	.009	.628	.564	1.0						
cyclic rtype	-.000	-.010	.557	.619	.911	1.0					
Kendall tau	.328	.241	-.000	.000	.085	.075	1.0				
reinsertion	.301	.182	.102	.100	.422	.392	.704	1.0			
deviation	.515	.395	.008	-.000	.020	-.000	.931	.650	1.0		
sq. deviation	.333	.255	-.000	-.000	.017	-.000	.984	.623	.947	1.0	
Lee	.556	.426	.019	.000	.014	-.000	.447	.452	.703	.455	1.0

Table 3 Eigenvalues of the PCs

PC	eigenvalue	proportion	cumulative
1	4.3644	0.3968	0.3968
2	3.1148	0.2832	0.6799
3	1.4740	0.1340	0.8139
4	0.8367	0.0761	0.8900
5	0.5465	0.0497	0.9397
6	0.2492	0.0227	0.9623
7	0.2120	0.0193	0.9816
8	0.1575	0.0143	0.9959
9	0.0315	0.0029	0.9988
10	0.0107	0.0010	0.9998
11	0.0026	0.0002	1.0000

Table 4 Eigenvectors of the first five PCs

distance	PC1	PC2	PC3	PC4	PC5
exact match	.2984	.0958	.5419	-.1573	.1423
interchange	.2487	.0695	.6058	-.0586	.3936
acyclic edge	.0854	-.4751	.1354	.4611	-.0635
cyclic edge	.0805	-.4768	.1194	.4674	-.0455
r-type	.1271	-.4873	-.0576	-.3803	.0517
cyclic r-type	.1153	-.4874	-.0666	-.3793	.0510
Kendall tau	.4216	.0928	-.3110	.1400	.2292
reinsertion	.3721	-.0848	-.2529	-.3795	-.0509
deviation	.4516	.1321	-.1089	.1630	-.0651
sq. deviation	.4140	.1189	-.2828	.2444	.2218
Lee	.3381	.1027	.2157	-.0476	-.8396

Table 5 Correlation between distances and first five PCs

distance	PC1	PC2	PC3	PC4	PC5
exact match	.6234	.1691	.6579	-.1439	.1052
interchange	.5196	.1227	.7355	-.0536	.2910
acyclic edge	.1784	-.8385	.1644	.4218	-.0470
cyclic edge	.1682	-.8415	.1450	.4276	-.0337
r-type	.2654	-.8600	-.0699	-.3479	.0382
cyclic r-type	.2410	-.8602	-.0808	-.3469	.0377
Kendall tau	.8808	.1638	-.3775	.1281	.1695
reinsertion	.7774	-.1497	-.3070	-.3472	-.0377
deviation	.9435	.2332	-.1322	.1491	-.0481
sq. deviation	.8649	.2099	-.3434	.2236	.1640
Lee	.7063	.1812	.2619	-.0436	-.6207

Kendall tau and reinsertion distances, by their definitions, measure similarity in terms of pairwise element precedences. The variations of deviation distance capture that same essence in that an element that is displaced a greater number of positions is likely involved in a greater number of precedence inversions (i.e., where a is prior to b in one permutation, and somewhere after in the other). These five permutation metrics are P-permutation distances, measuring permutation distance in terms of precedence related features.

PC2 (R-permutation): PC2 correlates very strongly with both forms of edge distance, and both forms of R-type distance ($|r| > 0.83$ in all four cases). These distances all focus on adjacency (i.e., edges) of permutation elements.

PC3 (A-permutation): PC3 strongly correlates to the exact match ($r = 0.6579$) and interchange distances ($r = 0.7355$). Both focus on absolute positions of permutation elements.

The fourth and fifth PCs identify subtypes. Their eigenvalues are less than 1, and account for

five PCs is in Table 5. The first three PCs correspond to the three types of permutation problem discussed earlier in Section 1.

PC1 (P-permutation): PC1 correlates extremely strongly (0.94) to deviation distance, very strongly to the Kendall tau and squared deviation distances, and reasonably strongly to the reinsertion and Lee distances (Table 5). The

Table 6 Permutation distance metric classification

type	subtype	distances
P-permutation	acyclic	Kendall tau, reinsertion, deviation, squared deviation
	cyclic	Lee
R-permutation	undirected	acyclic edge, cyclic edge, reversal edit
	directed	r-type, cyclic r-type
A-permutation		exact match, interchange

small portions of the eigenvalue sum (7.6% and 5%), but interpreting is interesting none-the-less.

PC4 (R-permutation, undirected): PC4's strongest correlations are to the two variations of edge distance, which consider permutations to represent sets of undirected edges.

PC5 (P-permutation, cyclic): PC5 correlates strongly ($|r| = 0.6207$) to Lee distance, and only weakly to the others. Lee distance also strongly correlates with PC1 (P-permutation), but is different than the other deviation-based metrics in that it computes positional deviation as if the end points are linked. In some sense, this is a cyclic subtype of P-permutation.

Table 6 summarizes this classification. There are three primary types: P-permutation, R-permutation, and A-permutation; and two are decomposed into subtypes. Although we excluded reversal edit distance in the analysis, we include it among the undirected R-permutation metrics as a reversal clearly replaces two undirected edges.

4 On Effects of Length

To derive the classification in Section 3, the PCA computed the correlation matrix via brute-force enumeration of permutations of length $n = 10$. To explore whether length affects the classes identified, we repeat the PCA using length $n = 50$, which is too long for exhaustive enumeration. We instead randomly sample the space of permutations, sampling 3628800 random permutations of length 50, chosen so number of data points is the same as Section 3. Table 7 shows the correlation matrix. Table 8 provides the eigenvalues, and Table 9 shows the eigenvectors of the first five PCs. Table 10 shows the correlations between the original metrics and the first five PCs.

In Table 10, PC1 again corresponds to the P-permutation metrics, correlating extremely strongly to the deviation, Kendall tau, and squared deviation distances ($|r| > 0.9$), and also correlating strongly to the reinsertion and Lee distances. Likewise, PC2 (as before) corresponds to the R-permutation metrics, with very strong correlation ($|r| > 0.89$) to both forms of edge distance and both forms of R-type distance. Also consistent with the shorter length results, PC3 corresponds to the A-permutation metrics, with very strong correlation to the exact match ($|r| = 0.8265$) and interchange distances ($|r| = 0.8525$). PC5 again correlates moderately to Lee distance ($|r| = 0.5258$) and only weakly to the others.

PC4 is the only inconsistency between the longer permutation results and the shorter permutation results. With shorter permutations, PC4 identified the two forms of edge distance (R-permutation undirected subtype). With longer randomly sampled permutations, PC4 identified reinsertion distance, and to a lesser extent Lee distance. This suggests that as length increases there may be a relationship between the reinsertion and Lee distances; or that reinsertion distance captures a different form of variability than does the other P-permutation metrics.

We stick with the earlier classification (Table 6), since four PCs directly correspond to that analysis, and since the distinct nature of reinsertion distance is not entirely clear.

5 Example Fitness Landscapes

We present five search landscapes as examples.

R-permutation (undirected) landscape (L_1): The first search landscape is a simple instance of the TSP with a known optimal solution. It has 20 cities arranged equidistantly on a circle of radius 1.0. The edge cost is Euclidean distance. The optimal solution is to either follow the cities clockwise or counterclockwise around the circle. There are 40 optimal permutations: 20 cities at which to begin, and two possible travel directions (clockwise and counterclockwise).

We compute FDC using 100000 randomly sampled permutations (Table 11). In this case, it is the correlation between tour cost, and distance to the nearest of the 40 optimal permutations. The highest FDC is for the two forms of edge distance, followed by the two forms of R-type (recall that

Table 7 Lower triangle of correlation matrix (permutation length 50)

exact match	1.0										
interchange	.578	1.0									
acyclic edge	.001	.009	1.0								
cyclic edge	.000	.009	.980	1.0							
rtype	.001	.000	.693	.679	1.0						
cyclic rtype	-.000	-.000	.679	.693	.980	1.0					
Kendall tau	.142	.082	-.000	-.000	.008	.007	1.0				
reinsertion	.140	.074	.060	.059	.176	.172	.532	1.0			
deviation	.226	.132	-.000	-.000	-.001	-.001	.944	.555	1.0		
sq. deviation	.143	.084	-.000	-.000	-.000	-.001	.995	.501	.949	1.0	
Lee	.248	.144	.000	-.000	-.001	-.001	.431	.439	.685	.433	1.0

Table 8 Eigenvalues of the PCs (permutation length 50)

PC	eigenvalue	proportion	cumulative
1	3.7755	0.3432	0.3432
2	3.3513	0.3047	0.6479
3	1.5162	0.1378	0.7857
4	0.7515	0.0683	0.8541
5	0.6604	0.0600	0.9141
6	0.4849	0.0441	0.9582
7	0.4111	0.0374	0.9955
8	0.0336	0.0031	0.9986
9	0.0069	0.0006	0.9992
10	0.0059	0.0005	0.9998
11	0.0027	0.0002	1.0000

Table 10 Correlation between distance and first five PCs.

distance	PC1	PC2	PC3	PC4	PC5
exact match	-.311	-.072	-.827	.009	.016
interchange	-.219	-.046	-.853	.131	.129
acyclic edge	-.185	.893	-.013	.209	-.272
cyclic edge	-.185	.893	-.013	.210	-.272
r-type	-.212	.893	.007	-.169	.251
cyclic r-type	-.211	.893	.007	-.167	.250
Kendall tau	-.908	-.202	.201	.268	.135
reinsertion	-.690	.003	.078	-.482	.236
deviation	-.956	-.218	.102	.086	-.080
sq. deviation	-.903	-.207	.198	.291	.115
Lee	-.666	-.149	-.100	-.441	-.526

Table 9 Eigenvectors of first five PCs (length 50)

distance	PC1	PC2	PC3	PC4	PC5
exact match	-.160	-.039	-.671	.011	.019
interchange	-.113	-.025	-.692	.151	.159
acyclic edge	-.095	.488	-.011	.242	-.335
cyclic edge	-.095	.488	-.010	.242	-.335
r-type	-.109	.488	.006	-.194	.309
cyclic r-type	-.108	.488	.006	-.192	.308
Kendall tau	-.468	-.110	.163	.309	.166
reinsertion	-.355	.002	.063	-.556	.290
deviation	-.492	-.119	.083	.099	-.099
sq. deviation	-.465	-.113	.161	.336	.142
Lee	-.343	-.081	-.082	-.509	-.647

Table 11 FDC for the metrics and example landscapes

distance	L_1	L_2	L_3	L_4	L_5
exact match	.1548	.1881	.6917	.2974	.4806
interchange	.1192	.0886	.5296	.2204	.3665
acyclic edge	.6052	.3474	.0118	.0020	.0186
cyclic edge	.6204	.3822	-.0002	.0006	.0026
r-type	.5442	.6333	.0148	.0790	.0136
cyclic r-type	.5562	.6595	-.0016	.0684	.0005
Kendall tau	.3423	.2408	.2245	.9022	.3862
reinsertion	.3382	.5349	.2080	.6364	.3887
deviation	.3898	.1875	.3544	.8410	.6072
sq. deviation	.3150	.1555	.2282	.8876	.3935
Lee	.4640	.2316	.3836	.4063	.8619

R-type distance uses directed edges, while edge distance uses undirected edges). Cyclic edge distance has slightly higher FDC over acyclic edge distance, which makes sense since a solution to a TSP is a cycle of the cities where the first and last permutation elements represent an edge.

R-permutation (directed) landscape (L_2): This landscape is a simple Asymmetric TSP (ATSP), with 20 cities arranged equidistantly on a circle of radius 1.0. Let city c_i be the city after c_{i-1} in counterclockwise order. The edge cost from c_i to c_j is Euclidean distance if $i < j$, and is otherwise a constant distance 2.0. There is one optimal tour, which visits the cities in counterclockwise order, and 20 permutations that correspond to this tour (20 starting cities).

For this landscape, the two forms of R-type distance offer the highest FDC (Table 11), and FDC is low for the other distance measures. Consistent with the cyclic nature of the ATSP, cyclic R-type has slightly higher FDC than the acyclic form.

A-permutation landscape (L_3): Landscape L_3 is a variation of the *Permutation in a Haystack* problem (Cicirello, 2016), where one must minimize distance to a predetermined optimal permutation p. It is the permutation analog of the OneMax (Ackley, 1985) bitstring problem often used in testing genetic algorithms. The Permutation in a Haystack enables defining fitness landscapes with a known optimal solution that possess a desired topology, via choice of distance function.

For L_3, we modify the Permutation in a Haystack to use a noisy distance function as the optimization objective. Given target p, the fitness of permutation q is $\alpha_q * \delta(p, q)$, where $\delta(p, q)$ is exact match distance between q and optimal solution p, and each α_q is uniformly random from the interval $[1, 1.5)$. We use a smaller permutation length of 10 for L_3 than we did for the first two.

In Table 11, we see that the two metrics, earlier identified as A-permutation by our PCA, both have high FDC to landscape L_3; and FDC is low for all other permutation metrics.

P-permutation (acyclic) landscape (L_4): We modify the noisy Permutation in a Haystack from L_3 to obtain a P-permutation landscape, L_4, with a known optimal solution by using the Kendall tau distance instead of exact match.

Three of the four metrics classified as acyclic P-permutation have very high FDC for landscape L_4 (Table 11), including the Kendall tau, deviation, and squared deviation distances. The fourth, reinsertion distance, also has reasonably high FDC for L_4; while FDC is low for all other metrics.

P-permutation (cyclic) landscape (L_5): The last example fitness landscape uses Lee distance in the noisy Permutation in a Haystack adapted from L_3 and L_4. Lee distance provides the highest FDC for this landscape (Table 11).

6 Mutation Classification

The metrics with highest FDC for each fitness landscape (Section 5) correspond to the metrics for the landscape's class in Table 6. We now explore how a corresponding mapping of mutation

Table 12 Summary of mutation operators

Mutation Operator	Runtime
AdjSwap	$O(1)$
Swap	$O(1)$
Insertion	$O(n)$
Reversal	$O(n)$
3opt	$O(n)$
BlockMove	$O(n)$
BlockSwap	$O(n)$
Cycle	$O(\min(n, k^2))$
Scramble	$O(n)$
Uniform	$O(n)$

operators for an EA can assist in selecting relevant operators for the optimization problem at hand.

We explore the behavior of a variety of mutation operators for problems of each type. All test problems are over the space of permutations of length 100. The EA is a mutation-only generational model such that children replace the parents in the population. We use elitism, keeping the best population member unaltered, and otherwise use Stochastic Universal Sampling (SUS) (Baker, 1987) for selection. All problems involve minimizing the cost $c(p)$ of permutation p. The EA defines fitness of p as: $f(p) = 1/(1 + c(p))$. The permutations selected by SUS in each generation undergo one mutation each. Population size is 100. Results are averages of 100 runs on 100 instances.

We compare several mutation operators, summarized with runtimes in Table 12. Adjacent Swap (AdjSwap) swaps a random pair of adjacent elements. Swap exchanges the positions of two random elements. Insertion removes a random element and reinserts it at a random index. Reversal reverses a random segment. 3opt assumes the permutation represents a set of edges and replaces three random edges (Lin, 1965). BlockMove removes a random segment and reinserts it at a random location. BlockSwap swaps the locations of two random segments. Cycle($kmax$) mutation, one of two forms of cycle mutation (Cicirello, 2022), induces a random k-cycle for random $k \in [2, kmax]$, where we use $kmax = 10$ in the experiments. Scramble randomizes the order of a random contiguous segment.

Uniform Scramble, believed to be new with this paper, randomizes the positions of a random set of elements, each element chosen with probability U. In the experiments, $U = 1/3$ to affect the same number of elements on average as Scramble.
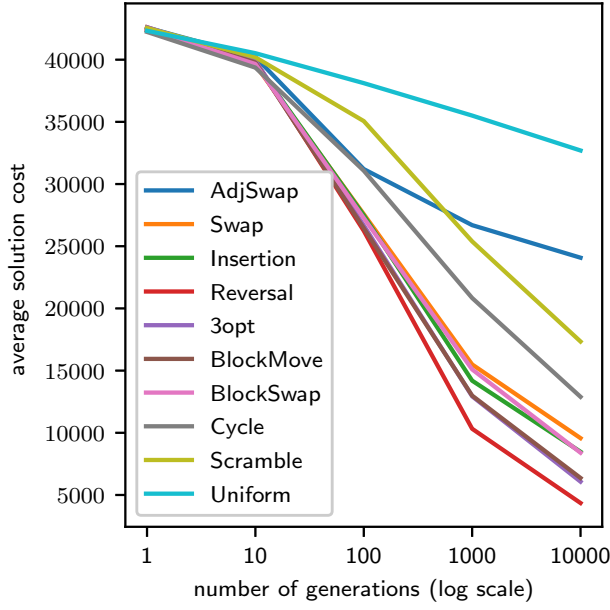
Fig. 1 Mutation operator comparison for the TSP

Fig. 2 Mutation operator comparison for the ATSP

Fig. 3 Mutation operator comparison for the Permutation in a Haystack with Exact Match distance

R-permutation (undirected) problem: In Figure 1, we see results for TSP instances generated from random symmetric distance matrices. The x-axis is number of generations at log scale. Reversal, equivalent to randomly replacing two undirected edges, performs best. Next best are BlockMove and 3opt (both replace three edges), followed closely by Insertion (changes three edges), BlockSwap and Swap (both replace four edges). The others lag behind, although Cycle is tunable via the maximum cycle length.

R-permutation (directed) problem: For ATSP instances generated from random asymmetric distance matrices (Figure 2), the best performing mutation is BlockMove, followed by Insertion, BlockSwap, and Swap. At 10000 generations, 3opt achieves equivalent performance, but underperforms earlier. The best performing mutations are similar to the undirected case, except Reversal performs poorly for directed edges, likely because reversing a segment flips the direction of $3n$ directed edges on average. This explains 3opt's mixed performance (some 3opt moves flip direction of many edges, while others do not).

A-permutation problem: The Permutation in a Haystack with Exact Match distance provides an A-permutation landscape (the original version, and not the noisy version of Section 5). Swap clearly dominates (Figure 3). 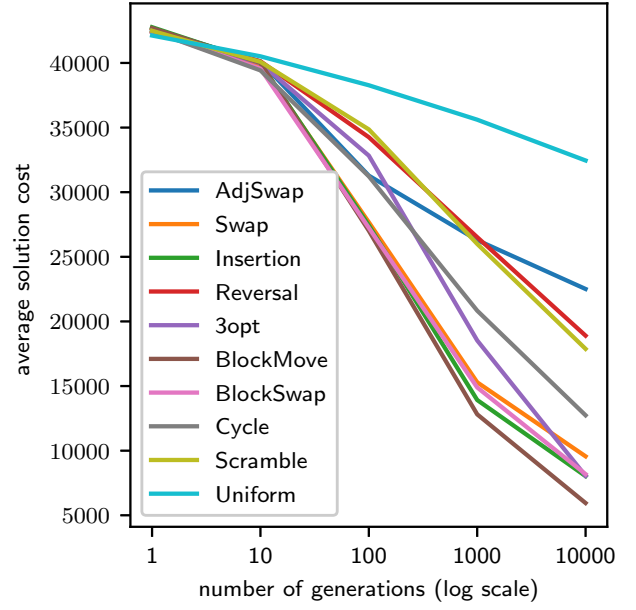The only other mutation worth considering for A-permutation problems is Cycle mutation, whose cycle length parameter may need fine-tuning.

P-permutation (acyclic) problem: We use the Permutation in a Haystack with Kendall tau distance to create an acyclic P-permutation problem (results in Figure 4). Many of the mutation operators are able to consistently optimally solve this problem for 10000 generation runs. Thus, we focus on earlier performance. At 1000 generations
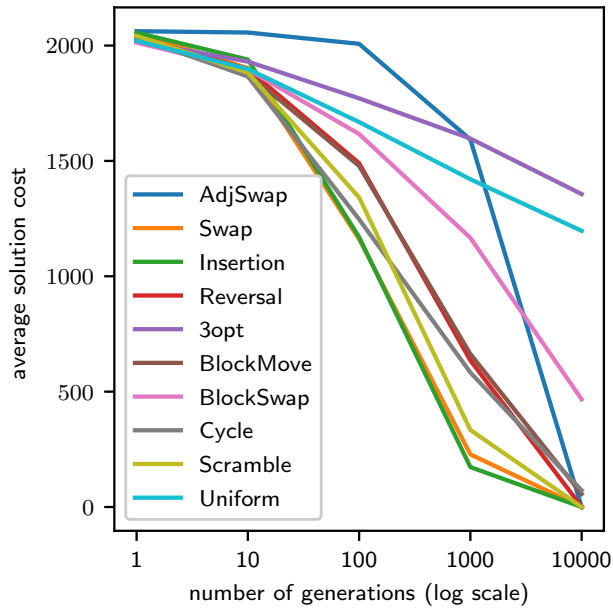
Fig. 4 Mutation operator comparison for the Permutation in a Haystack with Kendall tau distance
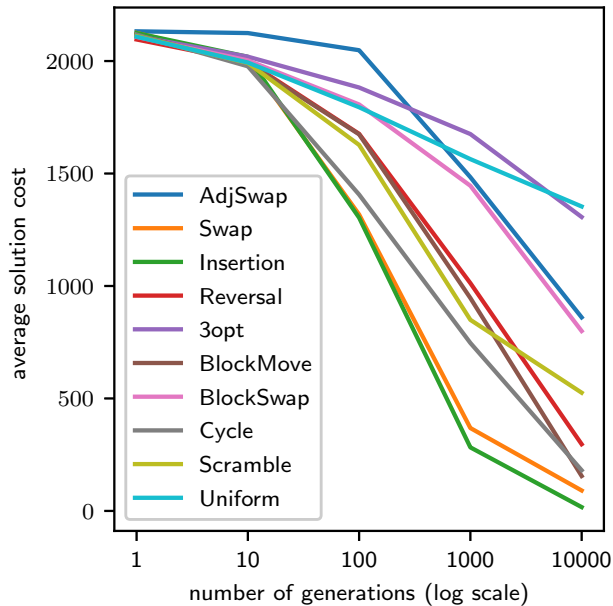

Fig. 5 Mutation operator comparison for the Permutation in a Haystack with Lee distance

Table 13 Mutation operator classification

type	subtype	mutation operators
P-permutation	acyclic	Insertion, Swap, Scramble
	cyclic	Insertion, Swap
R-permutation	undirected	Reversal, BlockMove, 3opt, Insertion, BlockSwap, Swap
	directed	BlockMove, Insertion, BlockSwap, Swap
A-permutation		Swap, Cycle

From the computational results, we derive a classification of the permutation mutation operators (Table 13) as a counterpart to the classification of permutation metrics. The two schemes can be used in combination to inform the design of search algorithms. When designing an EA, or other metaheuristic, an analysis of the fitness landscape for the problem can utilize the classes of distance functions (Table 6) to identify the permutation features with greatest impact on fitness. The mutation operator classification (Table 13) then provides a catalog of mutation operators that are well-suited to optimizing the problem at hand.

7 Discussion and Conclusions

Our first contribution is the classification of permutation metrics according to the features that influence each measure of distance. We derived the classification formally using PCA, and included all of the common measures of permutation distance, as well as a few less common metrics.

The classification aligns with an existing set of less formally derived problem classes, which leads to our next contribution, formal confirmation of those problem classes, in that FDC is highest for the metrics that correspond to a problem's class. Our PCA approach also lead to identifying new problem subtypes. With this alignment between metric classes and problem classes, the results aid in selecting problem-relevant metrics for use with fitness landscape analysis techniques, such as FDC. For example, if faced with a problem where permutations represent sets of edges (e.g., TSP), then the classification suggests using one of the forms of edge or r-type distance, depending upon whether edges are undirected or directed. If it is a P-permutation problem, where general

and earlier, the best performing mutation is Insertion, followed closely by Swap, and then most surprisingly by Scramble. The others lag behind.

P-permutation (cyclic) problem: The Permutation in a Haystack with Lee distance creates a cyclic P-permutation problem. Insertion and Swap are the only operators that consistently perform well throughout the run in this case (Figure 5).

pairwise element precedences have greatest impact on fitness (e.g., many scheduling problems), then you would choose a P-permutation metric such as Kendall tau, reinsertion, or one of the variations of deviation distance. Additionally, in this case, you may then factor in the runtimes of the metrics. For example, the Kendall tau and squared deviation distances correlate very strongly ($r = 0.984$, Table 2). However, Kendall tau is computed in $O(n \lg n)$ time, while squared deviation is computed in $O(n)$ time. Even if Kendall tau is the better match for your specific problem, squared deviation may be sufficient due to its strong correlation while saving computational cost.

Our third contribution is a comprehensive classification of permutation mutation operators, as a counterpart to the distance classification, that can inform the effective selection of a mutation operator during the design phase of an EA. The distance classes support fitness landscape analysis and problem class identification. The mutation operator classification then narrows in on the most relevant available mutation operators for the given problem class. We included all of the most common, as well as less common, mutation operators for permutations in this research.

This paper also contributes a new mutation operator, Uniform Scramble, which is a variation of Scramble. Although Uniform Scramble was not among the top-performing for any problem class, it has a tunable parameter that will be explored in future work, or it may be useful to give a stagnated search a kick (e.g., it is disruptive).

All of the distance metrics are implemented in the open-source JavaPermutationTools (JPT) library (Cicirello, 2018). JPT's source code is available at: https://github.com/cicirello/JavaPermutationTools. The EA implementation and all of the mutation operators are in the open-source Chips-n-Salsa library (Cicirello, 2020), whose source code is available at: https://github.com/cicirello/Chips-n-Salsa. Source code to replicate the analysis, experiments, and results of Sections 3–6 is available at: https://github.com/cicirello/MONE2022-experiments.

Declarations

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