Supplementary Material of The Automatic Design of Multi-Objective Ant Colony Optimization Algorithms

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Abstract

Multi-objective optimization problems are problems with several, typically conflicting criteria for evaluating solutions. Without any a priori preference information, the Pareto optimality principle establishes a partial order among solutions, and the output of the algorithm becomes a set of nondominated solutions rather than a single one. Various ant colony optimization (ACO) algorithms have been proposed in recent years for solving such problems. These multi-objective ACO (MOACO) algorithms exhibit different design choices for dealing with the particularities of the multi-objective context.

This paper proposes a classification of algorithmic components that suffices to describe most MOACO algorithms proposed so far. This classification also shows that existing MOACO algorithms often share equivalent design choices but they are described in different terms. Moreover, this classification is synthesised into a flexible algorithmic framework, from which not only existing MOACO algorithms may be instantiated, but also combinations of components that were never studied in the literature. In this sense, this paper goes beyond proposing a new MOACO algorithm, but it rather introduces a family of MOACO algorithms. Using this framework, this paper empirically compares existing MOACO algorithms, and possible variants, without the bias introduced by different implementations or different underlying ACO algorithms.

The flexibility of the proposed MOACO framework facilitates the application of automatic algorithm configuration techniques. The experimental results presented in this paper show that the automatically configured MOACO framework outperforms the MOACO algorithms that inspired the framework itself. To the best of our knowledge, this paper is also among the first to apply automatic algorithm configuration techniques to multi-objective algorithms.

Keywords: Multiobjective Optimization, Ant Colony Optimization, Travelling Salesman Problem, Automatic Configuration

1 Supplementary material

1.1 Configuring the multi-objective components of the MOACO framework

Table 1: Configurations obtained by five independent tuner runs, when configuring the multi-objective components of the proposed MOACO framework according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
$[\tau]$	single	multiple	multiple	multiple	multiple
$[\eta]$	multiple	multiple	multiple	multiple	multiple
Aggregation	w. product	w. product	w. product	w. product	w. product
N^{weights}	$N^{\text{a}}/3$	3	$N^{\text{a}}/2$	$N^{\text{a}}/3$	2
NextWeight	1wpi	1wpi	1wpi	1wpi	1wpi
PheromoneUpdate	ND	BO	BO	BO	BO
N^{upd}	1	2	2	2	1
N^{col}	10	5	10	10	10
MultiColonyWeights	disjoint	overlap	disjoint	overlap	overlap
MultiColonyUpdate	region	region	region	region	region

Table 2: Configurations obtained by five independent tuner runs, when configuring the multi-objective components of the proposed MOACO framework according to the epsilon measure.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
$[\tau]$	multiple	single	multiple	multiple	multiple
$[\eta]$	multiple	multiple	multiple	multiple	multiple
Aggregation	w. product	w. product	w. product	w. product	w. product
N^{weights}	2	$N^{\text{a}}/3$	$N^{\text{a}}/2$	N^{a}	N^{a}
NextWeight	awpi	1wpi	1wpi	1wpi	1wpi
PheromoneUpdate	BO	ND	BO	BO	BO
N^{upd}	1	1	2	2	2
N^{col}	10	10	5	10	10
MultiColonyWeights	overlap	overlap	overlap	overlap	overlap
MultiColonyUpdate	region	region	region	region	region

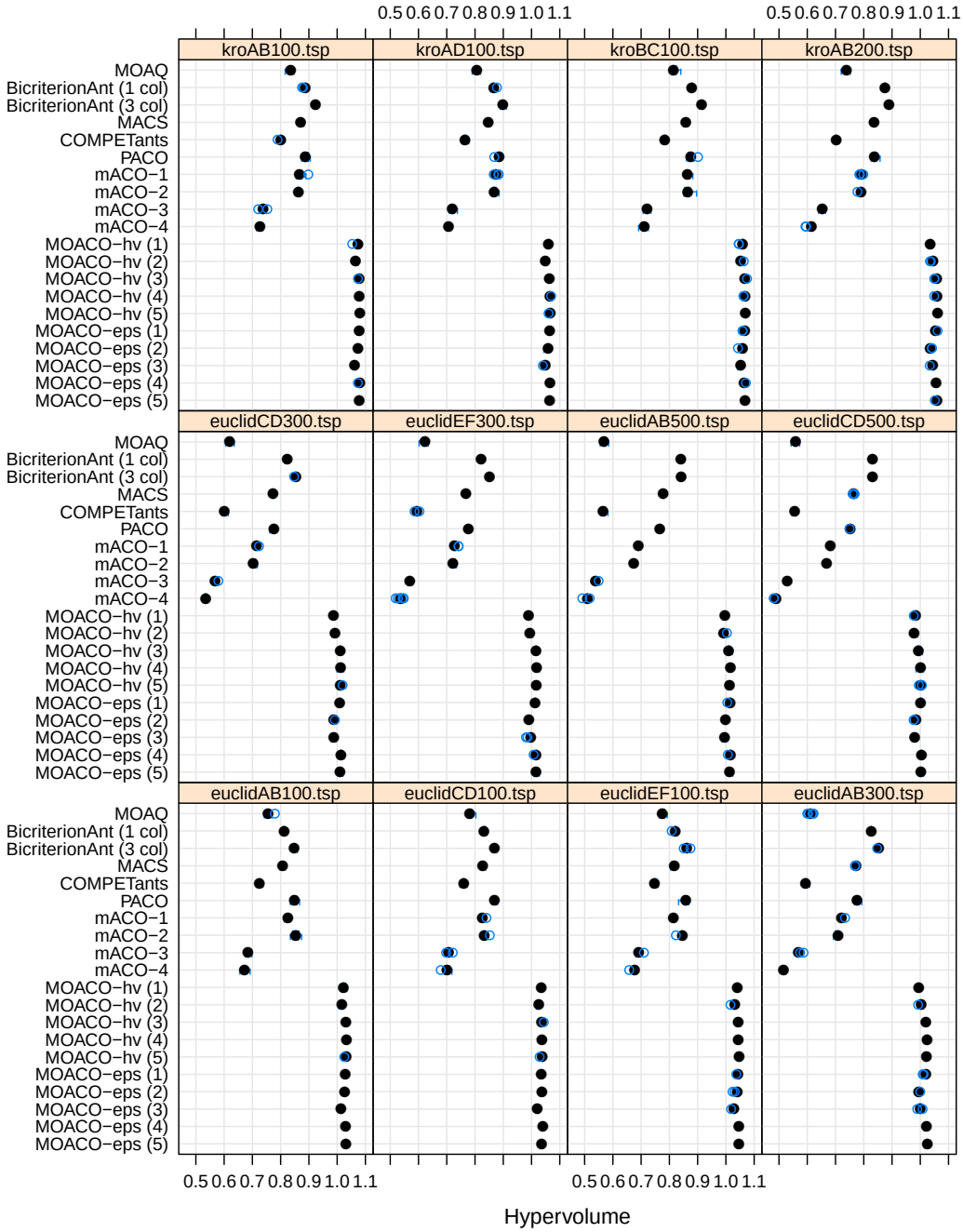

Figure 1: Boxplot of the hypervolume (larger is better) of 15 repetitions of each configuration of the MOACO framework on the test instances. The configurations from the literature are MOAQ, BicriterionAnt with 1 and 3 colonies, COMPETants, PACO, MACS, and the four variants of mACO. . MOACO-hv (1,2,3,4,5) and MOACO-eps (1,2,3,4,5) denote configurations found by five independent automatic configuration runs using hypervolume and epsilon measure, respectively, as evaluation criterion.

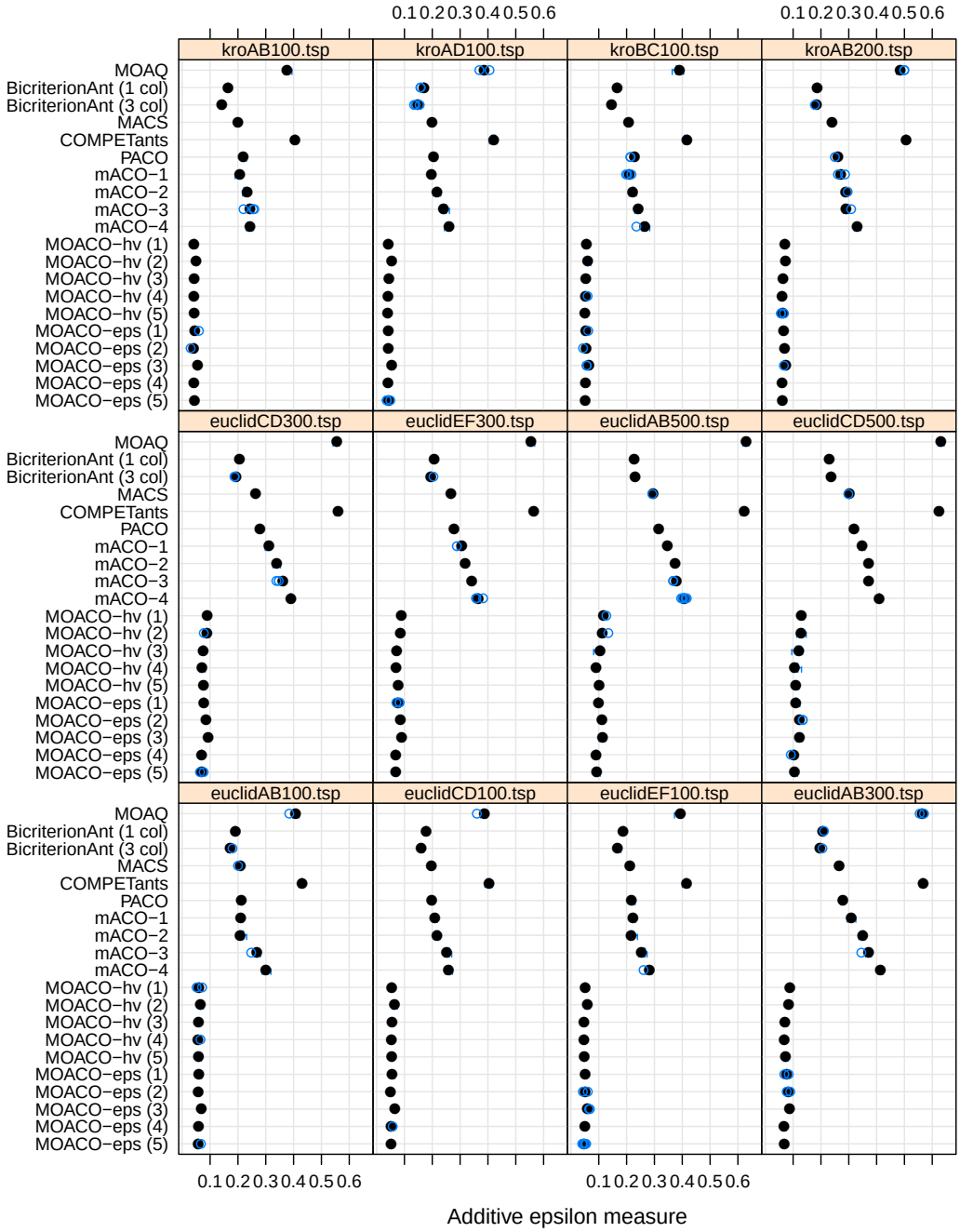

Figure 2: Boxplot of the epsilon measure (lower is better) of 15 repetitions of each configuration of the MOACO framework on the test instances. The configurations from the literature are MOAQ, BicriterionAnt with 1 and 3 colonies, COMPETants, PACO, MACS, and the four variants of mACO. MOACO-hv (1,2,3,4,5) and MOACO-eps (1,2,3,4,5) denote configurations found by five independent automatic configuration runs using hypervolume and epsilon measure, respectively, as evaluation criterion.

1.2 Configuring the ACO parameter settings of the MOACO framework

Table 3: Configurations obtained by configuring the ACO parameter settings of the MOACO framework according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
a_f	18	19	19	11	12
ρ	0.54	0.53	0.56	0.92	0.67
q_0	0.69	0.71	0.77	0.00	0.91
α	1.59	1.71	1.46	1.97	0.96
β	2.44	4.14	3.64	4.92	2.21

Table 4: Configurations obtained by configuring the ACO parameter settings of the MOACO framework according to the epsilon measure.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
a_f	24	23	16	23	13
ρ	0.82	0.52	0.39	0.46	0.93
q_0	0.89	0.54	0.88	0.65	0.70
α	1.04	1.98	1.63	1.22	1.56
β	2.79	4.46	3.57	2.65	3.95

Table 5: Configurations obtained by configuring the ACO parameter settings of BicriterionAnt (3 colonies) according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
a_f	18	10	14	4	8
ρ	0.98	0.99	0.82	0.87	0.94
q_0	0.99	0.92	0.91	0.98	0.94
α	3.68	2.38	1.75	4.93	2.7
β	3.1	2.94	4.95	2.23	2.26

Table 6: Configurations obtained by configuring the ACO parameter settings of BicriterionAnt (3 colonies) according to the epsilon measure

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
a_f	6	10	10	8	11
ρ	0.96	0.91	0.79	0.68	0.95
q_0	0.89	0.95	0.92	0.9	0.93
α	4.4	1.72	2.16	1.65	1.25
β	3.64	4.92	4.53	4.82	3.97

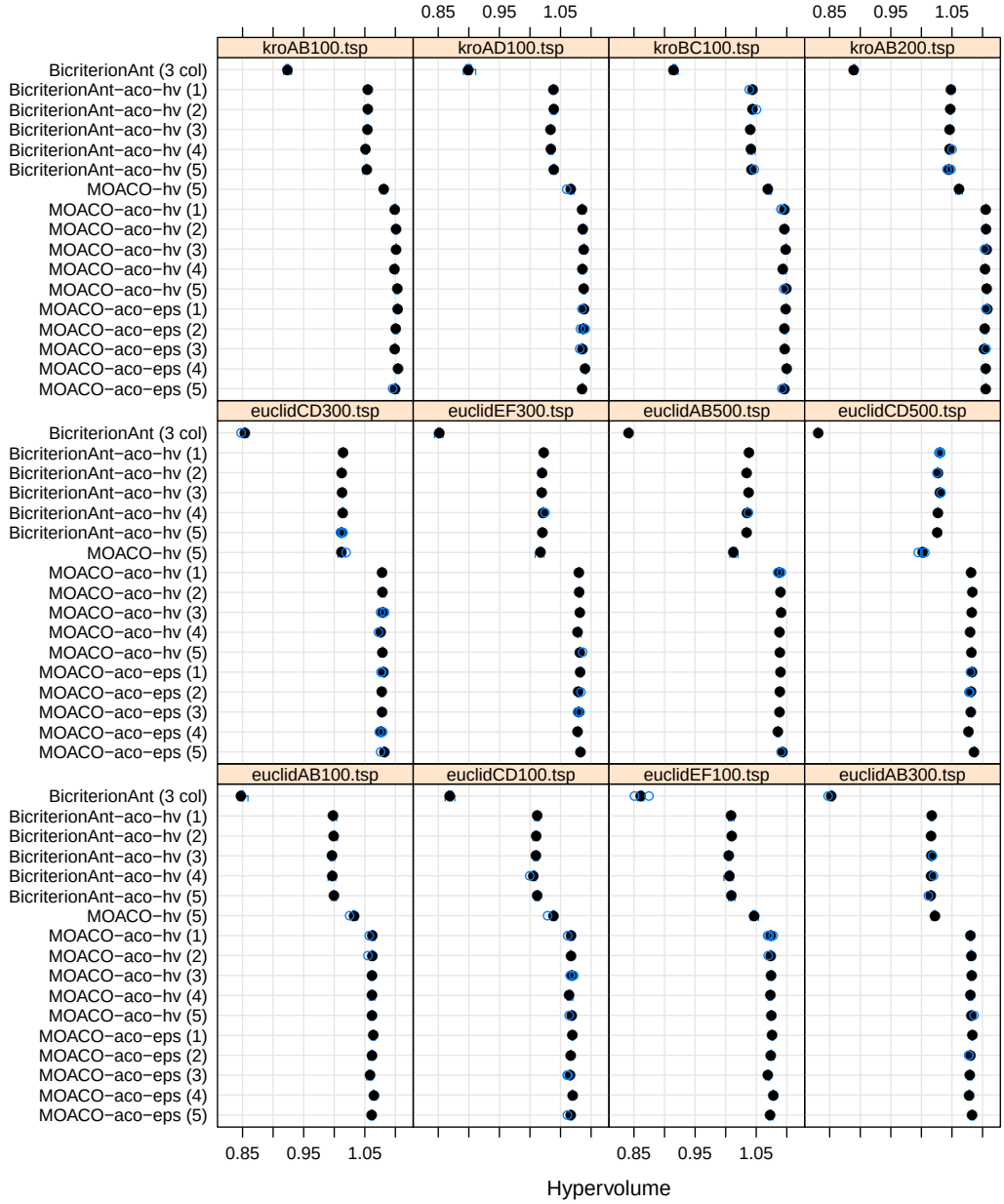

Figure 3: Boxplot of the hypervolume (larger is better) of 15 repetitions of each configuration of the MOACO framework on the test instances. BicriterionAnt (3 col) denotes BicriterionAnt with 3 colonies and default ACO algorithm settings; BicriterionAnt-aco-hv (1,2,3,4,5) denote the same configuration but with automatically configured ACO settings (five independent configuration runs); MOACO-hv (5) denotes the fifth configuration obtained when configuring the multi-objective components with default ACO algorithm settings; MOACO-aco-{hv,eps} (1,2,3,4,5) denote the same configuration but with automatically configured ACO settings (five independent configuration runs). The suffixes -hv and -eps denote that the configuration tool used, respectively, the hypervolume and the epsilon measure as the evaluation criterion.

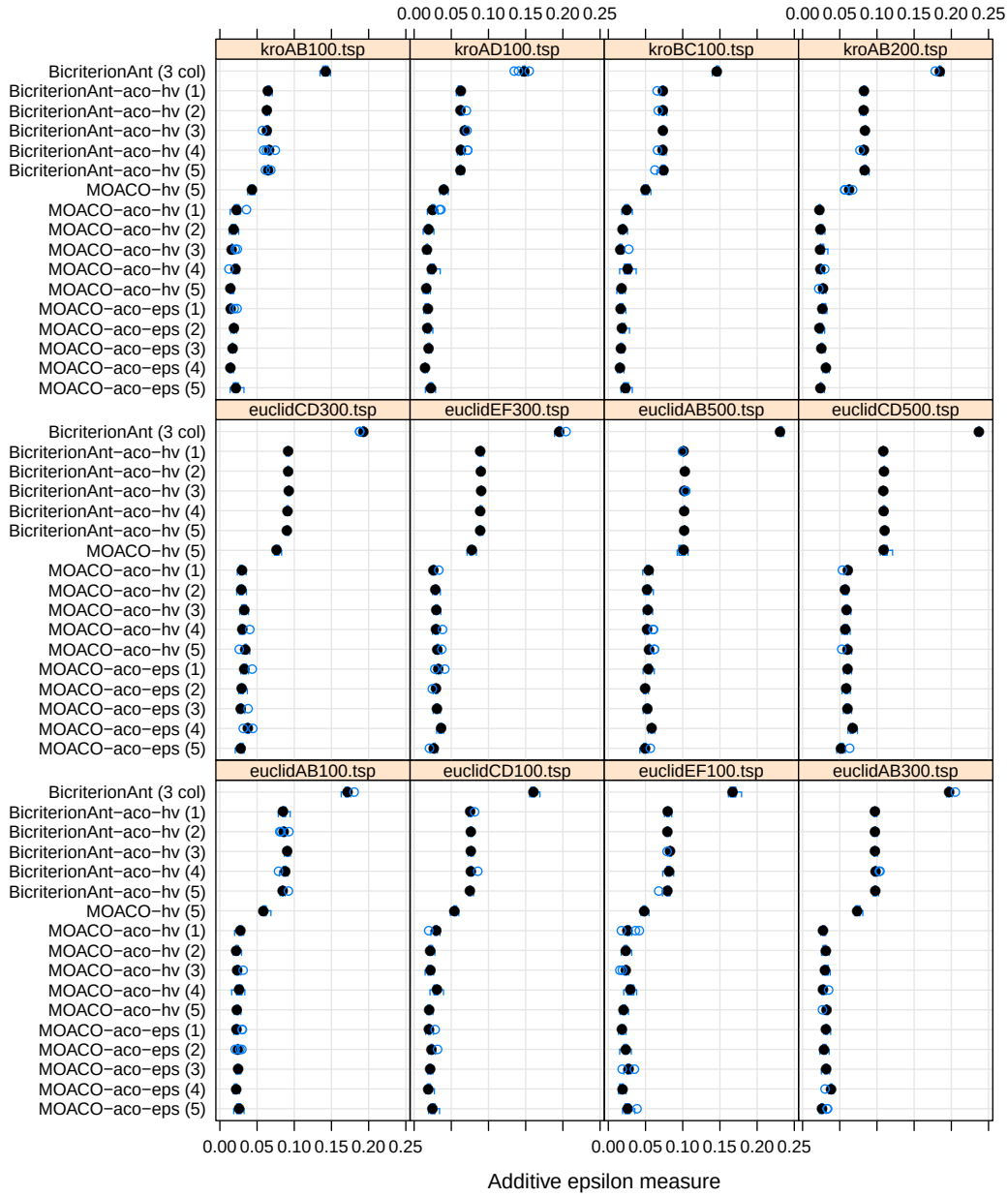

Figure 4: Boxplot of the epsilon measure (lower is better) of 15 repetitions of each configuration of the MOACO framework on the test instances. BicriterionAnt (3 col) denotes BicriterionAnt with 3 colonies and default ACO algorithm settings; BicriterionAnt-aco-hv (1,2,3,4,5) denote the same configuration but with automatically configured ACO settings (five independent configuration runs); MOACO-hv (5) denotes the fifth configuration obtained when configuring the multi-objective components with default ACO algorithm settings; MOACO-aco-{hv,eps} (1,2,3,4,5) denote the same configuration but with automatically configured ACO settings (five independent configuration runs). The suffixes -hv and -eps denote that the configuration tool used, respectively, the hypervolume and the epsilon measure as the evaluation criterion.

Table 7: Configurations obtained by configuring all parameters of the proposed MOACO framework according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
$[\tau]$	single	multiple	single	multiple	single
$[\eta]$	multiple	multiple	multiple	multiple	multiple
Aggregation	product	product	product	product	product
N^{weights}	N^{a}	N^{a}	2	2	2
NextWeight	1wpi	1wpi	1wpi	1wpi	1wpi
PheromoneUpdate	ND	ND	ND	BO	ND
N^{upd}	1	1	1	5	1
N^{col}	10	10	10	10	10
MultiColonyWeights	disjoint	overlapping	overlapping	overlapping	overlapping
MultiColonyUpdate	region	region	region	region	region
a	20	10	10	20	17
ρ	0.54	0.39	0.3	0.88	0.4
q_0	0.00	0.86	0.85	0.28	0.92
α	3.14	2.07	3.62	2.24	1.43
β	4.73	0.56	1.73	4.1	0.26

Table 8: Configurations obtained by configuring all parameters of the proposed MOACO framework according to the epsilon measure.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
$[\tau]$	multiple	single	multiple	single	single
$[\eta]$	multiple	multiple	multiple	multiple	multiple
Aggregation	product	product	product	product	product
N^{weights}	2	N^{a}	N^{a}	N^{a}	$N^{\text{a}}/3$
NextWeight	awpi	1wpi	1wpi	1wpi	1wpi
PheromoneUpdate	BO	ND	ND	ND	ND
N^{upd}	2	1	1	1	1
N^{col}	10	10	5	10	10
MultiColonyWeights	overlapping	disjoint	disjoint	overlapping	disjoint
MultiColonyUpdate	region	region	region	region	region
a	20	12	10	15	14
ρ	0.27	0.28	0.32	0.43	0.36
q_0	0.00	0.94	0.89	0.95	0.65
α	2.78	3.23	2.33	4.95	4.99
β	5	0.65	0.9	1.31	2.37

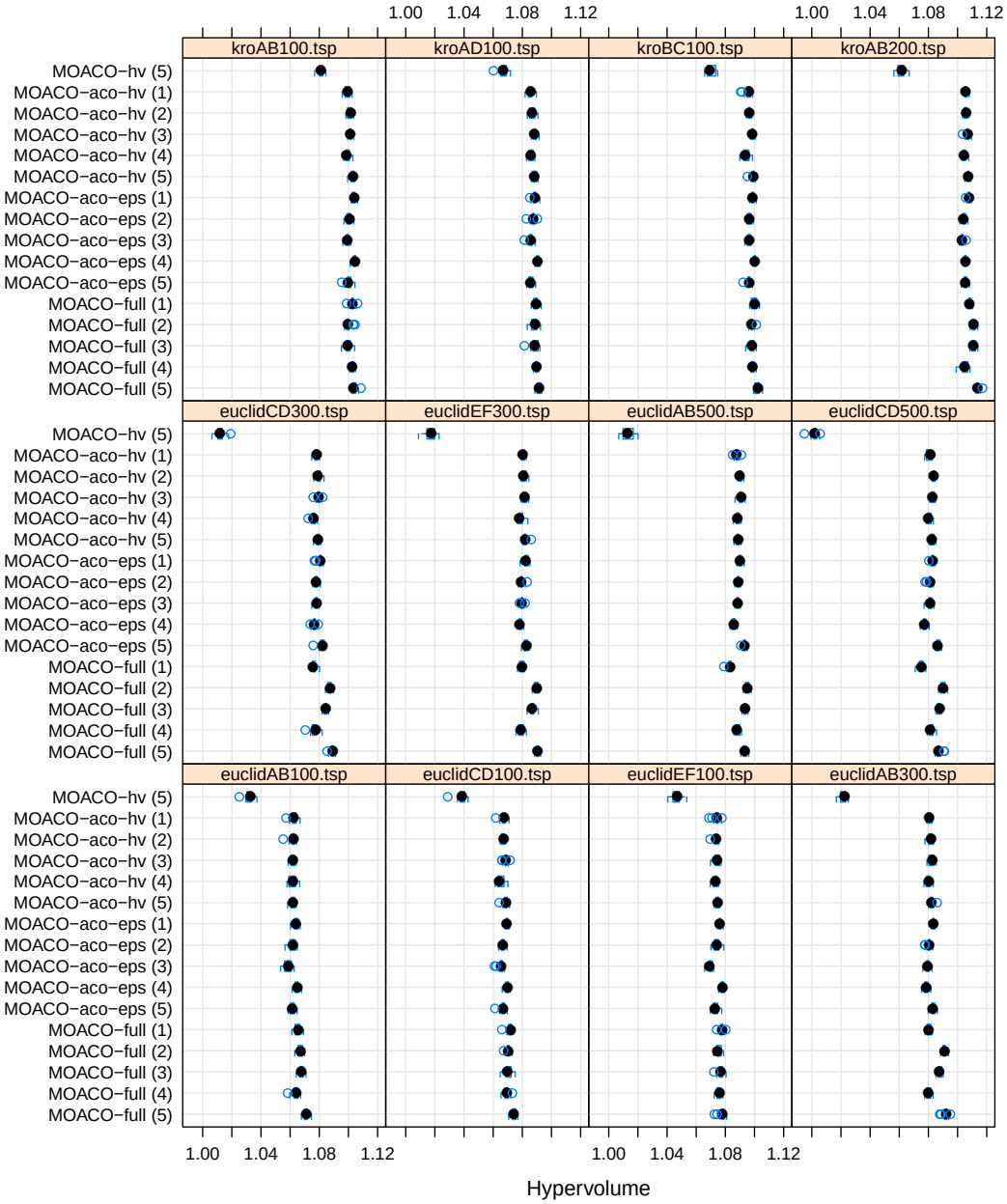

Figure 5: Boxplot of the hypervolume (larger is better) of 15 repetitions of each configuration of the MOACO framework on the test instances. MOACO-hv (5) denotes the fifth configuration obtained when configuring the multi-objective components with default ACO settings; MOACO-aco-{hv,eps} (1,2,3,4,5) denote the same configuration but with automatically configured ACO settings (five independent configuration runs); and MOACO-full (1,2,3,4,5) denote five configurations obtained by automatically configuring all parameter settings. The suffixes -hv and -eps denote that the configuration tool used, respectively, the hypervolume and the epsilon measure as the evaluation criterion.

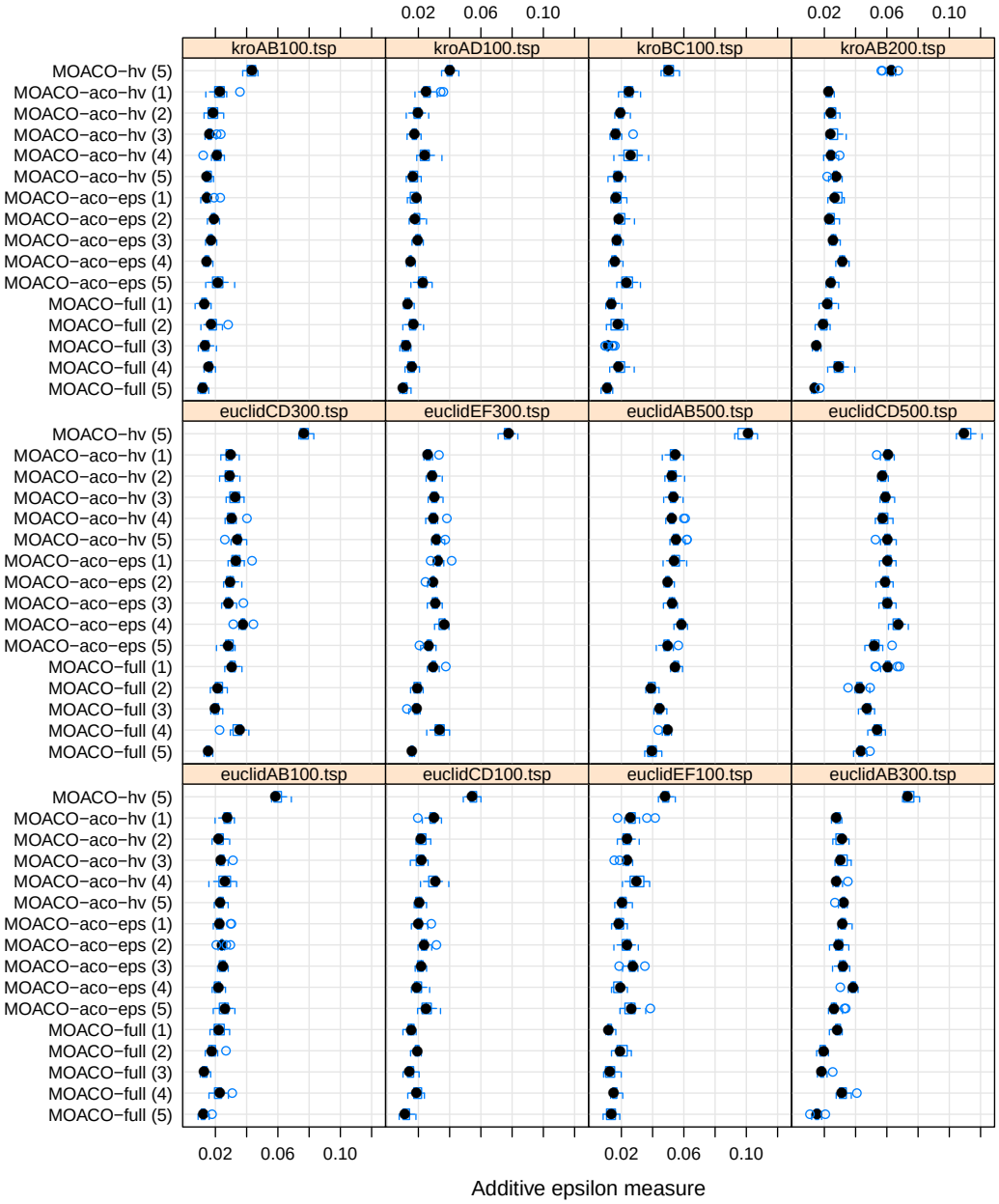

Figure 6: Boxplot of the epsilon measure (lower is better) of 15 repetitions of each configuration of the MOACO framework on the test instances. MOACO-hv (5) denotes the fifth configuration obtained when configuring the multi-objective components with default ACO settings; MOACO-aco-{hv,eps} (1,2,3,4,5) denote the same configuration but with automatically configured ACO settings (five independent configuration runs); and MOACO-full (1,2,3,4,5) denote five configurations obtained by automatically configuring all parameter settings. The suffixes -hv and -eps denote that the configuration tool used, respectively, the hypervolume and the epsilon measure as the evaluation criterion.

1.3 Configuring MOACO+ls

Table 9: Configurations obtained by configuring the multi-objective components of the proposed MOACO+ls framework according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
$[\tau]$	multiple	multiple	multiple	single	multiple
$[\eta]$	multiple	multiple	multiple	single	multiple
Aggregation	product	product	product	—	product
N^{weights}	$N^{\text{a}}/2$	$N^{\text{a}}/2$	N^{a}	N^{a}	N^{a}
NextWeight	1wpi	1wpi	1wpi	1wpi	1wpi
PheromoneUpdate	BO	BO	BO	ND	BO
N^{upd}	1	1	2	1	5
N^{col}	10	10	10	10	10
MultiColonyWeights	disjoint	disjoint	disjoint	disjoint	disjoint
MultiColonyUpdate	origin	origin	origin	origin	origin

Table 10: Configurations obtained by configuring the ACO parameter settings of the MOACO+ls framework according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
a_f	20	18	21	23	24
ρ	0.42	0.67	0.69	0.9	0.79
q_0	0.00	0.00	0.00	0.55	0.39
α	4.84	3.61	4.92	4.91	3.86
β	0.18	0.5	1.58	0.28	1.35

Table 11: Configurations obtained by configuring all parameters of the proposed MOACO+ls framework according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
$[\tau]$	single	multiple	multiple	multiple	multiple
$[\eta]$	multiple	single	multiple	multiple	single
Aggregation	product	product	sum	sum	sum
N^{weights}	N^{a}	$N^{\text{a}}/2$	$N^{\text{a}}/3$	$N^{\text{a}}/3$	$N^{\text{a}}/3$
NextWeight	1wpi	1wpi	1wpi	1wpi	1wpi
PheromoneUpdate	ND	BO	ND	BO	BO
N^{upd}	10	10	10	10	10
N^{col}	10	10	10	10	10
MultiColonyWeights	overlapping	overlapping	overlapping	overlapping	overlapping
MultiColonyUpdate	origin	origin	origin	origin	region
a_f	23	24	24	22	24
ρ	0.76	0.72	0.4	0.62	0.51
q_0	0.9	0.00	0.45	0.33	0.00
α	2.92	4.52	3.68	4.92	4.73
β	0.01	0.12	0.92	0.34	0.78

Table 12: Configurations obtained by configuring the ACO parameter settings of BicriterionAnt+ls (3 colonies) according to the hypervolume.

Component	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
a_f	14	25	17	20	23
ρ	0.72	0.52	0.37	0.98	0.7
q_0	0.61	0.00	0.35	0.45	0.53
α	3.84	4.95	4.35	4.22	3.68
β	0.15	0.21	0.38	0.11	0.04