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- Supplementary File •

Online Harmonizing Gradient Descent for Imbalanced Data Streams One-Pass Classification

Appendix A Theoretical Justification

(Update: May, 2024)

We have identified mistakes in the previous proof of Lemma 1 and will correct the proof promptly. However, our theoretical guarantee of sublinear regret for OHGD remains valid.

Appendix B Experimental Analysis

This section provides some details of experimental settings and results.

Appendix B.1 Settings

Twenty-four datasets from UCI repository and KEEL with different imbalance ratio were selected as the test rigs for performance evaluation. We compared our OHGD algorithms with various online learning algorithms for imbalanced data streams, including cost-sensitive online learning [1] (CSOGD), cost-sensitive online ensemble learning [2, 3] (onlineAdaC2, onlineCSB2, onlineUnderOverBagging, onlineRUSBoost, onlineEffectiveBagging) and resampling based online ensemble learning [4, 5] (onlineUnderBagging, onlineOverBagging, onlineWeightedUnderBagging, onlineWeightedOverBagging). Table.B1 summarizes the characteristics of different methods. Their parameters are set as the original works suggested. Note that, our method does not require any parameter settings for imbalance learning. As the purpose of the experiments is to make fair comparisons among different online algorithms, we chose OGD as the base learners of ensemble learning and the number of base learners M was set as 10. The learning rate η_t was set as $0.3/\sqrt{t}$.

Although our method focuses on one-pass data stream learning, we still compared it with some chunk based methods, including HDWE [6] and KNORAE2 [7]. The number of base learners M was set as 10 and other parameters were set as the original works suggested.

Appendix B.2 Parameter Sensitivity

Fig.C1-C24 illustrate the performance variation of algorithms under different parameter settings. Since none hyper-parameters is required in OHGD, its performance curves are horizontal lines. From these figures, it can be observed that OHGD is elegantly formulated without many hyper-parameters to tune, benefiting the easy implementation in practical applications.

Appendix B.3 Performance Comparison

Applying all algorithms for classifying all class imbalanced datasets in terms of AUC, G-mean and F1score, We reported the comparison results in Table.C1-C3. Summarizing the average ranks over all three performance metrics, we found that OHGD significantly outperforms other competitors in terms of each performance measure. Similar observations also can be found in the comparisons with the chunk-based methods (Table.C4-C6).

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Table B1 The descriptions of one-pass methods and their parameter settings.

Methods	Strategy	Classifier Type	Approaches for Imbalance	Parameter
CSOGD	Cost _I	Single	Cost-Sensitive	$c_p = 0.95, c_n = 0.05$
	Cost _{II}			$n_p = 0.5, n_n = 0.5$
	Sum _I		Under-Sampling	
	Sum _{II}			
onlineUnderBagging	—	Ensemble	Under-Sampling	$M = 10, \eta = 0.9$
onlineWeightedUnderBagging				
onlineOverBagging			Over-Sampling	
onlineWeightedOverBagging	—	Ensemble	Cost-Sensitive Hybrid-Resampling	$M = 10, c_p = 1, c_n = 0.8$
onlineAdaC2				
onlineCBS2			Hybrid-Resampling	
onlineRUSBoost	1	Ensemble	Cost-Sensitive Hybrid-Resampling	$M = 10, R = 0.7$
	2			
	3		Hybrid-Resampling	
onlineUnderOverBagging	—	Ensemble	Cost-Sensitive Hybrid-Resampling	$M = 10, R = IR$
onlineEffectiveBagging	—			
OHGD	—	Single	Gradient Harmonizing	—

Table B2 The descriptions of chunk based methods and their parameter settings.

Methods	Strategy	Classifier Type	Approaches for Imbalance	Parameter
HDWE	-	Ensemble	Hellinger Distance	$M = 10$
KNORAE2	NON ROS	Ensemble	Over-Sampling & Classifier Selection	$L = 5, M = 10$

Appendix B.4 Regret Analysis

We proceed to analyze the theoretical performance of OHGD in this sub-section. Particularly, we present the *Average Accumulative Loss* to show the regret trends:

$$AvgLoss_t = \frac{\sum_{i=1}^t \mathcal{L}_t}{t} \quad (B1)$$

Figure.C25 illustrate the *AvgLoss* trends of OHGD on all the datasets. We observe that all the curves decrease rapidly and generally converge to a constant which show the agreements with our $O(\sqrt{T})$ regret convergence expectations in the Theorem.??.

Appendix C *

References

- 1 Jialei Wang, Peilin Zhao, and Steven CH Hoi. Cost-sensitive online classification. *IEEE Transactions on Knowledge and Data Engineering*, 26(10):2425–2438, 2013.
- 2 Boyu Wang and Joelle Pineau. Online bagging and boosting for imbalanced data streams. *IEEE Transactions on Knowledge and Data Engineering*, 28(12):3353–3366, 2016.
- 3 Hongle Du, Yan Zhang, Ke Gang, Lin Zhang, and Yeh-Cheng Chen. Online ensemble learning algorithm for imbalanced data stream. *Applied Soft Computing*, 107:107378, 2021.
- 4 Shuo Wang, Leandro L Minku, and Xin Yao. A learning framework for online class imbalance learning. In *2013 IEEE Symposium on Computational Intelligence and Ensemble Learning (CIEL)*, pages 36–45. IEEE, 2013.
- 5 Shuo Wang, Leandro L Minku, and Xin Yao. Resampling-based ensemble methods for online class imbalance learning. *IEEE Transactions on Knowledge and Data Engineering*, 27(5):1356–1368, 2014.
- 6 Joanna Grzyb, Jakub Klikowski, and Michał Woźniak. Hellinger distance weighted ensemble for imbalanced data stream classification. *Journal of Computational Science*, 51:101314, 2021.
- 7 Paweł Zyblewski, Robert Sabourin, and Michał Woźniak. Preprocessed dynamic classifier ensemble selection for highly imbalanced drifted data streams. *Information Fusion*, 66:138–154, 2021.

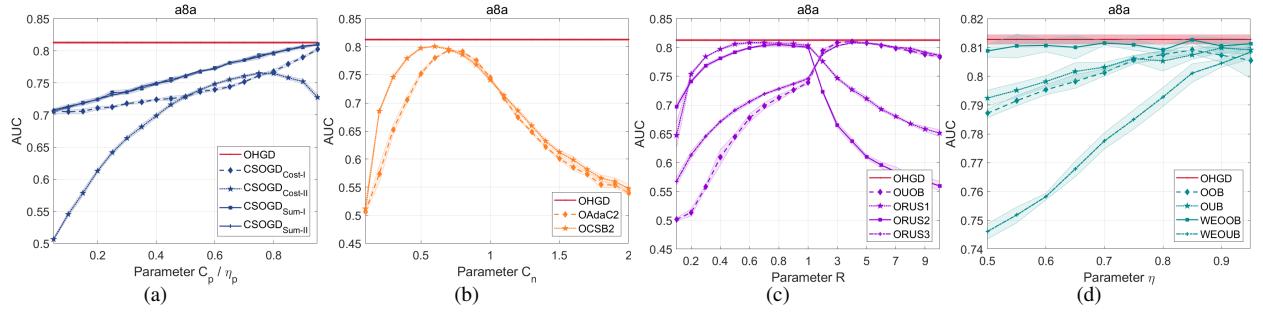


Figure C1 Performance evaluation with varying parameters on dataset a8a, in terms of AUC.

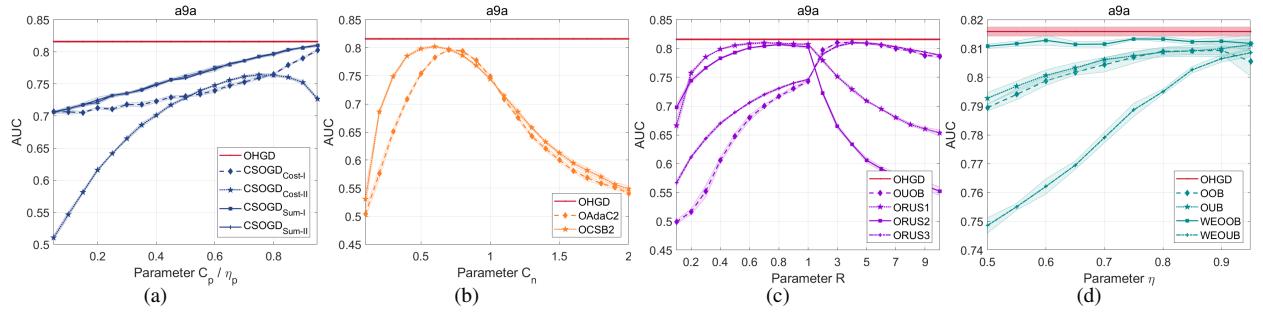


Figure C2 Performance evaluation with varying parameters on dataset a9a, in terms of AUC.

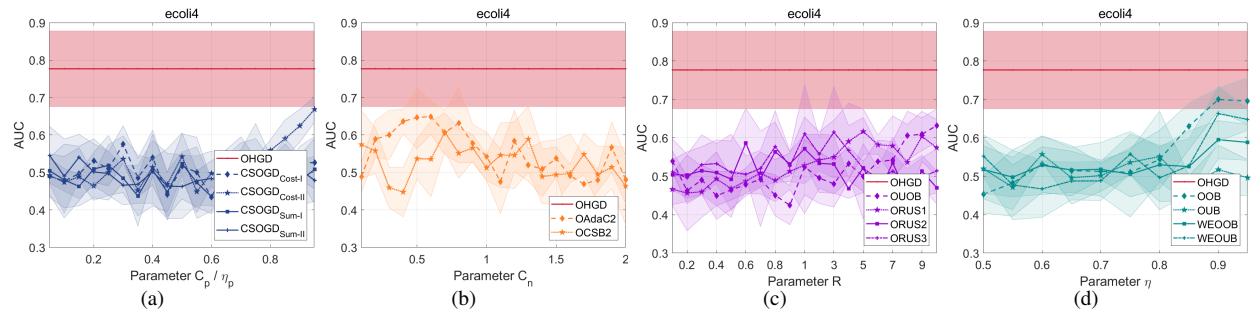


Figure C3 Performance evaluation with varying parameters on dataset ecoli4, in terms of AUC.

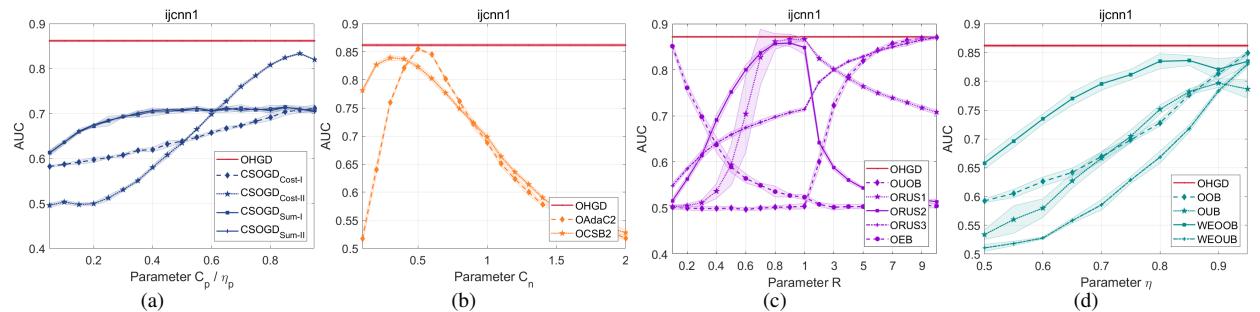


Figure C4 Performance evaluation with varying parameters on dataset ijcnn1, in terms of AUC.

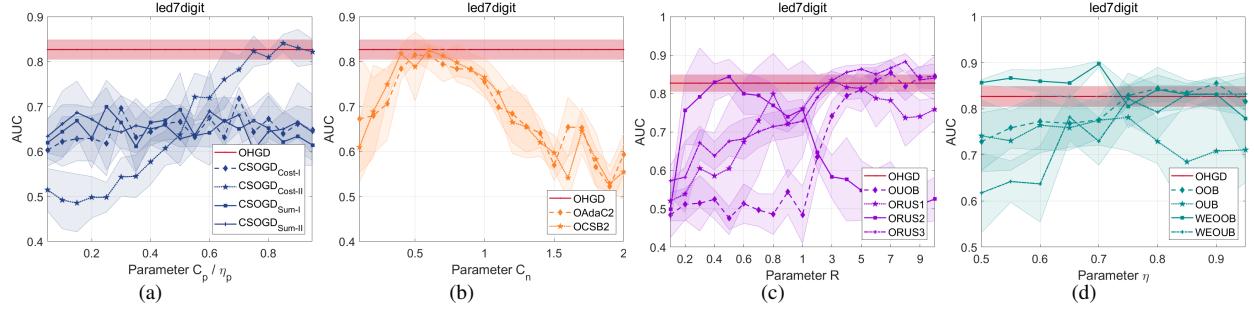


Figure C5 Performance evaluation with varying parameters on dataset led7digit, in terms of AUC.

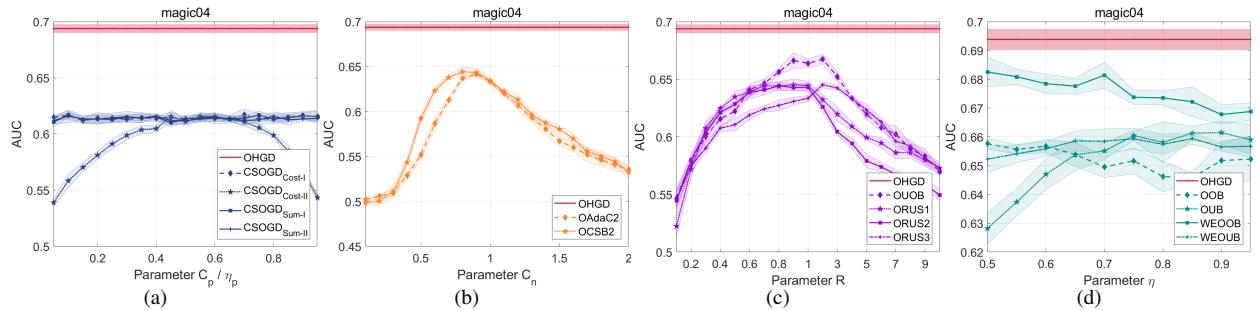


Figure C6 Performance evaluation with varying parameters on dataset magic04, in terms of AUC.

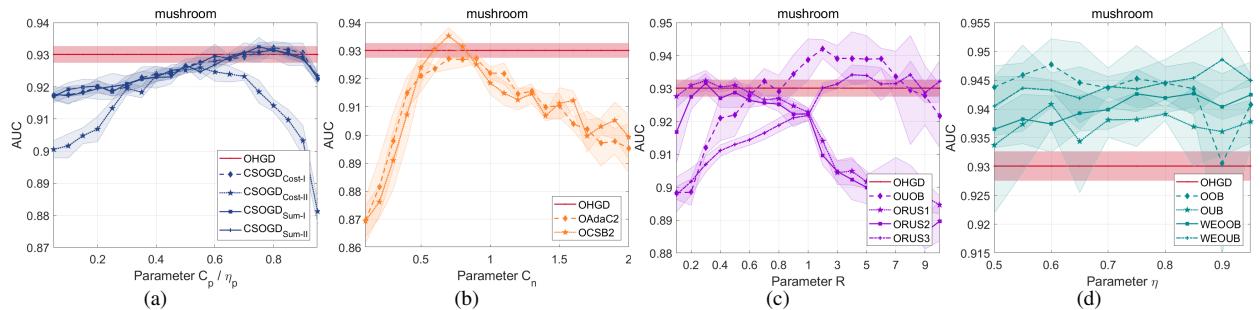


Figure C7 Performance evaluation with varying parameters on dataset mushroom, in terms of AUC.

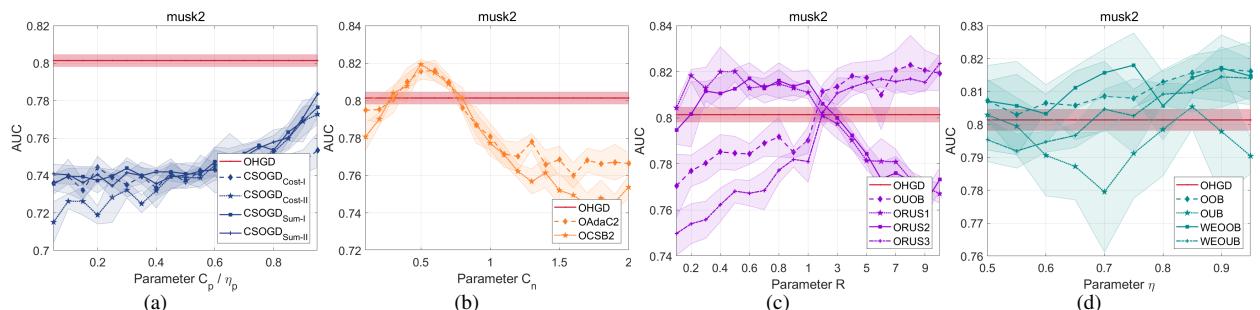


Figure C8 Performance evaluation with varying parameters on dataset musk2, in terms of AUC.

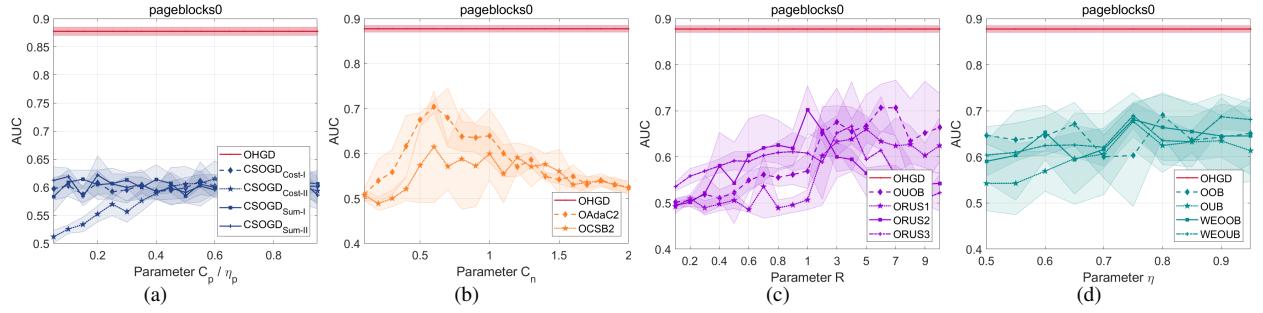


Figure C9 Performance evaluation with varying parameters on dataset pageblocks0, in terms of AUC.

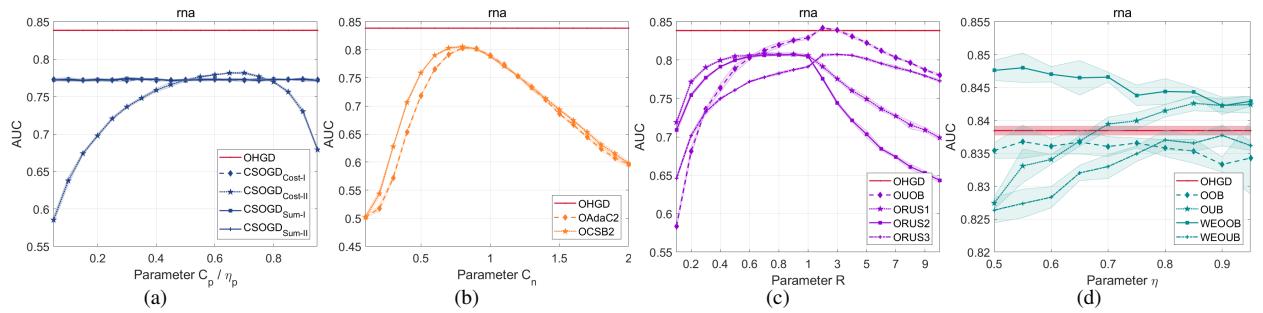


Figure C10 Performance evaluation with varying parameters on dataset rna, in terms of AUC.

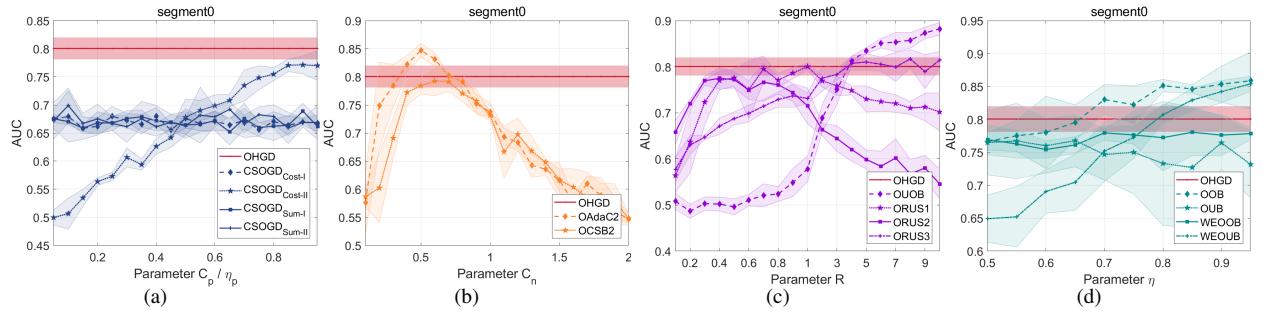


Figure C11 Performance evaluation with varying parameters on dataset segment0, in terms of AUC.

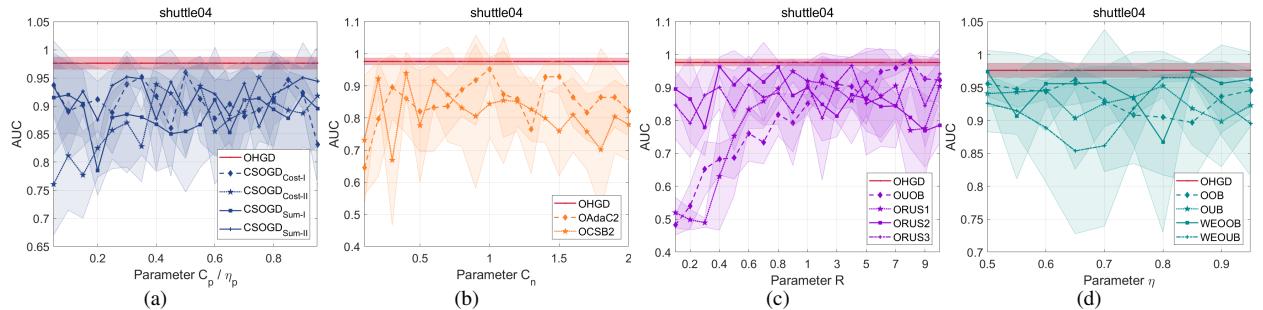


Figure C12 Performance evaluation with varying parameters on dataset shuttle04, in terms of AUC.

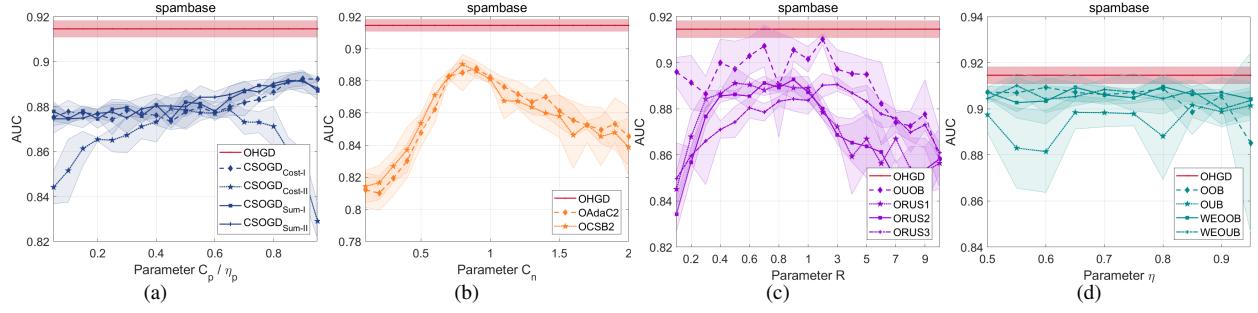


Figure C13 Performance evaluation with varying parameters on dataset spambase, in terms of AUC.

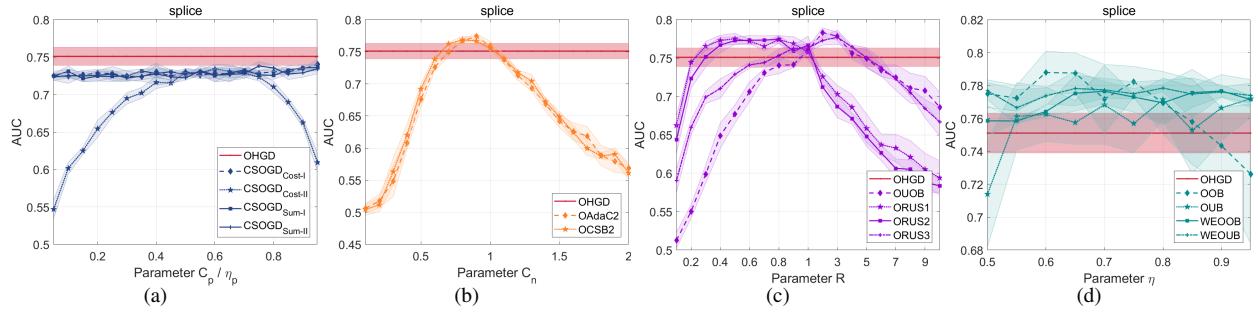


Figure C14 Performance evaluation with varying parameters on dataset splice, in terms of AUC.

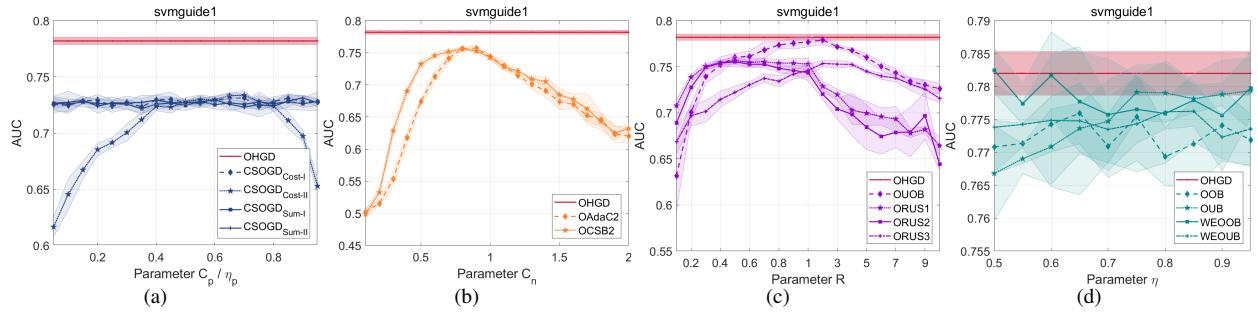


Figure C15 Performance evaluation with varying parameters on dataset svmguide1, in terms of AUC.

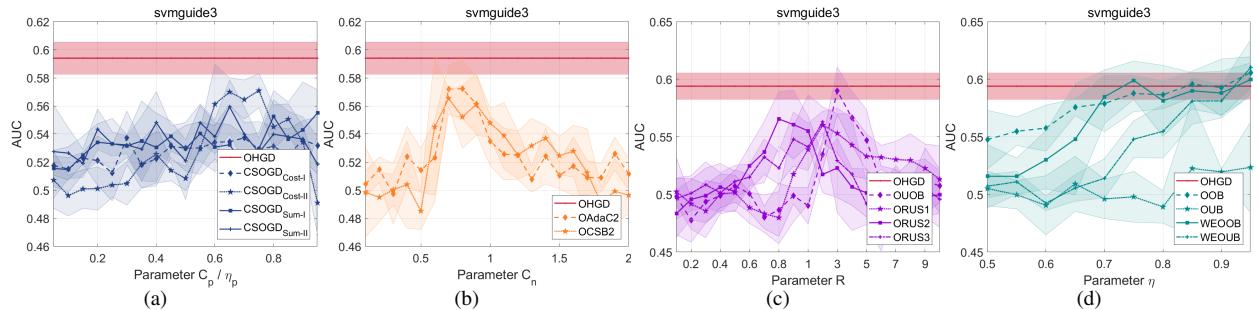


Figure C16 Performance evaluation with varying parameters on dataset svmguide3, in terms of AUC.

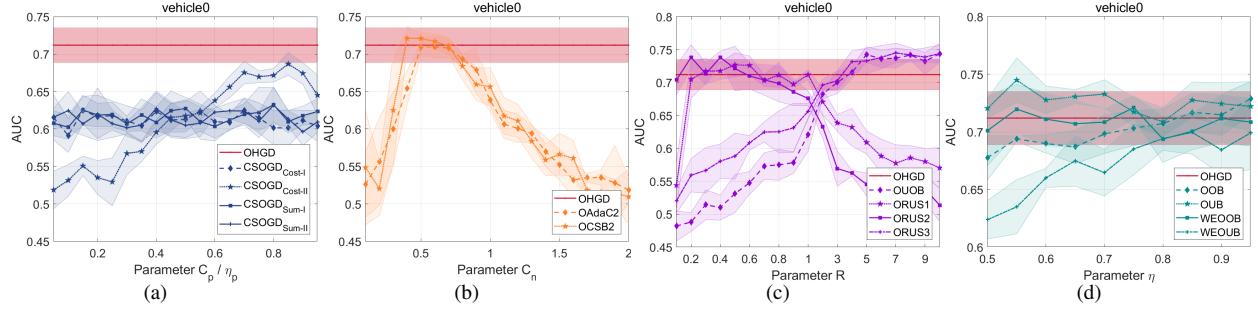


Figure C17 Performance evaluation with varying parameters on dataset vehicle0, in terms of AUC.

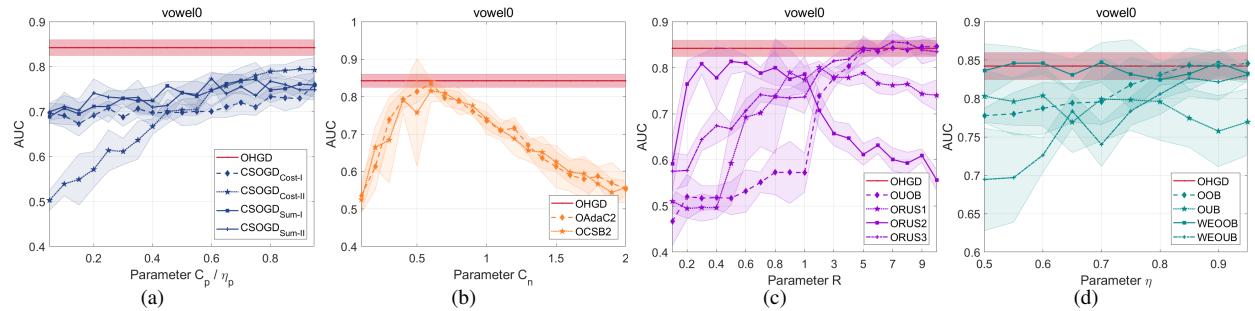


Figure C18 Performance evaluation with varying parameters on dataset vowel0, in terms of AUC.

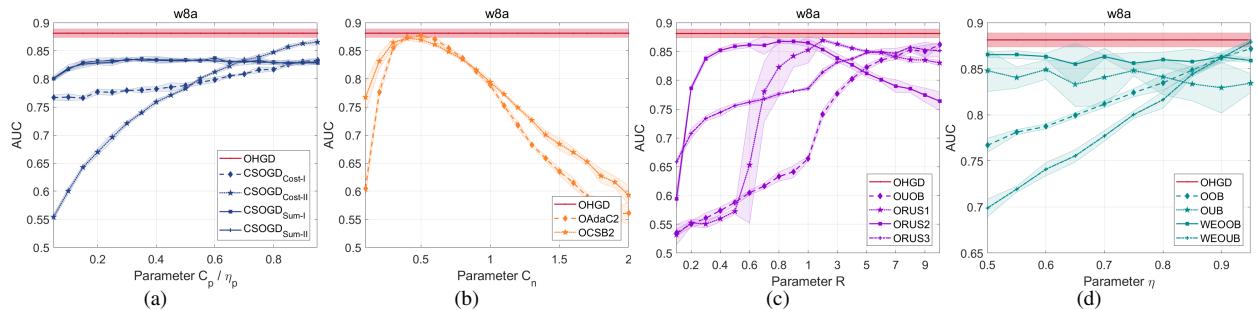


Figure C19 Performance evaluation with varying parameters on dataset w8a, in terms of AUC.

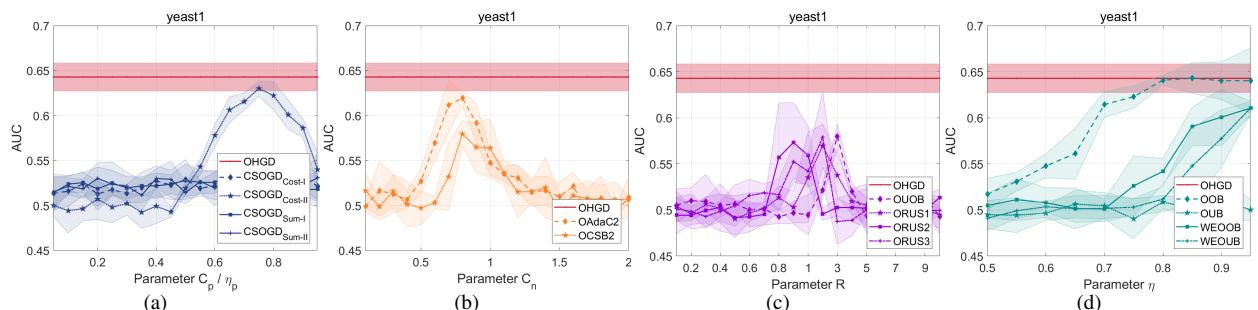


Figure C20 Performance evaluation with varying parameters on dataset yeast1, in terms of AUC.

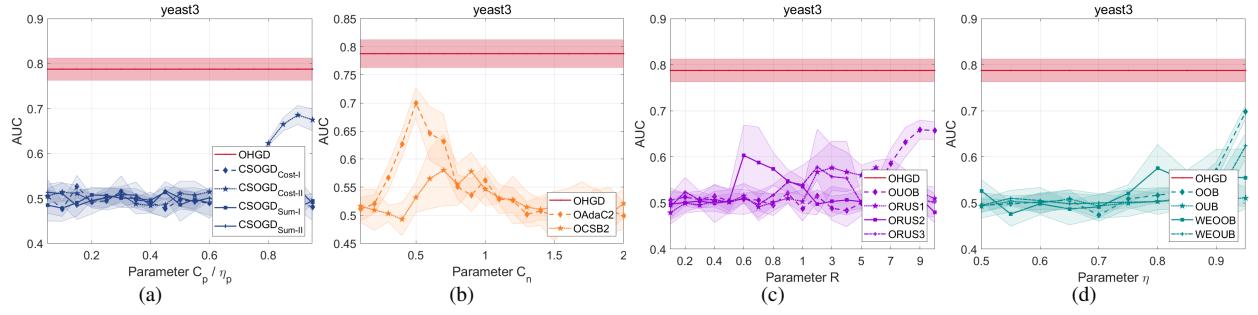


Figure C21 Performance evaluation with varying parameters on dataset yeast3, in terms of AUC.

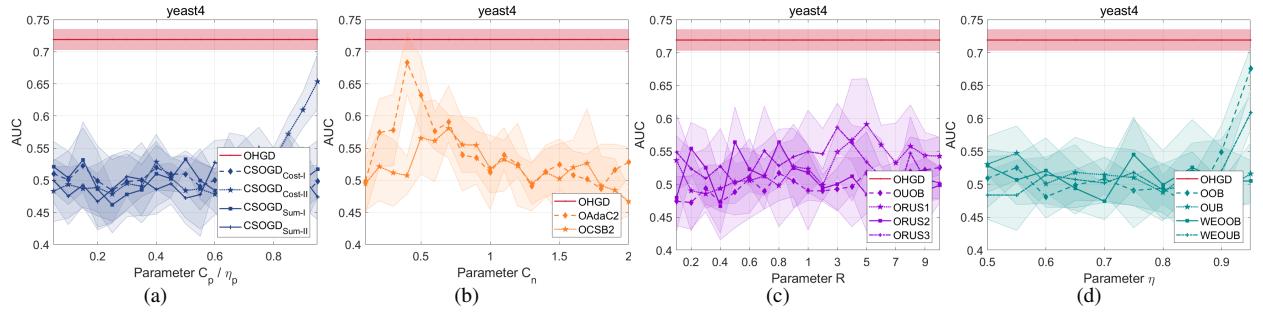


Figure C22 Performance evaluation with varying parameters on dataset yeast4, in terms of AUC.

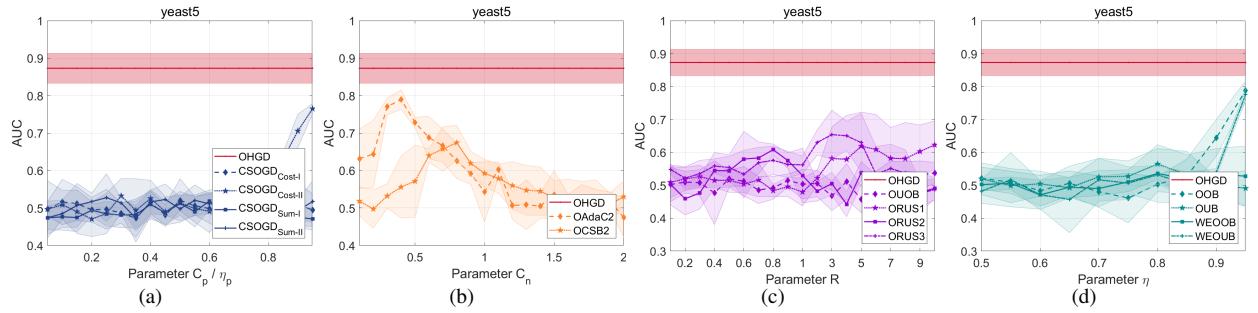


Figure C23 Performance evaluation with varying parameters on dataset yeast5, in terms of AUC.

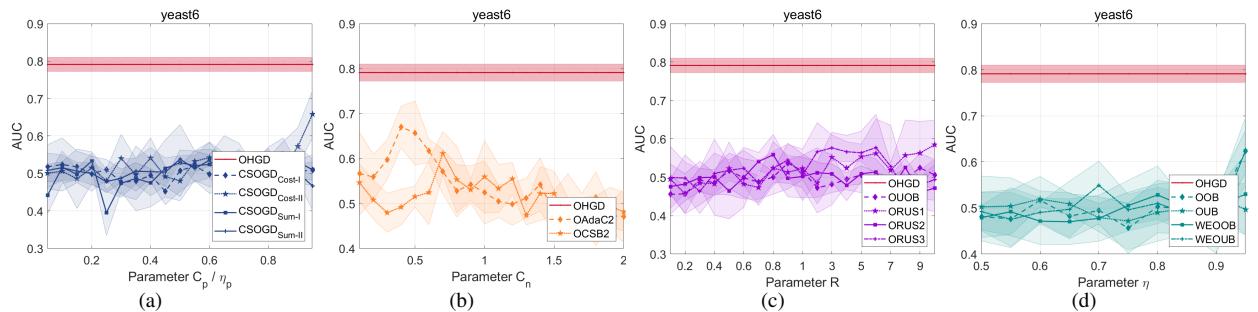


Figure C24 Performance evaluation with varying parameters on dataset yeast6, in terms of AUC.

Table C1 The results of different methods in terms of AUC.

AUC	OHGD	CSOGD				AdaC2	CSB2	UOB	RUSB			OOB	OUB	WOOB	WOUWB	OEB
		Cost _I	Cost _{II}	Sum _I	Sum _{II}				1	2	3					
a8a	0.816 ±0.003	0.791 ±0.002	0.737 ±0.002	0.782 ±0.002	0.805 ±0.002	0.802 ±0.002	0.814 ±0.002	0.812 ±0.003	0.814 ±0.005	0.805 ±0.001	0.815 ±0.001	0.814 ±0.002	0.798 ±0.003	0.808 ±0.002	0.81 ±0.003	0.807 ±0.004
a9a	0.815 ±0.002	0.797 ±0.001	0.735 ±0.002	0.786 ±0.002	0.804 ±0.001	0.803 ±0.002	0.815 ±0.001	0.814 ±0.002	0.815 ±0.002	0.806 ±0.001	0.816 ±0.002	0.815 ±0.001	0.801 ±0.002	0.81 ±0.003	0.811 ±0.001	0.809 ±0.002
ecoli4	0.791 ±0.094	0.505 ±0.059	0.612 ±0.062	0.498 ±0.056	0.636 ±0.047	0.543 ±0.084	0.568 ±0.042	0.667 ±0.036	0.498 ±0.056	0.568 ±0.099	0.482 ±0.056	0.544 ±0.035	0.471 ±0.042	0.479 ±0.063	0.573 ±0.081	0.536 ±0.006
ijcnn1	0.871 ±0.003	0.752 ±0.005	0.841 ±0.002	0.75 ±0.005	0.851 ±0.002	0.859 ±0.001	0.825 ±0.003	0.869 ±0.001	0.787 ±0.069	0.836 ±0.007	0.864 ±0.003	0.853 ±0.001	0.84 ±0.006	0.837 ±0.004	0.858 ±0.006	0.851 ±0.007
led7digit	0.834 ±0.038	0.533 ±0.046	0.83 ±0.02	0.548 ±0.058	0.841 ±0.034	0.806 ±0.036	0.816 ±0.016	0.838 ±0.029	0.5 ±0.064	0.802 ±0.031	0.695 ±0.129	0.85 ±0.029	0.685 ±0.098	0.822 ±0.029	0.856 ±0.036	0.732 ±0.088
magic	0.757 ±0.002	0.716 ±0.003	0.566 ±0.007	0.746 ±0.003	0.747 ±0.003	0.635 ±0.006	0.739 ±0.01	0.746 ±0.004	0.625 ±0.098	0.734 ±0.003	0.755 ±0.002	0.758 ±0.002	0.742 ±0.003	0.75 ±0.003	0.749 ±0.002	0.744 ±0.003
mushroom	0.931 ±0.002	0.889 ±0.002	0.888 ±0.005	0.937 ±0.002	0.937 ±0.002	0.923 ±0.006	0.919 ±0.003	0.899 ±0.007	0.93 ±0.002	0.928 ±0.002	0.931 ±0.003	0.929 ±0.004	0.918 ±0.011	0.921 ±0.007	0.903 ±0.005	0.911 ±0.006
musk2	0.798 ±0.007	0.769 ±0.006	0.796 ±0.007	0.784 ±0.008	0.813 ±0.004	0.823 ±0.006	0.78 ±0.005	0.783 ±0.006	0.75 ±0.012	0.758 ±0.007	0.769 ±0.009	0.794 ±0.005	0.709 ±0.012	0.791 ±0.008	0.711 ±0.009	0.709 ±0.008
pageblocks0	0.883 ±0.009	0.707 ±0.01	0.849 ±0.007	0.716 ±0.007	0.869 ±0.007	0.864 ±0.009	0.843 ±0.007	0.85 ±0.009	0.573 ±0.152	0.823 ±0.017	0.503 ±0.008	0.851 ±0.011	0.731 ±0.038	0.829 ±0.009	0.74 ±0.046	0.714 ±0.043
rna	0.91 ±0.003	0.816 ±0.001	0.866 ±0.002	0.907 ±0.001	0.922 ±0.001	0.902 ±0.002	0.504 ±0.003	0.822 ±0.004	0.501 ±0.002	0.879 ±0.003	0.862 ±0.003	0.897 ±0.003	0.692 ±0.011	0.84 ±0.003	0.81 ±0.003	0.800 ±0.006
segment0	0.97 ±0.011	0.752 ±0.009	0.939 ±0.008	0.752 ±0.013	0.962 ±0.012	0.947 ±0.012	0.918 ±0.012	0.927 ±0.015	0.554 ±0.061	0.835 ±0.056	0.869 ±0.02	0.958 ±0.008	0.791 ±0.032	0.945 ±0.005	0.845 ±0.011	0.834 ±0.049
shuttle04	0.982 ±0.007	0.877 ±0.011	0.982 ±0.005	0.874 ±0.018	0.971 ±0.008	0.967 ±0.005	0.965 ±0.012	0.98 ±0.006	0.693 ±0.22	0.94 ±0.035	0.904 ±0.036	0.976 ±0.007	0.873 ±0.043	0.968 ±0.01	0.932 ±0.028	0.886 ±0.048
spambase	0.911 ±0.004	0.892 ±0.003	0.825 ±0.006	0.915 ±0.003	0.915 ±0.004	0.879 ±0.006	0.895 ±0.005	0.906 ±0.003	0.91 ±0.003	0.905 ±0.003	0.911 ±0.003	0.906 ±0.009	0.899 ±0.006	0.911 ±0.004	0.906 ±0.005	0.905 ±0.004
splice	0.769 ±0.01	0.577 ±0.012	0.554 ±0.01	0.735 ±0.014	0.752 ±0.015	0.573 ±0.017	0.498 ±0.012	0.625 ±0.028	0.496 ±0.008	0.502 ±0.013	0.756 ±0.014	0.516 ±0.013	0.504 ±0.008	0.716 ±0.05	0.664 ±0.041	0.689 ±0.028
svmguide1	0.799 ±0.004	0.717 ±0.003	0.581 ±0.015	0.789 ±0.003	0.787 ±0.003	0.699 ±0.005	0.756 ±0.004	0.779 ±0.005	0.782 ±0.002	0.781 ±0.003	0.79 ±0.003	0.776 ±0.005	0.757 ±0.004	0.795 ±0.003	0.786 ±0.004	0.789 ±0.005
svmguide3	0.632 ±0.017	0.53 ±0.018	0.524 ±0.016	0.532 ±0.025	0.616 ±0.016	0.552 ±0.017	0.568 ±0.059	0.605 ±0.01	0.495 ±0.021	0.541 ±0.04	0.508 ±0.041	0.619 ±0.019	0.558 ±0.027	0.585 ±0.031	0.6 ±0.02	0.585 ±0.021
vehicle0	0.718 ±0.026	0.501 ±0.024	0.587 ±0.015	0.504 ±0.019	0.666 ±0.026	0.638 ±0.037	0.505 ±0.042	0.608 ±0.024	0.517 ±0.029	0.487 ±0.034	0.501 ±0.017	0.689 ±0.026	0.499 ±0.021	0.517 ±0.024	0.544 ±0.041	0.540 ±0.026
vowel0	0.863 ±0.02	0.56 ±0.034	0.839 ±0.011	0.565 ±0.028	0.835 ±0.024	0.834 ±0.017	0.806 ±0.027	0.84 ±0.019	0.674 ±0.122	0.805 ±0.021	0.805 ±0.052	0.837 ±0.013	0.667 ±0.038	0.822 ±0.03	0.823 ±0.016	0.518 ±0.062
w8a	0.901 ±0.003	0.78 ±0.005	0.894 ±0.002	0.779 ±0.004	0.891 ±0.001	0.89 ±0.003	0.87 ±0.002	0.899 ±0.002	0.709 ±0.164	0.891 ±0.001	0.894 ±0.004	0.873 ±0.005	0.849 ±0.011	0.867 ±0.005	0.888 ±0.004	0.873 ±0.012
yeast1	0.662 ±0.018	0.525 ±0.017	0.543 ±0.01	0.526 ±0.011	0.636 ±0.014	0.568 ±0.016	0.49 ±0.012	0.619 ±0.016	0.501 ±0.019	0.499 ±0.014	0.495 ±0.016	0.65 ±0.015	0.498 ±0.012	0.568 ±0.02	0.567 ±0.039	0.571 ±0.034
yeast3	0.743 ±0.024	0.513 ±0.027	0.657 ±0.012	0.498 ±0.023	0.683 ±0.022	0.646 ±0.058	0.527 ±0.054	0.614 ±0.028	0.484 ±0.036	0.569 ±0.056	0.512 ±0.028	0.522 ±0.02	0.524 ±0.021	0.493 ±0.016	0.516 ±0.039	0.515 ±0.037
yeast5	0.715 ±0.031	0.51 ±0.026	0.633 ±0.016	0.51 ±0.037	0.622 ±0.047	0.565 ±0.055	0.58 ±0.03	0.65 ±0.038	0.486 ±0.044	0.537 ±0.03	0.49 ±0.054	0.487 ±0.055	0.5 ±0.041	0.499 ±0.041	0.568 ±0.066	0.492 ±0.059
yeast6	0.856 ±0.048	0.502 ±0.036	0.743 ±0.038	0.512 ±0.056	0.753 ±0.04	0.654 ±0.048	0.621 ±0.092	0.785 ±0.048	0.509 ±0.041	0.546 ±0.051	0.524 ±0.044	0.511 ±0.046	0.493 ±0.03	0.499 ±0.041	0.593 ±0.056	0.527 ±0.034
yeast4	0.779 ±0.028	0.495 ±0.04	0.644 ±0.036	0.51 ±0.056	0.648 ±0.053	0.558 ±0.082	0.56 ±0.039	0.664 ±0.027	0.487 ±0.042	0.54 ±0.056	0.5 ±0.079	0.502 ±0.041	0.49 ±0.057	0.507 ±0.048	0.557 ±0.03	0.505 ±0.039

Table C2 The results of different methods in terms of GMEANS.

GMEANS	OHGD	CSOGD				AdaC2	CSB2	UOB	RUSB			OOB	OUB	WOOB	WOUWB	OEB			
		Cost _I	Cost _{II}	Sum _I	Sum _{II}				1	2	3								
									±0.002	±0.001	±0.003								
a8a		0.814 ±0.002	0.801 ±0.001	0.700 ±0.003	0.786 ±0.002	0.804 ±0.002	0.789 ±0.001	0.813 ±0.002	0.808 ±0.002	0.777 ±0.025	0.786 ±0.003	0.811 ±0.004	0.809 ±0.002	0.782 ±0.003	0.810 ±0.001	0.800 ±0.003	0.804 ±0.002		
a9a		0.815 ±0.001	0.803 ±0.001	0.699 ±0.002	0.787 ±0.002	0.803 ±0.001	0.789 ±0.002	0.814 ±0.001	0.810 ±0.001	0.794 ±0.018	0.790 ±0.002	0.811 ±0.002	0.811 ±0.001	0.786 ±0.004	0.811 ±0.001	0.802 ±0.002	0.805 ±0.002		
ecoli4		0.797 ±0.067	0.032 ±0.100	0.601 ±0.039	0.022 ±0.071	0.632 ±0.045	0.510 ±0.089	0.531 ±0.063	0.652 ±0.023	0.042 ±0.131	0.413 ±0.226	—	0.386 ±0.084	—	0.151 ±0.135	0.320 ±0.264	—		
ijcnn1		0.870 ±0.002	0.773 ±0.004	0.835 ±0.001	0.766 ±0.003	0.850 ±0.002	0.86 ±0.001	0.824 ±0.002	0.868 ±0.001	0.712 ±0.11	0.808 ±0.012	0.852 ±0.011	0.856 ±0.001	0.835 ±0.006	0.842 ±0.002	0.841 ±0.005	0.841 ±0.004		
led7digit		0.837 ±0.034	0.430 ±0.075	0.827 ±0.02	0.370 ±0.094	0.843 ±0.023	0.825 ±0.027	0.819 ±0.023	0.851 ±0.016	0.097 ±0.095	0.809 ±0.04	0.505 ±0.233	0.856 ±0.014	0.705 ±0.113	0.838 ±0.018	0.838 ±0.025	0.752 ±0.083		
magic		0.758 ±0.001	0.717 ±0.001	0.388 ±0.011	0.746 ±0.001	0.748 ±0.002	0.548 ±0.008	0.710 ±0.037	0.748 ±0.002	0.421 ±0.263	0.723 ±0.005	0.753 ±0.002	0.757 ±0.001	0.718 ±0.012	0.749 ±0.001	0.749 ±0.001	0.746 ±0.001		
mushroom		0.933 ±0.002	0.897 ±0.001	0.881 ±0.003	0.941 ±0.001	0.941 ±0.001	0.923 ±0.004	0.919 ±0.003	0.903 ±0.008	0.932 ±0.002	0.933 ±0.002	0.933 ±0.002	0.933 ±0.004	0.924 ±0.008	0.926 ±0.005	0.911 ±0.004	0.919 ±0.005		
musk2		0.778 ±0.007	0.767 ±0.003	0.775 ±0.004	0.781 ±0.005	0.792 ±0.003	0.804 ±0.004	0.768 ±0.005	0.765 ±0.006	0.743 ±0.019	0.753 ±0.012	0.761 ±0.015	0.775 ±0.005	0.695 ±0.017	0.775 ±0.003	0.705 ±0.013	0.707 ±0.0012		
pageblocks0		0.886 ±0.007	0.726 ±0.011	0.841 ±0.005	0.732 ±0.008	0.876 ±0.004	0.872 ±0.006	0.853 ±0.006	0.865 ±0.007	0.19 ±0.354	0.835 ±0.015	0.009 ±0.027	0.868 ±0.008	0.747 ±0.039	0.849 ±0.005	0.738 ±0.045	0.800 ±0.006		
rna		0.914 ±0.002	0.812 ±0.001	0.829 ±0.001	0.917 ±0.001	0.922 ±0.001	0.874 ±0.004	0.053 ±0.025	0.824 ±0.002	0.026 ±0.009	0.853 ±0.006	0.762 ±0.019	0.886 ±0.002	0.531 ±0.023	0.862 ±0.002	0.805 ±0.004	0.806 ±0.003		
segment0		0.964 ±0.011	0.832 ±0.007	0.907 ±0.007	0.834 ±0.01	0.957 ±0.005	0.941 ±0.009	0.927 ±0.01	0.911 ±0.012	0.242 ±0.166	0.809 ±0.088	0.755 ±0.025	0.946 ±0.008	0.801 ±0.017	0.949 ±0.007	0.806 ±0.026	0.826 ±0.019		
shuttle04		0.983 ±0.007	0.927 ±0.008	0.982 ±0.002	0.926 ±0.01	0.980 ±0.004	0.974 ±0.004	0.957 ±0.016	0.981 ±0.007	0.395 ±0.485	0.948 ±0.021	0.793 ±0.068	0.983 ±0.005	0.915 ±0.031	0.980 ±0.005	0.944 ±0.018	0.918 ±0.028		
spambase		0.911 ±0.003	0.897 ±0.001	0.814 ±0.005	0.914 ±0.002	0.914 ±0.002	0.873 ±0.004	0.892 ±0.004	0.907 ±0.002	0.91 ±0.003	0.906 ±0.003	0.912 ±0.003	0.905 ±0.009	0.901 ±0.003	0.91 ±0.003	0.905 ±0.004	0.906 ±0.003		
splice		0.768 ±0.009	0.507 ±0.022	0.283 ±0.017	0.746 ±0.005	0.75 ±0.003	0.353 ±0.039	0.012 ±0.037	0.597 ±0.067	0.044 ±0.036	0.027 ±0.027	0.753 ±0.006	0.305 ±0.14	0.281 ±0.134	0.717 ±0.026	0.643 ±0.024	0.633 ±0.024		
svmguide1		0.794 ±0.002	0.715 ±0.002	0.447 ±0.015	0.789 ±0.002	0.786 ±0.003	0.653 ±0.005	0.743 ±0.011	0.780 ±0.007	0.784 ±0.002	0.785 ±0.003	0.791 ±0.002	0.779 ±0.003	0.763 ±0.003	0.793 ±0.002	0.79 ±0.003	0.791 ±0.003		
svmguide3		0.631 ±0.015	0.266 ±0.024	0.305 ±0.039	0.282 ±0.021	0.617 ±0.014	0.44 ±0.035	0.445 ±0.245	0.603 ±0.005	0.059 ±0.093	0.464 ±0.116	0.161 ±0.195	0.62 ±0.013	0.518 ±0.066	0.519 ±0.043	0.587 ±0.022	0.572 ±0.049		
vehicle0		0.720 ±0.023	0.090 ±0.057	0.413 ±0.028	0.094 ±0.027	0.666 ±0.012	0.547 ±0.055	0.175 ±0.221	0.599 ±0.029	0.086 ±0.112	0.212 ±0.148	0.033 ±0.049	0.653 ±0.026	0.328 ±0.074	0.278 ±0.094	0.337 ±0.204	—		
vowel0		0.870 ±0.012	0.458 ±0.046	0.829 ±0.011	0.461 ±0.020	0.845 ±0.017	0.840 ±0.011	0.817 ±0.023	0.839 ±0.009	0.523 ±0.253	0.805 ±0.026	0.740 ±0.099	0.842 ±0.014	0.707 ±0.069	0.839 ±0.019	0.813 ±0.018	—		
w8a		0.903 ±0.002	0.798 ±0.004	0.897 ±0.002	0.797 ±0.003	0.892 ±0.002	0.895 ±0.001	0.877 ±0.002	0.902 ±0.001	0.584 ±0.274	0.897 ±0.002	0.887 ±0.013	0.884 ±0.004	0.865 ±0.008	0.879 ±0.003	0.891 ±0.009	0.879 ±0.009		
yeast1		0.663 ±0.014	0.342 ±0.027	0.311 ±0.028	0.332 ±0.03	0.637 ±0.011	0.381 ±0.048	0.084 ±0.079	0.603 ±0.03	0.031 ±0.051	0.174 ±0.158	0.008 ±0.024	0.574 ±0.016	0.224 ±0.049	0.461 ±0.049	0.388 ±0.154	0.531 ±0.102		
yeast3		0.747 ±0.019	0.027 ±0.044	0.591 ±0.019	—	0.681 ±0.013	0.612 ±0.062	0.292 ±0.229	0.607 ±0.029	0.034 ±0.072	0.475 ±0.212	—	0.327 ±0.068	0.527 ±0.048	0.090 ±0.042	0.283 ±0.191	—		
yeast5		0.717 ±0.029	0.014 ±0.044	0.642 ±0.022	—	0.626 ±0.021	0.480 ±0.072	0.503 ±0.035	0.651 ±0.029	0.004 ±0.012	0.38 ±0.107	—	—	0.014 ±0.044	—	0.412 ±0.189	—		
yeast6		0.872 ±0.031	—	0.76 ±0.029	—	0.761 ±0.025	0.658 ±0.043	0.547 ±0.223	0.789 ±0.024	—	0.391 ±0.202	—	0.122 ±0.092	—	—	0.452 ±0.219	—		
yeast4		0.778 ±0.029	—	0.645 ±0.044	—	0.664 ±0.039	0.485 ±0.103	0.502 ±0.036	0.675 ±0.014	—	0.461 ±0.082	—	—	—	—	0.281 ±0.223	—		

Table C3 The results of different methods in terms of F1 score.

F1	OHGD	CSOGD				AdaC2	CSB2	UOB	RUSB			OOB	OUB	WOOB	WOUWB	OEB
		Cost _I	Cost _{II}	Sum _I	Sum _{II}				1	2	3					
a8a	0.668 ±0.002	0.654 ±0.001	0.547 ±0.003	0.669 ±0.002	0.656 ±0.003	0.625 ±0.002	0.667 ±0.003	0.656 ±0.003	0.615 ±0.028	0.622 ±0.003	0.667 ±0.007	0.657 ±0.002	0.619 ±0.004	0.675 ±0.001	0.641 ±0.004	0.648 ±0.004
a9a	0.668 ±0.001	0.656 ±0.001	0.545 ±0.001	0.669 ±0.002	0.653 ±0.002	0.624 ±0.002	0.668 ±0.001	0.657 ±0.002	0.632 ±0.022	0.625 ±0.002	0.664 ±0.005	0.658 ±0.002	0.621 ±0.004	0.675 ±0.002	0.643 ±0.003	0.650 ±0.003
ecoli4	0.329 ±0.056	— —	0.151 ±0.018	— ±0.027	0.174 ±0.063	0.178 ±0.049	0.167 ±0.018	0.191 ±0.008	0.112 ±0.00	0.15 ±0.069	0.112 ±0.00	0.160 ±0.050	— —	— —	0.131 ±0.030	— —
ijcnn1	0.548 ±0.003	0.582 ±0.003	0.446 ±0.002	0.587 ±0.002	0.512 ±0.003	0.562 ±0.002	0.588 ±0.002	0.528 ±0.003	0.329 ±0.087	0.388 ±0.016	0.505 ±0.031	0.568 ±0.002	0.443 ±0.01	0.579 ±0.002	0.452 ±0.011	0.468 ±0.009
led7digit	0.492 ±0.063	0.292 ±0.076	0.420 ±0.026	0.237 ±0.096	0.504 ±0.052	0.530 ±0.047	0.505 ±0.066	0.515 ±0.03	0.157 ±0.003	0.519 ±0.099	0.219 ±0.054	0.605 ±0.059	0.520 ±0.057	0.647 ±0.062	0.470 ±0.092	0.460 ±0.041
magic	0.688 ±0.001	0.651 ±0.002	0.549 ±0.003	0.676 ±0.002	0.676 ±0.003	0.590 ±0.003	0.651 ±0.025	0.676 ±0.002	0.579 ±0.066	0.661 ±0.003	0.682 ±0.003	0.687 ±0.001	0.654 ±0.008	0.680 ±0.002	0.677 ±0.001	0.675 ±0.002
mushroom	0.930 ±0.002	0.891 ±0.001	0.891 ±0.002	0.938 ±0.002	0.939 ±0.001	0.924 ±0.004	0.920 ±0.003	0.897 ±0.008	0.930 ±0.002	0.930 ±0.002	0.931 ±0.002	0.930 ±0.004	0.921 ±0.009	0.923 ±0.006	0.907 ±0.004	0.915 ±0.006
musk2	0.482 ±0.007	0.487 ±0.004	0.478 ±0.004	0.504 ±0.005	0.498 ±0.003	0.514 ±0.006	0.474 ±0.006	0.469 ±0.006	0.449 ±0.019	0.459 ±0.012	0.468 ±0.017	0.479 ±0.005	0.404 ±0.014	0.479 ±0.003	0.412 ±0.011	0.415 ±0.0012
pageblocks0	0.641 ±0.017	0.616 ±0.009	0.474 ±0.009	0.625 ±0.010	0.601 ±0.011	0.633 ±0.014	0.668 ±0.01	0.647 ±0.016	0.254 ±0.146	0.632 ±0.013	0.185 ±0.000	0.688 ±0.009	0.617 ±0.023	0.702 ±0.008	0.602 ±0.031	0.586 ±0.0024
rna	0.874 ±0.002	0.742 ±0.001	0.761 ±0.001	0.879 ±0.001	0.884 ±0.001	0.810 ±0.005	0.501 ±0.001	0.765 ±0.003	0.500 ±0.003	0.787 ±0.007	0.694 ±0.016	0.828 ±0.002	0.579 ±0.007	0.820 ±0.002	0.734 ±0.005	0.743 ±0.003
segment0	0.875 ±0.044	0.805 ±0.009	0.667 ±0.018	0.809 ±0.011	0.858 ±0.016	0.795 ±0.024	0.808 ±0.029	0.684 ±0.032	0.268 ±0.027	0.539 ±0.149	0.437 ±0.024	0.806 ±0.03	0.494 ±0.02	0.862 ±0.037	0.49 ±0.03	0.535 ±0.026
shuttle04	0.912 ±0.06	0.854 ±0.016	0.892 ±0.009	0.862 ±0.011	0.932 ±0.024	0.909 ±0.022	0.807 ±0.07	0.887 ±0.076	0.381 ±0.34	0.808 ±0.092	0.309 ±0.124	0.943 ±0.036	0.803 ±0.048	0.959 ±0.009	0.758 ±0.052	0.748 ±0.047
spambase	0.889 ±0.004	0.871 ±0.002	0.790 ±0.004	0.894 ±0.002	0.893 ±0.002	0.843 ±0.004	0.864 ±0.005	0.884 ±0.003	0.886 ±0.003	0.881 ±0.003	0.889 ±0.003	0.882 ±0.001	0.877 ±0.004	0.889 ±0.004	0.882 ±0.004	0.854 ±0.005
splice	0.768 ±0.009	0.671 ±0.008	0.666 ±0.002	0.738 ±0.009	0.750 ±0.009	0.675 ±0.006	0.649 ±0.001	0.609 ±0.001	0.649 ±0.001	0.650 ±0.007	0.748 ±0.001	0.636 ±0.007	0.627 ±0.022	0.707 ±0.047	0.695 ±0.039	0.597 ±0.026
svmguide1	0.765 ±0.003	0.704 ±0.003	0.635 ±0.004	0.759 ±0.002	0.757 ±0.003	0.706 ±0.002	0.739 ±0.006	0.749 ±0.008	0.760 ±0.002	0.760 ±0.002	0.763 ±0.002	0.758 ±0.003	0.746 ±0.003	0.765 ±0.002	0.760 ±0.003	0.762 ±0.003
svmguide3	0.450 ±0.016	0.131 ±0.022	0.392 ±0.007	0.146 ±0.020	0.433 ±0.015	0.405 ±0.01	0.403 ±0.021	0.419 ±0.006	0.386 ±0.004	0.400 ±0.019	0.388 ±0.010	0.440 ±0.014	0.409 ±0.013	0.365 ±0.039	0.413 ±0.02	0.391 ±0.039
vehicle0	0.545 ±0.025	— ±0.007	0.416 ±0.011	0.019 ±0.014	0.485 ±0.022	0.447 ±0.009	0.377 ±0.013	0.423 ±0.002	0.38 ±0.003	0.379 ±0.003	0.381 ±0.001	0.492 ±0.017	0.375 ±0.007	0.143 ±0.081	0.402 ±0.019	— —
vowel0	0.545 ±0.019	0.339 ±0.053	0.431 ±0.021	0.342 ±0.023	0.503 ±0.020	0.529 ±0.022	0.555 ±0.033	0.479 ±0.020	0.257 ±0.098	0.471 ±0.042	0.337 ±0.073	0.546 ±0.032	0.473 ±0.026	0.595 ±0.024	0.412 ±0.048	— —
w8a	0.302 ±0.003	0.303 ±0.002	0.307 ±0.002	0.302 ±0.002	0.279 ±0.003	0.34 ±0.001	0.338 ±0.002	0.303 ±0.004	0.153 ±0.111	0.291 ±0.012	0.268 ±0.034	0.333 ±0.002	0.315 ±0.002	0.332 ±0.001	0.315 ±0.004	0.315 ±0.005
yeast1	0.533 ±0.016	0.202 ±0.028	0.462 ±0.005	0.193 ±0.031	0.503 ±0.013	0.471 ±0.008	0.449 ±0.002	0.486 ±0.014	0.449 ±0.001	0.448 ±0.006	0.448 ±0.000	0.514 ±0.008	0.445 ±0.004	0.33 ±0.043	0.474 ±0.017	0.407 ±0.105
yeast3	0.388 ±0.021	— ±0.007	0.258 —	— ±0.010	0.318 ±0.041	0.27 ±0.05	0.24 ±0.017	0.263 ±0.001	0.198 ±0.057	0.264 ±0.00	0.198 ±0.053	0.162 ±0.019	0.211 —	— —	0.207 ±0.014	— —
yeast5	0.152 ±0.015	— ±0.007	0.124 —	— ±0.007	0.106 ±0.040	0.161 ±0.029	0.135 ±0.010	0.119 ±0.000	0.066 ±0.023	0.095 ±0.000	0.066 ±0.000	— —	— —	— —	0.077 ±0.029	— —
yeast6	0.279 ±0.030	— ±0.013	0.188 —	— ±0.011	0.152 ±0.039	0.283 ±0.072	0.185 ±0.014	0.172 ±0.000	0.058 ±0.041	0.111 ±0.000	0.058 ±0.000	— —	— —	— —	0.08 ±0.024	— —
yeast4	0.141 ±0.021	— ±0.016	0.113 —	— ±0.011	0.086 ±0.041	0.145 ±0.023	0.107 ±0.012	0.095 ±0.000	0.046 ±0.000	0.081 ±0.035	0.046 ±0.000	— —	— —	— —	0.069 ±0.040	— —

Table C4 The comparison with chunk based methods in terms of AUC.

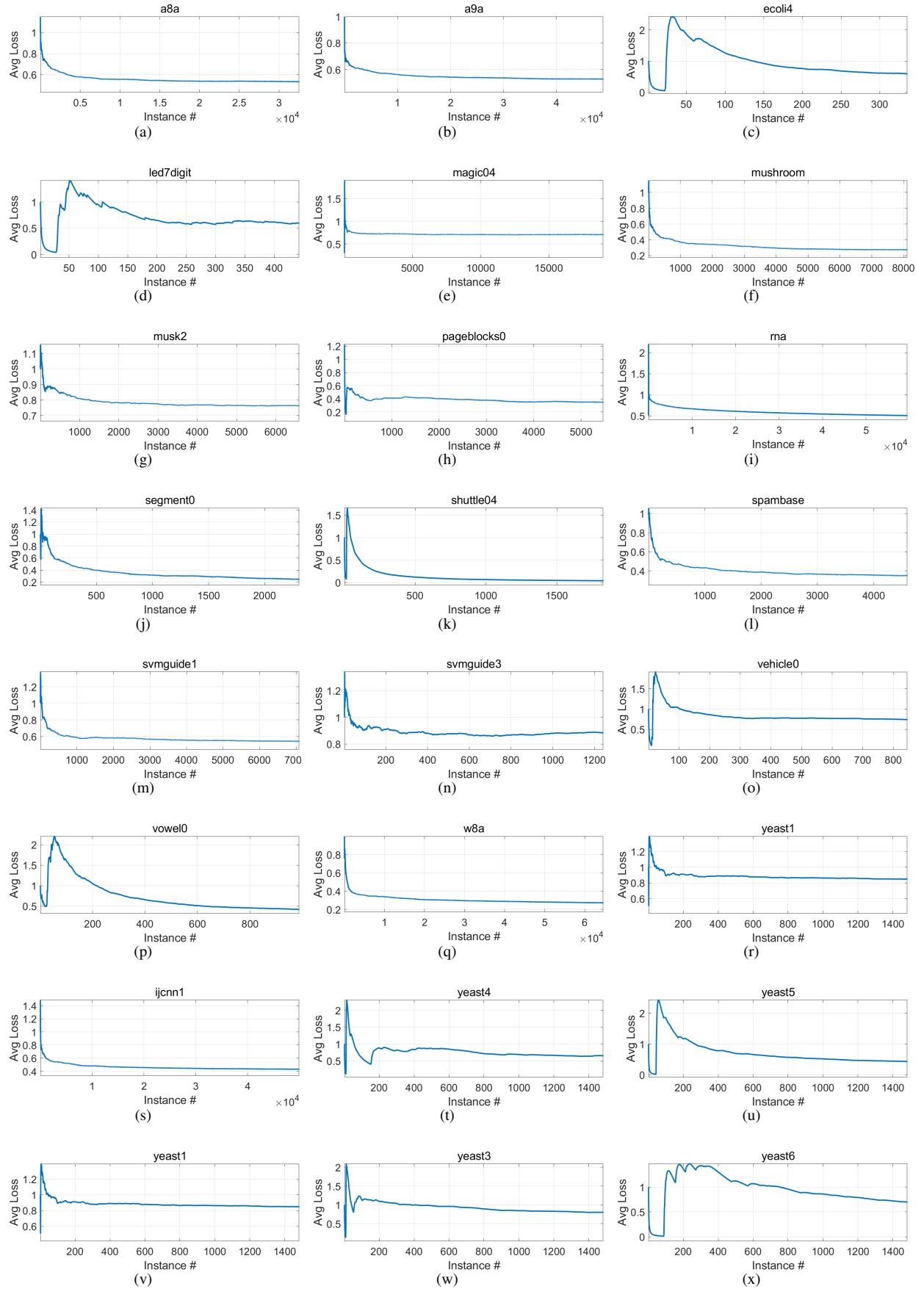
AUC	OHGD	HDWE	KNORAU2	
			NON	ROS
a8a	0.816 ±0.003	0.829 ±0.001	0.601 ±0.016	0.551 ±0.017
a9a	0.815 ±0.002	0.831 ±0.001	0.614 ±0.011	0.564 ±0.015
ecoli4	0.791 ±0.094	0.94 ±0.007	0.941 ±0.006	0.92 ±0.022
ijcnn1	0.871 ±0.003	0.903 ±0.000	0.903 ±0.000	0.703 ±0.004
led7digit	0.834 ±0.038	0.926 ±0.01	0.926 ±0.007	0.847 ±0.018
magic	0.757 ±0.002	0.457 ±0.033	0.675 ±0.004	0.423 ±0.02
mushroom	0.931 ±0.002	0.917 ±0.004	0.923 ±0.003	0.926 ±0.002
musk2	0.798 ±0.007	0.6 ±0.015	0.761 ±0.005	0.699 ±0.007
pageblocks0	0.883 ±0.009	0.871 ±0.045	0.905 ±0.003	0.888 ±0.014
rna	0.91 ±0.003	0.73 ±0.02	0.66 ±0.002	0.659 ±0.002
segment0	0.97 ±0.011	0.848 ±0.007	0.856 ±0.002	0.543 ±0.014
shuttle04	0.982 ±0.007	0.978 ±0.004	0.974 ±0.006	0.995 ±0.002
spambase	0.911 ±0.004	0.881 ±0.006	0.867 ±0.004	0.864 ±0.006
splice	0.769 ±0.01	0.546 ±0.027	0.524 ±0.002	0.786 ±0.002
svmguide1	0.614 ±0.022	0.794 ±0.005	0.813 ±0.007	0.883 ±0.008
svmguide3	0.632 ±0.017	0.762 ±0.003	0.403 ±0.037	0.399 ±0.016
vehicle0	0.718 ±0.026	0.782 ±0.024	0.731 ±0.029	0.667 ±0.014
vowel0	0.863 ±0.02	0.915 ±0.008	0.91 ±0.004	0.842 ±0.026
w8a	0.901 ±0.003	0.885 ±0.000	0.95 ±0.002	0.95 ±0.002
yeast1	0.662 ±0.018	0.711 ±0.003	0.413 ±0.013	0.409 ±0.007
yeast3	0.743 ±0.024	0.89 ±0.002	0.891 ±0.006	0.731 ±0.012
yeast5	0.715 ±0.031	0.97 ±0.001	0.97 ±0.001	0.94 ±0.004
yeast6	0.856 ±0.048	0.977 ±0.001	0.977 ±0.001	0.923 ±0.009
yeast4	0.779 ±0.028	0.965 ±0.001	0.965 ±0.001	0.869 ±0.009

Table C5 The comparison with chunk based methods in terms of GMEANS.

GMEANS	OHGD	HDWE	KNORAU2	
			NON	ROS
a8a	0.814 ±0.002	0.703 ±0.009	0.683 ±0.014	0.635 ±0.017
a9a	0.815 ±0.001	0.699 ±0.006	0.695 ±0.01	0.649 ±0.014
ecoli4	0.797 ±0.067	—	0.029 ±0.059	0.81 ±0.176
ijcnn1	0.870 ±0.002	—	—	0.617 ±0.008
led7digit	0.837 ±0.034	0.168 ±0.118	0.209 ±0.136	0.827 ±0.093
magic	0.758 ±0.001	0.349 ±0.096	0.262 ±0.03	0.326 ±0.043
mushroom	0.933 ±0.002	0.914 ±0.004	0.921 ±0.003	0.924 ±0.002
musk2	0.778 ±0.007	0.696 ±0.009	0.788 ±0.004	0.771 ±0.007
pageblocks0	0.886 ±0.007	0.085 ±0.061	0.396 ±0.044	0.791 ±0.027
rna	0.914 ±0.002	0.352 ±0.09	0.696 ±0.002	0.695 ±0.002
segment0	0.964 ±0.011	0.033 ±0.032	0.069 ±0.023	0.66 ±0.012
shuttle04	0.983 ±0.007	0.778 ±0.059	0.711 ±0.101	0.95 ±0.025
spambase	0.911 ±0.003	0.88 ±0.004	0.873 ±0.004	0.87 ±0.005
splice	0.768 ±0.009	0.255 ±0.09	0.056 ±0.01	0.484 ±0.061
svmguide1	0.794 ±0.002	0.767 ±0.005	0.758 ±0.011	0.883 ±0.008
svmguide3	0.631 ±0.015	0.024 ±0.018	0.412 ±0.028	0.417 ±0.017
vehicle0	0.720 ±0.023	0.457 ±0.158	0.749 ±0.028	0.743 ±0.015
vowel0	0.870 ±0.012	0.182 ±0.118	0.059 ±0.069	0.793 ±0.047
w8a	0.903 ±0.002	0.424 ±0.007	0.144 ±0.015	0.27 ±0.015
yeast1	0.663 ±0.014	—	0.39 ±0.02	0.383 ±0.016
yeast3	0.747 ±0.019	—	0.094 ±0.043	0.773 ±0.016
yeast5	0.717 ±0.029	—	—	0.553 ±0.094
yeast6	0.872 ±0.031	—	—	0.355 ±0.121
yeast4	0.778 ±0.029	—	—	0.455 ±0.064

Table C6 The comparison with chunk based methods in terms of F1 score.

F1	OHGD	HDWE	KNORAU2	
			NON	ROS
a8a	0.668 ±0.002	0.6 ±0.008	0.538 ±0.009	0.511 ±0.009
a9a	0.668 ±0.001	0.597 ±0.005	0.543 ±0.006	0.516 ±0.008
ecoli4	0.329 ±0.056	—	0.027 ±0.057	0.539 ±0.108
ijcnn1	0.548 ±0.003	—	—	0.261 ±0.006
led7digit	0.492 ±0.063	0.14 ±0.106	0.17 ±0.105	0.469 ±0.048
magic	0.688 ±0.001	0.283 ±0.09	0.798 ±0.002	0.214 ±0.05
mushroom	0.930 ±0.002	0.91 ±0.004	0.917 ±0.003	0.92 ±0.002
musk2	0.482 ±0.007	0.406 ±0.008	0.515 ±0.006	0.478 ±0.008
pageblocks0	0.641 ±0.017	0.067 ±0.047	0.291 ±0.032	0.566 ±0.035
rna	0.874 ±0.002	0.287 ±0.088	0.649 ±0.001	0.648 ±0.001
segment0	0.875 ±0.044	0.018 ±0.018	0.047 ±0.018	0.367 ±0.008
shuttle04	0.912 ±0.06	0.751 ±0.058	0.686 ±0.102	0.936 ±0.027
spambase	0.889 ±0.004	0.852 ±0.006	0.84 ±0.005	0.838 ±0.006
splice	0.768 ±0.009	0.233 ±0.093	0.682 ±0.001	0.481 ±0.064
svmguide1	0.765 ±0.003	0.828 ±0.01	0.856 ±0.004	0.892 ±0.008
svmguide3	0.450 ±0.016	0.015 ±0.012	0.392 ±0.01	0.392 ±0.009
vehicle0	0.545 ±0.025	0.362 ±0.134	0.588 ±0.021	0.576 ±0.016
vowel0	0.545 ±0.019	0.146 ±0.099	0.048 ±0.056	0.476 ±0.034
w8a	0.302 ±0.003	0.117 ±0.001	0.06 ±0.007	0.143 ±0.007
yeast1	0.533 ±0.016	—	0.477 ±0.006	0.476 ±0.006
yeast3	0.388 ±0.021	—	0.075 ±0.035	0.425 ±0.011
yeast5	0.152 ±0.015	—	—	0.307 ±0.047
yeast6	0.279 ±0.030	—	—	0.173 ±0.049
yeast4	0.141 ±0.021	—	—	0.184 ±0.024

**Figure C25** The accumulative loss curves of the proposed method.