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FREQUENTIST MODEL AVERAGING FOR THE NONPARAMETRIC ADDITIVE MODEL

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Abstract: This study develops an optimal frequentist model averaging approach for estimating the unknown conditional mean function in the nonparametric additive model when the covariates and the degree of smoothing are subject to uncertainty. Our weight choice criterion selects model weights by minimizing a plug-in estimator of the risk of the model average estimator under a squared error loss function. We derive the convergence rate of the model weights obtained from our proposed method to the infeasible optimal weights, and prove that the resultant model average estimators are asymptotically optimal. An extension to the additive autoregressive model for time series data is also considered. Our simulation analysis shows that the proposed model average estimators significantly outperform several commonly used model selection estimators and their model averaging counterparts in terms of the mean squared error in a large part of the parameter space. We further illustrate our methods using two real data studies.

Key words and phrases: Additive model, asymptotic optimality, autoregressive model, consistency, model averaging.

1. Introduction

The nonparametric additive model (AM) (Stone (1985); Hastie and Tibshirani (1990)) is a well-known statistical modeling approach. The AM belongs to a class of regression models in which the usual linear relationship between the response and the covariates is replaced by a sum of univariate smooth functions. AMs thus avoid much of the curse of dimensionality that afflicts fully nonparametric regression and afford more flexibility than traditional linear models with respect to the covariate effects. The smooth functions in AMs are commonly estimated by backfitting (Buja, Hastie and Tibshirani (1989); Mammen, Linton and Nielsen (1999); Opsomer (2000); Nielsen and Sperlich (2005); Ravikumar et al. (2009)), smoothing splines (Stone (1985); Doksum and Koo (2000); Huang and Yang (2004); Chen, Fan and Li (2018)), or marginal integration methods

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(Tjostheim and Auestad (1994); Linton and Nielsen (1995); Fan, Hardle and Mammen (1998)). AMs have been applied widely in many disciplines, including ecology, economics, environmental research, and medicine. Recent examples include the works of Eyto and Irvine (2007) and Bontemps, Simioni and Surry (2008), among others.

Model selection is a vital aspect of any statistical analysis. Within the framework of the AM, model selection typically involves choosing covariates and their degrees of smoothing. Huang and Yang (2004) proposed a spline-based Bayesian information criterion (BIC) for selecting the lag order in a nonlinear additive autoregressive model. They proved the consistency of the proposed method, and examined analogous spline-splitting methods based on the Akaike information criterion (AIC) and generalized cross-validation (GCV) in a simulation study. Xue (2009) introduced a penalized polynomial spline method for simultaneous model estimation and variable selection in AMs. Huang, Horowitz and Wei (2010) considered the group lasso. Belitz and Lang (2008) and Cantoni, Flemming and Ronchetti (2011) developed algorithms for component selection in AMs. Other well-known works on model selection in AMs include Härdle and Korostelev (1996), Chen, Liang and Wang (2011), and Fan, Feng and Song (2011), among others.

In recent years, model averaging has emerged as a viable alternative to model selection. Unlike model selection, which chooses one model for the data at hand, model averaging adopts a weighted ensemble approach that allows multiple models to contribute to the analysis in proportion to their estimated performance. In doing so, it captures all useful information of the models. Model averaging usually produces more stable estimates and more precise forecasts than those obtained from a single model. Furthermore, because model averaging properly accommodates uncertainty over models in situations where there is no predominant model to call on, it benefits statistical inference (Hjort and Claeskens (2003); Liu (2015); Zhang and Liu (2019)). Model averaging may be viewed as a smoothed extension of model selection from the point of view of estimation and prediction.

A major part of the model averaging literature focuses on choosing model weights. When approached from a Bayesian perspective, the model weights are usually determined by the individual models' posterior probabilities. Here, we adopt a frequentist approach to model averaging, which has become increasingly popular in statistics and data analysis in recent years. Frequentist model averaging (FMA) precludes the need to specify any prior distribution. However, choosing optimal weights using a data-driven method is arguably more challenging for the frequentist formulation than it is for its Bayesian counterpart.

The FMA strategies that have been developed include weighting by information criterion scores (Buckland, Burnham and Augustin (1997)), adaptive regression by mixing (Yang (2001)), Mallows model averaging (Hansen (2007)), jackknife model averaging (Hansen and Racine (2012); Ando and Li (2014)), optimal MSE averaging (Liang et al. (2011)), and averaging using Kullback–Leibler-type measures (Zhang et al. (2016)). Claeskens (2016) provides a survey of this rapidly expanding body of literature.

While the optimal choice of weights in FMA has been researched extensively, the majority of the literature focuses on parametric models. Optimal FMA methods are relatively less well developed for nonparametric and semiparametric models. Hansen (2014) suggested the jackknife criterion for choosing the weights for the nonparametric sieve regression averaging estimator. For the partially linear model (PLM), Zhang and Wang (2019) developed a Mallows-type weight choice criterion and studied the asymptotic optimality of the corresponding model averaging estimator. Zhu et al. (2019) proposed a weight choice criterion in a PLM with varying coefficients. Other studies of FMA on the choice of weights in nonparametric and semiparametric models include Gao (2015), Chen et al. (2018), and Li et al. (2018), among others.

The principal scientific contribution of this study is to develop optimal FMA approaches for nonparametric additive models and additive autoregressive models, which have not been studied thoroughly in the existing literature. Our weight choice criterion is based on minimizing a plug-in estimator of the squared error risk of the FMA estimator. We consider two plug-in estimators that have similar forms, but different penalties. We derive the convergence rate of our weights to the infeasible optimal weights, and prove that the model average estimators obtained from the weight choice criterion are asymptotically optimal in the sense of achieving the smallest possible squared error. Note that developing asymptotic theory in the present context is nontrivial, because in addition to the uncertainty in the covariate set, we also allow for uncertainty in the degree of smoothing and a dependent data structure.

The remainder of this paper is organized as follows. Section 2 describes the model setup, discusses the FMA scheme, and presents the main results on the asymptotic properties of the proposed model averaging method. In Section 3, we extend our analysis to additive autoregressive models. Section 4 reports the results of a simulation study that examines the finite-sample performance of the proposed model averaging estimators. Section 5 applies the proposed method to two real data sets related to medical and environmental research. Section 6 concludes the paper. All proofs of the results are contained in the Appendix.

2. Model Setup and the Weight Choice Criterion

Consider the nonparametric additive model

$$Y = \sum_{j=1}^{d_0} g_j(X^{(j)}) + e \equiv \mu + e, \tag{2.1}$$

where $Y = (y_1, \ldots, y_n)'$ is a random vector, $X^{(j)} = (x_{1j}, \ldots, x_{nj})'$ is the jth covariate, g_j are one-dimensional nonparametric functions with $g_j(X^{(j)}) = (g_j(x_{1j}), \ldots, g_j(x_{nj}))'$, and $e = (e_1, \ldots, e_n)'$ is a vector of disturbance terms, with e_i being independent with mean zero and variance σ^2. To prove the asymptotic optimality of the model average estimators, we need no distributional assumption on e. However, for the purpose of developing the weight choice criterion, we assume that e follows a multivariate normal distribution. The same approach was taken by Zhang, Zou and Carroll (2015), who examined model averaging in another context. Now, assume that there are M candidate models, each corresponding to a different covariate set and degree of smoothing. We let $\hat{\mu}_m = P_m Y$ be the estimator of μ under the mth candidate model, where P_m is a hat matrix. The form of P_m depends on the estimation method. As discussed in Section 1, backfitting, smoothing splines, and marginal integration are some of the common estimation methods studied in the literature.

The FMA estimator of μ can be expressed as $\hat{\mu}(w) = \sum_{m=1}^{M} w_m \widehat{\mu}_m = P(w)Y$, where $w \in \mathcal{W} = \{w \in [0,1]^M : \sum_{m=1}^{M} w_m = 1\}$ is the weight vector and $P(w) = \sum_{m=1}^{M} w_m P_m$. We assume that the Mth model has the largest dimension among all candidate models.

Our weight choice criterion is based on a minimization of a plug-in estimator of the risk of $\hat{\mu}(w)$ under a squared error loss function. Define the squared error loss function of $\hat{\mu}(w)$ as $L(w) = \|\mu - \hat{\mu}(w)\|^2$. Note that

$$\begin{aligned} L(w) &= \|Y - \hat{\mu}(w)\|^2 - 2e'(Y - \hat{\mu}(w)) + e'e \\ &= \|Y - \hat{\mu}(w)\|^2 - 2e'(I - P(w))(\mu + e) + e'e \\ &= \|Y - \hat{\mu}(w)\|^2 + 2e'P(w)e - 2e'(I - P(w))\mu - e'e. \end{aligned} \tag{2.2}$$

From (2.2), we obtain the following scaled risk function:

$$\begin{aligned} R^0(w) &= E\left(\frac{L(w)}{\sigma^2}\right) \\ &= E\left[\frac{\|Y - \hat{\mu}(w)\|^2}{\sigma^2} + 2\sum_{m=1}^{M} \frac{w_m e' P_m e}{\sigma^2}\right] - n. \end{aligned} \tag{2.3}$$

Although an ideal approach would be to choose w by minimizing $R^0(w)$ directly, this would not result in a solution, because $R^0(w)$ involves unknown expectations. Hence, we consider minimizing a plug-in estimator of $R^0(w)$. Ignoring the constant n in (2.3), our plug-in estimator of $R^0(w)$ takes the form

$$\frac{\|Y-\hat{\mu}(w)\|^2}{\widehat{\sigma}_M^2}+2\sum_{m=1}^{M} w_m E\left(\frac{e' P_m e}{\widetilde{\sigma}_m^2}\right), \tag{2.4}$$

where $\widehat{\sigma}_M^2=\widehat{e}_M'\widehat{e}_M/(n-tr(P_M))$ is the least squares estimator of σ^2 based on the largest model, $\widehat{e}_M=Y-\hat{\mu}_M$, and $\widetilde{\sigma}_m^2=\|Y-\hat{\mu}_m\|^2/n=Y'(I_n-P_m)'(I_n-P_m)Y/n$ is the maximum likelihood estimator of σ^2 based on the mth candidate model.

Our substitution of σ^2 by $\widehat{\sigma}_M^2$ in the first term on the right-hand side of (2.3) follows Mallows (1973), who used the same approach to derive Mallows' Cp criterion. On the other hand, $e'P_m e/\sigma^2$ can be thought of as the "penalty" for the mth model. Hence, it makes sense to estimate σ^2 in each of $e'P_m e/\sigma^2$ in (2.3) by $\widetilde{\sigma}_m^2$ so that there are different penalties for different models. This is similar to the idea of using different tuning parameters for different coefficients in the LASSO (Wang, Li and Tsai (2007)).

To use (2.4) as a weight choice criterion, an evaluation of $E(e'P_m e/\widetilde{\sigma}_m^2)$ is required. By Stein's lemma (Stein (1981)), we have

$$\begin{aligned}
& E\left(\frac{e'P_m e}{\widetilde{\sigma}_m^2}\right)\\
&= \sigma^2 Etr\left(\frac{\partial P_m e\widetilde{\sigma}_m^{-2}}{\partial Y'}\right)=\sigma^2 Etr\left(P_m\frac{\partial e\widetilde{\sigma}_m^{-2}}{\partial Y'}\right)\\
&= \sigma^2 tr\left\{P_m E\left(\widetilde{\sigma}_m^{-2}\right)+P_m E\left(e\frac{\partial\widetilde{\sigma}_m^{-2}}{\partial Y'}\right)\right\}\\
&= tr\left\{P_m E\left(\sigma^2\widetilde{\sigma}_m^{-2}\right)+\sigma^4 P_m E\left(\frac{\partial^2\widetilde{\sigma}_m^{-2}}{\partial YY'}\right)\right\}\\
&= tr\left\{P_m E\left(\sigma^2\widetilde{\sigma}_m^{-2}\right)+\sigma^4 P_m E\left(2\widetilde{\sigma}_m^{-6}\frac{\partial\widetilde{\sigma}_m^2}{\partial Y}\frac{\partial\widetilde{\sigma}_m^2}{\partial Y'}-\widetilde{\sigma}_m^{-4}\frac{\partial^2\widetilde{\sigma}_m^2}{\partial YY'}\right)\right\}.
\end{aligned}$$

Noting that $\partial\widetilde{\sigma}_m^2/\partial Y=2n^{-1}(I-P_m)'(I-P_m)Y$ and $\partial^2\widetilde{\sigma}_m^2/\partial YY'=2n^{-1}(I-P_m)'(I-P_m)$, we can write

$$\begin{aligned}
E\left(\frac{e'P_m e}{\widetilde{\sigma}_m^2}\right) &= E\{\sigma^2\widetilde{\sigma}_m^{-2}tr(P_m)+8n^{-2}\sigma^4\widetilde{\sigma}_m^{-6}Y'(I-P_m)'(I-P_m)P_m(I-P_m)'\\
&\qquad (I-P_m)Y-2n^{-1}\sigma^4\widetilde{\sigma}_m^{-4}tr\left((I-P_m)P_m(I-P_m)'\right)\}. \qquad (2.5)
\end{aligned}$$

Substituting (2.5) in (2.4), we obtain the following weight choice criterion:

$$\frac{\|Y-\hat{\mu}(w)\|^2}{\hat{\sigma}_M^2}+2\sum_{m=1}^{M} w_m \mathrm{df}_m, \tag{2.6}$$

where

$$\begin{aligned}\mathrm{df}_m = {} & \sigma^2\widetilde{\sigma}_m^{-2} tr(P_m)\\ & +8n^{-2}\sigma^4\widetilde{\sigma}_m^{-6}Y'(I-P_m)'(I-P_m)P_m(I-P_m)'(I-P_m)Y\\ & -2n^{-1}\sigma^4\widetilde{\sigma}_m^{-4} tr\left((I-P_m)P_m(I-P_m)'\right).\end{aligned}$$

For the special case of a symmetric and idempotent P_m, the weight choice criterion simplifies to

$$\frac{\|Y-\hat{\mu}(w)\|^2}{\hat{\sigma}_M^2}+2\sum_{m=1}^{M} w_m \frac{\sigma^2 tr(P_m)}{\widetilde{\sigma}_m^2}. \tag{2.7}$$

The unknown σ^2 in (2.7) may be replaced by the least squares estimator $\widehat{\sigma}_m^2 = \|Y-\hat{\mu}_m\|^2/(n-tr(P_m))$ based on the mth candidate model or its maximum likelihood counterpart $\widetilde{\sigma}_m^2$. Both are commonly used to estimate σ^2. We first consider replacing σ^2 in (2.7) by $\widehat{\sigma}_m^2$. This yields

$$\frac{\|Y-\hat{\mu}(w)\|^2}{\hat{\sigma}_M^2}+2\sum_{m=1}^{M} w_m \frac{n tr(P_m)}{n-tr(P_m)}. \tag{2.8}$$

In order to use (2.8), one needs an explicit form of the hat matrix P_m. As discussed earlier, the form of P_m depends on the method of estimation. Here, we consider the spline smoothing estimation method, which has the advantage of simplicity (Huang and Yang (2004)). Let a_m, b_m, and c_m represent some sequences varying with m. Denote the knot sequence as $\{a=\zeta_{j,0}<\zeta_{j,1}<\cdots<\zeta_{j,N_j^{a_m}}<\zeta_{j,N_j^{a_m}+1}=b\}$ for g_j, where $a<b$ are finite numbers and $N_j^{a_m}$ is the number of interior knots. Let φ be the polynomial spline space consisting of functions that are, first, polynomials of degree $l_j^{b_m}$ on intervals $[\zeta_{j,s},\zeta_{j,s+1})(s=0,\ldots,N_j^{a_m}-1)$ and $[\zeta_{j,N_j^{a_m}},\zeta_{j,N_j^{a_m}+1}]$, and second, $l_j^{b_m}-1$ times continuously differentiable on $[a,b]$ (Stone (1985); de Boor (2001); Xue (2009); Huang, Horowitz and Wei (2010)). We assume that there exists a basis $B_j^m(x)=(B_{j1}(x),\ldots,B_{jq_j^m}(x))'$ ($q_j^m=N_j^{a_m}+l_j^{b_m}$ and $x\in[a,b]$) for the spline space φ. Some examples include the truncated power basis and B-spline basis (de Boor (2001)). Without loss of generality, assume that $x_{ij}\in[a,b]$. Denote $B_j^m=(B_j^m(x_{1j}),\ldots,B_j^m(x_{nj}))'$. Let s_{c_m} be the index set of covariates under the mth model; that is, s_{c_m} is a subset

of $\{1,\ldots,d\}$. Because the candidate models may be misspecified, d is not necessarily equal to d_0 given in (2.1). For the mth candidate model, we can write the spline estimator of μ as $\hat{\mu}_m = \sum_{j\in s_{c_m}} B_j^m \hat{\theta}_j^m$, where $\hat{\theta}^m = [\hat{\theta}_j^{m\prime}]'_{j\in s_{c_m}}$ represents the $\sum_{j\in s_{c_m}} q_j^m$-dimensional vector satisfying

$$\hat{\theta}^m = \underset{\theta^m}{\operatorname{argmin}} \left\| Y - \sum_{j\in s_{c_m}} B_j^m \theta_j^m \right\|^2, \tag{2.9}$$

with $\theta^m = [\theta_j^{m\prime}]'_{j\in s_{c_m}}$. This yields $P_m = B^m(B^{m\prime}B^m)^{-1}B^{m\prime}$, which is symmetric and idempotent, where $B^m = [B_j^m]_{j\in s_{c_m}}$ is the $n \times \sum_{j\in s_{c_m}} q_j^m$ basis matrix. Substituting P_m in (2.8) results in the criterion

$$\phi(w) = \|Y - \hat{\mu}(w)\|^2 + 2\widehat{\sigma}_M^2 \sum_{m=1}^{M} w_m \frac{nr_m}{n - r_m}, \tag{2.10}$$

where $r_m = \sum_{j\in s_{c_m}} q_j^m$ and $q_j^m = N_j^{a_m} + l_j^{b_m}$. Write $\hat{w} = \operatorname{argmin}_{w\in\mathcal{W}}\phi(w)$, and label $\hat{\mu}(\hat{w})$, the FMA estimator of μ that uses $\hat{w}$, the additive model average (AMA) estimator.

Remark 1. The way in which a_m, b_m, and c_m vary with m determines their explicit expressions. Let h_1 and h_2 be the numbers of knot sequences and degrees, respectively. If, for example, a_m vary in $\{1,2,\ldots,h_1\}$ and b_m vary in $\{1,2,\ldots,h_2\}$, then we can write $a_m = m - h_1[(m-1)/h_1]$, $b_m = 1 + [(m-1 - h_1h_2[(m-1)/(h_1h_2)])/h_1]$, and $c_m = 1 + [(m-1)/(h_1h_2)]$, where $[A]$ denotes the integral part of A.

Remark 2. If the unknown σ^2 in the penalty term of (2.7) is replaced by the maximum likelihood estimator $\widetilde{\sigma}_m^2$ instead of $\widehat{\sigma}_m^2$, then (2.8) changes to

$$\frac{\|Y - \hat{\mu}(w)\|^2}{\hat{\sigma}_M^2} + 2\sum_{m=1}^{M} w_m tr(P_m). \tag{2.11}$$

Substituting P_m in (2.11) yields the alternative criterion

$$\phi_H(w) = \|Y - \hat{\mu}(w)\|^2 + 2\widehat{\sigma}_M^2 \sum_{m=1}^{M} w_m r_m, \tag{2.12}$$

which has the same form as Hansen's (2007) Mallows weight choice criterion for linear regression. Denote $\tilde{w} = \operatorname{argmin}_{w\in\mathcal{W}}\phi_H(w)$. We refer to the model average estimator $\hat{\mu}(\tilde{w})$ arising from $\phi_H(w)$ as the AMAH estimator. Clearly,

$\phi(w)$ and $\phi_H(w)$ are plug-in versions of the same criterion, and they differ only in the estimator of σ^2 being used in the penalty term of the criterion. Like Hansen (2007), $\phi_H(w)$ can actually be derived without the normality assumption on the error term. The estimators resulting from $\phi(w)$ and $\phi_H(w)$ have the same asymptotic properties, but different finite-sample properties. See Section 4 for details. In fact, because $\phi(w)$ imposes heavier penalties on larger models, it may have some merits over $\phi_H(w)$ in small samples.

Remark 3. Our weight choice scheme is formulated as a quadratic programming problem. For small to moderate values of M (say $M \leq 400$), the computation is manageable and can be performed efficiently via, for example, the function "solve.QP" in R. When M is large, one can first subset the models into a smaller candidate set via "model screening" before applying model averaging to the smaller set. Some well-known model screening methods include the "top M" method, based on AIC and/or BIC scores (Yuan and Yang (2005)), and the forward and backward stepwise procedures developed specifically for AMs when only the covariates are subject to uncertainty (Huang and Yang (2004)).

Now, denote the risk function and the minimum possible risk as $R(w) = E\left[\|\mu - \hat{\mu}(w)\|^2\right]$ and $\xi_n = \inf_{w \in \mathcal{W}} R(w)$, respectively. Let C be a generic positive constant that can take on different values in different contexts. Consider the following regularity conditions:

Condition 1. *$E(e_i^{4G}) \leq C < \infty$, and $M\xi_n^{-2G} \sum_{m=1}^{M} (R(w_{m0}))^G \to 0$, for some fixed integer $1 \leq G < \infty$, where w_{m0} is an $M \times 1$ vector with the mth element taking on the value of unity, and the others zero.*

Condition 2. *$\mu'\mu/n = O(1)$.*

Condition 3. *$r_M^2/n \leq C < \infty$.*

Conditions 1–3 are similar to those used by Wan, Zhang and Zou (2010). The first part of Condition 1 places a constraint on the moment of $\{e_i\}$, while the second part restricts the rate of increase of M. As an example, assume that ξ_n has the order of n^β with $\beta > 1/2$, which is a reasonable assumption for nonparametric regressions (Ando and Li (2014)), and $\max_{1 \leq m \leq M} R(w_{m0}) = O(n)$. Then, the second part of Condition 1 holds if $M^2/n^{G(2\beta-1)} \to 0$. It has been shown in other contexts that if the second part of Condition 1 is removed, then the asymptotic optimality of FMA estimators can only be established under a somewhat restricted weight set (Cheng, Ing and Yu (2015)). Condition 2 is mild and commonly used. Condition 3 restricts the rate at which r_M increases.

Theorem 1. *Under Conditions* 1–3*,*

$$\frac{L(\hat{w})}{\inf_{w\in\mathcal{W}} L(w)} \xrightarrow{p} 1, \tag{2.13}$$

and

$$\frac{L(\tilde{w})}{\inf_{w\in\mathcal{W}} L(w)} \xrightarrow{p} 1, \tag{2.14}$$

where $\hat{w} = argmin_{w\in\mathcal{W}}\phi(w)$ *and* $\tilde{w} = argmin_{w\in\mathcal{W}}\phi_H(w)$.

Proof. See the Appendix.

Theorem 1 shows that both the AMA and the AMAH estimators are asymptotically optimal in the sense of achieving the smallest possible squared error.

Remark 4. For the FMA estimator to approach the true nonparametric component of the model, it is necessary for the number of knots to increase with the sample size. Stone (1985) and Huang and Yang (2004) showed that the estimator of the nonparametric function can attain the optimal rate of convergence if the number of knots is of the order of $n^{1/5}$. In the following, we demonstrate that if the candidate model set includes the models associated with the spline estimators with the optimal rate of convergence given in Stone (1985), the asymptotic optimality stated in Theorem 1 remains valid, provided that some mild regularity conditions are fulfilled. Let us fix the polynomial degree and the number of covariates, allow the number of knots to vary, and assume that the candidate set comprises models of dimensions (r_m) in the order of $n^{1/5}$ (i.e., the number of knots has the order of $n^{1/5}$). Then, the mean squared error of the spline estimator (divided by n) has the order $n^{-4/5}$, which is the optimal rate of convergence for spline estimators (Stone (1985)). For the above example, Condition 3 clearly holds, and Theorem 1 remains valid if Condition 2 and the first part of Condition 1 are true and $M^2/n^{G/5} = o(1)$. The latter holds for appropriate M and G, and is a sufficient condition for the second part of Condition 1 to hold.

Remark 5. Like all model selection and averaging procedures, the performance of the proposed procedure depends heavily on the construction of the candidate set. We need to impose some conditions on the candidate model set in order for the proposed procedure to be asymptotically optimal. See Section 2 for a discussion of the conditions. In practice, one often looks to the context of the investigation for guidance in constructing candidate models. For example, econometric models are usually based on economic theories. In the absence of any context-specific information, one can consider a large number of candidate models with varying degrees of smoothness and different covariates in the initial stage, then apply model screening to reduce the candidate set to a manageable scale. See Remark 3 above.

Now, denote the (infeasible) optimal weight obtained from a direct minimization of $R(w)$ as $w^0 = \text{argmin}_{w\in\mathcal{W}} R(w)$. It is assumed that w^0 is an interior point of $\mathcal{W}$. Let $\lambda_{\min}(A)$ and $\lambda_{\max}(A) = \|A\|$ be the minimum and maximum singular values, respectively, of a general real matrix A. Denote $\Lambda_1 = (\hat{\mu}_1, \ldots, \hat{\mu}_M)$ and $\Lambda = \Lambda_1'\Lambda_1$. Consider the following regularity conditions:

Condition 4. *There are two positive constants κ_1 and κ_2, such that $Pr(0 < \kappa_1 < \lambda_{\min}(\Lambda/n) \le \lambda_{\max}(\Lambda/n) < \kappa_2 < \infty)$ tends to one as $n \to \infty$.*

Condition 5. *$\lambda_{\max}\left\{(B^{m\prime}B^m/n)^{-1}\right\} = O(1)$ uniformly in m.*

Condition 6. *$r_M/n = o(1)$ and $Mr_M/(n^{2\delta}\xi_n) = o(1)$, where δ is a positive constant.*

Condition 4 requires both the minimum and the maximum singular values of Λ/n to be bounded away from zero and infinity. Other studies that have used similar conditions include Fan and Peng (2004) and Bickel and Levina (2008). Condition 5 implies that the maximum singular value of $(B^{m\prime}B^m/n)^{-1}$ is bounded. Ravikumar et al. (2009) used a similar condition. Condition 6 allows M and r_M to increase with n, but also places a restriction on their diverging rates.

Theorem 2. *If Conditions 2, and 4–6 are satisfied, then there exist local minimizers $\hat{w}$ and $\tilde{w}$ of $\phi(w)$ and $\phi_H(w)$, respectively, such that*

$$\|\hat{w} - w^0\| = O_p\left(\xi_n^{1/2} n^{-1/2+\delta}\right) \tag{2.15}$$

and

$$\|\tilde{w} - w^0\| = O_p\left(\xi_n^{1/2} n^{-1/2+\delta}\right), \tag{2.16}$$

where δ is a positive constant defined under Condition 6.

Proof. See Appendix.

Theorem 2 shows that the weights obtained by minimizing $\phi(w)$ and $\phi_H(w)$ approach the optimal weights at the rate of $\xi_n^{1/2} n^{-1/2+\delta}$.

Remark 6. Condition 4 is mild when the dimension M of Λ is fixed; it is a strong condition when M diverges, although similar conditions are frequently used in literature, as explained above. In fact, in the latter event, one can consider substituting $\lambda_{\max}(\Lambda/n) = O_p(1)$ by the weaker condition $\lambda_{\max}(\Lambda/n) = O_p(M)$, which is a reasonable alternative because $\lambda_{\max}(\Lambda/n) \leq trace(\Lambda/n) = O_p(M)$ when the diagonal elements of Λ/n are uniformly $O_p(1)$. Now, assuming that $\lambda_{\max}(\Lambda/n) = O_p(M)$, all other things being equal, by following the steps of deriving Theorem 2, we can show that $\|\hat{w} - w^0\| = O_p(M^{1/2}\xi_n^{1/2}n^{-1/2+\delta})$, replacing the original conclusion of $\|\hat{w} - w^0\| = O_p(\xi_n^{1/2}n^{-1/2+\delta})$ obtained under Condition 4. In other words, the use of $\lambda_{\max}(\Lambda/n) = O_p(M)$ in lieu of $\lambda_{\max}(\Lambda/n) = O_p(1)$ implied by the stronger Condition 4 when M diverges results in a slower convergence rate of $\hat{w}$.

3. Weight Choice for Additive Autoregressive Models

The purpose of this section is to extend the preceding analysis to an additive autoregressive model. This model has the same structure as (2.1), except that $X^{(j)} = (y_{1-j}, \ldots, y_{n-j})'$, so that $g_j(X^{(j)}) = (g_j(y_{1-j}), \ldots, g_j(y_{n-j}))'$ and $B_j^m = (B_j^m(y_{1-j}), \ldots, B_j^m(y_{n-j}))'$, and the subscript i, which indexes the observation number, is replaced by the time index t $(1 \leq t \leq n)$; that is, x_{ij} is replaced by y_{t-j} everywhere. We assume that $\{y_t\}$ is a stationary time series process. Like AMs, additive autoregressive models are attractive alternatives to traditional nonparametric time series models, owing to their ability to alleviate the curse of dimensionality. Additive autoregressive models have been studied extensively in the literature. See Chen and Tsay (1993), Huang and Yang (2004), and Li and Yang (2007), among others.

Denote $A(w) = I - P(w)$, and let $\tilde{R}(w) = \|A(w)\mu\|^2 + \sigma^2 tr\left\{P^2(w)\right\}$ and $\tilde{\xi}_n = \inf_{w\in\mathcal{W}} \tilde{R}(w)$, where $\tilde{R}(w)$ is an analogue of $R(w)$ (they are the same under the case of independent data in Section 2). Now, consider the following regularity conditions:

Condition 7. $\max_{m\in\{1,\ldots,M\},j\in s_{c_m},i\in\{1,\ldots,q_j^m\}} E|B_{ji}^2(y_{t-j})| < \infty$.

Condition 8. $\lambda_{\max}\left\{(B^{m\prime}B^m/n)^{-1}\right\} = O_p(1)$ *uniformly, for* $1 \leq m \leq M$.

Condition 9. $\mu'\mu/n = O_p(1)$.

Condition 10. $r_M/n = o(1)$ *and* $r_M^{1/2}n^{1/2}\tilde{\xi}_n^{-1} = o_p(1)$.

Condition 7 is a standard moment condition for establishing asymptotic results. Conditions 8 and 9 are the counterparts of Conditions 5 and 2, respectively, in the context of a time series model. Condition 10 assumes that $\tilde{\xi}_n$ increases at a rate faster than $n^{1/2}$ for fixed r_M. The same assumption was used by Ando and Li (2014).

Theorem 3. *Provided that Conditions* 7–10 *hold and* $\{e_t\}$ *is mutually independent, Theorem* 1 *continues to hold.*

Proof. See the Appendix.

Theorem 4. *Provided that Conditions* 4 *and* 6–9 *hold and* $\{e_t\}$ *is mutually independent, Theorem* 2 *continues to hold.*

Proof. See the Appendix.

Theorems 3 and 4 extend the results on the asymptotic optimality and consistency for the AMA and AMAH estimators from independent data to stationary time series data. One important assumption for Theorems 3 and 4 is that the disturbances are independent. Our results can be further extended to the case where $\{e_t\}$ is weakly correlated. Consider the following regularity conditions:

Condition 11. $\{y_t, e_t\}$ *is* α*-mixing with size* $-\gamma/(\gamma-2)$ *with* $\gamma > 2$.

Condition 12. $E\,|B_{ji}(y_{t-j})e_t|^{\gamma} < \infty$ *uniformly for* i *and* j*, where* γ *is defined in Condition* 11*.*

Condition 13. $E\,\{B_{ji}(y_{t-j})e_t\} = O(1/\sqrt{n})$ *uniformly for* i *and* j*.*

Conditions 11 and 12 are frequently used to establish the Central Limit Theorem of estimators under dependent data (e.g., White (1984)). Condition 13 implies that $\{e_t\}$ is weakly correlated.

Theorem 5. *Provided that Conditions* 8–13 *are satisfied, Theorem* 1 *continues to hold.*

Proof. See the Appendix.

Theorem 6. *Provided that Conditions* 4, 6, 8, 9, *and* 11–13 *are satisfied, Theorem* 2 *continues to hold.*

Proof. See the Appendix.

4. Finite-Sample Analysis

In this section, we compare the finite-sample properties of the proposed AMA and AMAH estimators with a number of other estimators, including the AIC and BIC model selection estimators and the smoothed-AIC (SAIC) and smoothed-BIC (SBIC) model averaging estimators. The AIC and BIC scores for the mth model are defined as $\mathrm{AIC}^{(m)} = n\log\widetilde{\sigma}_m^2 + 2r_m$ and $\mathrm{BIC}^{(m)} = n\log\widetilde{\sigma}_m^2 + (\log n)r_m$, respectively. The AIC (BIC) estimator selects the model with the smallest AIC (BIC) score. The SAIC estimator is an FMA estimator that assigns the weight

$$w_{\mathrm{AIC},m} = exp\left(\frac{-\mathrm{AIC}^{(m)}}{2}\right) \Big/ \sum_{m=1}^{M} exp\left(\frac{-\mathrm{AIC}^{(m)}}{2}\right)$$

to the mth model, for $1 \leq m \leq M$. The SBIC estimator is defined analogously.

4.1. Simulations for the independent data case

We consider the model given in (2.1) with $\mu = (\mu_1, \ldots, \mu_n)'$, $e \sim N(0, \sigma^2 I_n)$, and $\sigma = 0.4, 1.0, 1.5$. The following process of μ is considered:

$$\begin{aligned}\mu_i = x_{i1} &+ (2x_{i2} - 1)^2 + \frac{\sin(2\pi x_{i3})}{2 - \sin(2\pi x_{i3})} \\ &+ \big\{0.1\sin(2\pi x_{i4}) + 0.2\cos(2\pi x_{i4}) + 0.3(\sin(2\pi x_{i4}))^2 \\ &+ 0.4(\cos(2\pi x_{i4}))^3 + 0.5(\sin(2\pi x_{i4}))^3\big\} + 0.5\alpha(\sin(2\pi U_i))^2. \qquad (4.1)\end{aligned}$$

We let $x_{ij} = (V_{ij} + kU_i)/(1+k)$, for $j = 1, \ldots, 7$, where V_{ij} and U_i are independent and identically distributed (i.i.d.) U[0,1] observations and $k = 0, 0.5, 1, 1.5, 2$. When $k \neq 0$, x_{ij} have common U_i for different j, that is, $E(x_{i1}x_{i2}) \neq 0$, and the data are correlated. We use the parameter α in (4.1) to control the degree of model misspecification.

We first consider the uncertainty of the choice of covariates. With seven covariates, there are 2^7 candidate models. Note that (4.1) is similar to the simulation setup of Xue (2009), who considered the special case of $\alpha = 0$. In our simulations, we set $\alpha = 1$ so that all candidate models are misspecified. In addition, we set the polynomial degree to three, and let the knots be equidistant. Following Huang and Yang (2004), we set the number of knots to be the smallest integer greater than or equal to $(2n)^{1/5} - 1$. We consider sample sizes of $n = 50, 70, 100, 150, 200$. Let $\tilde{\mu}$ be an estimator of μ. Our comparison of the performance of the estimators is based on the squared error $||\mu - \tilde{\mu}||^2$, averaged over 1,000 replications. Table 1 and Tables S.1 and S.2 in the Supplementary Material present the results. While the following commentary applies to all values of k considered, to conserve space, we only report results corresponding to $k = 0, 1, 1.5$. Results for other values of k are available upon request.

Our results show that the AMA and the AMAH estimators are almost always the two best estimators with respect to the averaged squared errors. In the rare cases where neither the AMA nor the AMAH produces the best estimates (e.g., when $\sigma = 0.4$, $k = 0$, and $n = 200$), they typically yield larger average squared

Table 1. Averaged squared errors ($\times 10^{-1}$) under independent data when covariate selection is subject to uncertainty and $\sigma = 0.4$.

	n	AIC	BIC	SAIC	SBIC	AMAH	AMA
$k = 0$	50	1.279	1.589	1.217	1.366	1.066	1.272
	70	1.031	1.178	0.976	1.087	0.921	1.024
	100	0.878	0.912	0.840	0.884	0.822	0.860
	150	0.634	0.602	0.615	0.601	0.597	0.605
	200	0.576	0.547	0.560	0.547	0.550	0.552
$k = 1$	50	1.206	1.259	1.128	1.088	0.875	0.970
	70	0.947	1.078	0.869	0.977	0.772	0.830
	100	0.771	0.941	0.719	0.872	0.678	0.710
	150	0.604	0.816	0.575	0.760	0.547	0.564
	200	0.534	0.691	0.514	0.647	0.497	0.504
$k = 1.5$	50	1.190	1.244	1.109	1.066	0.847	0.919
	70	0.921	1.061	0.838	0.951	0.732	0.782
	100	0.758	0.916	0.700	0.843	0.654	0.684
	150	0.605	0.777	0.572	0.727	0.534	0.549
	200	0.528	0.682	0.506	0.644	0.482	0.489

errors than the best estimator only by a small margin. On the other hand, when they dominate other estimators, they usually do so by a large margin. When $\sigma = 1.5$ (high noise levels), AMA performs better than AMAH, while the converse is observed when $\sigma = 0.4$ (low noise level), and the two estimators exhibit comparable performance when $\sigma = 1$ (moderate noise level). Without exception, the SAIC and SBIC estimators outperform their model selection counterparts, although both the SAIC and SBIC frequently exhibit inferior performance to the proposed AMA and AMAH estimators. In general, the ordinal rankings of the estimators are unaffected by the values of k.

We now consider the case where the covariates are certain, but the smoothing degree and the number of knots are uncertain. Specifically, we let $\alpha = 0$, and select the degree of smoothing and the number of knots from $\{1, 2, 3\}$ and $\{2, 3, \ldots, \textit{ceiling}\left((2n)^{1/5}\right) + 2\}$, respectively, where *ceiling* (A) denotes the smallest integer greater than or equal to A. Thus, there are $3\{\textit{ceiling}\left((2n)^{1/5}\right) + 1\}$ candidate models. Tables S.3–S.5 in the Supplementary Material, where the simulation results are reported, show that in the overwhelming majority of cases, the AMA estimator performs best. Either the AMAH or the SBIC estimator produces the second best estimates, and all of the AMA, AMAH, and SBIC estimators uniformly dominate the two model selection estimators. Although the SAIC estimator invariably yields more accurate estimates than the AIC estimator does, it can have inferior performance to the BIC estimator.

In addition, we considered cases where the error term follows nonnormal distributions, such as t distributions. The results (not reported here) show that the AMA estimator often performs the best, and the AMAH the second best. Furthermore, as suggested by a referee, we computed the average weights and selection frequencies of models by each method. The results are reported in Section S2 of the Supplementary Material.

4.2. Simulation for the dependent data case

Our simulation study is based on the following autoregressive process $\{y_t, t = 0, \pm 1, \ldots\}$:

$$y_t = \frac{-0.4(3 - y_{t-1}^2)}{1 + y_{t-1}^2} + \frac{0.6(3 - (y_{t-2} - 0.5)^3)}{1 + (y_{t-2} - 0.5)^4} + \alpha y_{t-10} + 0.1 e_t, \tag{4.2}$$

where $e_t = \rho e_{t-1} + \varepsilon_t$ and $\varepsilon_t \sim N(0,1)$. As in Subsection 4.1, we first consider the uncertainty of the choice of covariates. We set y_{t-1}, y_{t-2}, y_{t-3}, and y_{t-4} as potential covariates, and assume that all candidate models are in the form of the additive autoregressive model given in Section 3. This yields 2^4 candidate additive autoregressive models, with $y_t = b + e_t$ being the null model, where b is an intercept. When $\alpha = \rho = 0$, the process (4.2) reduces to the process considered by Huang and Yang (2004). In our simulations, we set $n = 80, 100, 200$ and $\alpha = 0.3, 0.4$ so that all candidate models are misspecified. As in Subsection 4.1, we set the polynomial degree to three and let the knots be equidistant. To assess the predictive performance of the methods, we calculate the squared prediction errors $(y_{n+1} - \tilde{y}_{n+1})^2$, averaged over 50,000 simulation trials, where $\tilde{y}_{n+1}$ is an estimator of y_{n+1}. Unlike the independent data case in Subsection 4.1, for which the results are based on 1,000 replications, a substantially larger number of replication trials are required here in order to obtain stable results.

The results, reported in Table 2 and Table S.6 in the Supplementary Material, show that in the majority of cases, the AMA estimator results in the best performance, with the AMAH estimator coming in a close second. In general, the values of α, ρ, and n have little effect on the ordinal ranking of the estimators, but they do have some bearing on the actual magnitudes of the squared prediction errors. As expected, as α increases, the prediction squared errors of all estimators increase, *ceteris paribus*. For most cases, the AIC (BIC) estimator is dominated by its model averaging counterpart. The BIC (SBIC) estimator is often preferred to the AIC (SAIC) estimator, although exceptions occur. For ex-

Table 2. Averaged squared prediction errors ($\times 10^{-1}$) under dependent data when covariate selection is subject to uncertainty and $\alpha = 0.3$.

	n	AIC	BIC	SAIC	SBIC	AMAH	AMA
$\rho = 0$	80	1.210	1.038	1.170	1.022	1.009	0.978
	100	0.921	0.873	0.903	0.858	0.825	0.819
	200	0.736	0.782	0.735	0.769	0.708	0.707
$\rho = 0.2$	80	1.136	0.997	1.100	0.978	0.953	0.928
	100	0.945	0.893	0.929	0.876	0.842	0.833
	200	0.793	0.840	0.793	0.827	0.758	0.756
$\rho = 0.4$	80	1.417	1.100	1.367	1.076	1.137	1.074
	100	1.034	0.947	1.019	0.932	0.921	0.908
	200	0.901	0.870	0.900	0.862	0.837	0.829

ample, when $n = 200$ and ρ is small, the AIC-based estimators may outperform their BIC-based counterparts.

We next consider uncertainty in the degree of smoothing within (4.2). We set $\alpha = 0$ and $\rho = 0, 0.2, 0.4$. The simulation results, reported in Table S.7 of the Supplementary Material, are again based on 50,000 simulation trials, and show that the AMA is uniformly the best estimator, followed by either the AMAH or the SBIC estimator. The worst estimates are always produced by the AIC estimator.

5. Empirical Data Applications

5.1. Example 1

In this subsection, we apply the proposed method to theophylline concentration data that are part of the “Theoph” data set from the R “datasets” package. Oral doses of theophylline are given to 12 individuals 11 times each, resulting in 132 observations. The response variable of interest is the theophylline concentration in the individual, labelled CON. The following are the covariates expected to influence CON: the amount of oral doses of theophylline administered to the individual, the time interval from drug administration to the time of sampling, and the weight of the individual. There are 2^3 combinations of these covariates, resulting in 2^3 candidate models. The basis of our analysis is the additive model (2.1). We set the polynomial degree to three, and let the knots be equidistant, with the number of knots equal to *ceiling* $\left((2n)^{1/5}\right) - 1$.

We consider all six estimators in the last section, and an alternative AMA estimator obtained with B^m in $P_m = B^m(B^{m\prime}B^m)^{-1}B^{m\prime}$ replaced by the regressor

Table 3. Results for Data Example 1.

n_1	AIC	BIC	SAIC	SBIC	AMAH	AMA	AMAli
80	0.458	0.430	0.442	0.430	0.417	0.421	0.953
100	0.413	0.409	0.405	0.410	0.385	0.390	0.942
120	0.386	0.402	0.391	0.403	0.375	0.377	0.941

matrix of the mth model. This essentially reduces the AM to a linear regression model, and as such, the corresponding model average estimator combines least squares estimators from linear regressions using (2.8) as the weight choice criterion. We refer to this estimator as AMAli, to distinguish it from the AMA and AMAH estimators that combine AMs. We randomly select $n_1 = 80, 100, 120$ observations from the sample as training data, and use the remaining $132 - n_1$ observations as test data. The following mean squared prediction error (MSPE) is used to gauge the performance of the estimators:

$$\frac{1}{(132 - n_1)} \sum_{i=1}^{132-n_1} \left(\mathrm{CON}_i - \widehat{\mathrm{CON}}_i\right)^2,$$

where CON_i and $\widehat{\mathrm{CON}}_i$ are the ith actual and predicted values, respectively, of CON in the test sample. We repeat the data splitting and estimation process 1,000 times, and compute the average of the MSPEs across the replications. The results are reported in Table 3.

The results show that regardless of the values of n_1, the AMAH and AMA estimators invariably deliver the best and second best estimates. In all cases, the AMAli estimator yields prediction outcomes that are inferior to those of other estimators by a large margin, which suggests that nonlinear AMs provide a more appropriate analytical framework than the linear model does for the data at hand.

5.2. Example 2

Our second data example is based on the "LakeHuron" data set from the R package "datasets". The objective is to forecast the level of Lake Huron, one of the five largest lakes in North America, using an additive autoregressive model. Data are available on the level (in feet) of the lake between 1875 and 1972, totaling 98 annual observations. We label the first difference of this time series as $\{y_t\}_{t=1}^{97}$. We let the maximum lag order be four. Thus, there are 2^4 candidate models, with the largest model being

$$y_t = g_1(y_{t-1}) + g_2(y_{t-2}) + g_3(y_{t-3}) + g_4(y_{t-4}) + e_t.$$

Table 4. Results for Data Example 2.

n_1	AIC	BIC	SAIC	SBIC	AMAH	AMA	AMAli
60	1.148	0.699	0.969	0.699	0.691	0.619	0.697
70	1.077	0.779	1.137	0.777	0.741	0.664	0.778
80	0.799	0.575	0.720	0.572	0.551	0.529	0.762

Here, $\{y_t\}_{t=g}^{n_1+k+g}(n_1 = 60, 70, 80, g = 1, \ldots, D)$ is used for model training and $y_{n_1+k+g+1}$ for prediction evaluation. We choose the same degree of smoothing and number of knots as in Subsection 5.1. We conduct $D = 97 - (n_1 + k + 1)$ one-step ahead predictions, with the forecast window being moved ahead by one observation each time. Table 4 presents the mean squared prediction error (MSPE), defined as $\sum_{t=n_1+k+2}^{97} (y_t - \hat{y}_t)^2 / D$, with $\hat{y}_t$ being the one-step ahead model average predictor of y_t.

We consider the same seven estimators as in the previous data example. Table 4 shows that in all cases, the AMA estimator yields the best predictions, followed by the AMAH estimator, whereas the AIC and SAIC estimators often deliver the worst forecasts. The AMAli estimator invariably performs worse than the AMA estimator; however, occasionally it outperforms the other selection and averaging estimators. This indicates that while the nonlinear additive autogressive model is a more appropriate analytical framework than the linear autoregressive model for this data set, functional form misspecification may be compensated for by a superior estimation technique.

6. Conclusion

We have proposed a plug-in model averaging approach for the nonparametric AM and the additive autoregressive model, and developed two estimators, the AMA and AMAH estimators. The numerical results support the use of model averaging in these models, and show that the AMA estimator is often a superior alternative to the AMAH estimator.

One aspect of the model specification that is not examined in our analysis is the assumption of a constant error variance. Extending the weight choice procedure and associated theories to the context of heteroscedastic disturbances is an area for future research. In addition, we emphasize the development of a weight choice method oriented toward improving efficiency with respect to point estimation. There is clearly a need to develop inference procedures based on the model averaging estimator. In this regard, the asymptotic distributions of some FMA estimators have been derived; see, for example, Hjort and Claeskens (2003), Liu (2015), and Zhang and Liu (2019). The asymptotic distribution theory for our proposed model averaging estimator deserves to be studied further. In addition, it would be interesting to study the adaptive estimation for unknown smoothness by model averaging (see Yang (2001) and Zhang, Lu and Zou (2013) for related results). This is left for future research.

Supplementary Material

The Supplementary Material contains additional simulation results (Tables S.1–S.15).

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A. Appendices

A.1. Lemma and its proof

Lemma 1. *If $\{e_t\}$ is mutually independent,*

$$\sup_{-\infty \leq t \leq \infty} E\{|e_t|^q\} < \infty, \tag{A.1}$$

for some $q \geq 2$, and

$$\max_{m \in \{1,\ldots,M\}, j \in s_{c_m}, i \in \{1,\ldots,q_j^m\}} E\left|B_{ji}^q(y_{t-j})\right| < \infty, \tag{A.2}$$

then

$$E\left[\max_{m \in \{1,\ldots,M\}} \left\|\frac{1}{\sqrt{n}} B^{m\prime} e\right\|^q\right] = O(r_M^{q/2}). \tag{A.3}$$

Proof of Lemma 1. Denote the t^{th} column of $B^{m\prime}$ as $B^m_{j \in s_{c_m}}(y_{t-j})$. Note that under Condition (A.2), there exists an $m^* \in \{1,\ldots,M\}$ such that

$$E\left[\max_{m \in \{1,\ldots,M\}} \left\|\frac{1}{\sqrt{n}} B^{m\prime} e\right\|^q\right]$$

$$
\begin{aligned}
&= E\left[\max_{m\in\{1,\ldots,M\}}\left\|\frac{1}{\sqrt{n}}\sum_{t=1}^{n}B^{m}_{j\in s_{c_m}}(y_{t-j})e_t\right\|^q\right]\\
&= E\left\{\sum_{j\in s_{c_{m^*}}}\sum_{i=1}^{q_j^{m^*}}\left(\frac{1}{\sqrt{n}}\sum_{t=1}^{n}B_{ji}(y_{t-j})e_t\right)^2\right\}^{q/2}\\
&\leq r_{m^*}^{q/2-1}\sum_{j\in s_{c_{m^*}}}\sum_{i=1}^{q_j^{m^*}}E\left|\frac{1}{\sqrt{n}}\sum_{t=1}^{n}B_{ji}(y_{t-j})e_t\right|^q\\
&\leq r_{m^*}^{q/2-1}\sum_{j\in s_{c_{m^*}}}\sum_{i=1}^{q_j^{m^*}}E\left|\frac{1}{n}\sum_{t=1}^{n}B^2_{ji}(y_{t-j})\right|^{q/2}\\
&\leq r_{m^*}^{q/2-1}\sum_{j\in s_{c_{m^*}}}\sum_{i=1}^{q_j^{m^*}}\frac{1}{n}\sum_{t=1}^{n}E\left|B^q_{ji}(y_{t-j})\right|\\
&\leq r_{m^*}^{q/2}\max_{j\in s_{c_{m^*}},i\in\{1,\ldots,q_j^{m^*}\}}E\left|B^q_{ji}(y_{t-j})\right|\\
&= O(r_M^{q/2}),
\end{aligned}
\tag{A.4}
$$

where the second inequality (on the fifth line of (A.4)) follows Condition (A.1) and Lemma 2 of Wei (1987) since $\{e_t, \varpi_t\}$ is a sequence of martingale differences with ϖ_t being the σ-algebra generated by $\{y_t, y_{t-1}, \ldots\}$. This completes the proof of Lemma 1.

A.2. Proof of Theorem 1

Note that

$$\phi_H(w) = \|Y - \hat{\mu}(w)\|^2 + 2\widehat{\sigma}_M^2\sum_{m=1}^{M}w_m r_m. \tag{A.5}$$

Hence we have

$$\phi(w) = \phi_H(w) + 2\widehat{\sigma}_M^2\sum_{m=1}^{M}w_m\left(\frac{nr_m}{n-r_m} - r_m\right). \tag{A.6}$$

From results of Wan, Zhang and Zou (2010), to prove (2.13) of Theorem 1, it suffices to show that

$$\sup_{w\in\mathcal{W}}\left[R^{-1}(w)\left|\phi_H(w) - R(w)\right|\right] = o_p(1) \tag{A.7}$$

and

$$\sup_{w\in\mathcal{W}}\left[R^{-1}(w)\left|\widehat{\sigma}^2_M\sum_{m=1}^{M}w_m\left(\frac{nr_m}{n-r_m}-r_m\right)\right|\right]=o_p(1). \tag{A.8}$$

Note that (A.7) can be verified from the proof of Theorem 2 in Wan, Zhang and Zou (2010). Now, let us consider (A.8). First, from Condition 2 and $E\|e\|^2=n\sigma^2=O(n)$, we have

$$\|Y\|\leq\|\mu\|+\|e\|=O_p(n^{1/2}). \tag{A.9}$$

Hence, by Condition 3,

$$\widehat{\sigma}^2_M=\frac{Y'(I_n-P_M)Y}{n-r_M}\leq\frac{\lambda_{\max}(I_n-P_M)\|Y\|^2}{n-r_M}=O_p(1). \tag{A.10}$$

Furthermore, by Condition 1,

$$\begin{aligned}&\sup_{w\in\mathcal{W}}\left[R^{-1}(w)\left|\widehat{\sigma}^2_M\sum_{m=1}^{M}w_m\left\{\frac{nr_m}{n-r_m}-r_m\right\}\right|\right]\\&\leq\xi_n^{-1}\widehat{\sigma}^2_M\frac{r_M^2}{n-r_M}\to 0.\end{aligned} \tag{A.11}$$

Therefore, (2.13) of Theorem 1 is true. In addition, by Wan, Zhang and Zou (2010) and (A.7), it is straightforward to show that (2.14) of Theorem 1 holds under Conditions 1–3. This completes the proof of Theorem 1.

A.3. Proof of Theorem 2

Denote $\epsilon_n=\xi_n^{1/2}n^{-1/2+\delta}$. By results of Fan and Peng (2004) and Chen et al. (2018), to prove (2.15) of Theorem 2, it suffices to show that there exists a constant C_0 such that for the $M\times 1$ vector $u=(u_1,\ldots,u_M)'$,

$$\lim_{n\to\infty}P\left(\inf_{\|u\|=C_0,(w^0+\epsilon_n u)\in\mathcal{W}}\phi(w^0+\epsilon_n u)>\phi(w^0)\right)=1. \tag{A.12}$$

This means that there exists a minimiser $\hat{w}$ in the set $\{w^0+\epsilon_n u:\|u\|\leq C_0,(w^0+\epsilon_n u)\in\mathcal{W}\}$ such that $\|\hat{w}-w^0\|=O_p\left(\epsilon_n\right)$.

Denote $\Omega_1=(\mu-\hat{\mu}_1,\ldots,\mu-\hat{\mu}_M)$. Let $\bar{\pi}=(\pi_1,\ldots,\pi_M)'$ with $\pi_m=nr_m/(n-r_m)$ for $1\leq m\leq M$. It is noted that

$$\begin{aligned}&\phi(w^0+\epsilon_n u)-\phi(w^0)\\&=\epsilon_n^2u'\Lambda u-2\epsilon_n w^{0\prime}\Omega_1'\Lambda_1 u-2e'P(\epsilon_n u)\mu-2e'P(\epsilon_n u)e+2\epsilon_n\widehat{\sigma}^2_M u'\bar{\pi}.\end{aligned} \tag{A.13}$$

As $\lambda_{\min}(\Lambda/n) > \kappa_1$ under Condition 4, we have

$$\epsilon_n^2 u'\Lambda u > \kappa_1 n\epsilon_n^2 \|u\|^2 > 0, \tag{A.14}$$

with probability approaching 1.

Recognising that $\|\Omega_1 w^0\| = O_p(\xi_n^{1/2})$ since $E\|\Omega_1 w^0\|^2 = E\|\mu - \hat{\mu}(w^0)\|^2 = \xi_n$, and $\|\Lambda_1\| = \lambda_{\max}^{1/2}(\Lambda) = O_p(n^{1/2})$ by Condition 4, we have

$$\begin{aligned}|\epsilon_n w^{0\prime}\Omega_1'\Lambda_1 u| &\le \epsilon_n \|\Lambda_1\|\|\Omega_1 w^0\|\|u\| \\ &= O_p(n^{1/2}\xi_n^{1/2}\epsilon_n)\|u\|. \end{aligned}\tag{A.15}$$

Hence, $\epsilon_n w^{0\prime}\Omega_1'\Lambda_1 u$ is dominated asymptotically by $\epsilon_n^2 u'\Lambda u$.

From Condition 5 and Lemma 1 for independent data cases,

$$\begin{aligned}&\max_{m\in\{1,\ldots,M\}} e'P_m e \\ &= \max_{m\in\{1,\ldots,M\}} \left\{e'B^m(B^{m\prime}B^m)^{-1}B^{m\prime}e\right\} \\ &\le \max_{m\in\{1,\ldots,M\}} \lambda_{\max}\left\{\left(\frac{B^{m\prime}B^m}{n}\right)^{-1}\right\} \max_{m\in\{1,\ldots,M\}} \left\|\frac{1}{\sqrt{n}}B^{m\prime}e\right\|^2 \\ &= O_p(r_M), \end{aligned}\tag{A.16}$$

which, together with (A.9), implies that

$$\max_{m\in\{1,\ldots,M\}} |e'P_m Y| \le \|Y\| \max_{m\in\{1,\ldots,M\}} \left(e'P_m e\right)^{1/2} = O_p(n^{1/2}r_M^{1/2}).$$

Hence,

$$\begin{aligned}|e'P(\epsilon_n u)\mu + e'P(\epsilon_n u)e| &= |e'P(\epsilon_n u)Y| \\ &\le \epsilon_n \|u\| \left(M \max_{m\in\{1,\ldots,M\}} |e'P_m Y|^2\right)^{1/2} \\ &\le O_p(n^{1/2}r_M^{1/2}M^{1/2}\epsilon_n)\|u\|. \end{aligned}\tag{A.17}$$

Using Condition 6, we have

$$\frac{n^{1/2}r_M^{1/2}M^{1/2}\epsilon_n}{n\epsilon_n^2} = \frac{n^{1/2}r_M^{1/2}M^{1/2}}{nn^{-1/2+\delta}\xi_n^{1/2}} = \frac{r_M^{1/2}M^{1/2}}{n^\delta \xi_n^{1/2}} = o(1), \tag{A.18}$$

and using (A.10),

$$|\epsilon_n \widehat{\sigma}_M^2 u'\bar{\pi}| \le \epsilon_n \widehat{\sigma}_M^2 \|(\pi_1, \ldots, \pi_M)'\|\|u\|$$

$$= \epsilon_n \widehat{\sigma}_M^2 \left(\sum_{m=1}^{M} (\pi_m)^2 \right)^{1/2} \|u\|$$
$$= O_p\left(\frac{n r_M M^{1/2}}{n - r_M} \epsilon_n \right) \|u\| = O_p\left(r_M M^{1/2} \epsilon_n \right) \|u\| . \qquad \text{(A.19)}$$

From (A.17), (A.19) and the first part of Condition 6, it is readily seen that $|\epsilon_n \widehat{\sigma}_M^2 u' \bar{\pi}|$ is dominated by $|e' P(\epsilon_n u) Y|$, and from (A.18), both of these terms are dominated asymptotically by $\epsilon_n^2 u' \Lambda u$. Thus, (2.15) of Theorem 2 is proved. Also, we see that (2.16) of Theorem 2 is true using the same proving steps. This completes the proof of Theorem 2.

A.4. Proof of Theorem 3

First, we consider (2.13). Note that

$$\begin{aligned}
\phi(w) &= \|Y - \hat{\mu}(w)\|^2 + 2\widehat{\sigma}_M^2 w' \bar{\pi} \\
&= \|\mu + e - \hat{\mu}(w)\|^2 + 2\widehat{\sigma}_M^2 w' \bar{\pi} \\
&= \|\mu - \hat{\mu}(w)\|^2 + 2e'(\mu - P(w)\mu - P(w)e) + \|e\|^2 + 2\widehat{\sigma}_M^2 w' \bar{\pi} \\
&= L(w) - 2e'P(w)\mu - 2e'P(w)e + \|e\|^2 + 2\mu' e + 2\widehat{\sigma}_M^2 w' \bar{\pi}. \qquad \text{(A.20)}
\end{aligned}$$

To prove (2.13), in light of the results of Wan, Zhang and Zou (2010), it suffices to show that

$$\sup_{w \in \mathcal{W}} \left[\tilde{R}^{-1}(w) \left| e' P(w) e \right| \right] = o_p(1), \qquad \text{(A.21)}$$
$$\sup_{w \in \mathcal{W}} \left[\tilde{R}^{-1}(w) \left| e' P(w) \mu \right| \right] = o_p(1), \qquad \text{(A.22)}$$
$$\sup_{w \in \mathcal{W}} \left[\tilde{R}^{-1}(w) \left| \widehat{\sigma}_M^2 w' \bar{\pi} \right| \right] = o_p(1), \qquad \text{(A.23)}$$

and

$$\sup_{w \in \mathcal{W}} \left[\tilde{R}^{-1}(w) \left| L(w) - \tilde{R}(w) \right| \right] = o_p(1). \qquad \text{(A.24)}$$

Let us consider (A.21). Note that

$$\begin{aligned}
&\sup_{w \in \mathcal{W}} \left[\tilde{R}^{-1}(w) \left| e' P(w) e \right| \right] \\
&\le \tilde{\xi}_n^{-1} \max_{m \in \{1,\ldots,M\}} e' P_m e \\
&= \tilde{\xi}_n^{-1} \max_{m \in \{1,\ldots,M\}} \left\{ e' B^m (B^{m\prime} B^m)^{-1} B^{m\prime} e \right\}
\end{aligned}$$

$$\begin{aligned}&\leq \tilde{\xi}_n^{-1} \max_{m\in\{1,\ldots,M\}} \lambda_{\max}\left\{\left(\frac{B^{m\prime}B^m}{n}\right)^{-1}\right\} \max_{m\in\{1,\ldots,M\}} \left\|\frac{1}{\sqrt{n}}B^{m\prime}e\right\|^2\\ &= O_p(r_M\tilde{\xi}_n^{-1}). \qquad (A.25)\end{aligned}$$

The last line of (A.25) is due to Conditions 7 and 8 and Lemma 1. Hence (A.21) is true under Condition 10. Similarly, we observe that

$$\begin{aligned}&\sup_{w\in\mathcal{W}}\left[\tilde{R}^{-1}(w)\left|e'P(w)\mu\right|\right]\\ &\leq \tilde{\xi}_n^{-1} \max_{m\in\{1,\ldots,M\}}\left(e'P_m\mu\mu'P_me\right)^{1/2}\\ &\leq \|\mu\|\tilde{\xi}_n^{-1} \max_{m\in\{1,\ldots,M\}}\left(e'P_me\right)^{1/2}\\ &= O_p(r_M^{1/2}n^{1/2}\tilde{\xi}_n^{-1}), \qquad (A.26)\end{aligned}$$

where the equality on the last line of (A.26) is due to (A.25) and Condition 9. Hence (A.22) is also true by virtue of (A.26) and Condition 10.

From (A.9) and (A.10), we can see that (A.23) is valid because

$$\begin{aligned}&\sup_{w\in\mathcal{W}}\left[\tilde{R}^{-1}(w)\left|\widehat{\sigma}_M^2 w'\bar{\pi}\right|\right]\\ &\leq \tilde{\xi}_n^{-1}\widehat{\sigma}_M^2\frac{\max_{m\in\{1,\ldots,M\}} nr_m}{n-r_m}\\ &= O_p(r_M\tilde{\xi}_n^{-1}) = o_p(1) \qquad (A.27)\end{aligned}$$

by virtue of Condition 10.

Now, note that

$$\begin{aligned}L(w)-\tilde{R}(w) &= \|\mu-P(w)\mu-P(w)e\|^2-\tilde{R}(w)\\ &= \|A(w)\mu-P(w)e\|^2-\tilde{R}(w)\\ &= e'P^2(w)e-2\mu'A(w)P(w)e-\sigma^2 tr\left\{P^2(w)\right\}. \qquad (A.28)\end{aligned}$$

Furthermore, we see from (A.25) that

$$\begin{aligned}&\sup_{w\in\mathcal{W}}\left[\tilde{R}^{-1}(w)e'P^2(w)e\right]\\ &\leq \sup_{w\in\mathcal{W}}\lambda_{\max}\left\{P(w)\right\}\sup_{w\in\mathcal{W}}\left[\tilde{R}^{-1}(w)e'P(w)e\right]\\ &= \left\{\max_{m\in\{1,\ldots,M\}}\lambda_{\max}\left(P_m\right)\right\}\sup_{w\in\mathcal{W}}\left[\tilde{R}^{-1}(w)e'P(w)e\right]\end{aligned}$$

$$\le \sup_{w\in\mathcal{W}} \left[\tilde{R}^{-1}(w)e'P(w)e\right] = O_p(r_M\tilde{\xi}_n^{-1}), \tag{A.29}$$

$$\begin{aligned}
&\sup_{w\in\mathcal{W}} \left[\tilde{R}^{-1}(w)\left|\mu' A(w)P(w)e\right|\right]\\
&\le \tilde{\xi}_n^{-1/2} \sup_{w\in\mathcal{W}} \left[\tilde{R}^{-1}(w)\left|e'P(w)A(w)\mu\mu' A(w)P(w)e\right|\right]^{1/2}\\
&= \|\mu\|\tilde{\xi}_n^{-1/2} \sup_{w\in\mathcal{W}} \left[\lambda_{\max}^{1/2}\left\{P(w)\right\}\lambda_{\max}\left\{A(w)\right\}\right] \sup_{w\in\mathcal{W}} \left[\tilde{R}^{-1}(w)e'P(w)e\right]^{1/2}\\
&= O(n^{1/2}\tilde{\xi}_n^{-1/2}) \sup_{w\in\mathcal{W}} \left[\tilde{R}^{-1}(w)e'P(w)e\right]^{1/2}\\
&= O_p(n^{1/2}\tilde{\xi}_n^{-1/2}r_M^{1/2}\tilde{\xi}_n^{-1/2}) = O_p(n^{1/2}r_M^{1/2}\tilde{\xi}_n^{-1}),
\end{aligned} \tag{A.30}$$

and

$$\begin{aligned}
&\sup_{w\in\mathcal{W}} \left[\tilde{R}^{-1}(w)tr\left\{P^2(w)\right\}\right]\\
&\le \tilde{\xi}_n^{-1} \max_{m,l\in\{1,\ldots,M\}} tr\left(P_mP_l\right)\\
&\le \tilde{\xi}_n^{-1} \max_{m,l\in\{1,\ldots,M\}} \left\{\lambda_{\max}\left(P_mP_l\right)\mathrm{rank}\left(P_mP_l\right)\right\}\\
&\le \tilde{\xi}_n^{-1} \max_{m,l\in\{1,\ldots,M\}} \left\{\lambda_{\max}\left(P_m\right)\lambda_{\max}\left(P_l\right)\mathrm{rank}\left(P_m\right)\right\}\\
&= O_p(r_M\tilde{\xi}_n^{-1}).
\end{aligned} \tag{A.31}$$

Together with Condition 10, these results imply that (A.24) and hence (2.13) are correct. Following the above proving steps, it is readily seen that (2.14) is also true. This completes the proof of Theorem 3.

A.5. Proof of Theorem 4

By Condition 7, (A.3) holds for $q = 2$. The remaining steps for proving Theorem 4 are nearly identical to those for proving Theorem 2, and thus are omitted for brevity.

A.6. Proof of Theorem 5

To prove Theorem 5, we first show that

$$\frac{1}{\sqrt{n}}\sum_{t=1}^{n} B_{ji}(y_{t-j})e_t = O_p(1), \tag{A.32}$$

uniformly for i and j. Note that

$$\begin{aligned}
&\left|\frac{1}{\sqrt{n}}\sum_{t=1}^{n} B_{ji}(y_{t-j})e_t\right| \\
&\leq \left|\frac{1}{\sqrt{n}}\sum_{t=1}^{n}\left[B_{ji}(y_{t-j})e_t - E\left\{B_{ji}(y_{t-j})e_t\right\}\right]\right| + \left|\sqrt{n}E\{B_{ji}(y_{t-j})e_t\right\}|. \quad \text{(A.33)}
\end{aligned}$$

By Condition 13, in order to prove (A.32), it suffices to verify that

$$Var\left(\frac{1}{\sqrt{n}}\sum_{t=1}^{n} B_{ji}(y_{t-j})e_t\right) \leq C, \tag{A.34}$$

uniformly for i and j. The proof of (A.34) is similar to that of Gao (2015). We first write

$$\begin{aligned}
&Var\left(\frac{1}{\sqrt{n}}\sum_{t=1}^{n} B_{ji}(y_{t-j})e_t\right) \\
&= \frac{1}{n}\sum_{t=1}^{n} Var\left(B_{ji}(y_{t-j})e_t\right) + \frac{2}{n}\sum_{t=1}^{n-1}\sum_{s=1}^{n-t} Cov(B_{ji}(y_{t-j})e_t, B_{ji}(y_{t-j+s})e_{t+s}). \quad \text{(A.35)}
\end{aligned}$$

Since $\{y_t, e_t\}$ is α-mixing with size $-\gamma/(\gamma-2)$, $\{B_{ji}(y_{t-j})e_t\}$ is also α-mixing with the same size (White (1984)). From results by Davydov (1968) and Gao (2015), we have

$$\begin{aligned}
&\left|Cov\left(B_{ji}(y_{t-j})e_t, B_{ji}(y_{t-j+s})e_{t+s}\right)\right| \\
&\leq 12\left[E\left|B_{ji}(y_{t-j})e_t\right|^{\gamma}\right]^{1/\gamma}\left[E\left|B_{ji}(y_{t-j+s})e_{t+s}\right|^{\gamma}\right]^{1/\gamma}\alpha(s)^{1-2/\gamma} \\
&\leq C\alpha(s)^{1-2/\gamma}, \qquad \text{(A.36)}
\end{aligned}$$

uniformly for i and j under Condition 12, where the mixing coefficient $\alpha(s) = O(s^{-\gamma/(\gamma-2)-\delta})$ with $\delta > 0$ by Condition 11. Therefore,

$$\begin{aligned}
&\sum_{s=1}^{n-t}\left|Cov\left(B_{ji}(y_{t-j})e_t, B_{ji}(y_{t-j+s})e_{t+s}\right)\right| \\
&\leq C\sum_{s=1}^{\infty} s^{-1-\delta(\gamma-2)/\gamma} \leq C, \qquad \text{(A.37)}
\end{aligned}$$

implying that the second term on the right-hand side of (A.35) is bounded. In addition, the boundedness of the first term on the right-hand side of (A.35) is implied by Condition 12. Hence, (A.34) and therefore (A.32) are true.

In light of (A.4) and (A.32), we have

$$\begin{aligned}
&\max_{m\in\{1,\dots,M\}} \left\| \frac{1}{\sqrt{n}} B^{m\prime} e \right\|^2 \\
&= \max_{m\in\{1,\dots,M\}} \sum_{j\in s_{c_m}} \sum_{i=1}^{q_j^m} \left| \frac{1}{\sqrt{n}} \sum_{t=1}^{n} B_{ji}(y_{t-j}) e_t \right|^2 \\
&= O_p(r_M). \qquad \text{(A.38)}
\end{aligned}$$

Together with the steps for proving Theorem 3, this implies that Theorem 5 is true.

A.7. Proof of Theorem 6

Theorem 6 follows from (A.38) and the proof of Theorem 2. The details are omitted for brevity.

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