Mixture Regression Model for Incomplete Data

**Loc Nguyen1****\*, Anum Shafiq2**

1 Advisory Board, Loc Nguyen’s Academic Network, An Giang, Vietnam

2 Department of Mathematics and Statistics, Preston University Islamabad, Islamabad, Pakistan

**Email Address**

[ng\_phloc@yahoo.com](mailto:ng_phloc@yahoo.com) (L. Nguyen), anumshafiq@ymail.com (A. Shafiq)

\*Correspondence: [Timothy.Schmutte@yale.edu](file:///C:\Users\Administrator\Desktop\精排文章\ITS%2020180709%20确认稿\EM_SP100120180705\Timothy.Schmutte@yale.edu)

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**Abstract:**

The Regression Expectation Maximization (REM) algorithm, which is a variant of Expectation Maximization (EM) algorithm, uses parallelly a long regression model and many short regression models to solve the problem of incomplete data. Experimental results proved resistance of REM to incomplete data, in which accuracy of REM decreases insignificantly when data sample is made sparse with loss ratios up to 80%. However, as traditional regression analysis methods, the accuracy of REM can be decreased if data varies complicatedly with many trends. In this research, we propose a so-called Mixture Regression Expectation Maximization (MREM) algorithm. MREM is the full combination of REM and mixture model in which we use two EM processes in the same loop. MREM uses the first EM process for exponential family of probability distributions to estimate missing values as REM does. Consequently, MREM uses the second EM process to estimate parameters as mixture model method does. The purpose of MREM is to take advantages of both REM and mixture model. Experimental results show that MREM is more accurate than REM.

**Keywords:**

Regression Model, Mixture Regression Model, Expectation Maximization Algorithm, Incomplete Data

1. **Introduction**

As a convention, regression model is a linear regression function *Z = α*0 *+ α*1*X*1 *+ α*2*X*2 *+ … + αnXn* in which variable *Z* is called response variable or dependent variable whereas each *Xi* is called regression variable, regressor, predictor, regression variable, or independent variable. Each *αi* is called regression coefficient. The essence of regression analysis is to calculate regression coefficients from data sample. When sample is complete, these coefficients are determined by least squares method [1, pp. 452-458]. When sample is incomplete, there are some approximation approaches to estimate regression coefficients such as complete case method, ad-hoc method, multiple imputation, maximum likelihood, weighting method, and Bayesian method [2]. We focus on applying expectation maximization (EM) algorithm into constructing regression model in case of missing data with note that EM algorithm belongs to maximum likelihood approach. In previous research [3], we proposed a so-called Regression Expectation Maximization (REM) algorithm to learn linear regression function from incomplete data in which some values of *Z* and *Xi* are missing. REM is a variant of EM algorithm, which is used to estimate regression coefficients. Experimental results in previous research [3] proved that accuracy of REM decreases insignificantly whereas loss ratios increase significantly. We hope that REM is accepted as a new standard method for regression analysis in case of missing data when there are currently 6 standard approaches such as complete case method, ad-hoc method, multiple imputation, maximum likelihood, weighting method, and Bayesian method [2]. Here we combine REM and mixture model to improve the accuracy, especially in case that data is incomplete and has many trends. Our proposed algorithm is called Mixture Regression Expectation Maximization (MREM) algorithm. The purpose of MREM is to take advantages of both REM and mixture model. Experimental results mentioned later show that MREM is more accurate than REM. Because this research is the successive one after our previous research [3], they share some common contents related to research survey and experimental design, but we confirm that their methods are not coincide although MREM is derived from REM.

Because MREM is the combination of REM and mixture model whereas REM is a variant of EM algorithm, we need to survey some works related to application of EM algorithm to regression analysis. Kokic [4] proposed an excellent method to calculate expectation of errors for estimating coefficients of multivariate linear regression model. In Kokic’s method, response variable *Z* has missing values. Ghitany, Karlis, Al-Mutairi, and Al-Awadhi [5] calculated the expectation of function of mixture random variable in the expectation step of EM algorithm and then used such expectation for estimating parameters of multivariate mixed Poisson regression model in the maximization step. Anderson and Hardin [6] used reject inference technique to estimate coefficients of logistic regression model when response variable *Z* is missing but characteristic variables (regressors *Xi*) are fully observed. Anderson and Hardin replaced missing *Z* by its conditional expectation on regressors *Xi* where such expectation is logistic function. Zhang, Deng, and Su [7] used EM algorithm to build up linear regression model for studying glycosylated hemoglobin from partial missing data. In other words, Zhang, Deng, and Su [7] aim to discover relationship between independent variables (predictors) and diabetes.

Besides EM algorithm, there are other approaches to solve the problem of incomplete data in regression analysis. Haitovsky [8] stated that there are two main approaches to solve such problem. The first approach is to ignore missing data and to apply the least squares method into observations. The second approach is to calculate covariance matrix of regressors and then to apply such covariance matrix into constructing the system of normal equations. Robins, Rotnitzki, and Zhao [9] proposed a class of inverse probability of censoring weighted estimators for estimating coefficients of regression model. Their approach is based on the dependency of mean vector of response variable *Z* on vector of regressors *Xi* when *Z* has missing values. Robins, Rotnitzki, and Zhao [9] assumed that the probability *λit*(*α*) of existence of *Z* at time point *t* is dependent on existence of *Z* at previous time point *t*–1 but independent from *Z*. Even though *Z* is missing, the probability *λit*(*α*) is also determined and so regression coefficients are calculated based on the inverse of *λit*(*α*) and *Xi*. The inverse of *λit*(*α*) is considered as weight for complete case. Robins, Rotnitzki, and Zhao used additional time-dependent covariates *Vit* to determine *λit*(*α*).

In the article “Much ado about nothing: A comparison of missing data methods and software to fit incomplete data regression models”, Horton and Kleinman [2] classified 6 methods of regression analysis in case of missing data such as complete case method, ad-hoc method, multiple imputation, maximum likelihood, weighting method, and Bayesian method. EM algorithm belongs to maximum likelihood method. According to complete case method, regression model is learned from only non-missing values of incomplete data [2, p. 3]. The ad-hoc method refers missing values to some common value, creates an indicator of missingness as new variable, and finally builds regression model from both existent variables and such new variable [2, p. 3]. Multiple imputation method has three steps. Firstly, missing values are replaced by possible values. The replacement is repeated until getting an enough number of complete datasets. Secondly, some regression models are learned from these complete datasets as usual [2, p. 4]. Finally, these regression models are aggregated together. The maximum likelihood method aims to construct regression model by maximizing likelihood function. EM algorithm is a variant of maximum likelihood method, which has two steps such as expectation step (E-step) and maximization step (M-step). In E-step, multiple entries are created in an augmented dataset for each observation of missing values and then probability of the observation is estimated based on current parameter [2, p. 6]. In M-step, regression model is built from the augmented dataset. The REM algorithm proposed in this research is different from the traditional EM for regression analysis because we replace missing values in E-step by expectation of sufficient statistics via mutual balance process instead of estimating the probability of observation. The weighting method determines the probability of missingness and then uses such probability as weight for the complete case. The aforementioned research of Robins, Rotnitzki, and Zhao [9] belongs to the weighting approach. Instead of replacing missing values by possible values like imputation method does, the Bayesian method imputes missing values by the estimation with a prior distribution on the covariates and the close relationship between the Bayesian approach and maximum likelihood method [2, p. 7].

Recall that MREM is the combination of REM and mixture model and so we need to survey other works related to regression model with support of mixture model. As a convention, such regression model is called mixture regression model. In literature, there are two approaches of mixture regression model:

* The first approach is to use logistic function to estimate the mixture coefficients.
* The second approach is to construct a joint probability distribution as product of the probability distribution of response variable *Z* and the probability distribution of independent variables *Xi*.

According to the first approach [10], the mixture probability distribution is formulated as follows:

Where Θ = (*αk*, *σk*2)*T* is compound parameter whereas *αk* and *σk*2 are regression coefficients and variance of the partial (component) probability distribution *Pk*(*Z*|*αkTX*, *σk*2). Note, mean of *Pk*(*Z*|*αkTX*, *σk*2) is *αkTX* and mixture coefficients are *ck*. In the first approach, regression coefficients *αk* are estimated by least squares method whereas mixture coefficients are estimated by logistic function as follows [10, p. 4]:

The mixture regression model is:

According to the second approach, the joint distribution is defined as follows [11, p. 4]:

Where *αk* are regression coefficients and *σk*2 is variance of the conditional probability distribution *Pk*(*Z*|*αkTX*, *σk*2) whereas *μk* and Σ*k* are mean vector and covariance matrix of the prior probability distribution *Pk*(*X*| *μk*, Σ*k*), respectively. The mixture regression model is [11, p. 6]:

Where,

The joint probability can be defined by different way as follows [12, p. 21], [13, p. 24], [14, p. 4]:

Where *mk*(*X*) and *σk*2 are mean and variance of *Z* given the conditional probability distribution *Pk*(*Z*|*mk*(*X*), *σk*2) whereas *μkX* and Σ*kX* are mean vector and covariance matrix of *X* given the prior probability distribution *Pk*(*X*| *μk*, Σ*k*). When *μkX* and Σ*kX* are calculated from data, other parameters *mk*(*X*) and *σk*2 are estimated for each *k*th component as follows [12, p. 23], [13, p. 25], [14, p. 5]:

For each *k*th component, *μkZ* is sample mean of *Z*, Σ*kZX* is vector of covariances of *Z* and *X*, and Σ*kZZ* is sample variance of *Z*. The mixture regression model becomes [13, p. 25]:

Where,

Grün & Leisch [15] mentioned the full application of mixture model into regression model in which regression coefficients are determined by inverse function of mean of conditional probability distribution as follows:

In general, the two approaches in literature do not implement regression mixture model according to EM process in full. They aim to simplify the estimation process in which mixture coefficients *ck* and regression coefficients *αk* are estimated one time. Note that EM process is an iterative process in which parameters are improved gradually until convergence. The EM process is slow, but it can balance many factors to reach most optimal parameters. Here we proposed a so-called Mixture Regression Expectation Maximization (MREM) which is the full combination of REM [3] and mixture model in which we use two EM processes in the same loop. Firstly, we use the first EM process for exponential family of probability distributions to estimate missing values as REM does. Secondly, we use the second EM process to estimate parameters as the full mixture model method does. Anyway, MREM supports fully EM mixture model.

In general, the ideology of combination of regression analysis and mixture model which produces mixture regression is not new, but our proposed MREM is different from methods in literature because of followings:

* MREM does not use the joint probability distribution. In other words, MREM does not concern the probability distribution of independent variables *Xi*. MREM does not either use logistic function to estimate mixture coefficients as the first approach does.
* MREM is the full combination of REM [3] and mixture model in which we use two EM processes in the same loop for estimating missing values and parameters.
* Variance *σk*2 and regression coefficient *αk* of the probability *Pk*(*Z*|*αkTX*, *σk*2) in MREM are estimated and balanced by both full mixture model and maximum likelihood estimation (MLE).
* Mixture regression models in literature are learned from complete data whereas MREM supports incomplete data.

The methodology of MREM is described in section 2. Section 3 includes experimental results and discussions. Section 4 is the conclusion.

1. **Methodology**

The probabilistic Mixture Regression Model (MRM) is a combination of normal mixture model and linear regression model. In MRM, the probabilistic Entire Regression Model (ERM) is sum of *K* weighted probabilistic Partial Regression Models (PRMs). Equation (1) specifies MRM [16, p. 3].

|  |  |
| --- | --- |
|  | (1) |

Where,

Note, Θ is called entire parameter,

The superscript “*T*” denotes transposition operator in vector and matrix. In equation (1), the probabilistic distribution *P*(*zi*|Θ) represents the ERM where *zi* is the response variable, dependent variable, or outcome variable. The probabilistic distribution *Pk*(*zi*|*Xi*, *αk*, *σk*2) represents the *k*th PRM *zi* = *αk*0 *+ αk*1*xi*1 *+ αk*2*xi*2 *+ … + αknxin* with suppose that each *zi* conforms to normal distribution according to equation (2) with mean *μk* = *αkTXi* and variance *σk*2.

|  |  |
| --- | --- |
|  | (2) |

The parameter *αk* = (*αk*0, *αk*1,…, *αkn*)*T* is called the *k*th Partial Regression Coefficient (PRC) and *Xi* = (1, *xi*1, *xi*2,…, *xin*)*T* is data vector. Each *xij* in every PRM is called a regressor, predictor, or independent variable.

In equation (1), each mixture coefficient *ck* is the prior probability that any *zi* belongs to the *k*th PRM. Let *Y* be random variable representing PRMs, *Y* = 1, 2,…, *K*. The mixture coefficient *ck* is also called the *k*th weight, which is defined by equation (3). Of course, there are *K* mixture coefficients, *K* PRMs, and *K* PRCs.

|  |  |
| --- | --- |
|  | (3) |

For each *k*th PRM, suppose each has an inverse regression model (IRM) *xij* = *βkj*0 *+ βkj*1*zi*. In other words, *xij* now is considered as the random variable conforming to normal distribution according to equation (4) [17, p. 8].

|  |  |
| --- | --- |
|  | (4) |

Where *βkj* = (*βkj*0, *βkj*1)*T* is an inverse regression coefficient (IRC) and (1, *zi*)*T* becomes an inverse data vector. The mean and variance of each *xij* with regard to the inverse distribution *Pkj*(*xij*|*zi*, *βkj*) are *βkjT*(1, *zi*)*T* and *τkj*2, respectively. Of course, for each *k*th PRM, there are *n* IRMs *Pkj*(*xij*|*zi*, *βkj*) and *n* associated IRCs *βkj*. Totally, there are *n*\**K* IRMs associated with *n*\**K* IRCs.

In this research, we focus on estimating the entire parameter Θ = (*ck*, *αk*, *σk*2, *βkj*)*T*. In other words, we aim to estimate *ck*, *αk*, *σk*2, and *βkj* for determining the ERM in case of missing data. As a convention, let Θ\* = (*ck*\*, *αk*\*, (*σk*2)\*, *βkj*\*)*T* be the estimate of Θ = (*ck*, *αk*, *σk*2, *βkj*)*T*, respectively. Let ***D*** = (***X***, ***Z***) be collected sample in which ***X*** is a set of regressors and ***Z*** is a set of outcome variables plus values 1, respectively [17, p. 8] with note that both ***X*** and ***Z*** are incomplete. In other words, ***X*** and ***Z*** have missing values. As a convention, let *zi*– and *xij*– denote missing values of ***Z*** and ***X***, respectively.

|  |  |
| --- | --- |
|  | (5) |

The expectation of sufficient statistic *zi* regard to the *k*th PRM *Pk*(*zi*|*Xi*, *αk*, *σk*2) is specified by equation (6) [3].

|  |  |
| --- | --- |
|  | (6) |

Where *xi*0=1 for all *i*. The expectation of the sufficient statistic *xij* with regard to each IRM *Pkj*(*xij*|*zi*, *βj*) of the *k*th PRM *Pk*(*zi*|*Xi*, *αk*, *σk*2) is specified by equation (7) [3].

|  |  |
| --- | --- |
|  | (7) |

Please pay attention to equations (6) and (7) because missing values of data ***X*** and data ***Z*** will be estimated by these expectations later.

Because ***X*** and ***Z*** are incomplete, we apply expectation maximization (EM) algorithm into estimating Θ\* = (*ck*\*, *αk*\*, (*σk*2)\*, *βkj*\*)*T*. According to [18], EM algorithm has many iterations and each iteration has expectation step (E-step) and maximization step (M-step) for estimating parameters. Given current parameter Θ(*t*) = (*ck*(*t*), *αk*(*t*), (*σk*2)(*t*), *βkj*(*t*))*T* at the *t*th iteration, missing values *zi*– and *xij*– are calculated in E-step so that ***X*** and ***Z*** become complete. In M-step, the next parameter Θ(*t*+1) = (*ck*(*t*+1), *αk*(*t*+1), (*σk*2)(*t*+1), *βkj*(*t*+1))*T* is determined based on the complete data ***X*** and ***Z*** fulfilled in E-step. Here we proposed a so-called Mixture Regression Expectation Maximization (MREM) which is the full combination of Regression Expectation Maximization (REM) algorithm [3] and mixture model in which we use two EM processes in the same loop. Firstly, we use the first EM process for exponential family of probability distributions to estimate missing values in E-step. The technique is the same to the technique of REM in previous research [3]. Secondly, we use the second EM process to estimate Θ\* for full mixture model in M-step.

Firstly, we focus on fulfilling missing values in E-step. The most important problem in our research is how to estimate missing values *zi*– and *xij*–. Recall that, for each *k*th PRM, every missing value *zi*– is estimated as the expectation based on the current parameter *αk*(*t*), according to equation (6) [3].

Note, *xi*0 = 1. Let *Mi* be a set of indices of missing values *xij*– with fixed *i* for each *k*th PRM. In other words, if then, *xij* is missing. The set *Mi* can be empty. The equation (6) is re-written for each *k*th PRM as follows [3]:

According to equation (7), missing value *xij*– is estimated by [3]:

Combining equation (6) and equation (7), we have [3]:

It implies [3]:

As a result, equation (8) is used to estimate or fulfill missing values for each *k*th PRM [3].

|  |  |
| --- | --- |
|  | (8) |

Now in M-step we use EM algorithm again to estimate the next parameter Θ(*t*+1) = (*ck*(*t*+1), *αk*(*t*+1), (*σk*2)(*t*+1), *βkj*(*t*+1))*T* with current known parameter Θ(*t*) = (*ck*(*t*), *αk*(*t*), (*σk*2)(*t*), *βkj*(*t*+1))*T* given data ***X*** and data ***Z*** fulfilled in E-step. The conditional expectation *Q*(Θ| Θ(*t*)) with unknown Θ is determined as follows [16, p. 4]:

The next parameter Θ(*t*+1) is an constrained optimizer of *Q*(Θ| Θ(*t*)). This is the optimization problem.

By applying Lagrange method, each next mixture coefficient *ck*(*t*+1) is specified by equation (9) [16, p. 7].

|  |  |
| --- | --- |
|  | (9) |

Where *P*(*Y*=*k* | *Xi*, *zi*, *αk*(*t*), (*σk*2)(*t*)) is specified equation (10) [16, p. 3]. It is the conditional probability of the *k*th PRM given *Xi* and *zi*. Please pay attention to this important probability. Appendix A1 is the proof of equation (10).

|  |  |
| --- | --- |
|  | (10) |

Note, *Pk*(*zi*|*Xi*, *αk*(*t*), (*σk*2)(*t*)) is determined by equation (2).

By applying Lagrange method, each next regression coefficient *αk*(*t*+1) is solution of equation (11) [16, p. 7].

|  |  |
| --- | --- |
|  | (11) |

Where **0** = (0, 0,…, 0)*T* is zero vector and *P*(*Y*=*k* | *Xi*, *zi*, *αk*(*t*), (*σk*2)(*t*)) is specified equation (10). Equation (11) is equivalent to equation (12):

|  |  |
| --- | --- |
|  | (12) |

Let,

Note,

The left-hand side of equation (12) becomes:

Where ***U***(*t*) is specified by equation (13).

|  |  |
| --- | --- |
|  | (13) |

Let,

Note,

The right-hand side of equation (12) becomes:

Where *Vi*(*t*) is specified by equation (14).

|  |  |
| --- | --- |
|  | (14) |

Equation (12) becomes:

Which is equivalent to the following equation:

As a result, the next regression coefficient *αk*(*t*+1), which is solution of equation (11), is specified by equation (15).

|  |  |
| --- | --- |
|  | (15) |

Where ***X***, ***U***(*t*), and *Vi*(*t*) are specified by equations (5), (13), and (14), respectively. The proposed equation (15) is most important in this research because it is the integration of least squares method and mixture model. If we think deeply, it is the key to combine REM and mixture model. In other words, it is the key to combine two EM processes in the same loop.

By applying Lagrange method, each next partial variance (*σk*2)(*t*+1) is specified by equation (16) [16, p. 7].

|  |  |
| --- | --- |
|  | (16) |

Where *P*(*Y*=*k* | *zi*, *αk*(*t*), (*σk*2)(*t*)) is specified by equation (10) and *αk*(*t*+1) is specified by equation (15). Appendix A2 is the proof of equations (9), (11), and (16).

By using maximum likelihood estimation (MLE) method [17, pp. 8-9], we retrieve equation (17) to estimate each next IRC *βkj*(*t*+1) [1, p. 457].

|  |  |
| --- | --- |
|  | (17) |

Where ***Z*** and *Xj* are specified in equation (5). Not ***Z*** and *Xj* are fulfilled in E-step. In general, MREM is the full combination of REM and mixture model in which two EM process are applied into the same loop of E-step and M-step. These steps are described in Table 1.

***Table 1.*** *Mixture Regression Expectation Maximization (MREM) Algorithm.*

|  |
| --- |
| 1. E-step: This is the first EM process. Missing values *zi*– and *xij*– for each *k*th PRM are fulfilled by equation (8) given current parameter Θ(*t*). 2. M-step: This is the second EM process. The next parameter Θ(*t*+1) is determined by equations (9), (15), (16), and (17) and the complete data (***X****k*, ***Z****k*) fulfilled in E-step. Please pay attention that each *k*th PRM owns the particular complete data (***X****k*, ***Z****k*). In other words, original sample (***X***, ***Z***) has *K* complete versions (***X****k*, ***Z****k*) fulfilled in E-step for *K* PRMs. Note, such *K* complete versions are changed over each iteration. Of course, ***U***k(*t*) is the *k*th version of ***U****k* and *Vki*(*t*) is the *k*th version of *Vi*(*t*).   Where,  The next parameter Θ(*t*+1) becomes current parameter in the next iteration. |

EM algorithm stops if at some *t*th iteration, we have Θ(*t*) = Θ(*t*+1) = Θ*\**. At that time, Θ\* = (*ck*\*, *αk*\*, (*σk*2)\*, *βkj*\*) is the optimal estimate of EM algorithm. Note, Θ(1) at the first iteration is initialized arbitrarily. Here MREM stops if ratio deviation between Θ(*t*) and Θ(*t*+1) is smaller than a small enough terminated threshold *ε* > 0 or MREM reaches a large enough number of iterations. The smaller the terminated threshold is, the more accurate MREM is. MREM uses both the terminated threshold *ε* = 0.1% = 0.001 and the maximum number of iterations (10000). The maximum number of iterations prevents MREM from running for a long time.

We use the complete case method mentioned in [2, p. 3] to improve the convergence of MREM. The parameters (*αk*(1), *βkj*(1))*T* at the first iteration of EM process are initialized in proper way instead that they are initialized in arbitrary way [19]. Let ***X****k*’ be the complete matrix, which is created by removing all rows whose values are missing from ***X****k*. Similarly, let ***Z****k*’ be the complete matrix, which is created by removing rows whose weights are missing from ***Z****k*. The advanced parameters (*αk*(1), *βkj*(1))*T* are initialized by equation (18) [1, p. 457].

|  |  |
| --- | --- |
|  | (18) |

Where *Zk*’ is the complete vector of non-missing outcome values for each *k*th PRM and *Xkj*’ is the complete column vector of non-missing regressor values for each *k*th PRM.

The evaluation of MREM follows fully mixture model. For example, given input data vector *X*0 = (*x*01, *x*02,…, *x*0*n*), let *z*1, *z*2,…, *zK* are values evaluated from *K* PRMs with optimal PRCs *αk*\* resulted from MREM shown in Table 1.

|  |  |
| --- | --- |
|  | (19) |

Where *x*00 = 1. The final evaluation *z* is calculated based on mixture coefficients as seen in equation (20).

|  |  |
| --- | --- |
|  | (20) |

Where each *zk* is calculated by equation (19) before. Note, *wk*(*X*) is a function of *X*, which is considered as the weight of *zk*. In fact, it is the conditional probability of the *k*th PRM given *X* and it is re-computed whenever *z* is evaluated. Equation (21) specifies *wk*(*X*), which is a variant of equation (10).

|  |  |
| --- | --- |
|  | (21) |

Where *ck*\*, *αk*\*, and (*σk*2)\* are optimal mixture coefficents, optimal PRCs, and optimal partial variances, respectively, resulted from EM process shown in Table 1. Note, each *Pl*(*zl*|*X*, *αl*\*, (*σl*2)\*) is determined by equation (2) and each *zl* is calculated by equation (19) before. In general, equation (20) is the final regression model of MREM.

Another problem in MREM is how to determine the number *K* of PRMs. The easiest way is to use clustering methods to determine the number of clusters as the number *K* of PRMs.

1. **Results and Discussions**

We use two data samples for testing MREM. The first one is the gestational dataset of 1027 cases in which each case includes ultrasound measures (regressors) and fetus weight (response variable). Ultrasound measures are bi-parietal diameter (*bpd*), head circumference (*hc*), abdominal circumference (*ac*), and fetal length (*fl*). The unit of *bpd*, *hc*, *ac*, and *fl* is millimeter whereas the unit of fetal weight is gram. Ho and Phan [20], [21] collected the ultrasound measure sample of pregnant women at Vinh Long General Hospital – Vietnam with obeying strictly all medical ethical criteria. These women and their husbands are Vietnamese. Their periods are regular and their last periods are determined. Each of them has only one alive fetus. Fetal age is from 28 weeks to 42 weeks. Delivery time is not over 48 hours since ultrasound scan.

The second sample is the dataset which contains 9568 data points collected from a Combined Cycle Power Plant (CCPP) [22]. Regressors in CCPP dataset are hourly average Ambient Temperature (*AT*), Ambient Pressure (*AP*), Relative Humidity (*RH*) and Exhaust Vacuum (*V*) to predict the net hourly electrical energy output (PE) as response variable. *AT* is in the range 1.81°C and 37.11°C. *AP* is in the range 992.89-1033.30 millibar. *RH* is in the range 25.56% to 100.16%. *V* is in the range 25.36-81.56 cm Hg. *PE* is in the range 420.26-495.76 MW.

In general, we have two samples such as gestational sample and CCPP sample. The dataset is split separately into one training dataset (50% sample) and one testing dataset (50% sample). Later on, the training dataset is made sparse with loss ratios 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%, which is similar to our previous research [19]. Missing values are made randomly regardless of regressors or response variable. For example, the gestational training dataset (50% gestational sample) has 50%\*1027 ≈ 513 rows and each row has 5 columns (*bpd*, *hc*, *ac*, *fl*, *weight*) and so the training dataset has 513\*5 = 2565 cells. If loss ratio is 10%, there are only 10%\*2565 ≈ 256 missing values which are made randomly among such 2565 cells. In other words, the incomplete training dataset with loss ratio 10% has 2565 – 256 = 2309 non-missing values. Of course, the testing dataset (50% sample) is not made sparse. Each pair of incomplete training dataset and testing dataset is called testing pair. There are ten testing pairs for each sample. As a convention, the origin testing pair which has no missing value in training dataset is the 0th pair. The 0th pair is called complete pair whereas the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, 8th, and 9th pairs are called incomplete pairs.

Firstly, we test MREM with gestational sample. Table 2 [19] shows ten testing pairs of gestational sample.

***Table 2.*** *Ten testing pairs of gestational sample.*

|  |  |  |  |
| --- | --- | --- | --- |
| Pair | Training dataset | Testing dataset | Loss ratio |
| 0 | Ges.sample.base | Ges.sample.test | 0% |
| 1 | Ges.sample.base.0.1.miss | Ges.sample.test | 10% |
| 2 | Ges.sample.base.0.2.miss | Ges.sample.test | 20% |
| 3 | Ges.sample.base.0.3.miss | Ges.sample.test | 30% |
| 4 | Ges.sample.base.0.4.miss | Ges.sample.test | 40% |
| 5 | Ges.sample.base.0.5.miss | Ges.sample.test | 50% |
| 6 | Ges.sample.base.0.6.miss | Ges.sample.test | 60% |
| 7 | Ges.sample.base.0.7.miss | Ges.sample.test | 70% |
| 8 | Ges.sample.base.0.8.miss | Ges.sample.test | 80% |
| 9 | Ges.sample.base.0.9.miss | Ges.sample.test | 90% |

MREM will be better than REM if MREM has a large enough number of PRMs and each PRM has such many regressors as REM. Thus, for fair testing, the number of PRMs in MREM is equal to the number of regressors and each PRM has only one regressor. Table 3 shows ten resulted regression models of REM corresponding to ten testing pairs, given gestational sample.

***Table 3.*** *Ten resulted regression models of REM given gestational sample.*

|  |  |
| --- | --- |
| Pair | Regression model |
| 0 | *weight* = -5686.8907 + 46.2369\*(*bpd*) + 1.7148\*(*hc*) + 14.3173\*(*fl*) + 9.3881\*(*ac*) |
| 1 | *weight* = -5685.7848 + 43.1103\*(*bpd*) + 1.4912\*(*hc*) + 17.0387\*(*fl*) + 9.8929\*(*ac*) |
| 2 | *weight* = -5853.1212 + 39.5619\*(*bpd*) + 2.4174\*(*hc*) + 21.7261\*(*fl*) + 9.5005\*(*ac*) |
| 3 | *weight* = -6198.2399 + 44.6901\*(*bpd*) + 5.2472\*(*hc*) + 20.4527\*(*fl*) + 6.6325\*(*ac*) |
| 4 | *weight* = -5941.9821 + 39.9089\*(*bpd*) + 2.6238\*(*hc*) + 23.3260\*(*fl*) + 9.2312\*(*ac*) |
| 5 | *weight* = -6496.2424 + 44.6131\*(*bpd*) + 3.9980\*(*hc*) + 25.8861\*(*fl*) + 7.7759\*(*ac*) |
| 6 | *weight* = -5940.9170 + 31.6952\*(*bpd*) + 2.8293\*(*hc*) + 34.1356\*(*fl*) + 9.0107\*(*ac*) |
| 7 | *weight* = -6296.7603 + 66.8602\*(*bpd*) + 2.7111\*(*hc*) + 16.8848\*(*fl*) + 4.0660\*(*ac*) |
| 8 | *weight* = -5362.1163 + 35.6642\*(*bpd*) + 4.7398\*(*hc*) + 14.8123\*(*fl*) + 8.2385\*(*ac*) |
| 9 | *weight* = -5923.3220 + 87.5165\*(*bpd*) + 3.4471\*(*hc*) - 0.2822\*(*fl*) - 0.0753\*(*ac*) |

Table 4 shows ten resulted semi-mixture regression models of MREM corresponding to ten testing pairs, given gestational sample.

***Table 4.*** *Ten resulted semi-mixture regression models of MREM given gestational sample.*

|  |  |
| --- | --- |
| Pair | Semi-mixture regression model |
| 0 | {*weight* = -6651.5534 + 108.5531\*(*bpd*): coeff=0.2721, var=113888.6649},  {*weight* = -4986.7292 + 24.6736\*(*hc*): coeff=0.2041, var=188973.6069},  {*weight* = -4505.6926 + 109.6790\*(*fl*): coeff=0.2450, var=119971.2307},  {*weight* = -3385.5925 + 19.4249\*(*ac*): coeff=0.2788, var=97458.0445} |
| 1 | {*weight* = -6802.9586 + 110.3231\*(*bpd*): coeff=0.2700, var=98865.5195},  {*weight* = -5089.2989 + 25.0105\*(*hc*): coeff=0.2012, var=163173.8380},  {*weight* = -4744.7739 + 113.4482\*(*fl*): coeff=0.2426, var=103291.1775},  {*weight* = -3515.6183 + 19.8394\*(*ac*): coeff=0.2862, var=77538.8650} |
| 2 | {*weight* = -6977.8017 + 112.5302\*(*bpd*): coeff=0.2628, var=86798.8614},  {*weight* = -5312.2016 + 25.7209\*(*hc*): coeff=0.2000, var=138635.9025},  {*weight* = -4866.0218 + 115.1670\*(*fl*): coeff=0.2514, var=78089.6011},  {*weight* = -3615.3155 + 20.1265\*(*ac*): coeff=0.2858, var=61080.1223} |
| 3 | {*weight* = -7044.9992 + 113.0877\*(*bpd*): coeff=0.2850, var=49040.4530},  {*weight* = -5765.6434 + 27.0933\*(*hc*): coeff=0.2164, var=74811.7832},  {*weight* = -4850.8460 + 114.8885\*(*fl*): coeff=0.2321, var=60022.4336},  {*weight* = -3639.0104 + 20.2068\*(*ac*): coeff=0.2665, var=47595.5654} |
| 4 | {*weight* = -7176.0173 + 115.2133\*(*bpd*): coeff=0.2716, var=38495.8850},  {*weight* = -5580.7794 + 26.5639\*(*hc*): coeff=0.1939, var=71575.3627},  {*weight* = -5143.9012 + 119.9590\*(*fl*): coeff=0.2319, var=46756.6663},  {*weight* = -3824.3390 + 20.8679\*(*ac*): coeff=0.3026, var=29724.0337} |
| 5 | {*weight* = -7660.3431 + 120.8204\*(*bpd*): coeff=0.2693, var=30819.8738},  {*weight* = -6110.0704 + 28.2196\*(*hc*): coeff=0.2138, var=48373.8766},  {*weight* = -5331.1994 + 122.4455\*(*fl*): coeff=0.2369, var=36807.6503},  {*weight* = -3967.5178 + 21.3295\*(*ac*): coeff=0.2800, var=27240.5556} |
| 6 | {*weight* = -8097.3745 + 125.7068\*(*bpd*): coeff=0.2302, var=22289.0842},  {*weight* = -7015.6149 + 31.3566\*(*hc*): coeff=0.2103, var=28635.3775},  {*weight* = -5480.6406 + 125.3284\*(*fl*): coeff=0.2674, var=13952.3164},  {*weight* = -3676.3555 + 20.3238\*(*ac*): coeff=0.2920, var=11540.1306} |
| 7 | {*weight* = -7076.9202 + 112.8536\*(*bpd*): coeff=0.3705, var=3375.2380},  {*weight* = -5497.9202 + 26.2185\*(*hc*): coeff=0.1612, var=18787.3282},  {*weight* = -4947.5898 + 117.8865\*(*fl*): coeff=0.2113, var=9967.0914},  {*weight* = -3653.8140 + 20.3827\*(*ac*): coeff=0.2569, var=8618.4241} |
| 8 | {*weight* = -7018.2030 + 112.6524\*(*bpd*): coeff=0.2678, var=3654.3436},  {*weight* = -5235.5481 + 25.2899\*(*hc*): coeff=0.2162, var=5459.5803},  {*weight* = -5647.3688 + 127.7972\*(*fl*): coeff=0.2054, var=5974.4689},  {*weight* = -3285.2965 + 19.3967\*(*ac*): coeff=0.3106, var=2526.1926} |
| 9 | {*weight* = -6350.5284 + 104.5601\*(*bpd*): coeff=0.1787, var=204.7618},  {*weight* = -5140.6601 + 24.4881\*(*hc*): coeff=0.0745, var=1245.6621},  {*weight* = -6791.1342 + 152.4635\*(*fl*): coeff=0.3553, var=68.6443},  {*weight* = -3831.9687 + 21.4992\*(*ac*): coeff=0.3915, var=53.0970} |

In Table 4, each semi-mixture regression model is wrapped in two brackets “{.}”. Notation “coeff” denotes mixture coefficient and notation “var” denotes the variance of a PRM.

Given gestational sample, we compare MREM with REM given with regard to the ratio mean absolute error (*RMAE*) and the number *t* of iterations. The number *t* reflects the speed of an algorithm. The smaller the number *t* is, the faster the algorithm is. Let *W* = {*w*1, *w*2,…, *wK*} and *V* = {*v*1, *v*2,…, *vK*} be sets of actual weights and estimated weights, respectively. Equation (15) specifies the *RMAE* metric [23, p. 814].

|  |  |
| --- | --- |
|  | (15) |

The smaller the *RMAE* is, the more accurate the algorithm is. Table 5 is the comparison of REM and MREM with regard to *RMAE* and *t* given gestational sample.

***Table 5.*** *Comparison of REM and MREM regarding RMAE and t, given gestational sample*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Pair | *RMAE*  (REM) | *RMAE*  (MREM) | *t*  (REM) | *t*  (MREM) |
| 0 | 0.0711 | 0.0786 | 1 | 2 |
| 1 | 0.0722 | 0.0759 | 4 | 4 |
| 2 | 0.0739 | 0.0738 | 6 | 4 |
| 3 | 0.0724 | 0.0720 | 7 | 4 |
| 4 | 0.0746 | 0.0727 | 11 | 5 |
| 5 | 0.0780 | 0.0721 | 18 | 5 |
| 8 | 0.0777 | 0.0745 | 22 | 4 |
| 7 | 0.0709 | 0.0706 | 37 | 5 |
| 8 | 0.0729 | 0.0752 | 112 | 4 |
| 9 | 0.0853 | 0.1147 | 444 | 4 |
| Average | 0.0749 | 0.0780 | 66.2 | 4.1 |

From Table 5, given gestational sample, MREM is more accurate than REM according RMAE metric. Note [19], values of paired t-test statistic *t*0 of RMAE for REM and MREM are 5.3294 and 6.4541, respectively. Because all these values are larger than the percentage point *t*0.05, 3 = 2.353 given significant level 95%, the resistance of REM and MREM to missing values given gestational sample is proved.

We continue to test MREM with CCPP sample. Table 6 shows ten testing pairs of CCPP sample.

***Table 6.*** *Ten testing pairs of CCPP sample.*

|  |  |  |  |
| --- | --- | --- | --- |
| Pair | Training dataset | Testing dataset | Loss ratio |
| 0 | CCPP.sample.base | CCPP.sample.test | 0% |
| 1 | CCPP.sample.base.0.1.miss | CCPP.sample.test | 10% |
| 2 | CCPP.sample.base.0.2.miss | CCPP.sample.test | 20% |
| 3 | CCPP.sample.base.0.3.miss | CCPP.sample.test | 30% |
| 4 | CCPP.sample.base.0.4.miss | CCPP.sample.test | 40% |
| 5 | CCPP.sample.base.0.5.miss | CCPP.sample.test | 50% |
| 6 | CCPP.sample.base.0.6.miss | CCPP.sample.test | 60% |
| 7 | CCPP.sample.base.0.7.miss | CCPP.sample.test | 70% |
| 8 | CCPP.sample.base.0.8.miss | CCPP.sample.test | 80% |
| 9 | CCPP.sample.base.0.9.miss | CCPP.sample.test | 90% |

Table 7 shows ten resulted regression models of REM corresponding to ten testing pairs, given CCPP sample.

***Table 7.*** *Ten resulted regression models of REM given CCPP sample.*

|  |  |
| --- | --- |
| Pair | Regression model |
| 0 | *PE* = 469.7296 - 1.9885\*(*AT*) - 0.2332\*(*V*) + 0.0474\*(*AP*) - 0.1602\*(*RH*) |
| 1 | *PE* = 415.9687 - 1.9131\*(*AT*) - 0.2579\*(*V*) + 0.0979\*(*AP*) - 0.1272\*(*RH*) |
| 2 | *PE* = 416.5671 - 1.8401\*(*AT*) - 0.2940\*(*V*) + 0.0963\*(*AP*) - 0.1047\*(*RH*) |
| 3 | *PE* = 401.8042 - 1.8324\*(*AT*) - 0.2999\*(*V*) + 0.1099\*(*AP*) - 0.0869\*(*RH*) |
| 4 | *PE* = 369.4165 - 1.7559\*(*AT*) - 0.3281\*(*V*) + 0.1410\*(*AP*) - 0.0789\*(*RH*) |
| 5 | *PE* = 346.6202 - 1.7208\*(*AT*) - 0.3237\*(*V*) + 0.1615\*(*AP*) - 0.0633\*(*RH*) |
| 6 | *PE* = 341.1562 - 1.6900\*(*AT*) - 0.3300\*(*V*) + 0.1647\*(*AP*) - 0.0383\*(*RH*) |
| 7 | *PE* = 346.4257 - 1.6501\*(*AT*) - 0.3776\*(*V*) + 0.1618\*(*AP*) - 0.0467\*(*RH*) |
| 8 | *PE* = 302.7665 - 1.5758\*(*AT*) - 0.3174\*(*V*) + 0.1942\*(*AP*) + 0.0391\*(*RH*) |
| 9 | *PE* = 564.1434 - 2.1327\*(*AT*) + 0.0188\*(*V*) - 0.0684\*(*AP*) + 0.0205\*(*RH*) |

Table 8 shows ten resulted semi-mixture regression models of MREM corresponding to ten testing pairs, given CCPP sample.

***Table 8.*** *Ten resulted semi-mixture regression models of MREM given CCPP sample.*

|  |  |
| --- | --- |
| Pair | Semi-mixture regression model |
| 0 | {*PE* = 497.0645 - 2.1763\*(*AT*): coeff=0.4227, var=29.6573},  {*PE* = 517.8105 - 1.1672\*(*V*): coeff=0.2769, var=71.6045},  {*PE* = -1058.5211 + 1.4933\*(*AP*): coeff=0.1597, var=211.5011},  {*PE* = 421.6716 + 0.4486\*(*RH*): coeff=0.1406, var=248.4670} |
| 1 | {*PE* = 497.4977 - 2.1979\*(*AT*): coeff=0.4280, var=24.2516},  {*PE* = 519.3656 - 1.1965\*(*V*): coeff=0.2768, var=60.5493},  {*PE* = -1214.8271 + 1.6475\*(*AP*): coeff=0.1584, var=180.1064},  {*PE* = 417.8420 + 0.5020\*(*RH*): coeff=0.1368, var=217.2895} |
| 2 | {*PE* = 497.6871 - 2.2081\*(*AT*): coeff=0.4291, var=20.0817},  {*PE* = 520.7027 - 1.2180\*(*V*): coeff=0.2841, var=48.7344},  {*PE* = -1304.3280 + 1.7359\*(*AP*): coeff=0.1541, var=157.6827},  {*PE* = 413.7453 + 0.5563\*(*RH*): coeff=0.1327, var=189.0623} |
| 3 | {*PE* = 498.5778 - 2.2479\*(*AT*): coeff=0.4453, var=13.8541},  {*PE* = 522.2781 - 1.2467\*(*V*): coeff=0.2830, var=37.3203},  {*PE* = -1512.8163 + 1.9414\*(*AP*): coeff=0.1472, var=128.9238},  {*PE* = 405.7745 + 0.6610\*(*RH*): coeff=0.1245, var=156.3326} |
| 4 | {*PE* = 498.5320 - 2.2546\*(*AT*): coeff=0.4335, var=10.5627},  {*PE* = 523.8185 - 1.2793\*(*V*): coeff=0.2961, var=26.0347},  {*PE* = -1714.4568 + 2.1407\*(*AP*): coeff=0.1511, var=91.7893},  {*PE* = 401.0777 + 0.7325\*(*RH*): coeff=0.1192, var=123.9264} |
| 5 | {*PE* = 498.4271 - 2.2470\*(*AT*): coeff=0.4353, var=7.9534},  {*PE* = 523.2183 - 1.2717\*(*V*): coeff=0.2939, var=19.5630},  {*PE* = -1857.9068 + 2.2820\*(*AP*): coeff=0.1528, var=67.4559},  {*PE* = 392.9270 + 0.8393\*(*RH*): coeff=0.1181, var=90.1255} |
| 6 | {*PE* = 498.0319 - 2.2315\*(*AT*): coeff=0.4395, var=5.0596},  {*PE* = 524.2077 - 1.2912\*(*V*): coeff=0.2861, var=13.3621},  {*PE* = -1963.7000 + 2.3864\*(*AP*): coeff=0.1552, var=42.8344},  {*PE* = 387.3950 + 0.9189\*(*RH*): coeff=0.1192, var=60.0808} |
| 7 | {*PE* = 498.3792 - 2.2522\*(*AT*): coeff=0.4358, var=2.9110},  {*PE* = 525.1901 - 1.3086\*(*V*): coeff=0.2879, var=7.2515},  {*PE* = -2134.9587 + 2.5554\*(*AP*): coeff=0.1520, var=23.8247},  {*PE* = 381.4177 + 0.9984\*(*RH*): coeff=0.1243, var=29.7061} |
| 8 | {*PE* = 496.4571 - 2.1705\*(*AT*): coeff=0.4590, var=1.1633},  {*PE* = 524.3892 - 1.2790\*(*V*): coeff=0.2884, var=3.3270},  {*PE* = -2349.5928 + 2.7669\*(*AP*): coeff=0.1334, var=12.5737},  {*PE* = 369.4027 + 1.1507\*(*RH*): coeff=0.1192, var=16.3293} |
| 9 | {*PE* = 497.3288 - 2.1356\*(*AT*): coeff=0.5466, var=0.1691},  {*PE* = 532.0547 - 1.4489\*(*V*): coeff=0.2210, var=1.0673},  {*PE* = -2537.2255 + 2.9526\*(*AP*): coeff=0.1349, var=2.7906},  {*PE* = 369.2398 + 1.1183\*(*RH*): coeff=0.0975, var=4.1247} |

In Table 8, each semi-mixture regression model is wrapped in two brackets “{.}”. Notation “coeff” denotes mixture coefficient and notation “var” denotes the variance of a PRM.

Table 9 is the comparison of REM and MREM with regard to *RMAE* and *t* given CCPP sample.

***Table 9.*** *Comparison of REM and MREM regarding RMAE and t, given CCPP sample*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Pair | *RMAE*  (REM) | *RMAE*  (MREM) | *t*  (REM) | *t*  (MREM) |
| 0 | 0.0081 | 0.0123 | 1 | 2 |
| 1 | 0.0081 | 0.0119 | 5 | 5 |
| 2 | 0.0081 | 0.0116 | 10 | 7 |
| 3 | 0.0082 | 0.0111 | 27 | 8 |
| 4 | 0.0082 | 0.0109 | 23 | 10 |
| 5 | 0.0083 | 0.0109 | 68 | 10 |
| 8 | 0.0084 | 0.0109 | 994 | 9 |
| 7 | 0.0084 | 0.0109 | 47 | 8 |
| 8 | 0.0089 | 0.0110 | 90 | 13 |
| 9 | 0.0101 | 0.0104 | 1780 | 23 |
| Average | 0.0085 | 0.0112 | 304.5 | 9.5 |

From Table 9, given CCPP sample, MREM is more accurate than REM according to RMAE metric. Note [19], values of paired t-test statistic *t*0 of RMAE for REM and MREM are 6.1786 and 5.9070, respectively. Because all these values are larger than the percentage point *t*0.05, 3 = 2.353 given significant level 95%, the resistance of REM and MREM to missing values given CCPP sample is proved.

From experimental results of both gestational sample and CCPP sample, the convergence of MREM is always faster than the convergence of REM because MREM decomposes a long regression model with many shorter regression models. In optimization process of MREM, of course each short model with only one independent variable in two-dimension space will converge faster than the long model whereas the long model needs many iterations to reach and balance the optimal point (optimizer) in a multi-dimension space with many independent variables.

1. **Conclusions**

In general, the essence of MREM is to integrate two EM processes (one for exponential estimation of missing values and one for mixture model estimation of parameters) into the same loop in order to take advantages of both REM in fulfilling incomplete data and mixture model in processing complicatedly varied data. As a result, MREM not only solve the problem of incomplete data but also improves the accuracy of regression analysis. The proposed equation (15) is the key to combine REM and mixture model. However, given complete data, the drawback of MREM is complex computation in a loop whereas traditional mixture regression analysis methods in literation is simpler and faster. For further research, we try our best to improve MREM in programming technique so as to save computational cost.

**Appendix**

***A1. Proof of equations (10)***

Equation (10) is established■

***A2. Proof of equations (9), (11), and (16)***

This proof is found in [16, pp. 5-6]■

**Conflicts of Interest**

The authors declare that there is no conflict of interest regarding the publication of this article.

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