

EFFECTS OF SAMPLE SIZE RATIO ON THE PERFORMANCE OF THE QUADRATIC DISCRIMINANT FUNCTION

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ABSTRACT

This study investigated the performance of the heteroscedastic discriminant function under the non-optimal condition of unbalanced group representation in the populations. The asymptotic performance of the classification function with respect to increased Mahalanobis' distance (under this condition) was considered. Results obtained have shown that the misclassification of observations from the smaller group escalates when the sample size ratio 1:2 is exceeded (for small sample sizes). Results also show more sensitivity to sample size than the distance function when the data set is balanced, while the performance of the function in the classification of the underrepresented group improved by increasing the distance function. More robustness with unbalanced data was also observed with the Quadratic Function than the Linear Discriminant Function.

Keywords: Heteroscedastic, Unbalanced data, Discriminant function, prior probabilities,
Misclassification 2000 Mathematics Subject Classification: 62H30, 62C05, 00A72.

INTRODUCTION

In this study we restrict ourselves to the two group classification problem when the covariance structures and mean vectors are unequal. We define two groups R_1 and R_2 with Multivariate Normal density functions $f_1(x)$ and $f_2(x)$ respectively. $R_1 \sim Np(\mu_1, \Sigma_1)$ and $R_2 \sim Np(\mu_2, \Sigma_2)$ where $\mu_i \in \mathbb{R}^p$ and $\Sigma_i \in$

$\mathbb{R}^{p \times p}$. The i th group conditional density $f_i(X_i, \theta_i)$ is given by

$$f_i(X_i, \theta_i) = \varphi(X_i; \mu_i, \Sigma_i)$$

$$= (2\pi)^{-\frac{p}{2}} |\Sigma_i|^{-\frac{1}{2}} \exp \left\{ -\frac{1}{2} (X - \mu_i)^T \Sigma_i^{-1} (X - \mu_i) \right\} \dots\dots\dots (1.1)$$

and θ_i consists of the elements of μ_i and the $(1/2)P(P + 1)$ distinct elements of Σ_i ($i = 1, \dots, g$). It is assumed that each Σ_i is nonsingular. The elements of the vector P of the mixing proportions for the populations sum up to 1.

Observations from these groups constitute the training sample. A classification function will be constructed using the training sample on the basis of which future observations (of unknown group memberships) will be classified. This is done by comparing the function to a predetermined cut-off value. The procedure is often utilized (but not limited to) the Social Sciences, Medical sciences, Education and Psychology.

MATERIALS AND METHODS

The Model

The optimal discriminant rule that minimizes the total probability of misclassification is given by the log ratio of densities. That is:

$$Q(X) = \log f_1(X) / \log f_2(X) \tag{2.1}$$

This reduces to:

$$Q(X) = \left(\frac{1}{2}\right) \left[(x - \mu_2)' \Sigma_2^{-1} (x - \mu_2) - (x - \mu_1)' \Sigma_1^{-1} (x - \mu_1) \right] + \left(\frac{1}{2}\right) \log |\Sigma_2| / |\Sigma_1| \tag{2.2}$$

This is a quadratic classification function here after referred to as the Quadratic Discriminant

Function (QDF). This function contains population parameters and the sample estimates

will be obtained from the training data. $Q(X)$ is the general equation. Equation (2.2) above can be written as

$$Q(x) = x' Ax + b' x + c \tag{2.3}$$

where

$$\begin{aligned} A &= \left(\frac{1}{2}\right) (\Sigma_2^{-1} - \Sigma_1^{-1}) \\ b &= \Sigma_1^{-1} \mu_1 - \Sigma_2^{-1} \mu_2 \end{aligned} \tag{2.4}$$

The quadratic

$$\begin{aligned} \delta(x; \mu_i, \Sigma_i)' &= (x - \mu_i)' \Sigma_i^{-1} (x - \mu_i) \\ &= D_i^2(x) \end{aligned} \tag{2.5}$$

is the squared Mahalanobis' distance between x and μ_i with respect to Σ .

The cut-off point is determined by the log ratios of the costs of misclassification and prior

probabilities. We define $C(i|j) \ i \neq j$ as the cost of misclassifying an observed vector as belonging to group R_i when it actually belongs to R_j and $C(j|i)$ as the converse.

Consequently, $C(i|i) = C(j|j) = 0$. Also, the assumption $C(j|i) = C(i|j)$ is the exception and not the norm in practice. This rule is however regularly applied when the misclassification costs are unknown.

Let $P_i \ i=1, 2$ be the prior probability of an observation belonging to group R_i and this information is often obtained from the training sample composition. An observed P-variate vector x is assigned to R_1 if

$$Q(x) > \log \left[\frac{C(1|2)P_2}{C(2|1)P_1} = \eta \right] \tag{2.6}$$

The total probability of misclassification (TPM) gives a measure of the performance of the function. This is a proportion of misclassified observations from the training sample and is given as:

$$TPM = P_1P[Q(x) < \eta | x \in R_1] + P_2P[Q(x) > \eta | x \in R_2] \tag{2.7}$$

Denote $R^0 = (R_1^0, R_2^0)$, where R_1^0 and R_2^0 are the distributions that generated the training samples, the TPM using the QDF will be represented as

$$Q(x; R^0) = x' A(R^0)x + b(R^0)'x + c(R^0) \tag{2.8}$$

where

$$A(R^0) = (1/2)(C_2(R^0)^{-1} - C_1(R^0)^{-1}) \tag{2.9}$$

$$b(R^0) = C_1(R^0)^{-1}T_1(R^0)^{-1} - C_2(R^0)^{-1}T_2(R^0)^{-1} \tag{2.10}$$

$$c(R^0) = (1/2)\log(|C_2(R^0)| |C_1(R^0)|) + (1/2)(T_2(R^0)'C_2(R^0)^{-1}T_2(R^0) - T_1(R^0)'C_1(R^0)^{-1}T_1(R^0)) \tag{2.11}$$

This is analogous to the quadratic function and equations 2.9 to 2.11 are the values of a location function T at the distributions R_1^0 and R_2^0 .

That is, $T_1(R^0) = E_{R_1^0}(X)$ and $T_2(R^0) = E_{R_2^0}(X)$ Similarly, $C_1(R^0)$ and $C_2(R^0)$ are the values of the covariance matrix function C at the distributions R_1^0 and R_2^0 .

Thus, $C_1(R^0) = Cov_{R_1^0}(X)$ and $C_2(R^0) = Cov_{R_2^0}(X)$ When the data follow a normal distribution,

$$T_1(R^0) = \mu_1, T_2(R^0) = \mu_2, C_1(R^0) = \Sigma_1 \text{ and } C_2(R^0) = \Sigma_2 \text{ (Joossens(5)).}$$

McFarland and Richards(7) have provided exact misclassification probabilities for the finite sample from a normal distribution. The future data are supposed to be a normal mixture of the training data and the observations of unknown group membership. This gives a TPM for the mixture as

$$TPM(R^0, R) = P_1 C(2|1)(R^0, R) + P_2 C(1|2)(R^0, R) \tag{2.12}$$

The theoretical derivations have been provided by Jossens(5), McFarlan and Richards (7) and McLachlan (8).

The Simulation Experiment

We consider two populations $R_1 \sim N(\mu_1, \Sigma_1)$ and $R_2 \sim N(\mu_2, \Sigma_2)$ with $\mu_1 = (0,0,0,0)$ and $\mu_2 = (\delta,0,0,0)$, $\Sigma_1 = I$ and $\Sigma_2 = kI$. For our case we set $k=6$ (Adebanji and Nokoe(1)) and $\delta=1, 2, 3$ and 4 . Different values of δ are considered to see if there is any observable change in the performance of the functions from very close samples to well separated samples. Twenty one sample sizes (ranging from 25 to 500) are generated for R_1 and the number of corresponding observations generated from R_2 is determined by the sample size ratio composition under consideration. We consider $n_1 : n_2 = 1:1, 1:2, 1:3$ and $1:4$; that is from balanced to extremely unbalanced data sets. The large sample sizes are considered in order to enable us observe the performance of the QDF when the population parameters are known.

The four sample size ratio combinations are considered for every value of δ under consideration. Random samples are generated and 100 replications of each sample specification is generated using SAS V(8) (1996).

The large number of replications minimizes between sample variability. The QDF is constructed and the leave-one-out error rate estimation procedure (Lachembbruch and Mickey (6)) is used for estimating the TPM.

Results of Simulation

In the results, the total probability of misclassification (averaged over 100 replications) is denoted as decimals, and the associated standard deviations (SD) are also denoted as decimals. The coefficient of variation (CV) (denoted as percentages) are presented. Results are also presented for different values of δ and sample size ratio combinations.

Scheme 1: Equal Sample sizes ($n_1:n_2=1:1$)

When the sample size ratios are equal, the performance of the function for group G_1 with an identity covariance structure is slightly better than that for G_2 with the covariance structure $\Sigma=kI$ though not significantly different in values. Higher reduction in error rates and SD was observed for increased sample sizes than for increase in the δ value. The results stabilized around sample size 1200 beyond which no signifi-

cant improvement was recorded in the performance of the function.

Scheme 2: Unequal Sample sizes ($n_1 : n_2=1:2$)

The ratio of the error rates for $G_2: G_1$ was 1:5 and this increased to 1:10 when the sample size 1200 was attained for $\delta=1$. This high misclassification of the under-represented group underscored the improvement in the performance of the function as can be observed from the total error

rates. The SD shows a steady decline to sample size 900 at which it stabilizes. The CV reduces more gradually to sample size 1200 and remained stable afterwards. For $\delta=2$, the ratio was 1:3 for smaller sample sizes and 1:6 when the sample size 1200 was attained. For $\delta=3$, the ratio increased to 1:4 and similar results was observed for $\delta=4$. The group error rates for this scheme are presented in Table 1.

Table 1: Group Error for $\delta = 1, 2, 3$ and $4(n_1:n_2 = 1 : 2)$

| n1 | Sample Size | $\delta = 1$ | | $\delta = 2$ | | $\delta = 3$ | | $\delta = 4$ | |
|-----|-------------|--------------|-------|--------------|-------|--------------|-------|--------------|-------|
| | | G1 | G2 | G1 | G2 | G1 | G2 | G1 | G2 |
| 25 | 75 | 0.306 | 0.065 | 0.231 | 0.086 | 0.146 | 0.082 | 0.115 | 0.053 |
| 50 | 225 | 0.305 | 0.047 | 0.230 | 0.047 | 0.151 | 0.048 | 0.114 | 0.031 |
| 75 | 225 | 0.305 | 0.032 | 0.225 | 0.043 | 0.151 | 0.047 | 0.114 | .029 |
| 100 | 300 | 0.304 | 0.033 | 0.228 | 0.044 | 0.170 | 0.037 | 0.113 | 0.030 |
| 200 | 600 | 0.303 | 0.029 | 0.228 | 0.042 | 0.148 | 0.046 | 0.113 | 0.027 |
| 300 | 900 | 0.302 | 0.026 | 0.227 | 0.040 | 0.168 | 0.036 | 0.113 | 0.028 |
| 400 | 1200 | 0.301 | 0.027 | 0.225 | 0.040 | 0.157 | 0.039 | 0.112 | 0.027 |

Scheme 3: Unequal Sample sizes ($n_1 : n_2=1:3$)

The ratio of the error rates $G_2 : G_1$ for $\delta = 1$ increased from 1:9 to 1:26 at sample size 1200, for $\delta = 2$, it rose from 1:4 to 1:9. At $\delta = 3$, the change was from 1:4 to 1:6 and 1:2 to 1:4 for $\delta = 4$. The high error rate for the smaller group further underscores the performance of the function. There was a steady reduction in the SD until sample size 800 beyond which it remained relatively constant. A similar pattern was observed for the CV which recorded only a slight im-

provement beyond sample size 800. Refer to Table 2 below for the group error rates.

Scheme 4: Unequal Sample sizes ($n_1 : n_2=1:4$)

The widening in the gap of the ratio $G_2:G_1$ was not as rapid as had earlier been observed. For $\delta = 1$ the increase was from 1:9 to 1:11, while for $\delta = 2, 3$ and 4 the recorded values were 1:4 to 1:7, 1:6 to 1:8 and 1:5 to 1:9 respectively. See Table 3 below for details of change in error rates.

Table 2: Group Error for $\delta = 1, 2, 3$ and $4(n_1 : n_2=1:3)$

| n1 | Sample Size | $\delta = 1$ | | $\delta = 2$ | | $\delta = 3$ | | $\delta = 4$ | |
|-----|-------------|--------------|-------|--------------|-------|--------------|-------|--------------|-------|
| | | G1 | G2 | G1 | G2 | G1 | G2 | G1 | G2 |
| 25 | 100 | 0.412 | 0.043 | 0.279 | 0.065 | 0.193 | 0.054 | 0.139 | 0.046 |
| 50 | 200 | 0.412 | 0.027 | 0.283 | 0.045 | 0.195 | 0.054 | 0.135 | 0.033 |
| 75 | 300 | 0.411 | 0.018 | 0.284 | 0.042 | 0.195 | 0.044 | 0.133 | 0.029 |
| 100 | 400 | 0.410 | 0.020 | 0.299 | 0.036 | 0.205 | 0.038 | 0.127 | 0.032 |
| 200 | 800 | 0.410 | 0.016 | 0.280 | 0.040 | 0.193 | 0.039 | 0.125 | 0.032 |
| 300 | 1200 | 0.409 | 0.016 | 0.297 | 0.031 | 0.204 | 0.035 | 0.122 | 0.031 |
| 400 | 1600 | 0.409 | 0.016 | 0.288 | 0.035 | 0.198 | 0.034 | 0.084 | 0.044 |

Table 3: Group Error for $\delta = 1, 2, 3$ and $4(n_1 : n_2=1:4)$

| n1 | Sample Size | $\delta = 1$ | | $\delta = 2$ | | $\delta = 3$ | | $\delta = 4$ | |
|-----|-------------|--------------|-------|--------------|-------|--------------|-------|--------------|-------|
| | | G1 | G2 | G1 | G2 | G1 | G2 | G1 | G2 |
| 25 | 125 | 0.426 | 0.049 | 0.351 | 0.047 | 0.105 | 0.018 | 0.179 | 0.036 |
| 50 | 250 | 0.423 | 0.048 | 0.348 | 0.034 | 0.098 | 0.017 | 0.178 | 0.027 |
| 75 | 375 | 0.427 | 0.048 | 0.351 | 0.033 | 0.091 | 0.017 | 0.178 | 0.027 |
| 100 | 500 | 0.442 | 0.046 | 0.363 | 0.027 | 0.093 | 0.012 | 0.178 | 0.022 |
| 200 | 1000 | 0.424 | 0.047 | 0.348 | 0.030 | 0.089 | 0.016 | 0.169 | 0.025 |
| 300 | 1500 | 0.440 | 0.047 | 0.361 | 0.025 | 0.087 | 0.016 | 0.177 | 0.020 |
| 400 | 2000 | 0.432 | 0.047 | 0.355 | 0.028 | 0.087 | 0.015 | 0.177 | 0.020 |

Mean Error rates, SD and CV

The graphs for the total (mean) error rates, standard deviation (SD) and coefficient of variation are presented in a series of Figures 1.1 to 4.3. Figures 1.1, 1.2 and 1.3 are the graphs of the mean error rates, SD and CV for the balanced data set. Figures 2.1, 2.2 and 2.3 represent the mean error rates, SD and CV for sample size composition $n_1 : n_2=1:2$. The graphs for sample size ratios 1:3 and 1:4 are presented in Figures 3.1 to 3.3 and 4.1 to 4.3 respectively.

DISCUSSION

When the data set is balanced, the ODF benefits more from increase in sample size than increase in the distance function. More robustness was also observed in using the function for unbalanced data over the linear discriminant function (Adebanji *et al.*) (2).

The performance of the function in classifying unbalanced data also improved significantly when the between group squared distance is relatively large (i.e data sets are well separated). The performance, however, deteriorates in classifying the smaller group when the total sample size is large.

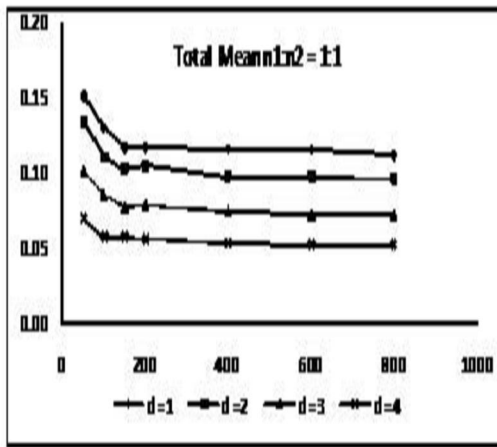


Figure 1.1

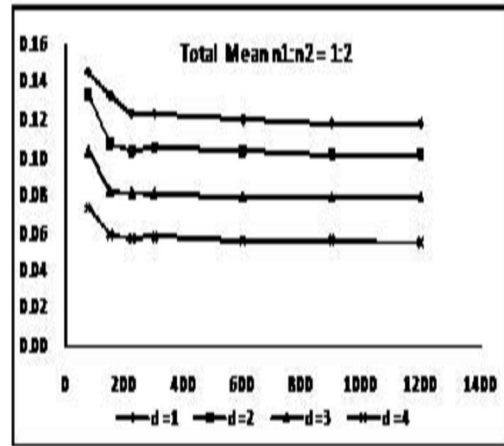


Figure 2.1

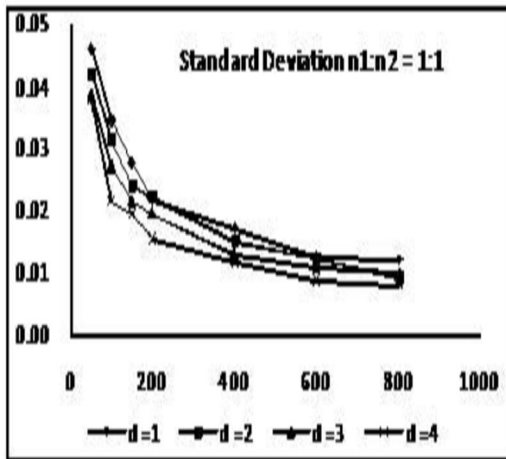


Figure 1.2

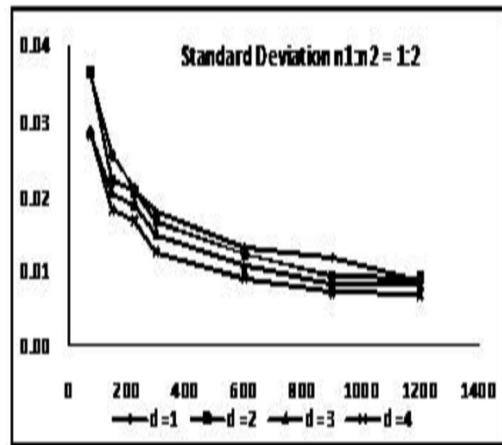


Figure 2.2

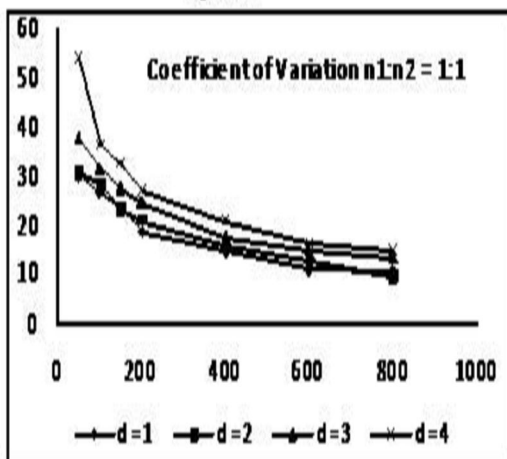


Figure 1.3

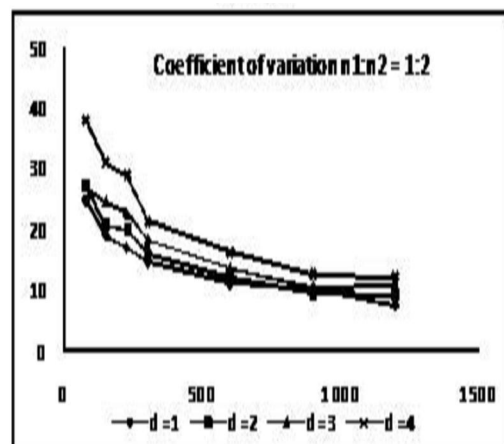


Figure 2.3

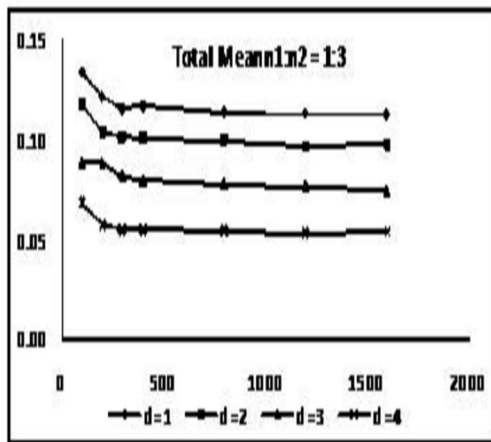


Figure 3.1

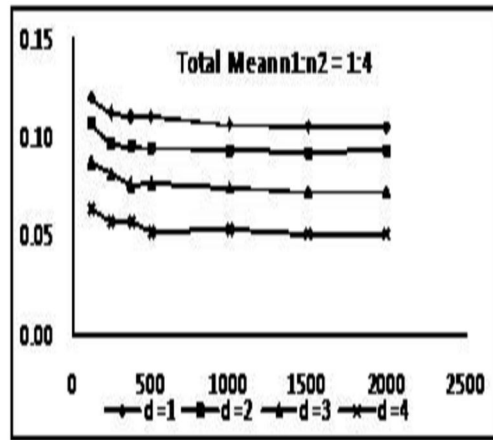


Figure 4.1

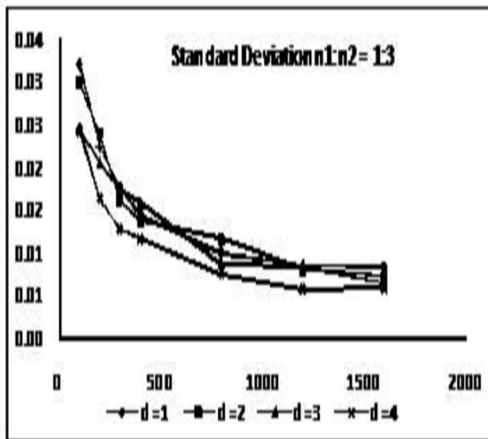


Figure 3.2

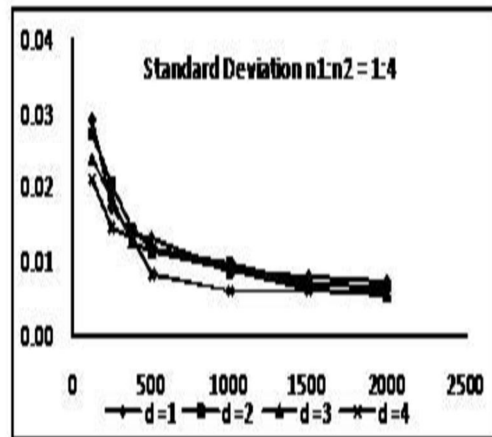


Figure 4.2

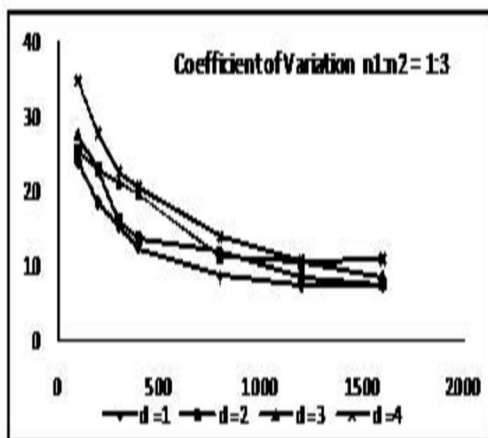


Figure 3.3

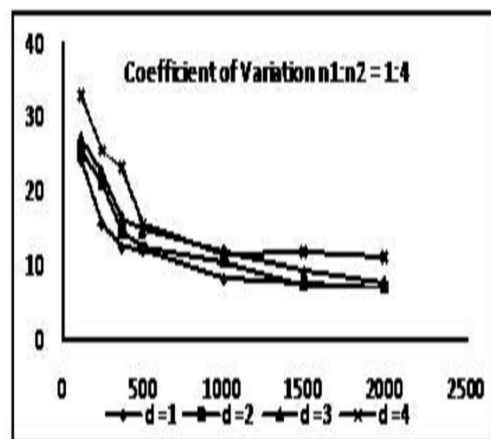


Figure 4.3

CONCLUSION

In conclusion, using the QDF for the classification of unbalanced data will not be recommended beyond sample size ratio 1:2 when the data sets are relatively close, and ratio 1:3 when the observations are well separated (subject to moderate sample size).

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