




calzone: A Python package for measuring calibration of probabilistic models for classification

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Summary

calzone is a Python package for evaluating the calibration of probabilistic outputs of classifier models. It provides a set of functions for visualizing calibration and computing of calibration metrics given a representative dataset with the model's predictions and the true class labels. The metrics provided in calzone include: Expected Calibration Error (ECE), Maximum Calibration Error (MCE), Hosmer-Lemeshow (HL) statistic, Integrated Calibration Index (ICI), Spiegelhalter's Z-statistics and Cox's calibration slope/intercept. The package is designed with versatility in mind. For many of the metrics, users can adjust the binning scheme and toggle between top-class or class-wise calculations.

Statement of need

Classification is one of the most common applications in machine learning. Classification models may output predicted probabilities that an input observation belongs to a particular class, and those probabilities are often evaluated by a proper scoring rule - a scoring function that assigns the best score when predicted probabilities match the true probabilities - such as cross-entropy or mean square error (Gneiting & Raftery, 2007). Examination of the discrimination performance (resolution), such as AUC or Se/Sp are also used to evaluate model performance. These metrics may be sufficient if the output of the model is not meant to be a calibrated probability.

Diamond (1992) showed that the resolution (i.e., high performance) of a model does not indicate the reliability/calibration (i.e., how well predicted probabilities match true probabilities) of the model. Bröcker (2009) later showed that any proper scoring rule can be decomposed into the resolution and reliability. Thus, even if the model has high resolution, it may not be a reliable model. In many high-risk machine learning applications, such as medical diagnosis and prognosis, reliability greatly aids in the interpretability of the model when deciding among multiple treatment options.

We define calibration as the agreement between the predicted probability and the true posterior probability of a class-of-interest, $P(D = 1|\hat{p} = p) = p$. This has been defined as moderate calibration by Van Calster & Steyerberg (2018) and is also referred as the reliability of the model.

In the calzone package, we provide a set of functions and classes for visualizing calibration and evaluating calibration metrics given a representative dataset from the intended population. Existing libraries such as scikit-learn lacks calibration metrics that are widely used in the statistical literature. Other libraries such as uncertainty-toolbox are focused on implementing calibration methods and not calibration assessment. (Chung et al., 2021).

41 Software description

42 Input data

43 To evaluate the calibration of a model, users need a representative dataset from the intended
44 population. The dataset should contain the true class labels and the model's predicted proba-
45 bilities. In calzone, the dataset can be loaded from a CSV file using the data_loader function.
46 The description of the input CSV file format can be found in the calzone documentation.
47 Alternatively, users can pass the true class labels and the model's predicted probabilities as
48 NumPy arrays to the calzone functions.

49 Reliability Diagram

50 The reliability diagram (also referred to as the calibration plot) is a graphical representation of
51 the calibration of a classification model (Bröcker & Smith, 2007; Murphy & Winkler, 1977). It
52 groups the predicted probabilities into bins and plots the mean predicted probability against the
53 empirical frequency in each bin. The reliability diagram can be used to qualitatively assess the
54 calibration of the model and to identify any systematic errors in the predictions. In addition,
55 calzone gives the option to also plot the confidence interval of the empirical frequency in each
56 bin. The confidence intervals are calculated using the Wilson's score interval (Wilson, 1927).
57 We provide example data in the example_data folder which are simulated using a beta-binomial
58 distribution (Griffiths, 1973). More description can be found in the documentation. In the
59 example code below, we will instead use the scikit-learn function to simulate a random 2-class
60 dataset of correlated normally distributed data and fit a simple logistic model to illustrate.
61 Figure 1 shows an example of the reliability diagram for class 1 with 15 equal-width bins for a
62 well-calibrated dataset, where the x-axis is the mean predicted probability and the y-axis is the
63 empirical frequency.

```
from calzone.utils import reliability_diagram
from calzone.vis import plot_reliability_diagram

# Generate a random binary classification dataset
import sklearn.linear_model
import sklearn.datasets

features, labels = sklearn.datasets.make_classification(
    n_samples=5000,
    n_features=5,
    n_informative=5,
    n_redundant=0,
    n_classes=2,
    n_clusters_per_class=1,
    class_sep=0.2,
    random_state=1
)
model = sklearn.linear_model.LogisticRegression()
model.fit(features, labels)
probs = model.predict_proba(features)

reliability, confidence, bin_edges, bin_counts = reliability_diagram(
    labels,
    probs,
    num_bins=15,
    class_to_plot=1
)
```

```
plot_reliability_diagram(
    reliability,
    confidence,
    bin_counts,
    error_bar=True,
    title='Reliability diagram'
)
```

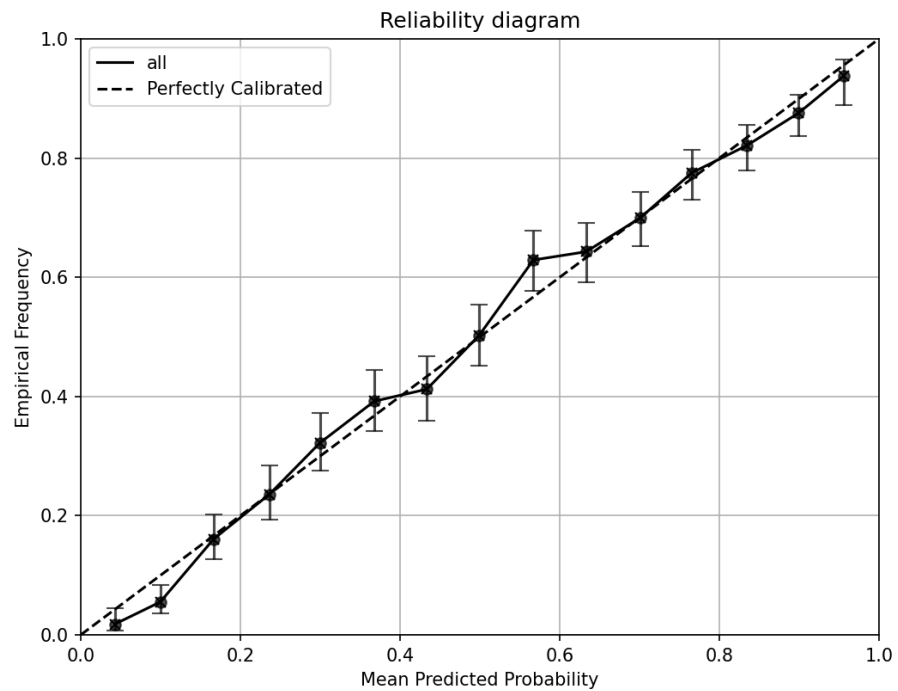


Figure 1: Reliability Diagram for class 1 with simulated data.

Calibration metrics

calzone provides functions to compute various calibration metrics. The `CalibrationMetrics()` class allows the user to compute the calibration metrics in a more convenient way. The following are metrics that are currently supported in calzone:

Expected Calibration Error (ECE) and Maximum Calibration Error (MCE)

Expected Calibration Error (ECE) and Maximum Calibration Error (MCE) (Guo et al., 2017; Pakdaman Naeini et al., 2015) aim to measure the average and maximum absolute deviation between the predicted probability and true probability. We provide the option to use equal-width binning or equal-count binning, labeled as ECE-H and ECE-C respectively. Users can also choose to compute the metrics for the class-of-interest or the top-class. Top-class mean only the calibration of the class with the highest probability is evaluated. In the case of class-of-interest, calzone will evaluate the calibration of a one-vs-rest classification problem. The following snippet demonstrates how these metrics are calculated in our package:

```
from calzone.metrics import calculate_ece_mce
```

```
reliability, confidence, bin_edges, bin_counts = reliability_diagram(
    labels,
    probs,
    num_bins=10,
    class_to_plot=1,
    is_equal_freq=False
)
### Both ECE and MCE are calculated at the same time
ece_h_classone, mce_h_classone = calculate_ece_mce(
    reliability,
    confidence,
    bin_counts=bin_counts
)
```

77 Hosmer-Lemeshow statistic (HL)

78 The Hosmer-Lemeshow (HL) statistical test ([Hosmer & Lemeshow, 1980](#)) is for evaluating the
 79 calibration of a probabilistic model. It is a chi-square-based test that compares the observed
 80 and expected number of events in each bin. The null hypothesis is that the model is well
 81 calibrated. HL-test first bins data into predicted probability bins (equal-width H or equal-count
 82 C) and the test statistic is calculated as:

$$HL = \sum_{m=1}^M \frac{(O_{1,m} - E_{1,m})^2}{E_{1,m} \left(1 - \frac{E_{1,m}}{N_m}\right)} \sim \chi_{M-2}^2$$

83 where $E_{1,m}$ is the expected number of class-of-interest events in the m^{th} bin, $O_{1,m}$ is the
 84 observed number of class-of-interest events in the m^{th} bin, N_m is the total number of
 85 observations in the m^{th} bin, and M is the number of bins. In calzone, the HL-test can be
 86 computed as follows:

```
from calzone.metrics import hosmer_lemeshow_test

HL_H_ts, HL_H_p, df = hosmer_lemeshow_test(
    reliability,
    confidence,
    bin_count = bin_counts,
    df = len(bin_counts) - 2,
)
```

87 When performing the HL test on validation sets that are not used in training, the degree
 88 of freedom of the HL test changes from $M - 2$ to M ([Hosmer Jr et al., 2013](#)). Intuitively,
 89 $\frac{(O_{1,m} - E_{1,m})^2}{E_{1,m} \left(1 - \frac{E_{1,m}}{N_m}\right)}$ is the difference squared divided by the variance of a binomial distribution and
 90 follows a chi-square distribution with 1 degree of freedom. Hence, the sum of M chi-square
 91 distributions with 1 degree of freedom is a chi-square distribution with M degrees of freedom if
 92 the data has no effect on the model. The increase in degree of freedom for validation samples
 93 has often been overlooked but it is crucial for the test to maintain the correct type 1 error
 94 rate. In calzone, the default degree of freedoms is $M - 2$ and users should specify the degree
 95 of freedom of the HL test by setting the df parameter.

96 Cox's calibration slope/intercept

97 Cox's calibration slope/intercept is a regression analysis method for assessing the calibration
 98 of a probabilistic model ([COX, 1958](#)), which doesn't require binning. A logistic regression
 99 model is fit to the data, with the predicted odds ($\frac{p}{1-p}$) as the independent variable and the
 100 outcome as the dependent variable. The slope and intercept of the regression line are then

101 used to assess the calibration of the model. A slope of 1 and intercept of 0 indicates perfect
102 calibration. To test whether the model is calibrated, fix the slope to 1 and fit the intercept.
103 If the intercept is significantly different from 0, the model is not calibrated. Then, fix the
104 intercept to 0 and fit the slope. If the slope is significantly different from 1, the model is not
105 calibrated. Alternatively, the slope and intercept can be fitted and tested simultaneously using
106 a bivariate distribution (McCullagh & Nelder, 1989). This feature is not provided in calzone
107 but user can extract the covariance matrix by printing the result and perform the test manually.
108 In calzone, Cox's calibration slope/intercept can be computed as follows:

```
from calzone.metrics import cox_regression_analysis

cox_slope, cox_intercept, cox_slope_ci, cox_intercept_ci = cox_regression_analysis(
    labels,
    probs,
    class_to_calculate=1,
    print_results=True,
    fix_slope=True
)
```

109 The slope and intercept values indicate the type of miscalibration. A slope >1 shows overcon-
110 fidence at high probabilities and underconfidence at low probabilities (and vice versa). In other
111 word, a slope < 1 (> 1) indicates that the spread of the predicted risks is too large (small)
112 relative to the true risks. A positive intercept indicates general overconfidence (and vice versa).
113 However, even with ideal slope and intercept values, the model may still be miscalibrated due
114 to non-linear effects that Cox's analysis cannot detect.

115 Integrated calibration index (ICI)

116 The integrated calibration index (ICI) is very similar to Expected calibration error (ECE). It also
117 tries to measure the average deviation between the predicted probability and true probability.
118 However, ICI does not use binning to estimate the true probability of a group of samples with
119 similar predicted probability. Instead, ICI uses curve smoothing techniques to fit a regression
120 curve and uses the regression result as the true probability (Austin & Steyerberg, 2019). The
121 ICI is then calculated using the following formula:

$$ICI = \frac{1}{n} \sum_{i=1}^n |f(p_i) - p_i|$$

122 where f is the fitting function and p is the predicted probability. The curve fitting is usually
123 done with Locally Weighted Scatterplot Smoothing (LOWESS). However, it is possible to
124 use any curve fitting method to calculate the ICI. One possible alternative is to use the Cox
125 calibration result and calculate the average difference between the predicted probability and the
126 estimated true probability from the curve. In calzone, we provide the Cox ICI and LOWESS
127 ICI support while the user can also use any curve fitting method to calculate the ICI using
128 functions in calzone.

```
from calzone.metrics import (
    cox_regression_analysis,
    lowess_regression_analysis,
    cal_ICI_cox
)

### calculating cox ICI
cox_ici = cal_ICI_cox(
    cox_slope,
    cox_intercept,
    probs,
```

```

class_to_calculate=1
)

### calculating LOWESS ICI
lowess_ici, lowess_fit_p, lowess_fit_p_correct = lowess_regression_analysis(
    labels,
    probs,
    class_to_calculate=1,
    span=0.5,
    delta=0.001,
    it=0
)

```

129 Notice that flexible curve fitting methods such as LOWESS regression are very sensitive to
 130 the choice of span and delta parameters. The user can visualize the fitting result to avoid
 131 overfitting or underfitting.

132 Spiegelhalter's Z-test

133 Spiegelhalter's Z-test is a test of calibration proposed by Spiegelhalter in 1986 (Spiegelhalter,
 134 1986). It uses the fact that the Brier score can be decomposed into:

$$B = \frac{1}{N} \sum_{i=1}^N (x_i - p_i)^2 = \frac{1}{N} \sum_{i=1}^N (x_i - p_i)(1 - 2p_i) + \frac{1}{N} \sum_{i=1}^N p_i(1 - p_i)$$

135 And the test statistic (TS) of Z test is defined as:

$$Z = \frac{B - E(B)}{\sqrt{\text{Var}(B)}} = \frac{\sum_{i=1}^N (x_i - p_i)(1 - 2p_i)}{\sum_{i=1}^N (1 - 2p_i)^2 p_i(1 - p_i)}$$

136 and it is asymptotically distributed as a standard normal distribution. In calzone, it can be
 137 calculated using:

```

from calzone.metrics import spiegelhalter_z_test

z, p_value = spiegelhalter_z_test(
    labels,
    probs,
    class_to_calculate=1
)

```

138 Metrics class

139 calzone also provides a class called CalibrationMetrics() to calculate all the metrics men-
 140 tioned above. The user can also use this class to calculate a list of metrics or all the metrics
 141 within a single function call. The function will return a dictionary containing the metrics name
 142 and their values. The metrics can be specified as a list of strings. The string 'all' can be used
 143 to calculate all the metrics.

```

from calzone.metrics import CalibrationMetrics

metrics = CalibrationMetrics(class_to_calculate=1)

metrics.calculate_metrics(
    labels,
    probs,
    metrics='all'
)

```

Other features

Confidence intervals

In addition to point estimates of calibration performance, calzone also provides functionality to compute confidence intervals for all metrics. For most metrics, this is computed through bootstrapping. The only exception is the confidence intervals from the reliability diagram which calculates Wilson's score intervals. The user can specify the number of bootstrap samples and the confidence level.

```
from calzone.metrics import CalibrationMetrics

metrics = CalibrationMetrics(class_to_calculate=1)

CalibrationMetrics.bootstrap(
    labels,
    probs,
    metrics='all',
    n_samples=1000
)
```

and a structured NumPy array will be returned.

Subgroup analysis

calzone will perform subgroup analysis by default in the command line user interface. If the user input CSV file contains a subgroup column, the program will compute metrics for the entire dataset and for each subgroup. A detailed description of the input format can be found in the documentation.

Prevalence adjustment

calzone also provides prevalence adjustment to account for prevalence changes between training data and testing data. Since calibration is defined using posterior probability, a mere shift in the disease prevalence of the testing data will result in miscalibration. It can be fixed by searching for the optimal derived original prevalence such that the adjusted probability minimizes a proper scoring rule such as cross-entropy loss. The formula of prevalence adjusted probability is:

$$P'(D = 1|\hat{p} = p) = \frac{\eta'/(1 - \eta')}{(1/p - 1)(\eta/(1 - \eta))} = p'$$

where η is the prevalence of the testing data, η' is the prevalence of the training data, and p is the predicted probability (Chen et al., 2018; Gu & Pepe, 2010; Horsch et al., 2008; Tian et al., 2020). We search for the optimal η' that minimizes the cross-entropy loss. The user can also specify η' and adjust the probability output directly if the training set prevalence is available.

Multiclass extension

calzone provides a multiclass extension for multiclass classification. The user can specify the class to calculate the metrics using a 1-vs-rest approach and test the calibration of each class. Alternatively, the user can transform the data and make the problem become a top-class calibration problem. The top-class calibration has a similar format to binary classification, but the class 1 probability is defined as the probability of the class with the highest probability and the class 0 probability is defined as 1 minus the probability of the class with the highest probability. The labels are transformed into whether the predicted class equals the true highest probability class, 0 if not and 1 if yes. Notice that the interpretation of some metrics may

177 change in the top-class transformation because the probability of class 1 after transformation
178 is not tied to a specific class in the original dataset.

179 Verification of methods

180 We compared the results calculated by calzone with external packages for some metrics
181 to ensure the correctness of the implementation. For the reliability diagram verification,
182 we compared the result with the `sklearn.calibration.calibration_curve()` function in
183 `scikit-learn` (Pedregosa et al., 2011) with the reliability diagram produced by calzone. For
184 the top-class ECE and Spiegelhalter's Z scores, we compared the result with the MAPIE package
185 (Taquet et al., 2022). For the Hosmer-Lemeshow statistic, we compared the result with the
186 `ResourceSelection` package in R language (Lele et al., 2024). The difference in result for all
187 functions tested were within 0.1%, indicating calzone output values are very consistent with
188 the values produced by other packages. We include the verification codes and comparison in
189 our documentation.

190 Command line interface

191 calzone also provides a command line interface. Users can visualize the calibration curve,
192 calculate calibration metrics and their confidence intervals using the this. For help on running
193 this functionality, the user can run `python cal_metrics.py -h`.

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203 Conflicts of interest

204 The authors declare no conflicts of interest.

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