Instructions for Paper Submissions to AISTATS 2023

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Abstract

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1 INTRODUCTION

Recently, ML has flourished in critical domains, such as healthcare and finance. In these areas, we need ML system with the capability to explain their predictions, apart from predicting with accuracy. For this reason there is an increased interest in Explainable AI (XAI), the field that provides interpretations about the behavior of complex black-box models. XAI literature distinguishes between local and global explainability techniques (Molnar et al., 2020a). Local methods explain a specific prediction, whereas global methods explain the entire model behavior. Global methods provide a universal explanation, summarizing the numerous local ones into a single interpretable outcome, usually a number or a plot. If a user wants to get a rough overview about which features are significant (feature importance) or whether a particular feature has a positive or negative effect on the output (feature effect), they should opt for a global explainability technique. On the other hand, aggregating the individual explanations for producing a concise global one is vulnerable to misinterpretations; Under strong feature interactions, the global explanation may obfuscate heterogeneous effects (Herbinger et al., 2022) that exist under the hood; a phenomenon called aggregation bias (Mehrabi et al., 2021).

Feature effect (FE) (Grömping, 2020) is a fundamental category of global explainability methods. The objective of FE is to the isolate and visualize the impact of a single feature on the output. [1] FE methods suffer from aggregation bias because, often, the rationale behind the average effect might be unclear. For example, a feature with zero average effect may indicate that the feature has no effect on the output or, contrarily, it has a highly positive effect in some cases and a highly negative in others. There are three widely-used FE methods; Partial Dependence Plots (PDP)(Friedman, 2001), Marignal Plots (MP)(Apley and Zhu, 2020) and Aggregated Local Effects (ALE)(Apley and Zhu, 2020). PDP and MP have been criticized for computing erroneous effects when the input features are (highly) correlated, which is a frequent scenario in many ML problems. Therefore, ALE has been established as the state-of-the-art FE method.

However, ALE faces two crucial drawbacks. First, it does not inform the user about potential heterogeneous effects hidden behind the average effect. In contrast, in the case of PDP, the heterogeneous effects can be spotted by exploring the Individual Conditional Expectations (ICE)(Goldstein et al., 2015). Second, ALE approximation from the samples of the training set requires partitioning the axis of the feature of interest in a sequence of non-overlapping intervals and estimating a single effect from the population of samples in each interval. We refer to this step using the term *bin-splitting problem*. Deciding on the sequence of intervals has important implications because ALE's interpretation in cases of correlated features is meaningful only inside each interval (Molnar, 2022). However, this crucial step has not been given the appropriate attention, making the approximation vulnerable to potential misinterpretations.

In this paper, we extend ALE with a probabilistic component for measuring the uncertainty of the explanation. The uncertainty of the global explanation expresses how certain we are that the averaged explanation is valid if applied to an instance drawn at random and reveals the heterogeneous effects. Given that ALE's interpretation (expected effect and uncertainty) is meaningful only inside each interval, we design a principled framework, where we treat the bin-splitting step as a data-driven clustering problem, search-

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[1] FE methods also isolate the effect of a pair of features to the output. Combinations of more than two features are not usual, because they encounter, among others, visualization difficulties.

ing for the optimal splitting given available instances of the training set. We, also, present a computationally-grounded algorithm for finding the optimal solution.

Contributions. The contribution of this paper is NAME, a feature effect method that:

- Extends ALE with a probabilistic component to quantify the heterogeneous effects behind the global explanation.
- Automatically extracts regions with similar effects, improving the estimation and the interpretability of ALE plots.

We provide empirical evaluation of the method in artificial and real datasets. The implementation of our method and the code for reproducing all the experiments is provided in the submission and will become publicly available upon acceptance.

2 BACKGROUND AND RELATED WORK

Notation. We refer to random variables (rv) using uppercase X, whereas to simple variables with plain lowercase x. Bold denotes a vector; $\mathbf{x}$ for simple variables or $\mathbf{X}$ for rvs. Often, we partition the input vector $\mathbf{x} \in \mathbb{R}^D$ to the feature of interest $x_s \in \mathbb{R}$ and the rest of the features $\mathbf{x_c} \in \mathbb{R}^{D-1}$. For convenience we denote it as $(x_s, \mathbf{x}_c)$, but we clarify that it corresponds to the vector $(x_1, \cdots, x_s, \cdots, x_D)$. Equivalently, we denote the corresponding rv as $X = (X_s, \mathbf{X}_c)$. The black-box function is $f : \mathbb{R}^D \to \mathbb{R}$ and the FE of the s-th feature is $f^{<\texttt{method}>}(x_s)$, where $<\texttt{method}>$ is the name of the FE method.[2]

Feature Effect Methods. The three well-known feature effect methods are: PDP, MP and ALE. PDP formulates the FE of the s-th attribute as an expectation over the marginal distribution $\mathbf{X}_c$, i.e., $f^{\texttt{PDP}}(x_s) = \mathbb{E}_{\mathbf{X}_c}[f(x_s, \mathbf{X}_c)]$, whereas MP formulates it as an expectation over the conditional $\mathbf{X}_c|X_s$, i.e., $f^{\texttt{MP}}(x_s) = \mathbb{E}_{\mathbf{X}_c|X_s=x_s}[f(x_s, \mathbf{X}_c)]$. ALE computes the global effect at x_s as the accumulation of the averaged local effects:

$$f^{\texttt{ALE}}(x_s) = \int_{z_{s,min}}^{x_s} \mathbb{E}_{\mathbf{X}_c|X_s=z}\left[\frac{\partial f(z, \mathbf{X}_c)}{\partial z}\right] \partial z \qquad (1)$$

ALE has specific advantages which gain particular value in cases of correlated input features. In these cases, PDP integrates over unrealistic instances, due to the use of the marginal distribution $\mathbf{X}_c$, and MP computes aggregated effects, i.e., imputes the combined effect of sets of features to a single feature. ALE manages to resolve both issues, and is therefore a trust able FE method in cases of correlated features.

Quantify the Heterogeneous Effects. FE methods answer the question *what is expected to happen to the output (expected effect), if the value of a specific feature is increased/decreased*. Having an answer to the question above, it comes naturally to also wonder *how certain we are about the expected change (uncertainty)*. For this reason, the quantification of the uncertainty along with the expected effect has attracted a lot of interest. The level of uncertainty is mostly quantified by measuring the existence of heterogeneous effects, i.e. whether there are local explanations that deviate from the expected global effect. ICE and d-ICE plots provide a visual understanding of the heterogeneous effects on top of PDPs. Another approach targets on grouping the heterogeneous effects, e.g., allocating ICE plots in homogeneous clusters, by dividing the input space.(Molnar et al., 2020b) Some other approaches, like H-Statistic, Greenwel, move a step behind and try to quantify the level of interaction between the input features, a possible cause of heterogeneous effects. In this case, the interpretation is indirect, since a strong interaction index is only an indicator of heterogeneous effects. The aforementioned approaches are under two limitations; They either do not quantify the uncertainty of the FE directly or they are based on PDPs, and, therefore, they are subject to the failure modes of PDPs in cases of correlated features. To the best of our knowledge, no method so far targets on quantifying the uncertainty of ALE.

Bin-Splitting for ALE estimation. In real ML scenarios, the FE is estimated from the limited instances of the training set. (Apley and Zhu, 2020) proposed dividing the s-th axis in K bins and estimating the local effects in each bin by evaluating the black box-function at the bin limits:

$$\hat{f}^{\texttt{ALE}}(x_s) = \sum_{k=1}^{k_x} \frac{1}{|\mathcal{S}_k|} \sum_{i:\mathbf{x}^i \in \mathcal{S}_k} \left[f(z_k, \mathbf{x_c}^i) - f(z_{k-1}, \mathbf{x_c}^i))\right] \qquad (2)$$

We denote as k_x the index of the bin that x_s belongs to, i.e. $k_x : z_{k_x-1} \leq x_s < z_{k_x}$ and $\mathcal{S}_k$ is the set of training instance that lie in the k-th bin, i.e. $\mathcal{S}_k = \{\mathbf{x}^i : z_{k-1} \leq x_s^i < z_k\}$. Afterwards, (cite) proposed the Differential ALE (DALE) for computing the local effects on the training instances using auto-differentiation:

$$\hat{f}^{\texttt{DALE}}(x_s) = \Delta x \sum_{k=1}^{k_x} \frac{1}{|\mathcal{S}_k|} \sum_{i:\mathbf{x}^i \in \mathcal{S}_k} \frac{\partial f}{\partial x_s}(\mathbf{x}^i) \qquad (3)$$

Their method has the advantages of remaining on-distribution even when bins become wider and, most importantly, allows the recomputation of the accumulated effect with different bin-splitting with near-zero computational cost. However, none of the approximations above

[2] An extensive list of all symbols used in the paper is provided in the helping material.

deals with the crucial problem of bin-splitting. As indicated by (Molnar, 2022), in ALE the effects are computed per interval (region) and the interpretation of the effect can only be local.

3 THE NAME METHOD

The NAME method extends ALE for measuring the uncertainty of the expected effect and automatically extracts regions with homogeneous effects. In Section 3.1 we define the component for the uncertainty quantification. In Section 3.2, we show how to estimate the average effect and the uncertainty on a specific interval from the limited samples of the training set. We, also, make an important proof about the aggregated variance defined over a bin. In Section 3.3, we define and solve the problem of optimal bin-splitting for automatically extract regions with homogeneous effects. Finally, in Section 3.4, we illustrate the appropriate visualization of NAME for facilitating its interpretation by a non-expert and we discuss important aspects of the method.

3.1 Uncertainty Quantification

ALE defines the local effect of the s-th feature at point $(x_s, \mathbf{x_c})$ as $\frac{\partial f}{\partial x_s}(x_s, \mathbf{x_c})$. All the local explanations at x_s are, then, weighted by the conditional distribution $p(\mathbf{x_c}|x_s)$ and are averaged, to produce the summarized effect at x_s:

$$\mu(x_s) = \mathbb{E}_{\mathbf{X}_c|x_s}\left[\frac{\partial f}{\partial x_s}(x_s, \mathbf{X}_c)\right] \tag{4}$$

The FE at x_s is the accumulation of the averaged local effects from $x_{s,min}$[3] until x_s, i.e. $f^{\texttt{ALE}}(x_s) = \int_{x_{s,min}}^{x_s} \mu(z)\partial z$. Limiting the explanation to the expected value level does not shed light to potential heterogeneous effects behind the averaged explanation. Therefore, we model the uncertainty of the local effects $\mathcal{H}(x_s)$ with the variance of the local explanations:

$$\mathcal{H}(x_s) := \sigma^2(x_s) = \mathrm{Var}_{\mathbf{X}_c|x_s}\left[\frac{\partial f}{\partial x_s}(x_s, \mathbf{X}_c)\right] \tag{5}$$

The uncertainty of the explanation emerges from the natural characteristics of the experiment, i.e., the data generating distribution and the properties of the black-box function. In Section 3.4, we propose appropriate visualizations for easier interpretation of Eq. (5). ALE defines the FE at x_s as the accumulation of the averaged local effects from x_{min} until x_s. Equivalently, we define the accumulated uncertainty (variance) until x_s, as the integral of the variances of the local effects:

$$f^{\texttt{ALE}}_{\sigma^2}(x_s) = \int_{z_{s,min}}^{x_s} \sigma^2(z)\partial z \tag{6}$$

[3] $x_{s,min}$ is the minimum value the s-th attribute can take. In estimations, it is the minimum s-th attribute value among the training set instances.

The accumulated uncertainty is not a directly interpretable quantity, since it measures the total uncertainty that characterizes the s-th feature effect plot. As stated in the Introduction, ALE outcomes should be interpreted at a local level, therefore, the only $\mathcal{H}(x_s)$ is the directly interpretable quantity. However, the accumulated uncertainty will help us define a sensible objective for the bin-splitting step, as we will discuss in Section 3.3.

3.2 Interval-Based Estimation

In real scenarios, we have ignorance about the data-generating distribution $p(x_s, \mathbf{x}_c)$, so, the estimations are based on the limited instances of the training set. Estimating Eqs. (4), (5) at the granularity of a point is impossible, because the probability of observing a sample inside the interval $[x_s - h, x_s + h]$ tends to zero, when $h \to 0$. We are, therefore, obliged to split the axis of x_s into a sequence of non-overlapping intervals (bins) and estimate the mean and the variance from the samples that lie inside each bin. The mean effect at an interval $[z_1, z_2)$ is defined as the mean of the expected effects:

$$\mu(z_1, z_2) = \frac{1}{z_2 - z_1}\int_{z_1}^{z_2} \mathbb{E}_{\mathbf{x_c}|x_s=z}\left[\frac{\partial f}{\partial x_s}\right]\partial z \tag{7}$$

Similarly, the accumulated variance at an interval $[z_1, z_2)$ is defined as:

$$\sigma^2(z_1, z_2) = \int_{z_1}^{z_2} \mathbb{E}_{\mathbf{x_c}|x_s=z}\left[(\frac{\partial f}{\partial x_s} - \mu(z_1, z_2))^2\right]\partial z \tag{8}$$

Theorem 1. If we define the residual $\rho(z)$ as the difference between the expected effect at x_s and the mean expected effect at the interval, i.e $\rho(z) = \mu(z) - \mu(z_1, z_2)$, then, the accumulated variance $\sigma^2(z_1, z_2)$ equals to the accumulation of the point-wise variances plus the squared residuals inside the interval:

$$\sigma^2(z_1, z_2) = \int_{z_1}^{z_2} \sigma^2(z) + \rho^2(z)\partial z \tag{9}$$

The proof is in the Appendix. Theorem 1 decouples the total uncertainty inside a bin $\mathcal{H}_{bin}(z_1, z_2) := \sigma^2(z_1, z_2)$ into two terms. The first term quantifies the accumulated uncertainty due to the natural characteristics of the experiment, i.e., $\mathcal{H}(z_1, z_2) = \int_{z_1}^{z_2} \mathcal{H}(z)\partial z$, and the second term adds extra nuisance uncertainty due to limiting the resolution $\mathcal{H}_n(z_1, z_2) := \int_{z_1}^{z_2} \rho^2(z)\partial z$. In other words, the creation of a bin burdens the estimation with a nuisance uncertainty:

$$\mathcal{H}_{bin}(z_1, z_2) = \mathcal{H}(z_1, z_2) + \mathcal{H}_n(z_1, z_2) \tag{10}$$

Eqs. (7), (8) can be directly estimated from the set $\mathcal{S}$ of the dataset instances with the s-th feature lying inside the interval, i.e., $\mathcal{S} = \{\mathbf{x}^i : z_1 \leq x_s^i < z_2\}$. The mean effect at

the interval, Eq. (7) is approximated by:

$$\hat{\mu}(z_1, z_2) = \frac{1}{|\mathcal{S}|} \sum_{i:\mathbf{x}^i \in \mathcal{S}} \left[\frac{\partial f}{\partial x_s}(\mathbf{x}^i) \right] \tag{11}$$

and the accumulated variance, Eq. (8) can be approximated by

$$\hat{\sigma}^2(z_1, z_2) = \frac{z_2 - z_1}{|\mathcal{S}|} \sum_{i:\mathbf{x}^i \in \mathcal{S}} \left(\frac{\partial f}{\partial x_s}(\mathbf{x}^i) - \hat{\mu}(z_1, z_2) \right)^2 \tag{12}$$

The approximation is unbiased only if the points are uniformly distributed in $[z_1, z_2]$. Elaborate.

3.3 Bin-Splitting: Finding Regions With Homogeneous Effects

As we discussed in the Introduction, when the features are (strongly) correlated, ALE provides meaningful interpretations only inside a bin. The accumulation of the mean effects inside each bin is done only for a producing smooth curve for easier visual exploration. Therefore, the extraction of regions with common effects is particularly important for a correct interpretation.

We formulate the bin-splitting as an unsupervised clustering problem. We want to partition the axis of the s-th feature into a sequence of variable-size non-overlapping intervals, so that the regions that will be created to provide meaningful explanations. A region with a meaningful explanation means that it clusters together points with similar expected (averaged) effects. On the other hand, since we estimate all the quantities from the limited samples of the training set, we need enough samples inside each bin for robustly estimate the expected effect and the variance. Therefore, we transform the bin-splitting problem to the following optimization problem:

$$\begin{aligned} \min_{\{z_0,\ldots,z_K\}} \quad & \mathcal{L} = \sum_{k=1}^{K} \hat{\sigma}^2(z_{k-1}, z_k) \\ \text{s.t.} \quad & |\mathcal{S}_k| \geq N \\ & z_0 = x_{s,min} \\ & z_K = x_{s,max} \end{aligned} \tag{13}$$

We search for the sequence of intervals $z_0, \ldots, z_K$ covering the axis of the s-th feature, $z_0 = x_{s,min}, z_K = x_{s,max}$ that minimize the sum of bin variances. The constraint of at least N points in each bin sets the limit for the minimum number of points inside each bin, to robustly estimate the mean effect and the variance. There is no constraint about the bin size and the number of bins K.

The objective function is the sum of the approximations of the bin variances. As we prove in Theorem 1, the observable bin variance can can be split in the accumulation of point-wise variances plus the residuals. In Corollary 1, we show that the accumulation of the point-wise variances is independent of the bin-splitting procedure. Therefore by minimizing L, we minimize the accumulation of the point-wise residuals in each bin, searching for bins that cluster together points with a common expected effect. An additional interpretation is that we search for the bin-splitting that adds the minimum the nuisance uncertainty over the lower-bound of the uncertainty due to the natural characteristics of the experiment.

3.3.1 Solve Bin-Splitting with Dynamic Programming

For achieving a computationally-grounded solution we set a threshold K_{max} on the maximum number of bins which also discretizes the solution space. The width of the bin can take discrete values that are multiple of the minimum step $u = \frac{x_{s,max} - x_{s,min}}{K}$. For defining the solution, we use two indexes. The index $i \in \{0, \ldots, K_{max}\}$ denotes the i-th limit (z_i) and the index $j \in \{0, \ldots, K_{max}\}$ denotes the j-th position along the axis $(x_j = x_{s,min} + j \cdot u)$. The recursive cost function $T(i, j)$ is the cost of setting the i-th limit z_i to x_j:

$$\mathcal{T}(i, j) = \min_{l \in \{0,\ldots,K_{max}\}} [\mathcal{T}(i-1, l) + \mathcal{B}(x_l, x_j)] \tag{14}$$

where $\mathcal{T}(0, j)$ equals zero if $j = 0$ and ∞ in any other case. $\mathcal{B}(x_l, x_j)$ denotes the cost of creating a bin with limits $[x_l, x_j)]$:

$$\mathcal{B}(x_l, x_j) = \begin{cases} \infty, & \text{if } x_j > x_l \text{ or } |\mathcal{S}_{(x_j, x_l)}| < N \\ 0, & \text{if } x_j = x_l \\ \hat{\sigma}^2(x_j, x_l), & \text{if } x_j \leq x_l \end{cases} \tag{15}$$

The optimal solution is given by solving $\mathcal{L} = \mathcal{T}(K_{max}, K_{max})$ and keeping track of the sequence of steps.

- Computational complexity

3.4 Visualization and Interpretation

- Discuss about the meaning of ALE, to find intervals with some effect

4 EXPERIMENTS

The experimental section is divided in simulation and real-world examples. The simulation examples, where the data-generating distribution $p(\mathbf{X})$ and the predictive function $f(\cdot)$ are defined by us, are used for comparing all methods against a solid ground-truth. In particular, we design two end-to-end simulation examples; At the first one, we focus on comparing NAME method versus PDP-ICE in terms of quantifying the heterogeneous effects for a range of different black-box functions. At the second one, we provide empirical clues that NAME method achieves a better approximation compared to traditional ALE, due to appropriate bin-splitting. Afterwards, we also apply the methods on some real-world datasets. In these cases, it is infeasible to obtain ground truth information, therefore, we perform evaluation at two levels. First, we compare visually NAME versus PDP with ICE plots. Second, we hold as ground-truth the effects computed on the full training-set and we, then, perform subsampling to evaluate the robustness of the bin-splitting method.

Metrics. Describe the metrics used for comparing methods.

4.1 Synthetic Example 1: Uncertainty Quantification

This synthetic example aims to showcase the superiority of NAME method in quantifying the main effect and the uncertainty compared to PDP with ICE plots. For being able to compare the two methods against a solid ground-truth, we limit ourserlves a simple evaluation framework based on following piecewise linear function:

$$f(\mathbf{x}) = \begin{cases} f_{\texttt{lin}} + \alpha f_{\texttt{int}} & \text{if } f_{\texttt{lin}} < 0.5 \\ 0.5 - f_{\texttt{lin}} + \alpha f_{\texttt{int}} & \text{if } 0.5 \leq f_{\texttt{lin}} < 1 \\ \alpha f_{\texttt{int}} & \text{otherwise} \end{cases} \quad (16)$$

where $f_{\texttt{lin}}(\mathbf{x}) = a_1 x_1 + a_2 x_2$ and $f_{int}(\mathbf{x}) = x_1 x_3$. As we observe, the linear term $f_{\texttt{lin}}$ includes the two correlated features and the term $f_{\texttt{int}}$ interacts the two non-correlated variables. The samples that we use in all examples are coming from the following distribution: $p(\mathbf{x}) = p(x_3)p(x_2|x_1)p(x_1)$ where $x_1 \sim \mathcal{U}(0,1)$, $x_2 \sim \mathcal{N}(x_1, \sigma_2^2 = 0)$ and $x_3 \sim \mathcal{N}(0, \sigma_3^2)$. We will test three variations by changing the parameters of the black-box function and of the generative distribution. Despite the model's simplicity, as we will see below, PDP with ICE plot fail completely to capture the ground-truth effect, due to the correlation between features X_1 and X_2. Furthermore, besides not the focus of the current example, NAME method manages to automatically extract the regions with constant effect. Details for obtaining the ground truth effects and the experimental set-up are in the Appendix.[4]

No Interaction, Equal weights. We test the feature effect when no interaction term is apparent, i.e. $\alpha = 0$, and the weights are equal $a_1 = a_2 = 1$. In this case, ground truth effect for $f^{\texttt{GT}}(x_1)$ is x_1 when $0 \leq x_1 < 0.25$, $-x_1$ when $0.25 \leq x_1 < 0.5$ and zero otherwise. In each position x_1, there is complete absence of heterogeneous effects, and therefore, the uncertainty of the global explanation is zero, i.e. $f_{\sigma^2}^{\mathcal{GT}}(x_1) = 0$. In Figure 4 we see that PDP effect is completely wrong and ICE plots imply heterogeneous effects. In contrast, ALE captures correctly the average effect and the zero uncertainty.

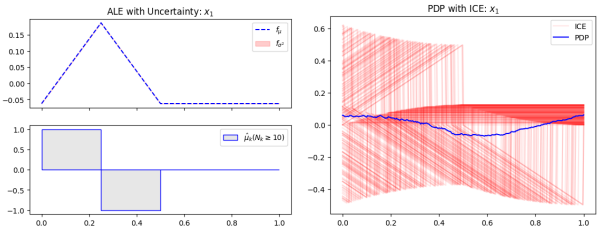

Figure 1: Feature effect for x_1; NAME method at the left and PDP with ICE at the right.

No Uncertainty, Different weights. As before, there is no interaction term, i.e. $\alpha = 0$, and uncertainty about the value of x_2, i.e. $x_2 = x_1$, but we give different weight to each feture $a_1 = 2, a_2 = 0.5$. Again, we observe that ALE quantifies perfectly the ground truth effect and the zero-uncertainty in contrast to PDP with ICE.

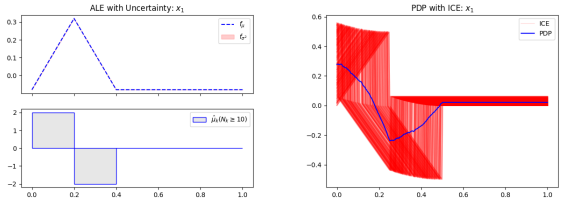

Figure 2: Figure 1

Uncertainty, Equal weights. In this case we activate the interaction term, i.e. $a = 1$, and we set equal weights $a_1 = a_2 = 1$. In contrast with above, the interaction term provokes heterogeneous effects for features x_1, x_3; at any position x_1, the local effects dependend on the unknown value of X_3 and vice-versa. The effect of x_2 continues to have zero-uncertainty, since it does not appear in any interaction term. NAME captures perfectly the effect of all features, and the uncertainty in the case of x_1, x_2. On the contrary, PDP-ICE quantify the effect and the uncertainty

[4]The Appendix contains the effects for all the features, some of them are ommited here for compact presentation.

correctly only in the case of x_3. For all other features, both the average effect and the uncertainty implied by ICE plots are wrong.

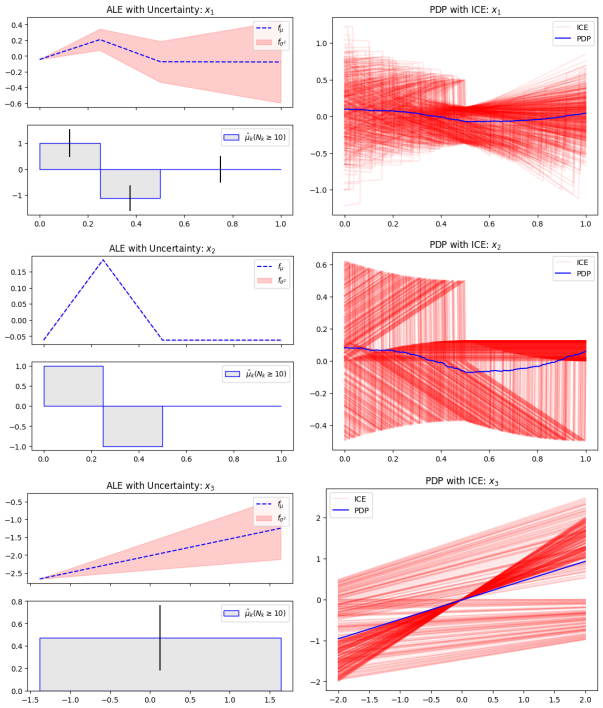

Figure 3: Figure 1

Discussion. The examples presented above, do not cover all cases. Therefore, they are not sufficiect to prove that NAME method quantifies the effect correctly in all cases. Their main objective is to highlight that PDP indifference for correlated features provoques erroneous effects, even in very simple cases. Unfortunately, the methods that are based on PDP and ICE to quantify heterogeneity are also vulnerable to the same errors.

The examples above do not cover the case where the interaction term include correlated features, x_1, x_2 for our example. In this case, there is controversy about the ground-truth effect (Grömping, 2020).

4.2 Synthetic Example 2: Bin-Splitting

The aim of this example is to illustrate the advantages of automatic bin-splitting based on the objective of Eq.(13). For evaluating our approach, we create the following validation framework; We generate a big dataset using dense sampling $N = 10^6$ and we treat as ground-truth the ALE estimation using dense fixed-size binning $K = 10^3$. Afterwards, we generate less samples $X = 500$ and we compare (a) the fixed-size ALE estimation for many different K versus (b) the auto-bin splitting algorithm. In all cases, the data generating distribution is $p(\mathbf{x}) = p(x_2|x_1)p(x_1)$ where $x_1 \sim \mathcal{U}(0,1)$, $x_2 \sim \mathcal{N}(x_1, \sigma_2^2 = 2)$.

We denote as $\mathcal{Z}^{\texttt{DP}} = \{z_{k-1}^{\texttt{DP}}, \cdots, z_K^{\texttt{DP}}\}$ the sequence obtained by automatic-splitting based on the optimisation problem of Eq. (13) and with $\mathcal{Z}^{\texttt{K}}\}$ the corresponding fixed-sized splitting. The comparison is done using three metrics; (a) $\mathcal{L}^{\mu}_{\texttt{DP}|\texttt{K}} = \frac{1}{|\mathcal{Z}^{\texttt{DP}|\texttt{K}}|}\sum_{k=1}^{K}|\mu_k - \hat{\mu}_k|$ quantifies the average error in estimating the the expected effect, (b) $\mathcal{L}^{\sigma^2}_{\texttt{DP}|\texttt{K}} = \frac{1}{|\mathcal{Z}^{\texttt{DP}|\texttt{K}}|}\sum_{k=1}^{K}|\sigma_k^2 - \hat{\sigma}_k^2|$ the average error in estimating the variance of the effect and (c) $\mathcal{L}^{\rho^2}_{\texttt{DP}|\texttt{K}} = \frac{1}{|\mathcal{Z}^{\texttt{DP}|\texttt{K}}|}\sum_{k=1}^{K}\rho_k^2$ the average extra nuisance uncertainty.

Example 1. In this example, we defin a black-box function $f_1(x_1) = a_1 x_1 + x_1 x_2$ with 6 piecewise-linear regions of different-size, i.e., a_1 equals to $= \{2, -2, 5, -10, 0.5\}$ in the regions defined by the sequence $\{0, 0.2, 0.4, 0.45, 0.5, 1\}$. The example highlights the importance of variable-size splitting. Given that the smalest intervals size is 0.05 any fixed-size splitting with less than $\frac{1}{\Delta x} = 20$ bins, will mix together effects and increase the variance error $\mathcal{L}_{\texttt{K}}^{\sigma^2}$ due to the increase of the residual $\mathcal{L}_{\texttt{K}}^{\rho^2} > 0$. This is evident in figure. On the other hand, a large number of bins divides homogeneuos regions, i.e. region $[0.5, 1)$, into smaller ones with more unstable estimations which increases $\mathcal{L}_{\texttt{K}}^{\mu}$ Figure. Variable-size binning leads to the optimal solution. As we see in figure automatic-bin splitting small bins in areas with fine-grain effects and merges together regions with similar effects, leading to a near optimal bin splitting.

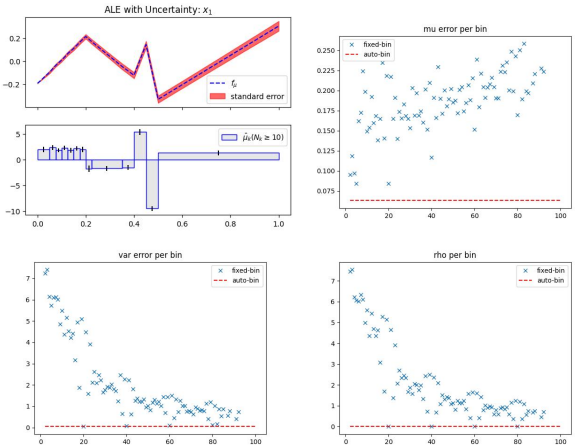

Figure 4: Figure 1

Example 2. The black-box function $f(\mathbf{x}) = 4x_1^2 + x_2^2 + x_1 x_2$

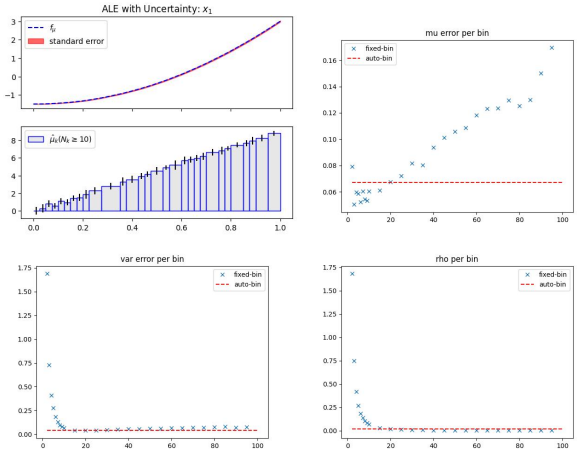

Figure 5: Figure 1

5 REAL-WORLD EXAMPLES

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