Aggregated Shapley effects: nearest-neighbor estimation procedure and confidence intervals. Application to snow avalanche modeling.

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Natural phenomena are complex.
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Given some initial conditions:

\[
\begin{align*}
\frac{\partial h}{\partial t} + \frac{\partial hv}{\partial x} &= 0 \\
\frac{\partial hv}{\partial t} + \frac{\partial}{\partial x} \left( hv^2 + \frac{h^2}{2} \right) &= h(g \sin \phi - F)
\end{align*}
\]

where \( v = \|\mathbf{v}\| \) is the flow velocity, \( h \) is the flow depth, \( \phi \) is the local angle, \( t \) is the time, \( g \) is the gravity constant and \( F = \|\mathbf{F}\| \) is the Voellmy frictional force,

\[
F = \mu g \cos \phi + \frac{g}{\xi h} v^2,
\]

where \( \mu \) and \( \xi \) are the friction parameters (see more detail in [Naaim et al., 2004]).
Natural phenomena are complex.

Black box model
Aggregated Shapley effects

Motivation

Inputs: $\mu$, $\xi$, $x_{\text{start}}$

Black Box

Outputs: $f$

$$Y = \begin{cases} 
  v : D = [x_{\text{min}}, x_{\text{max}}] \subset \mathbb{R} \rightarrow \mathbb{R} \\
  h : D = [x_{\text{min}}, x_{\text{max}}] \subset \mathbb{R} \rightarrow \mathbb{R} \\
  x_{\text{runout}} \in \mathbb{R}^+ 
\end{cases}$$
Motivation

Inputs

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\[
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  x_{\text{runout}} \in \mathbb{R}^+
\end{cases}
\]
To get meaningful samples, we apply acceptance-rejection (AR) sampling:
Framework of our application

The ingredients for our global sensitivity analysis (GSA) problem are:

- input parameters leading to significant snow avalanches are dependent,
- the sample is given from the AR sampling and not drawn based on a specific estimation strategy (pick-freeze, replicated designs,...),
- two of the three outputs are functional.
GSA framework

We aim at determining which input parameters contribute the most to a given quantity of interest (defined from the output of the model).
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\[ X = (X_1, \ldots, X_d) \]
\[ X_i : \Omega \to \mathbb{R} \quad \forall i \in \{1, \ldots, d\} \]

\[ f(X) = Y \]
\[ Y : \Omega \to \mathbb{R}^p \]
We aim at determining which input parameters contribute the most to a given quantity of interest (defined from the output of the model).

Depending on the quantities of interest:
- variance-based (Sobol’ indices [Sobol’, 1993], Shapley effects [Owen, 2014]),
- density-based indices or moment-free measures [Borgonovo, 2007, Da Veiga, 2015],
- derivative-based measures [Sobol’ and Kucherenko, 2009, Lamboni et al., 2013].
GSA framework

We aim at determining which input parameters contribute the most to a given quantity of interest (defined from the output of the model).

Shapley effects are the ideal framework to our problem!
- they are meaningful even for dependent inputs [Owen and Prieur, 2017, Iooss and Prieur, 2019],
- there exists a given data estimation method [Broto et al., 2020].

Moreover,
- we can extend them to multivariate and functional outputs adapting the propositions in [Campbell et al., 2006, Lamboni et al., 2009, Gamboa et al., 2013, Alexanderian et al., 2020],
- we propose a bootstrap strategy to build confidence intervals.
Shapley effects

If $Y$ is scalar.

Shapley effect [Owen, 2014] (coopetative game theory [Shapley, 1953]) of $i$:

$$Sh_i = \frac{1}{d \text{Var}(Y)} \sum_{u \subseteq \{-i\}} \left( \frac{d - 1}{|u|} \right)^{-1} (\text{Var}(E(Y|X_{u \cup i})) - \text{Var}(E(Y|X_u))).$$
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[Shapley, 1953] proved that this is the fairest way to divide a price among players (efficiency, symmetry, dummy, additive).
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$$Sh_i = \frac{1}{d \text{Var}(Y)} \sum_{u \subseteq \{-i\}} \left( \frac{d-1}{|u|} \right)^{-1} \left( \text{Var} \left( \mathbb{E}(Y|X_u \cup i) \right) - \text{Var} \left( \mathbb{E}(Y|X_u) \right) \right).$$

[Shapley, 1953] proved that this is the fairest way to divide a price among players (efficiency, symmetry, dummy, additive).

**Shapley effect properties:**

- $0 \leq Sh_i \leq 1$ for all $i \in \{1, \ldots, d\}$,
- $\sum_{i=1}^{d} Sh_i = 1$. 

[Diagram of Inputs (coop. game players), Price, Shapley value]
Aggregated Shapley effects

If output is multivariate or the discretization of a functional output \( Y = (Y_1, \ldots, Y_p) \).

Aggregated Shapley effects of input \( X_i \):

\[
G_{Sh_i} = \frac{\sum_{j=1}^{p} \text{Var}(Y_j) Sh_{ji}}{\sum_{j=1}^{p} \text{Var}(Y_j)},
\]

Aggregated Shapley effects accomplish the natural requirements for a sensitivity measure [Heredia et al., 2020]:

- \( 0 \leq G_{Sh_i} \leq 1 \),
- \( G_{Sh_i}(\lambda f(X)) = G_{Sh_i}(f(X)) \) for all \( \lambda \in \mathbb{R} \),
- \( G_{Sh_i}(O f(X)) = G_{Sh_i}(f(X)) \) for all \( O \in \mathbb{R}^{p \times p} \) and \( O^t O = I \).

If the output dimension \( p >> 1 \), dimension reduction techniques such as pca, fpca [Yao et al., 2005] [Ramsay and Silverman, 2005] should be performed.
Estimation using nearest neighbors

For all $1 \leq i \leq d$ and all $1 \leq j \leq p$ to estimate $S_{hi}^j$ and $G_{hi}$, we need to estimate

$$\text{Var} \left( \mathbb{E}(Y_j|X_u) \right) \quad \text{or} \quad \mathbb{E} \left( \text{Var}(Y_j|X_{-u}) \right)$$

for all $u \subseteq \{1, \ldots, d\}$, with $-u = \{1, \ldots, d\} \setminus u$. In our context, we have to estimate from the given data $(X, Y)$ obtained from the AR sampling.
Estimation using nearest neighbors

For all $1 \leq i \leq d$ and all $1 \leq j \leq p$ to estimate $Sh^j_i$ and $GSh_i$, we need to estimate

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In our context, we have to estimate from the given data $(X, Y)$ obtained from the AR sampling.

[Broto et al., 2020] proposed to estimate $E_u = \mathbb{E} \left( \text{Var}(Y_j | X_{-u}) \right)$ using nearest-neighbors. The estimator $\hat{E}_u$ converges in probability to $E_u$ under mild assumptions (theorem 6.6 of [Broto et al., 2020]).

Combining what they call the subset W-aggregation procedure with the estimates $\hat{E}_u$, [Broto et al., 2020, proposition 6.12] propose a consistent estimator for each Shapley effect.
Adaptation to the estimation of both Shapley and aggregated Shapley effects, with the construction of bootstrap confidence intervals:

Inputs: (i) a $n$ sample $(x, y)$, (ii) $N_{tot}$ the estimation cost, (iii) $1 \leq N_u \leq n$, the cost for estimation of $E_u$ ($N_u$ depends on $N_{tot}$ and can be chosen in order to minimize the variance of the estimation), (iv) a $N_u$ random sample $(s_\ell)_{1 \leq \ell \leq N_u}$ from $\{1, \ldots, n\}$, (v) $N_I$ number of neighbors.
Adaptation to the estimation of both Shapley and aggregated Shapley effects, with the construction of bootstrap confidence intervals:

Inputs: (i) a \( n \) sample \((x, y)\), (ii) \( N_{\text{tot}} \) the estimation cost, (iii) \( 1 \leq N_u \leq n \), the cost for estimation of \( E_u \) (\( N_u \) depends on \( N_{\text{tot}} \) and can be chosen in order to minimize the variance of the estimation), (iv) a \( N_u \) random sample \((s_\ell)_{1 \leq \ell \leq N_u}\) from \( \{1, \ldots, n\} \), (v) \( N_I \) number of neighbors.

1. For all \( u \subset \{1, \ldots, d\} \) and for all \( 1 \leq \ell \leq N_u \), compute:

\[
\hat{E}^j_{u, s_\ell} = \frac{1}{N_I - 1} \sum_{v, x_{-u}^v \in \mathcal{B}_{-u, \ell}} \left( y_j^v - \frac{1}{N_I} \bar{y}_{s_\ell} \right)^2 \quad \text{with} \quad \bar{y}_{s_\ell} = \frac{1}{N_I} \sum_{v, x_{-u}^v \in \mathcal{B}_{u, \ell}} y_j^v
\]

with \( \mathcal{B}_{-u, \ell} \) the set of \( N_I \) closest neighbors of \( x_{-u}^{s_\ell} \) where \( x_{-u}^{s_\ell} = (x_{w_1}^{s_\ell}, \ldots, x_{w_k}^{s_\ell}) \) with \( -u = \{w_1, \ldots, w_k\} \) and \( k = |-u| \).
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Inputs: (i) a \( n \) sample \((x, y)\), (ii) \( N_{\text{tot}} \) the estimation cost, (iii) \( 1 \leq N_u \leq n \), the cost for estimation of \( E_u \) (\( N_u \) depends on \( N_{\text{tot}} \) and can be chosen in order to minimize the variance of the estimation), (iv) a \( N_u \) random sample \((s_\ell)_{1 \leq \ell \leq N_u}\) from \( \{1, \ldots, n\} \), (v) \( N_I \) number of neighbors.

1. For all \( u \subset \{1, \ldots, d\} \) and for all \( 1 \leq \ell \leq N_u \), compute:

\[
\hat{E}_{u,s_\ell}^j = \frac{1}{N_I - 1} \sum_{v : x_v \in \mathcal{B}_{-u,\ell}} \left( y_j^v - \frac{1}{N_I} \bar{y}_{s_\ell} \right)^2 \quad \text{with} \quad \bar{y}_{s_\ell} = \frac{1}{N_I} \sum_{v : x_v \in \mathcal{B}_{u,\ell}} y_j^v
\]

with \( \mathcal{B}_{-u,\ell} \) the set of \( N_I \) closest neighbors of \( x_{s_\ell}^u \) where
\( x_{s_\ell}^u = (x_{w_1}^u, \ldots x_{w_k}^u) \) with \( -u = \{w_1, \ldots, w_k\} \) and \( k = |{-u}| \).
2.1 Compute for all $u \subset \{1, \ldots, d\}$.

$$\widehat{E}_u^j = \frac{1}{N_u} \sum_{\ell=1}^{N_u} \widehat{E}_{u,s_\ell}^j. \quad (1)$$

2.2 Compute $B$ bootstrap samples (the idea of block-bootstrap is adapted from [Benoumechiara and Elie-Dit-Cosaque, 2019]) from (1):

2.2.1 Create $N_u$ bootstrap samples from $\widehat{E}_{u,s_\ell}^j$ by sampling with replacement from $(\widehat{E}_{u,s_\ell}^j)_{1 \leq \ell \leq N_u}$.

2.2.2 Compute for all $b \in \{1, \ldots, B\}$:

$$\widehat{E}_{u}^{j,(b)} = \frac{1}{N_u} \sum_{\ell=1}^{N_u} \widehat{E}_{u,s_\ell}^{j,(b)}. \quad (2)$$
3.1. Compute $\widehat{SH}_i^j$ for all $j \in \{1, \ldots, p\}$ according to:

$$\widehat{SH}_i^j = \frac{1}{d\hat{\sigma}_j^2} \sum_{u \subset -i} \left( \frac{d-1}{|u|} \right)^{-1} \left( \widehat{E}_{u \cup \{i\}}^j - \widehat{E}_u^j \right),$$

where $\hat{\sigma}_j^2$ is the empirical variance of $y_j$.

3.2 Compute $B$ bootstrap samples of $\widehat{SH}_i^j$ using (2) in (3):

$$\widehat{SH}_i^{j,(b)} = \frac{1}{d\hat{\sigma}_j^{2(b)}} \sum_{u \subset -i} \left( \frac{d-1}{|u|} \right)^{-1} \left( \widehat{E}_{u \cup \{i\}}^{j,(b)} - \widehat{E}_u^{j,(b)} \right),$$

where $\hat{\sigma}_j^{2(b)}$ is the empirical variance of a bootstrap sample of $y_j$. 
4.1 Compute $\hat{G}_{Sh_i}$ for all $i \in \{1, \ldots, d\}$ according to:

$$\hat{G}_{Sh_i} = \frac{1}{d \sum_{j=1}^{p} \hat{\sigma}_j^2} \sum_{j=1}^{p} \sum_{u \subset -i} (d - 1)^{-1} \left( \hat{E}_{u \cup \{i\}}^j - \hat{E}_u^j \right),$$

4.2 compute $B$ bootstrap samples of $\hat{G}_{hi}$:

$$\hat{G}_{Sh_i}^{(b)} = \frac{1}{d \sum_{j=1}^{p} \hat{\sigma}_j^{2,(b)}} \sum_{j=1}^{p} \sum_{u \subset -i} (d - 1)^{-1} \left( \hat{E}_{u \cup \{i\}}^{j,(b)} - \hat{E}_u^{j,(b)} \right).$$
4.1 Compute $\hat{GSh}_i$ for all $i \in \{1, \ldots, d\}$ according to:

$$
\hat{GSh}_i = \frac{1}{d \sum_{j=1}^{p} \hat{\sigma}_j^2} \sum_{j=1}^{p} \sum_{u \subseteq -i} \left( \frac{d - 1}{|u|} \right)^{-1} \left( \hat{E}_{u \cup \{i\}} - \hat{E}_u \right),
$$

4.2 Compute $B$ bootstrap samples of $\hat{Gh}_i$:

$$
\hat{GSh}_i^{(b)} = \frac{1}{d \sum_{j=1}^{p} \hat{\sigma}_j^{2,(b)}} \sum_{j=1}^{p} \sum_{u \subseteq -i} \left( \frac{d - 1}{|u|} \right)^{-1} \left( \hat{E}_{u \cup \{i\}}^{(b)} - \hat{E}_u^{(b)} \right).
$$

5 Compute simultaneous bootstrap confidence intervals (correction of Bonferroni) with bias correction (see e.g., [Efron, 1981]).
Linear Gaussian model with two inputs

Model from [Iooss and Prieur, 2019].

\[ Y = \beta_0 + \beta^t X \]

with \( X_i \sim \mathcal{N}(0, 1) \), \( \beta_1 = 1 \), \( \beta_2 = 0 \), \( X_1 \) and \( X_2 \) correlated \( \rho = 0.4 \).

Figure: Mean absolute error of the estimation of scalar Shapley effects in \( N=300 \) i.i.d. samples in function of \( N_{tot} \). \( N_I = 3 \). The 0.05 and 0.95 pointwise quantiles of the absolute error are drawn with gray polygons. The probability of coverage of the 90% bootstrap simultaneous intervals (Bonferroni correction) is displayed with dotted lines. The theoretical probability of coverage 0.9 is shown with a plain gray line. The bootstrap sample size is fixed to \( B = 500 \).
Multivariate Linear Gaussian model with two inputs

\[ Y = (Y_1, Y_2, Y_3) = \beta_0 + \beta^T X \]

with \( X_i \sim \mathcal{N}(0, 1) \), \( X_1 \) and \( X_2 \) correlated \( \rho = 0.4 \), and \( \beta \in \mathbb{R}^{2 \times 3} \):

\[ \beta = \begin{bmatrix} 1 & 4 & 0.1 \\ 1 & 3 & 0.9 \end{bmatrix}. \]

Figure: Mean absolute error of the estimation of aggregated Shapley effects in \( N=300 \) i.i.d. samples in function of \( N_{tot} \). \( N_I \). The 0.05 and 0.95 pointwise quantiles of the absolute error are drawn with gray polygons. The probability of coverage of the 90% bootstrap simultaneous intervals (Bonferroni correction) is displayed with dotted lines. The theoretical probability of coverage 0.9 is shown with a plain gray line.
Aggregated Shapley effects
Application: Snow avalanche modeling

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>Static friction coefficient</td>
<td>$\mathcal{U}[0.05, 0.65]$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Turbulent friction [m/s$^2$]</td>
<td>$\mathcal{U}[400, 10000]$</td>
</tr>
<tr>
<td>$l_{start}$</td>
<td>Length of the release zone [m]</td>
<td>$\mathcal{U}[5, 300]$</td>
</tr>
<tr>
<td>$h_{start}$</td>
<td>Mean snow depth in the release zone [m]</td>
<td>$\mathcal{U}[0.05, 3]$</td>
</tr>
<tr>
<td>$x_{start}$</td>
<td>Release abscissa [m]</td>
<td>$\mathcal{U}[0, 1600]$</td>
</tr>
</tbody>
</table>

We consider $\text{vol}_{start} = l_{start} \times h_{start} \times 72.3 / \cos(35^\circ)$ instead of $h_{start}$ and $l_{start}$.

**AR rules:**
- avalanche simulation is flowing in $[1600m, 2412m]$,
- $\text{vol} > 7000m^3$,
- runout distance < 2500m (end of the path).

From $n_0 = 100000$, AR sample size $n_1 = 6152$. 
AR rules:

- avalanche simulation is flowing in \([1600 \, \text{m}, 2412 \, \text{m}]\),
- \(vol > 7000 \, \text{m}^3\),
- runout distance < 2500m (end of the path).

From \(n_0 = 100000\), AR sample size \(n_1 = 6152\).
Ubiquitous Shapley effects

Figure: Shapley effects are estimated with a sample of size 6152 and Ntot=2002. The local slope is displayed with a white line. A gray dotted rectangle box is displayed at interval [2017, 2412] where snow avalanche return periods vary from 10 to 10 000 years. The bootstrap sample size is fixed to B = 500.
Aggregated Shapley effects

Figure: Aggregated Shapley effects are estimated with a sample of size 6152 and $N_{tot}=2002$. Effects are estimated using the first fPCs explaining more than 95% of the output variance. The local slope is displayed with a gray line. A gray dotted rectangle is displayed at [2017m, 2412m] where snow avalanche return periods vary from 10 to 10 000 years. The bootstrap sample size is fixed to $B = 500$. 

Conclusions

- We extended Shapley effects to models with multivariate or functional outputs.
- We proposed an algorithm to construct bootstrap confidence intervals for estimation.
- The bootstrap confidence intervals have accurate coverage probability.
- Aggregated Shapley effects are more stable and easier to interpret (observed by [Alexanderian et al., 2020] for Sobol’ indices).

Perspectives

- In order to estimate with samples of higher size, build a surrogate model of our avalanche model.
- To perform a GSA in several corridors in order to see if there exist correlations between the local slope and the ubiquitous effects.
- To study theoretically the asymptotic properties of our estimator.
Thanks! Questions?
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Appendix
Shapley value [Shapley, 1953]

Given a set of \( d \) players in a coalitional game and a characteristic function \( \text{val} : 2^d \rightarrow \mathbb{R} \), \( \text{val}(\emptyset) = 0 \), the Shapley value \((\phi_1, \ldots, \phi_d)\) is the only distribution of the total gains \( \text{val}({1, \ldots, d}) \) to the players satisfying the desirable properties listed below:

1. **(Efficiency)** \( \sum_{i=1}^{d} \phi_i = \text{val}({1, \ldots, d}) \).
2. **(Symmetry)** If \( \text{val}(u \cup \{i\}) = \text{val}(u \cup \{\ell\}) \) for all \( u \subseteq \{1, \ldots, d\} - \{i, j\} \), then \( \phi_i = \phi_\ell \).
3. **(Dummy)** If \( \text{val}(u \cup \{i\}) = \text{val}(u) \) for all \( u \subseteq \{1, \ldots, d\} \), then \( \phi_i = 0 \).
4. **(Additivity)** If \( \text{val} \) and \( \text{val}' \) have Shapley values \( \phi \) and \( \phi' \) respectively, then the game with characteristic function \( \text{val} + \text{val}' \) has Shapley value \( \phi_i + \phi'_i \) for \( i \in \{1, \ldots, d\} \).

It is proved in [Shapley, 1953] that according to the Shapley value, the amount that player \( i \) gets given a coalitional game \((\text{val}, d)\) is:

\[
\phi_i = \frac{1}{d} \sum_{u \subseteq \{i\}} \left( \frac{d-1}{|u|} \right)^{-1} (\text{val}(u \cup \{i\}) - \text{val}(u)) \quad \forall \, i \in \{1, \ldots, d\}.
\]
Functional principal component analysis [Yao et al., 2005]
We have a collection of $n$ independent trajectories of a smooth random function $f(.,X)$ with unknown mean $\mu(s) = \mathbb{E}(f(s,X)), s \in \tau$, where $\tau$ is a bounded and closed interval in $\mathbb{R}$, and covariance function:

$$G(s_1, s_2) = \text{Cov}(f(s_1,X), f(s_2,X)), s_1, s_2 \in \tau.$$ 

We assume that $G$ has a $L^2$ orthogonal expansion in terms of eigenfunction $\xi_k$ and non increasing eigenvalues $\lambda_k$ such that:

$$G(s_1, s_2) = \sum_{k \geq 1} \lambda_k \xi_k(s_1,X) \xi_k(s_2,X), s_1, s_2 \in \tau.$$ 

The Karhunen-Loève orthogonal expansion of $f(s,X)$ is:

$$f(s,X) = \mu(s) + \sum_{k \geq 1} \alpha_k(X) \xi_k(s) \approx \mu(s) + \sum_{k=1}^q \alpha_k(X) \xi_k(s), s \in \tau, \quad (4)$$

where $\alpha_k(X) = \int_\tau f(s,X) \xi_k(s) \, ds$ is the $k$-th functional principal component (fPC) and $q$ is a truncation level.

For fPCs estimation, the authors in [Yao et al., 2005] propose first to estimate $\hat{\mu}(s)$ using local linear smoothers and to estimate $\hat{G}(s_1, s_2)$ using local linear surface smoothers ([Fan and Gijbels, 1996]).
The estimates of eigenfunctions and eigenvalues correspond then to the solutions of the following integral equations:

\[ \int_\tau \hat{G}(s_1, s) \hat{\xi}_k(s_1) ds_1 = \hat{\lambda}_k \hat{\xi}_k(s), s \in \tau, \]

with \( \int_\tau \hat{\xi}(s) ds = 1 \) and \( \int_\tau \hat{\xi}_k(s) \hat{\xi}_m(s) = 0 \) for all \( m \neq k \leq q \). The problem is solved by using a discretization of the smoothed covariance (see further details in [Rice and Silverman, 1991] and [Capra and Müller, 1997]). Finally, fPCs \( \hat{\alpha}_k(X) = \int_\tau f(s, X) \hat{\xi}_k(s) ds \) are solved by numerical integration.

**Aggregated Shapley effects** are computed with only the \( q \) first fPCs:

\[
\widetilde{GSh}_i = \frac{1}{d \sum_{k=1}^{q} \lambda_k} \sum_{k=1}^{q} \sum_{u \subseteq -i} \left( d - 1 \right)^{-1} \left( \mathbb{E}(\text{Var}(\alpha_k(X)|X_{u \cup \{i\}})) - \mathbb{E}(\text{Var}(\alpha_k(X)|X_u)) \right).
\]

(5)
Theorem (Theorem 6.6 [Broto et al., 2020])

If $f$ is bounded, the $\hat{E}_u$ converges to $E_u$ in probability when $n$ and $N_u$ if:

- For all $i \in \{1, \ldots, d\}$, $(\mathcal{X}_i, d_i)$ is a Polish space with metric $d_i$, with $\mathcal{X}_i$ the domain of $X_i$, and $X = (X_1, \ldots, X_d)$ has a density $f_X$ with respect to a finite measure $\mu = \otimes_{i=1}^d \mu_i$ which is bounded and $\mathbb{P}_X$ almost everywhere continuous.

- The closest neighbors in $\mathcal{B}_u, \ell$ are two by two distinct.
The bias-corrected percentile method [Efron, 1981]

Given bootstrap samples $B$ of $\hat{GSh}_i$, $\mathcal{R}_i = \{\hat{GSh}_i^{(1)}, \ldots, \hat{GSh}_i^{(B)}\}$.

We compute a bias correction constant $z_0$:

$$
\hat{z}_0 = \Phi^{-1} \left( \frac{\#\{\hat{GSh}_i^{(b)} \in \mathcal{R}_i \text{ s. t. } \hat{GSh}_i^{(b)} \leq \hat{GSh}_i \}}{B} \right)
$$

where $\Phi$ the standard normal cumulative distribution function.

The corrected quantile estimate $\hat{q}(\beta)$:

$$
\hat{q}_i(\beta) = \Phi(2\hat{z}_0 + z_\beta),
$$

where $z_\beta$ satisfies $\Phi(z_\beta) = \beta$.

To guarantee the validity of the previous BC corrected confidence interval $[\hat{q}_i(\alpha/2), \hat{q}_i(1 - \alpha/2)]$, there must exist an increasing transformation $g$, $z_0 \in \mathbb{R}$ and $\tau > 0$ such that $g(\hat{GSh}_i) \sim \mathcal{N}(GSh_i - \tau z_0, \tau^2)$ and $g(\hat{GSh}_i^*) \sim \mathcal{N}(\hat{GSh}_i - \tau z_0, \tau^2)$ where $\hat{GSh}_i^*$ is the bootstrapped $\hat{GSh}_i$ for fixed sample (see [Efron, 1981]).
Probability of coverage with Bonferroni correction
The probability of coverage with Bonferroni correction is the probability that \([\hat{q}_i(\alpha/(2d)), \hat{q}_i(1 - \alpha/(2d))]\) contains \(GSh_i\) for all \(i \in \{1, \ldots, d\}\) simultaneously.

The POC is estimated as

\[
\widehat{POC} = \sum_{k=1}^{N} \frac{w^k}{N},
\]

where \(w^k\) is equal to 1 if \(\hat{q}_i(\alpha/(2d)) \leq GSh_i \leq \hat{q}_i(1 - \alpha/(2d))\) for all \(i\), and 0 otherwise.