Introduction

Management of environmental ressources often requires the analysis of multivariate extreme values. In climate studies, extreme events represent a major challenge due to their consequences. The problem of missing data is present in many fields above all in environmental research (see [Xia et al., 1999]), usually due to instrument errors, communication and processing errors. In a time series setting, the observation periods of a multivariate series could be different and overlap only partially. Rigourous inference methods for assessing extremal dependencies which handle missing values are thus in demand. In this paper, we are particularly interested in the dependence structure of multivariate extreme value distribution. This concept is defined as follows.

Formally, let $(\Omega, \mathcal{A}, \mathbb{P})$ be a probability space and $\mathbf{X} = (X_1, \dots, X_d)$ be a d-dimensional random vector with values in $(\mathbb{R}^d, \mathcal{B}(\mathbb{R}^d))$ with $d \geq 2$. This random vector has a joint distribution function F and its margins are denoted by $F_j(x) = \mathbb{P}\{X_j \leq x\}$ for all $x \in \mathbb{R}$ and $j \in \{1, \dots, d\}$. A function $C : [0,1]^d \rightarrow [0,1]$ is called a d-dimensional copula if it is the restriction to $[0,1]^d$ of a distribution function whose margins are given by the uniform distribution on the interval $[0,1]$. Since the work of [Sklar, 1959], it is well known that every distribution function F can be decomposed as $F(\mathbf{x}) = C(F_1(x_d), \dots, F_d(x_d))$, for all $\mathbf{x} \in \mathbb{R}^d$. Under the framework of extreme, the notion of copulas leads to the so-called extreme value copulas (see [Gudendorf and Segers, 2010])

$$C(\mathbf{u}) = exp\left(-\ell(-log(u_1), \dots, -log(u_d)\right), \quad \mathbf{u} \in (0,1]^d, \tag{1}$$

with $\ell : [0,\infty)^d \rightarrow [0,\infty)$ the stable tail dependence function. The tail dependence function ℓ is convex, homogeneous of order one, that is $\ell(cx_1, \dots, cx_d) = c\ell(x_1, \dots, x_d)$ for $c > 0$ and satisfies $\max(x_1, \dots, x_d) \leq \ell(x_1, \dots, x_d) \leq x_1 + \dots + x_d$, $\forall (x_1, \dots, x_d) \in [0,\infty)^d$. By homogeneity, it is characterized by the *Pickands dependence function* $A : \Delta^{d-1} \rightarrow [1/d, 1]$, which is the restriction of ℓ to the unit simplex Δ^{d-1} :

$$\ell(x_1, \dots, x_d) = (x_1 + \dots + x_d) A(w_1, \dots, w_d), \quad w_j = \frac{x_j}{x_1 + \dots + x_d}, \tag{2}$$

for $(x_1, \dots, x_d) \in [0,\infty)^d \setminus \{0\}$. Notice that, for every $\mathbf{w} \in \Delta^{d-1}$

$$C(u^{w_1}, \dots, u^{w_d}) = u^{A(\mathbf{w})}. \tag{3}$$

Based on the madogram concept from geostatistics, [Naveau et al., 2009] introduced the λ-madogram in order to capture bivariate extremal dependencies. This quantity leads to its extension in higher dimension the $\mathbf{w}$-madogram defined in [Marcon et al., 2017]

$$\nu(\mathbf{w}) = \mathbb{E}\left[\bigvee_{j=1}^{d} \{F_j(X_j)\}^{1/w_j} - \frac{1}{d}\sum_{j=1}^{d}\{F_j(X_j)\}^{1/w_j}\right], \tag{4}$$

if $w_j = 0$ and $0 < u < 1$, then $u^{1/w_j} = 0$ by convention.

Paragraphe sur l'apport du papier + insertion dans la littérature (revue de littérature et contribution)

In order to shorten formulas, notations

$$\mathbf{u}_j(t) := (u_1, \dots, u_{j-1}, t, u_{j+1}, \dots, u_d),$$
$$\mathbf{u}_{jk}(s,t) := (u_1, \dots, u_{j-1}, s, u_{j+1}, \dots, u_{k-1}, t, u_{k+1}, \dots, u_d),$$

will be adopted for $s, t \in [0,1]$, $(u_1, \dots, u_{j-1}, u_{j+1}, \dots, u_d) \in [0,1]^{d-1}$ and $j, k \in \{1, \dots, d\}$ with $j < k$.

Also, the following notations are used. Given $\mathcal{X} \subset \mathbb{R}^2$, let $\ell^\infty(\mathcal{X})$ denote the spaces of bounded real-valued function on $\mathcal{X}$. For $f : \mathcal{X} \to \mathbb{R}$, let $||f||_\infty = sup_{x \in \mathcal{X}}|f(x)|$. Here, we use the abbreviation $Q(f) = \int f dQ$ for a given measurable function f and signed measure Q. The arrows $\overset{a.s.}{\to}$, $\overset{d}{\to}$ denote almost sure convergence and convergence in distribution of random vectors. Weak convergence of a sequence of maps will be understood in the sense of J.Hoffman-Jørgensen (see Part 1 in the monograph by [van der Vaart and Wellner, 1996]). Given that $n \in \mathbb{N}^*, X, X_n$ are maps from $(\Omega, \mathcal{A}, \mathbb{P})$ into a metric space $\mathcal{X}$ and that X is Borel measurable, $(X_n)_{n \geq 1}$ is said to converge weakly to X if $\mathbb{E}^* f(X_n) \to \mathbb{E} f(X)$ for every bounded continuous real-valued function f defined on $\mathcal{X}$, where $\mathbb{E}^*$ denotes outer expectation in the event that X_n may not be Borel measurable. In what follows, weak convergence is denoted by $X_n \rightsquigarrow X$.

Paragraphe annonce du plan

1 Non parametric estimation of the Madogram with missing data

Under the notation of the introduction, we assume that the copula C is an extreme value copula as in Equation 1. Starting from independent and identically distributed *i.i.d.* copies $\mathbf{X}_1, \dots, \mathbf{X}_n$ of $\mathbf{X}$, suppose we observe a $2d$-tuple such as

$$(\mathbf{I}_i \mathbf{X}_i, \mathbf{X}_i), \quad i \in \{1, \dots, n\}, \tag{5}$$

where $\mathbf{I}_i\mathbf{X}_i = (X_{i,1}I_{i,1}, \dots, X_{i,d}I_{i,d})$ and if $X_{i,j}$ is missing then $I_{i,j} = 0$, otherwise $I_{i,j} = 1$, *i.e.* at each $i \in \{1, \dots, n\}$, several entries may be missing. For $j \in \{1, \dots, d\}$, we suppose that for all $i \in \{1, \dots, n\}$, $I_{i,j}$ are sampled from a Bernoulli random variable I_j with probability $p_j = \mathbb{P}(I_j = 1)$. We denote by p the probability of observing completely a realization from $\mathbf{X}$, that is $p = \mathbb{P}(I_1 = 1, \dots, I_d = 1)$. Let us now define the empirical cumulative distribution of X_j (resp. F) in case of missing data, we note for notational convenience $\{\mathbf{X}_i \leq \mathbf{x}\} := \{X_{i,1} \leq x_1, \dots, X_{i,d} \leq x_d\}$,

$$\hat{F}_{n,j}(x) = \frac{\sum_{i=1}^n \mathbb{1}_{\{X_{i,j} \leq x\}} I_{i,j}}{\sum_{i=1}^n I_{i,j}}, \forall x \in \mathbb{R}, \quad \hat{F}_n(\mathbf{x}) = \frac{\sum_{i=1}^n \mathbb{1}_{\{\mathbf{X}_i \leq \mathbf{x}\}} \Pi_{j=1}^d I_{i,j}}{\sum_{i=1}^n \Pi_{j=1}^d I_{i,j}}, \forall \mathbf{x} \in \mathbb{R}^d. \quad (6)$$

The idea raised here is to estimate separately margins with the complete information given by the realizations of X_j. We thus estimate the $\mathbf{w}$-madogram under the complete database. We recall the definition of the *hybrid copula estimator* introduced by [Segers, 2015]

$$\hat{C}_n^{\mathcal{H}}(\mathbf{u}) = \hat{F}_n(\hat{F}_{n,1}^{\leftarrow}(u_1), \dots, \hat{F}_{n,d}^{\leftarrow}(u_d)), \quad \mathbf{u} \in [0,1]^d.$$

Where $F^{\leftarrow}$ denotes the generalized inverse function of F as $F^{\leftarrow}(u) = \inf\{x \in \mathbb{R} | F(x) \geq u\}$ with $0 < u < 1$. The normalized estimation error of the hybrid copula estimator is

$$\mathbb{C}_n^{\mathcal{H}}(\mathbf{u}) = \sqrt{n}\left(\hat{C}_n^{\mathcal{H}}(\mathbf{u}) - C(\mathbf{u})\right), \quad \mathbf{u} \in [0,1]^d.$$

On the condition that the first-order partial derivatives of the copula function C exists and are continuous on a subset of the unit hypercube, [Segers, 2012] obtained weak convergence of the normalized estimation error of the empirical copula process. To satisfy this condition, we introduce the following assumption as suggested in [Segers, 2012] in Example 5.3.

Assumption A.

(i) The distribution function F has continuous margins $F_1, \dots, F_d$.

(ii) For every $j \in \{1, \dots, d\}$, the first-order partial derivative $\dot{\ell}_j$ of ℓ with respect to x_j exists and is continuous on the set $\{x \in [0, \infty)^d : x_j > 0\}$.

The Assumption A *(i)* guarantees that the representation $F(\mathbf{x}) = C(F_1(x_1), \dots, F_d(x_d))$ is unique on the range of $(F_1, \dots, F_d)$. Under the Assumption A *(ii)*, the first-order partial derivatives of C with respect to u_j denoted as $\dot{C}_j$ exists and are continuous on the set $\{\mathbf{u} \in [0,1]^d : 0 < u_j < 1\}$. We now define our estimator of Equation (4) in the general context (allowing missing data).

Definition 1. *Let $(\boldsymbol{I}_i\boldsymbol{X}_i, \boldsymbol{I}_i)_{i=1}^n$ be a sample given by Equation (5), we define the hybrid* *estimator of the* $\mathbf{w}$*-madogram by*

$$\hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) = \frac{1}{\sum_{i=1}^n \Pi_{j=1}^d I_{i,j}} \sum_{i=1}^n \left[\bigvee_{j=1}^d \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} - \frac{1}{d} \sum_{j=1}^d \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} \right] \Pi_{j=1}^d I_{i,j}, \tag{7}$$

where $\hat{F}_{n,j}(x)$ *are defined on Equation (6).*

The intuitive idea here is to estimate the margins by the complete series for each variables but estimate $\nu(\mathbf{w})$ only based on the time period where all series were recorded simultaneously. One may verify that in the complete data framework, *i.e.* when $p = \mathbf{1}$ we retrieve the $\mathbf{w}$-madogram such as defined in [Marcon et al., 2017], namely

$$\hat{\nu}_n(\mathbf{w}) = \frac{1}{n} \sum_{i=1}^n \left[\bigvee_{j=1}^d \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} - \frac{1}{d} \sum_{j=1}^d \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} \right],$$

with $\hat{F}_{n,j}(x)$ the empirical cumulative distribution function of X_j.

Remark 1. *Our estimator, unlike* ν*, defined in Equation (7) does not verify* $\hat{\nu}_T^{\mathcal{H}}(\boldsymbol{e}_j) = (d-1)/2d$*, where* $\mathbf{e}_j$ *is the jth vector of the canonical basis. In addition, the variance at* $\boldsymbol{e}_j$ *does not equal 0. Indeed, suppose that we evaluate this statistic at* $\mathbf{w} = \boldsymbol{e}_j$*, we thus obtain the following quantity :*

$$\hat{\nu}_n^{\mathcal{H}}(\boldsymbol{e}_j) = \frac{1}{\sum_{i=1}^n \Pi_{j=1}^d I_{i,j}} \sum_{i=1}^n \left[\hat{F}_{n,j}(X_{i,j}) - \frac{1}{d}\hat{F}_{n,j}(X_{i,j}) \right] \Pi_{j=1}^d I_{i,j}.$$

In this situation, the sample $(X_{i,1}, \dots, X_{i,j-1}, X_{i,j+1}, \dots, X_{i,d})_{i=1}^n$ *is taken into account through the indicators sequence* $(I_{i,1}, \dots, I_{i,j-1}, I_{i,j+1}, \dots, I_{i,d})_{i=1}^n$ *and induce a supplementary variance when estimating.*

An is [Naveau et al., 2009], the endpoint constraints $\nu(\mathbf{e}_j) = (d-1)/2d$ for $j \in \{1, \dots, d\}$ can be imposed as follows. Given continuous functions $\lambda_1, \dots, \lambda_d : \Delta^{d-1} \to \mathbb{R}$ verifying $\lambda_j(\mathbf{e}_k) = \delta_{jk}$ (the Kronecker delta) for $j, k \in \{1, \dots, d\}$. This leads to a slightly modified version of the $\mathbf{w}$-madogram.

Definition 2. *Under the notation of Definition 1, we define the hybrid corrected estimator of the* $\mathbf{w}$*-madogram by*

$$\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) = \hat{\nu}_n(\mathbf{w}) - \sum_{j=1}^d \frac{\lambda_j(\mathbf{w})(d-1)}{d} \left[\frac{1}{\sum_{i=1}^n \Pi_{j=1}^d I_{i,j}} \sum_{i=1}^n \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} \Pi_{j=1}^d I_{i,j} - \frac{w_j}{1+w_j} \right]. \tag{8}$$

Remark 2. *One has often that endpoint corrections does not have an impact to the asymptotic behavior with complete data framework and unknown margins (see Section 2.3 and 2.4 of [Genest and Segers, 2009]). That is not always the case in the missing data framework and this feature is somehow wanted as discussed in Remark 1.*

We present with Theorem 1 in this Section a functional central limit theorem concerning the weak convergence of the following processes

$$\sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) - \nu(\mathbf{w})\right), \quad \sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) - \nu(\mathbf{w})\right). \tag{9}$$

Before spelled it, we introduce a specific assumption on the missing mechanism as detailed below. With the help of this assumption, we also state the stong consistency of our hybrid estimators of the $\mathbf{w}$-madogram.

Assumption B. *We suppose that for all $i \in \{1, \dots, n\}$, the vector $\boldsymbol{I}_i$ and $\boldsymbol{X}_i$ are independent, the data are missing completely at random (**MCAR**). Furthermore, we suppose that there exists at least one $i \in \{1, \dots, n\}$ such that $\Pi_{j=1}^d I_{i,j} \neq 0$.*

Proposition 1 (Strong consistency). *Let $(\boldsymbol{I}_i \boldsymbol{X}_i, \boldsymbol{X}_i)_{i=1}^n$ a i.i.d sample given by Equation (5). We have, under Assumption B for a fixed $\mathbf{w} \in \Delta^{d-1}$, as $n \to \infty$*

$$\hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) \xrightarrow{a.s.} \nu(\mathbf{w}), \quad \hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) \xrightarrow{a.s.} \nu(\mathbf{w}).$$

Details of the proof are given in Section 2.1.

Without missing data, the weak convergence of the normalized estimation error of the empirical copula process has been proved by [Fermanian et al., 2004] under a more restrictive condition than Assumption A. With the hybrid copula estimator, we need a technical assumption in order to guarantee the weak convergence of the process $\mathbb{C}_T^{\mathcal{H}}$ (see [Segers, 2015]). Before saying it, we note for convenience the marginal distribution and quantile functions into vector valued functions $\mathbf{F}$ and $\mathbf{F}^{\leftarrow}$:

$$\mathbf{F}(\mathbf{x}) = (F_1(x_1), \dots, F_d(x_d)), \quad \mathbf{x} \in \mathbb{R}^d, \quad \mathbf{F}^{\leftarrow}(\mathbf{u}) = (F_1^{\leftarrow}(u_1), \dots, F^{\leftarrow}(u_d)), \quad \mathbf{u} \in [0,1]^d.$$

Assumption C. *In the space $\ell^\infty(\mathbb{R}^d) \otimes (\ell^\infty(\mathbb{R}), \dots, \ell^\infty(\mathbb{R}))$ equipped with the topology of uniform convergence, we have the joint weak convergence*

$$\begin{aligned}&\left(\sqrt{n}(\hat{F}_n - F); \sqrt{n}(\hat{F}_{n,1} - F_1), \dots, \sqrt{n}(\hat{F}_{n,d} - F_d)\right) \\ &\qquad \rightsquigarrow \left(\alpha \circ \boldsymbol{F}, \beta_1 \circ F_1, \dots, \beta_d \circ F_d\right).\end{aligned}$$

The stochastic processes α and $\beta_j, j \in \{1, \dots, d\}$ take values in $\ell^\infty([0,1]^d)$ and $\ell^\infty([0,1])$

respectively, and are such that $\alpha \circ F$ and $\beta_j \circ F_j$ have continuous trajectories on $[-\infty, \infty]^d$ and $[-\infty, \infty]$ almost surely.

Under Assumptions A and C, the stochastic process $\mathbb{C}_T^{\mathcal{H}}$ converges weakly to the tight Gaussian process S_C defined by

$$S_C(\mathbf{u}) = \alpha(\mathbf{u}) - \sum_{j=1}^{d} \dot{C}_j(\mathbf{u})\beta_j(u_j), \quad \forall \mathbf{u} \in [0,1]^d.$$

Considering the same statistical framework and missing mechanism as [Segers, 2015] (in Example 3.5) but in higher dimension, we show that the processes α, β_j takes the following closed form

$$\begin{aligned}
\beta_j(u_j) &= p_j^{-1}\mathbb{G}\left(\mathbb{1}_{\{X_j \leq F_j^{\leftarrow}(u_j), I_j=1\}} - u_j \mathbb{1}_{\{I_j=1\}}\right), \quad j \in \{1,\dots,d\}, \\
\alpha(\mathbf{u}) &= p^{-1}\mathbb{G}\left(\mathbb{1}_{\{\mathbf{X} \leq \mathbf{F}^{\leftarrow}(\mathbf{u}), \mathbf{I}=\mathbf{1}\}} - C(\mathbf{u})\mathbb{1}_{\{\mathbf{I}=\mathbf{1}\}}\right),
\end{aligned}$$

where $\mathbb{G}$ is a tight Gaussian process and $\{\mathbf{X} \leq \mathbf{F}^{\leftarrow}(\mathbf{u})\} = \{X_1 \leq F^{\leftarrow}(u_1), \dots, X_d \leq F^{\leftarrow}(u_d)\}$. Furthermore, we are able to compute their covariance functions given in the following lemma.

Lemma 1. *The covariance function of the process $\beta_j(u_j)$, $\alpha(\boldsymbol{u})$ are, for $(\boldsymbol{u}, \boldsymbol{v}, v_k) \in [0,1]^{2d+1}$, and for $j \in \{1,\dots,d\}$ and $j < k$*

$$\begin{aligned}
cov\left(\beta_j(u_j), \beta_j(v_j)\right) &= p_j^{-1}\left(u_j \wedge v_j - u_j v_j\right), \\
cov\left(\beta_j(u_j), \beta_k(v_k)\right) &= \frac{p_{jk}}{p_j p_k}\left(C(\boldsymbol{1}_{j,k}(u_j, v_k)) - u_j v_k\right),
\end{aligned}$$

and

$$\begin{aligned}
cov\left(\alpha(\boldsymbol{u}), \alpha(\boldsymbol{v})\right) &= \mathrm{p}^{-1}\left(C(\boldsymbol{u} \wedge \boldsymbol{v}) - C(\boldsymbol{u})C(\boldsymbol{v})\right), \\
cov\left(\alpha(\boldsymbol{u}), \beta_j(v_j)\right) &= p_j^{-1}\left(C(\boldsymbol{u}_j(u_j \wedge v_j)) - C(\boldsymbol{u})v_j\right).
\end{aligned}$$

Where we denote by $\boldsymbol{u} \wedge \boldsymbol{v}$ the vector of componentwise minima and $p_{jk} = \mathbb{P}(I_j = 1, I_k = 1)$.

Proof of Lemma 1 is postponed to Section 2.2.

We have all tools in hand to consider the weak convergence of the stochastic processes in Equation (9).

Theorem 1 (Functional central limit theorem with missing data). *Under Assumptions A, B, C we have the weak convergence in $\ell^{\infty}(\Delta^{d-1})$ for the hybrid estimator defined* *in Equations (7) and (8), as $n \to \infty$,*

$$\sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) - \nu(\mathbf{w})\right) \rightsquigarrow \left(\frac{1}{d}\sum_{j=1}^{d}\int_{[0,1]} \alpha(\boldsymbol{1}_j(x^{w_j})) - \beta_j(x^{w_j})dx \right.$$
$$\left. - \int_{[0,1]} S_C(x^{w_1}, \dots, x^{w_d})dx\right)_{\mathbf{w}\in\Delta^{d-1}},$$

$$\sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) - \nu(\mathbf{w})\right) \rightsquigarrow \left(\frac{1}{d}\sum_{j=1}^{d}(1+\lambda_j(\mathbf{w})(d-1))\int_{[0,1]} \alpha(\boldsymbol{1}_j(x^{w_j})) - \beta_j(x^{w_j})dx \right.$$
$$\left. - \int_{[0,1]} S_C(x^{w_1}, \dots, x^{w_d})dx\right)_{\mathbf{w}\in\Delta^{d-1}}.$$

We use empirical process arguments formulated in [van der Vaart and Wellner, 1996] to establush such a result. Details can be found in Section 2.1.

As a linear transformation of a tight Gaussian process, we know that, for a fixed $\mathbf{w} \in \Delta^{d-1}$, the random variables, as $n \to \infty$

$$\sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) - \nu(\mathbf{w})\right) \xrightarrow{d} \mathcal{N}\left(0, \mathcal{S}^{\mathcal{H}}(\mathbf{p}, \mathbf{w})\right), \quad \sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) - \nu(\mathbf{w})\right) \xrightarrow{d} \mathcal{N}\left(0, \mathcal{S}^{\mathcal{H}*}(\mathbf{p}, \mathbf{w})\right),$$

with $\mathbf{p} = (p_1, \dots, p_d, p)$. Furthermore, the following proposition gives a closed form of these asymptotic variances.

Proposition 2. *For $\mathbf{w} \in \Delta^{d-1}$, if C is an extreme copula with Pickands dependence function A, then the asymptotic variance of the random variables $\sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) - \nu(\mathbf{w})\right)$ and $\sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) - \nu(\mathbf{w})\right)$ are given by*

$$\begin{aligned}\mathcal{S}^{\mathcal{H}}(\mathbf{p}, \boldsymbol{w}) =& \frac{1}{d^2}\sum_{j=1}^{d}(p^{-1} - p_j^{-1})\sigma_j^2(\mathbf{w}) + \sigma_{d+1}^2(\mathbf{p}, \mathbf{w}) \\ &+ \frac{2}{d^2}\sum_{j<k}\left(p^{-1} - p_j^{-1} - p_k^{-1} + \frac{p_{jk}}{p_j p_k}\right)\sigma_{jk}(\mathbf{w}) - \frac{2}{d}\sum_{j=1}^{d}(p^{-1} - p_j^{-1})\sigma_j^{(1)}(\mathbf{w}) \\ &+ \frac{2}{d}\sum_{j=1}^{d}\sum_{j<k}\left(p_k^{-1} - \frac{p_{jk}}{p_j p_k}\right)\sigma_{jk}^{(2)}(\mathbf{w}) + \frac{2}{d}\sum_{j=1}^{d}\sum_{k<j}\left(p_k^{-1} - \frac{p_{kj}}{p_j p_k}\right)\sigma_{kj}^{(2)}(\mathbf{w}),\end{aligned}$$

and

$$\begin{aligned}\mathcal{S}^{\mathcal{H}*}(\mathbf{p},\boldsymbol{w}) =& \frac{1}{d^2}\sum_{j=1}^{d}(p^{-1}-p_j^{-1})(1+\lambda_j(\mathbf{w})(d-1))^2\sigma_j^2(\mathbf{w})+\sigma_{d+1}^2(\mathbf{p},\mathbf{w}) \\ &+\frac{2}{d^2}\sum_{j<k}\left(p^{-1}-p_j^{-1}-p_k^{-1}+\frac{p_{jk}}{p_jp_k}\right)(1+\lambda_j(\mathbf{w})(d-1))(1+\lambda_k(\mathbf{w})(d-1))\sigma_{jk}(\mathbf{w}) \\ &-\frac{2}{d}\sum_{j=1}^{d}(p^{-1}-p_j^{-1})(1+\lambda_j(\mathbf{w})(d-1))\sigma_j^{(1)}(\mathbf{w}) \\ &+\frac{2}{d}\sum_{j=1}^{d}\sum_{j<k}\left(p_k^{-1}-\frac{p_{jk}}{p_jp_k}\right)(1+\lambda_j(\mathbf{w})(d-1))\sigma_{jk}^{(2)}(\mathbf{w}) \\ &+\frac{2}{d}\sum_{j=1}^{d}\sum_{k<j}\left(p_k^{-1}-\frac{p_{kj}}{p_jp_k}\right)(1+\lambda_j(\mathbf{w})(d-1))\sigma_{kj}^{(2)}(\mathbf{w}),\end{aligned}$$

where expressions of the functions $\sigma_j^2(\mathbf{w})$ for $j\in\{1,\dots,d\}$, $\sigma_{d+1}^2(\mathbf{w},\boldsymbol{p})$, $\sigma_{jk}(\mathbf{w})$ with $j<k$, $\sigma_j^{(1)}(\mathbf{w})$ with $j\in\{1,\dots,d\}$, $\sigma_{jk}^{(2)}(\mathbf{w})$ for $j<k$ and $\sigma_{kj}^{(2)}(\mathbf{w})$ as $k<j$ are given in Section 2.1 for the sake of readibility.

Technical details are available on Section 2.1. Considering the special case of independent copula, Corollary 1 below gives a closed form of the limit variance which no longer depends of the integral of the Pickands dependence function.

Corollary 1. *In the framework of Theorem 1 and if $C(\boldsymbol{u})=\Pi_{j=1}^d u_j$, then the functions $\sigma_{d+1}^2(\mathbf{w},\boldsymbol{p})$, $\sigma_j^{(1)}(\mathbf{w})$ with $j\in\{1,\dots,d\}$, has the following forms, for $\mathbf{w}\in\Delta^{d-1}$*

$$\begin{aligned}\sigma_{d+1}(\boldsymbol{p},\mathbf{w}) &= \frac{1}{4}\left(p^{-1}-\sum_{j=1}^{d}p_j^{-1}\frac{w_j}{4-w_j}\right), \\ \sigma_j^{(1)}(\mathbf{w}) &= \frac{1}{2}\left[\frac{1}{3}-\frac{1}{1+w_j}\right]+\frac{w_j}{3(1+w_j)(3+w_j)},\end{aligned}$$

and $\sigma_{jk}(\mathbf{w})=0$ for $j<k$, $\sigma_{jk}^{(2)}(\mathbf{w})=0$ for $j<k$ and $\sigma_{kj}^{(2)}(\mathbf{w})=0$ with $k<j$.

2 Proof

2.1 Proof of the main results

We first establish the strong consistency of our estimators.

Proof of Proposition 1 We write, for notational convenience $n_i=\Pi_{j=1}^d I_{i,j}$ and $N=\sum_{i=1}^n n_i$. We prove it for $\hat{\nu}_n^{\mathcal{H}}(\mathbf{w})$ as the strong consistency for $\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w})$ use the same arguments. Before going into the main arguments, we need the following lemma

Lemma 2. *We have,* $\forall i \in \{1, \dots, n\}$

$$\left| \bigvee_{j=1}^{d} \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} - \bigvee_{j=1}^{d} \left\{ F_j(X_j) \right\}^{1/w_j} \right| \leq \sup_{j \in \{1,\dots,d\}} \left| \hat{F}_{n,j}(X_{i,j})^{1/w_j} - F_j(X_j)^{1/w_j} \right|.$$

Thus, the estimator $\hat{\nu}_n(\mathbf{w})$ is strongly consistent since it holds

$$\begin{aligned} |\hat{\nu}_n(\mathbf{w}) - \nu(\mathbf{w})| &= \left| \hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) - \nu_n(\mathbf{w}) + \nu_n(\mathbf{w}) - \nu(\mathbf{w}) \right|, \\ &\leq \left| \hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) - \nu_n(\mathbf{w}) \right| + |\nu_n(\mathbf{w}) - \nu(\mathbf{w})|, \end{aligned}$$

where

$$\nu_n(\mathbf{w}) = \frac{1}{N} \sum_{i=1}^{n} \left(\bigvee_{j=1}^{d} \left\{ F_j(X_{i,j}) \right\}^{1/w_j} - \frac{1}{d} \sum_{j=1}^{d} \left\{ F_j(X_{i,j}) \right\}^{1/w_j} \right) n_i,$$

By direct application of Assumption B and the law of large number, we have that

$$|\nu_n(\mathbf{w}) - \nu(\mathbf{w})| \overset{a.s.}{\to} 0$$

For the second term, we write :

$$\begin{aligned} \left| \hat{\nu}_n^{\mathcal{H}}(\mathbf{w}) - \nu(\mathbf{w}) \right| \leq & \frac{1}{N} \sum_{i=1}^{n} \left| \bigvee_{j=1}^{d} \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} - \bigvee_{j=1}^{d} \left\{ F_j(X_j) \right\}^{1/w_j} \right| n_i \\ & + \frac{1}{Nd} \sum_{i=1}^{n} \sum_{j=1}^{d} \left| \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} - \left\{ F_j(X_{i,j}) \right\}^{1/w_j} \right| n_i \\ \leq & 2 \sup_{j \in \{1,\dots,d\}} \sup_{i \in \{1,\dots,n\}} \left| \left\{ \hat{F}_{n,j}(X_{i,j}) \right\}^{1/w_j} - \left\{ F_j(X_{i,j}) \right\}^{1/w_j} \right|, \end{aligned}$$

Where we used Lemma 2 to obtain the second inequality. The right term converges almost surely to zero by Glivencko-Cantelli. □

The following proof gives arguments used to establish the functional central limit theorem of our processes defined in Equation (9).

Proof of Theorem 1 We do the proof for $\hat{\nu}_n^{\mathcal{H}*}$ as the proof for $\hat{\nu}_n^{\mathcal{H}}$ is similar. Using that $\mathbb{E}[F_j(X_j)^\alpha] = (1+\alpha)^{-1}$ for $\alpha \neq 1$, we can write $\nu(\mathbf{w})$ as :

$$\begin{aligned}\nu(\mathbf{w}) =& \mathbb{E}\left[\bigvee_{j=1}^d \{F_j(X_j)\}^{1/w_j} - \frac{1}{d}\sum_{j=1}^d \{F_j(X_j)\}^{1/w_j}\right] + \\ & \sum_{j=1}^d \frac{\lambda_j(\mathbf{w})(d-1)}{d}\left(\frac{w_j}{1+w_j} - \mathbb{E}\left[\{F_j(X_j)\}^{1/w_j}\right]\right), \\ =& \mathbb{E}\left[\bigvee_{j=1}^d \{F_j(X_j)\}^{1/w_j}\right] - \frac{1}{d}\sum_{j=1}^d (1+\lambda_j(\mathbf{w})(d-1))\mathbb{E}\left[\{F_j(X_j)\}^{1/w_j}\right] + a(\mathbf{w}),\end{aligned}$$

with $a(\mathbf{w}) = (d-1)d^{-1}\sum_{j=1}^d \lambda_j(\mathbf{w})w_j/(1+w_j)$. Let us note by $g_{\mathbf{w}}$ the function defined as

$$g_{\mathbf{w}} : [0,1]^d \to [0,1], \quad \mathbf{u} \mapsto \bigvee_{j=1}^d u_j^{1/w_j} - \frac{1}{d}\sum_{j=1}^d (1+\lambda_j(\mathbf{w})(d-1))u_j^{1/w_j}.$$

We are to write our estimator of the $\mathbf{w}$-madogram and the $\mathbf{w}$-madogram in missing data framework as an integral with respect to the hybrid copula estimator and the copula function. We thus have:

$$\begin{aligned}&\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) = \frac{1}{N}\sum_{i=1}^n g_{\mathbf{w}}\left(\hat{\mathbf{F}}_n(\mathbf{X}_i)\right)\Pi_{j=1}^d I_{i,j} + c(\mathbf{w}) = \int_{[0,1]^d} g_{\mathbf{w}}(\mathbf{u})\, d\hat{C}_n^{\mathcal{H}}(\mathbf{u}) + a(\mathbf{w}), \\ &\nu(\mathbf{w}) = \int_{[0,1]^d} g_{\mathbf{w}}(\mathbf{u})\, dC(\mathbf{u}) + a(\mathbf{w}).\end{aligned}$$

Where $\hat{\mathbf{F}}_n(\mathbf{X}_i) = (\hat{F}_{n,1}(X_{i,1}), \dots, \hat{F}_{n,d}(X_{i,d}))$. We obtain, proceeding as in Theorem 2.4 of [Marcon et al., 2017] :

$$\begin{aligned}\sqrt{n}\left(\hat{\nu}_n^{\mathcal{H}*}(\mathbf{w}) - \nu(\mathbf{w})\right) =& \frac{1}{d}\sum_{j=1}^d (1+\lambda_j(\mathbf{w})(d-1))\int_{[0,1]} \mathbb{C}_n^{\mathcal{H}}(\mathbf{1}_j(x^{w_j}))dx \\ & - \int_{[0,1]} \mathbb{C}_n^{\mathcal{H}}(x^{w_1}, \dots, x^{w_d})\, dx.\end{aligned}$$

Consider the function $\phi : \ell^\infty([0,1]^d) \to \ell^\infty(\Delta^{d-1}), f \mapsto \phi(f)$, defined by

$$(\phi)(f)(\mathbf{w}) = \frac{1}{d}\sum_{j=1}^d (1+\lambda_j(\mathbf{w})(d-1))\int_{[0,1]} f(\mathbf{1}_j(x^{w_j}))dx - \int_{[0,1]} f(x^{w_1}, \dots, x^{w_d})dx.$$

this function is linear and bounded thus continuous. The continous mapping theorem

(Theorem 1.3.6 of [van der Vaart and Wellner, 1996]) implies, as $n \to \infty$

$$\sqrt{n}(\hat{\nu}_n^{\mathcal{H}*} - \nu) = \phi(\mathbb{C}_n^{\mathcal{H}}) \rightsquigarrow \phi(S_C),$$

in $\ell^\infty(\Delta^{d-1})$. We note that $S_C(\mathbf{1}_j(x^{w_j})) = \alpha(\mathbf{1}_j(x^{w_j})) - \beta_j(u_j)$ and we obtain our statement. □

The following proof use technical arguments to exhibits the closed expressions of the asymptotic variances of the Gaussians limit law of our estimators defined in Equation (7) and (8).

Proof of Proposition 2 We first show in details the closed form for $\sigma_{d+1}(\mathbf{p}, \boldsymbol{w})$, the others form are given without explanations as the technical tools used are those used for $\sigma_{d+1}(\mathbf{p}, \boldsymbol{w})$. This quantity can be explained as a linear combination of the probabilities of missing such as :

$$\sigma_{d+1}^2(\mathbf{p}, \mathbf{w}) = p^{-1}\gamma_1^2(\mathbf{w}) + \sum_{j=1}^d p_j^{-1}\gamma_j^2(\mathbf{w}) - 2\sum_{j=1}^d p_j^{-1}\gamma_{1j}(\mathbf{w}) + 2\sum_{j<k}\frac{p_{jk}}{p_j p_k}\tau_{jk}(\mathbf{w}). \tag{10}$$

Let us before exhibit a useful form of the partial derivatives of the extreme value copula which use the following lemma.

Lemma 3. *If $\ell(x_1, \dots, x_d)$ is homogeneous of degree 1, then for any $i \in \{1, \dots, d\}$ the partial derivative $\dot{\ell}_j(x_1, \dots, x_d)$ is homogeneous of degree 0.*

We have $\forall j \in \{1, \dots, d\}$:

$$\dot{C}_j(\mathbf{u}) = \frac{C(\mathbf{u})}{u_j}\dot{\ell}_j(-log(u_1), \dots, -log(u_d)).$$

Furthermore, using Lemma 3, we obtain a suitable form of the partial derivatives of the extreme value copula for $u \in]0,1[$ and $\mathbf{w} \in \Delta^{d-1}$:

$$\begin{aligned}\dot{C}_j(u^{w_1}, \dots, u^{w_d}) &= \frac{u^{A(\mathbf{w})}}{u^{w_j}}\dot{\ell}_j(-w_1 log(u), \dots, -w_d log(u)) = \frac{u^{A(\mathbf{w})}}{u^{w_j}}\dot{\ell}_j(-w_1, \dots, -w_d) \\ &= \frac{u^{A(\mathbf{w})}}{u^{w_j}}\mu_j(\mathbf{w}).\end{aligned}$$

Now, let us compute

$$
\begin{aligned}
p^{-1}\gamma_1^2(\mathbf{w}) &= \mathbb{E}\left[\int_{[0,1]} S_C(u^{w_1},\dots,u^{w_d})du \int_{[0,1]} S_C(v^{w_1},\dots,v^{w_d})dv\right], \\
&= \frac{2}{p}\int_{[0,1]}\int_{[0,v]} u^{A(\mathbf{w})}(1-v^{A(\mathbf{w})})duv.
\end{aligned}
$$

Using linearity of the integral and the definition of the covariance function of B_C, we obtain

$$
\gamma_1^2(\mathbf{w}) = 2\int_{[0,1]}\int_{[0,v]} u^{A(\mathbf{w})}(1-v^{A(\mathbf{w})})duv = \frac{1}{(1+A(\mathbf{w}))^2}\frac{A(\mathbf{w})}{2+A(\mathbf{w})}.
$$

The quantity $\gamma_j^2(\mathbf{w})$ is defined by the following

$$
\begin{aligned}
p_j^{-1}\gamma_j^2(\mathbf{w}) &= \mathbb{E}\bigg[\int_{[0,1]} \beta_j(u^{w_j})\dot{C}_j(u^{w_1},\dots,u^{w_d})du \int_{[0,1]} \beta_j(u^{w_j})\dot{C}_j(v^{w_1},\dots,v^{w_d})dv\bigg], \\
&= \frac{2}{p_j}\int_{[0,1]}\int_{[0,v]} u^{w_j}(1-v^{w_j})\mu_j(\mathbf{w})\mu_j(\mathbf{w})u^{A(\mathbf{w})-w_j}v^{A(\mathbf{w})-w_j}duv.
\end{aligned}
$$

It is clear that

$$
\begin{aligned}
\gamma_j^2(\mathbf{w}) &= 2\int_{[0,1]}\int_{[0,v]} u^{w_j}(1-v^{w_j})\mu_j(\mathbf{w})\mu_j(\mathbf{w})u^{A(\mathbf{w})-w_j}v^{A(\mathbf{w})-w_j}duv, \\
&= \left(\frac{\mu_j(\mathbf{w})}{1+A(\mathbf{w})}\right)^2 \frac{w_j}{2A(\mathbf{w})+1+1-w_j}.
\end{aligned}
$$

We now deal with cross product terms, the first we define is

$$
\begin{aligned}
p_j^{-1}\gamma_{1j}(\mathbf{w}) &= \mathbb{E}\bigg[\int_{[0,1]} S_C(u^{w_1},\dots,u^{w_d})du \int_{[0,1]} \beta_j(v^{w_j})\dot{C}_j(v^{w_1},\dots,v^{w_d})dv\bigg], \\
&= p_j^{-1}\int_{[0,1]^2}\Big(C(u^{w_1},\dots,(u\wedge v)^{w_j},\dots,u^{w_d}) - u^{A(\mathbf{w})}v^{w_j}\Big)\dot{C}_j(v^{w_1},\dots,v^{w_d})duv.
\end{aligned}
$$

Under the cube $[0,1]\times[0,v]$, we have

$$
\begin{aligned}
\gamma_{1j}(\mathbf{w}) &= \int_{[0,1]\times[0,v]}\Big(C(u^{w_1},\dots,u^{w_j},\dots,u^{w_d}) - u^{A(\mathbf{w})}v^{w_j}\Big)\dot{C}_j(v^{w_1},\dots,v^{w_d})duv, \\
&= \int_{[0,1]\times[0,v]} u^{A(\mathbf{w})}(1-v^{w_j})v^{A(\mathbf{w})-w_j}\mu_j(\mathbf{w})duv = \frac{\mu_j(\mathbf{w})}{2(1+A(\mathbf{w}))^2}\frac{w_j}{2A(\mathbf{w})+1+(1-w_j)}.
\end{aligned}
$$

Under the cube $[0,1]\times[0,u]$, we have for the right term

$$
\int_{[0,1]\times[0,u]} u^{A(\mathbf{w})}v^{w_j}v^{A(\mathbf{w})-w_j}\mu_j(\mathbf{w})dvu = \frac{\mu_j(\mathbf{w})}{2(1+A(\mathbf{w}))^2}.
$$

For the left term, by definition, we have

$$\int_{[0,1]\times[0,u]} C(u^{w_1},\ldots,v^{w_j},\ldots,u^{w_d})\dot{C}_j(v^{w_1},\ldots,v^{w_d})dvu.$$

Let us consider the substitution $x = v^{w_j}$ and $y = u^{1-w_j}$, we obtain

$$\frac{1}{w_j(1-w_j)}\int_{[0,1]}\int_{[0,y^{w_j/(1-w_j)}]} C\left(y^{w_1/(1-w_j)},\ldots,x,\ldots,y^{w_d/(1-w_j)}\right)$$
$$\times\dot{C}_j\left(x^{w_1/w_j},\ldots,x^{w_d/w_j}\right)x^{(1-w_j)/w_j}y^{w_j/(1-w_j)}dxy.$$

Let us compute the quantity

$$\dot{C}_j(x^{w_1/w_j},\ldots,x^{w_d/w_j}) = \frac{C(x^{w_1/w_j},\ldots,x^{w_d/w_j})}{x}\mu_j(\mathbf{w}).$$

Using Equation (1), we have

$$\begin{aligned} C(x^{w_1/w_j},\ldots,x^{w_d/w_j}) &= exp\left(-\ell\left(-\frac{log(x)}{w_j}w_1,\ldots,\frac{log(x)}{w_j}w_d\right)\right) \\ &= exp\left(-\frac{log(x)}{w_j}\ell\left(-w_1,\ldots,-w_d\right)\right) = x^{A(\mathbf{w})/w_j} =: x^{A_j(\mathbf{w})}. \end{aligned}$$

Where we use the homogeneity of order one of ℓ and that $-\ell(-w_1,\ldots,-w_d) = A(\mathbf{w})$ because of Equation (2) and that $\mathbf{w}\in\Delta^{d-1}$. Now, consider the substitution $x = w^{1-s}$ and $y = w^s$, the jacobian of this transformation is given by $-log(w)$, we have

$$-\frac{\mu_j(\mathbf{w})}{w_j(1-w_j)}\int_{[0,1]}\int_{[0,1-w_j]} C\left(w^{sw_1/(1-w_j)},\ldots,w^{1-s},\ldots,w^{sw_d/(1-w_j)}\right)$$
$$\times w^{(1-s)\left[A_j(\mathbf{w})+\frac{1-w_j}{w_j}-1\right]+s\frac{w_j}{1-w_j}}log(w)dsw,$$

Where we note by $A_j(\mathbf{w}) := A(\mathbf{w})/w_j$ with $j\in\{1,\ldots,d\}$. We now compute the quantity

$$C\left(w^{sw_1/(1-w_j)},\ldots,w^{1-s},\ldots,w^{sw_d/(1-w_j)}\right).$$

Using the same methods as above, we have

$$\begin{aligned} &C\left(w^{sw_1/(1-w_j)},\ldots,w^{1-s},\ldots,w^{sw_d/(1-w_j)}\right) \\ &= exp\left(-\ell\left(-\frac{sw_1}{1-w_j}log(w),\ldots,-(1-s)log(w),\ldots,-\frac{sw_d}{1-w_j}log(w)\right)\right), \\ &= exp\left(-log(w)\ell\left(-\frac{sw_1}{1-w_j},\ldots,-(1-s),\ldots,-\frac{sw_d}{1-w_j}\right)\right). \end{aligned}$$

Now, using that $\mathbf{w} \in \Delta^{d-1}$, remark that $s\sum_{i\neq j} w_i/(1-w_j) = s$, we have, using Equation (2)

$$-\ell\left(-\frac{sw_1}{1-w_j}, \dots, -(1-s), \dots, -\frac{sw_d}{1-w_j}\right) = A\left(\mathbf{z}_j(1-s)\right),$$

where $\mathbf{z} = (sw_1/(1-w_j), \dots, sw_d/(1-w_j))$. So we have

$$\begin{aligned}
\gamma_{1j}(\mathbf{w}) &= -\frac{\mu_j(\mathbf{w})}{w_j(1-w_j)} \int_{[0,1-w_j]} \int_{[0,1]} w^{A(\mathbf{z}_j(1-s)) + (1-s)\left(A_j(\mathbf{w}) + \frac{1-w_j}{w_j} - 1\right) + s\frac{w_j}{1-w_j}} log(w) dws, \\
&= \frac{\mu_j(\mathbf{w})}{w_j(1-w_j)} \int_{[0,1-w_j]} \left[A\left(\mathbf{z}_j(1-s)\right) + (1-s)\left(A_j(\mathbf{w}) + \frac{1-w_j}{w_j} - 1\right) + s\frac{w_j}{1-w_j} + 1\right]^{-2} ds.
\end{aligned}$$

No further simplifications can be obtained. For $j < k$, let us define the quantity τ_{jk} such as

$$\tau_{jk}(\mathbf{w}) = \mathbb{E}\Bigg[\int_{[0,1]} B_C(\mathbf{1}_j(u^{w_j}))\dot{C}_j(u^{w_1}, \dots, u^{w_d}) du B_C(\mathbf{1}_k(v^{w_k}))\dot{C}_k(v^{w_1}, \dots, v^{w_d}) dv\Bigg]. \quad (11)$$

Again, we have

$$\tau_{jk}(\mathbf{w}) = \int_{[0,1]^2} \left(C(\mathbf{1}_{jk}(u^{w_j}, v^{w_j})) - u^{w_j}v^{w_j}\right)\dot{C}_j(u^{w_1}, \dots, u^{w_d})\dot{C}_k(v^{w_1}, \dots, v^{w_d}) duv.$$

We set $x = u^{w_j}$ and $y = v^{w_k}$, the left side become

$$\begin{aligned}
\tau_{jk}(\mathbf{w}) &= \frac{1}{w_j(1-w_k)} \int_{[0,1]^2} C(\mathbf{1}_{jk}(x,y)) \\
&\quad \times \dot{C}_j(x^{w_1/w_j}, \dots, x^{w_d/w_j})\dot{C}_k(y^{w_1/w_k}, \dots, y^{w_d/w_k}) x^{(1-w_j)/w_j} y^{(1-w_k)/w_k} dxy, \\
&= \frac{\mu_j(\mathbf{w})\mu_k(\mathbf{w})}{w_j w_k} \int_{[0,1]^2} C(\mathbf{1}_{jk}(x,y)) x^{A_j(\mathbf{w}) + (1-w_j)/w_j - 1} y^{A_k(\mathbf{w}) + (1-w_k)/w_k - 1} dxy.
\end{aligned}$$

Now, we set $x = w^{1-s}$ and $y = w^s$ and we obtain

$$\begin{aligned}
\tau_{jk}(\mathbf{w}) =& \frac{\mu_j(\mathbf{w})\mu_k(\mathbf{w})}{w_j w_k} \int_{[0,1]} \Bigg[A(\mathbf{0}_{jk}(1-s,s)) + (1-s)\left(A_j(\mathbf{w}) + \frac{1-w_j}{w_j} - 1\right) \\
& + s\left(A_k(\mathbf{w}) + \frac{1-w_k}{w_k} - 1\right) + 1\Bigg]^{-2} ds.
\end{aligned}$$

The right side of Equation (11) is given by

$$\int_{[0,1]^2} u^{w_j} v^{w_k} \dot{C}_j(u^{w_1}, \dots, u^{w_d})\dot{C}_k(v^{w_1}, \dots, v^{w_d}) duv = \frac{\mu_j(\mathbf{w})\mu_k(\mathbf{w})}{(1+A(\mathbf{w}))^2}.$$

Hence the result for $\sigma^2_{d+1}(\boldsymbol{w})$. Using the same techniques, we show that for $j \in \{1, \dots, d\}$

$$\sigma_j^2(\mathbf{w}) = \int_{[0,1]^2} (u \wedge v)^{w_j} - u^{w_j} v^{w_j} duv = \frac{1}{(1+w_j)^2} \frac{w_j}{2+w_j}.$$

For $j < k$, we compute

$$\begin{aligned}
\sigma_{jk}(\mathbf{w}) &= \int_{[0,1]^2} C(1_{jk}(u^{w_j}, v^{w_k})) - u^{w_j} v^{w_k} duv, \\
&= \frac{1}{w_j w_k} \int_{[0,1]} \left[A(0_{jk}(1-s,s)) + (1-s)\frac{1-w_j}{w_j} + s\frac{1-w_k}{w_k} + 1 \right]^{-2} ds \\
&- \frac{1}{1+w_j} \frac{1}{1+w_k}.
\end{aligned}$$

Let $j \in \{1, \dots, d\}$, thus

$$\begin{aligned}
\sigma_j^{(1)}(\mathbf{w}) &= \int_{[0,1]^2} C\left(u^{w_1}, \dots, (u \wedge v)^{w_j}, \dots, u^{w_d}\right) - C(u^{w_1}, \dots, u^{w_d}) v^{w_j} ds, \\
&= \frac{1}{w_j(1-w_j)} \int_{[0,1]} \left[A(\mathbf{z}_j(1-s) + (1-s)\frac{1-w_j}{w_j} + s\frac{w_j}{1-w_j} + 1 \right]^{-2} ds \\
&+ \frac{1}{1+A(\mathbf{w})} \left[\frac{1}{2+A(\mathbf{w})} - \frac{1}{1+w_j} \right].
\end{aligned}$$

Now, if $j < k$, we have :

$$\begin{aligned}
\sigma_{jk}^{(2)}(\mathbf{w}) = \frac{\mu_k(\mathbf{w})}{w_j w_k} \int_{[0,1]} &\left[A(0_{jk}(1-s,s)) + (1-s)\frac{1-w_j}{w_j} \right. \\
&\left. + s\left(A_k(\mathbf{w}) + \frac{1-w_k}{w_k} - 1 \right) + 1 \right]^{-2} ds - \frac{\mu_k(\mathbf{w})}{1+A(\mathbf{w})} \frac{1}{1+w_j}.
\end{aligned}$$

If $k < j$, we obtain

$$\begin{aligned}
\sigma_{kj}^{(2)}(\mathbf{w}) = \frac{\mu_k(\mathbf{w})}{w_j w_k} \int_{[0,1]} &\left[A(0_{kj}(1-s,s)) + s\frac{1-w_j}{w_j} \right. \\
&\left. + (1-s)\left(A_k(\mathbf{w}) + \frac{1-w_k}{w_k} - 1 \right) + 1 \right]^{-2} ds - \frac{\mu_k(\mathbf{w})}{1+A(\mathbf{w})} \frac{1}{1+w_j}.
\end{aligned}$$

Hence the statement. □

2.2 Proof of lemmata

Proof of Lemma 1 Following [Segers, 2015] Example 3.5, we consider the function from

$\{0,1\}^d \times \mathbb{R}^d$ into $\mathbb{R}$: for $\mathbf{x} \in \mathbb{R}^d$, and $j \in \{1, \dots, d\}$

$$f_j(\mathbf{I}, \mathbf{X}) = \mathbb{1}_{\{I_j=1\}}, \quad g_{j,x_j}(\mathbf{I}, \mathbf{X}) = \mathbb{1}_{\{X_j \le x_j, I_j=1\}},$$
$$f_{d+1} = \Pi_{j=1}^d f_j, \quad g_{d+1,\mathbf{x}} = \Pi_{j=1}^d g_{j,x_j}.$$

Let P denote the common distribution of the tuple $(\mathbf{I}, \mathbf{X})$. The collection of functions

$$\mathcal{F} = \{f_1, \dots, f_d, f_{d+1}\} \cup \bigcup_{j=1}^d \{g_{j,x_j}, x_j \in \mathbb{R}\} \cup \{g_{d+1,\mathbf{x}}, \mathbf{x} \in \mathbb{R}^d\}$$

is a finite union of VC-classes and thus P-Donsker (for more information, see Chapter 2.6 of [van der Vaart and Wellner, 1996]). The empirical process $\mathbb{G}_n$ defined by

$$\mathbb{G}_n(f) = \sqrt{n}\left(\frac{1}{n}\sum_{i=1}^n f(\mathbf{I}_i, \mathbf{X}_i) - \mathbb{E}[f(\mathbf{I}_i, \mathbf{X}_i)]\right), \quad f \in \mathcal{F},$$

converges in $\ell^\infty(\mathcal{F})$ to a P-browian bride $\mathbb{G}$. For $\mathbf{x} \in \mathbb{R}^d$,

$$\hat{F}_{n,j}(x_j) = \frac{p_j F_j(x_j) + n^{-1/2}\mathbb{G}_n g_{j,x_j}}{p_j + n^{-1/2}\mathbb{G}_n f_j},$$
$$\hat{F}_n(\mathbf{x}) = \frac{pF(\mathbf{x}) + n^{-1/2}\mathbb{G}_n g_{d+1,\mathbf{x}}}{p + n^{-1/2}\mathbb{G}_n f_{d+1}}$$

We obtain for the second one

$$p\left(\hat{F}_n(\mathbf{x}) - F(\mathbf{x})\right) = n^{-1/2}\left(\mathbb{G}_n(g_{d+1,\mathbf{x}}) - \hat{F}_n(\mathbf{x})\mathbb{G}_n(f_{d+1})\right),$$
$$= n^{-1/2}\left(\mathbb{G}_n(g_{d+1,\mathbf{x}} - F(\mathbf{x})f_{d+1})\right) - n^{-1/2}\mathbb{G}_n(f_{d+1})(\hat{F}_n(\mathbf{x}) - F(\mathbf{x})).$$

We thus have

$$\sqrt{n}\left(\hat{F}_n(\mathbf{x}) - F(\mathbf{x})\right) = p^{-1}\left(\mathbb{G}_n(g_{d+1,\mathbf{x}} - F(\mathbf{x})f_{d+1})\right) - p^{-1}\mathbb{G}_n(f_{d+1})(\hat{F}_n(\mathbf{x}) - F(\mathbf{x})).$$

Applying the central limit theorem gives that $\mathbb{G}_n(f_{d+1}) \xrightarrow{d} \mathcal{N}(0, \mathbb{P}(f_{d+1} - \mathbb{P}f_{d+1})^2)$, the law of large numbers gives also $\hat{F}_n(\mathbf{x}) - F(\mathbf{x}) = \circ_{\mathbb{P}}(1)$. Using Slutsky's lemma gives us

$$\sqrt{n}\left(\hat{F}_n(\mathbf{x}) - F(\mathbf{x})\right) = p^{-1}\left(\mathbb{G}_n(g_{d+1,\mathbf{x}} - F(\mathbf{x})f_{d+1})\right) + \circ_{\mathbb{P}}(1).$$

Similar reasoning might be applied to the margins, as a consequence, Condition B is fulfilled with for $\mathbf{u} \in [0,1]^d$,

$$\begin{aligned}
\beta_j(u_j) &= p_j^{-1} \mathbb{G}\left(g_{j,F_j^{\leftarrow}(u_j)} - u_j f_j\right), \\
\alpha(\mathbf{u}) &= p^{-1} \mathbb{G}\left(g_{d+1,\mathbf{F}^{\leftarrow}(\mathbf{u})} - C(\mathbf{u}) f_{d+1}\right).
\end{aligned}$$

Let us compute one covariance function, the method still the same for the others, without loss of generality, suppose that $j < k$, we have for $u_j, v_k \in [0,1]$

$$\begin{aligned}
cov(\beta_j(u_j), \beta_k(v_k)) &= \mathbb{E}\left[p_j^{-1} \mathbb{G}\left(g_{j,F_j^{\leftarrow}(u_j)} - u_j f_j\right) p_k^{-1} \mathbb{G}\left(g_{k,F_k^{\leftarrow}(v_k)} - v_k f_k\right)\right], \\
&= \frac{1}{p_j p_k} \mathbb{E}\left[\mathbb{G}\left(g_{j,F_j^{\leftarrow}(u_i)} - u_j f_j\right) \mathbb{G}\left(g_{k,F_k^{\leftarrow}(v_j)} - v_k f_k\right)\right], \\
&= \frac{1}{p_j p_k} \mathbb{P}\left\{X_j \leq F_j^{\leftarrow}(u_j), X_k \leq F_k^{\leftarrow}(v_k), I_j = 1, I_k = 1\right\} - \frac{p_{jk}}{p_j p_k} u_j v_k, \\
&= \frac{1}{p_j p_k} \mathbb{P}\left\{X_j \leq F_j^{\leftarrow}(u_j), X_k \leq F_k^{\leftarrow}(v_k)\right\} \mathbb{P}\left\{I_j = 1, I_k = 1\right\} - \frac{p_{jk}}{p_j p_k} u_j v_k, \\
&= \frac{p_{jk}}{p_j p_k} \left(C(\mathbf{1}_{jk}(u_j, v_k)) - u_j v_k\right).
\end{aligned}$$

Hence the result. □

Proof of Lemma 2 The lemma becomes trivial once we write, $\forall i \in \{1, \ldots, n\}$ and $j \in \{1, \ldots, d\}$

$$\begin{aligned}
\left\{\hat{F}_{n,j}(X_{i,j})\right\}^{1/w_j} &= F_j(X_j)^{1/w_j} + \hat{F}_{n,j}(X_{i,j})^{1/w_j} - F_j(X_j)^{1/w_j}, \\
&\leq F_j(X_j)^{1/w_j} + \sup_{j \in \{1,\ldots,d\}} \left|\hat{F}_{n,j}(X_{i,j})^{1/w_j} - F_j(X_j)^{1/w_j}\right|, \\
&\leq \bigvee_{j=1}^{d} \{F_j(X_j)\}^{1/w_j} + \sup_{j \in \{1,\ldots,d\}} \left|\hat{F}_{n,j}(X_{i,j})^{1/w_j} - F_j(X_j)^{1/w_j}\right|.
\end{aligned}$$

Taking the max over $j \in \{1, \ldots, d\}$ gives

$$\bigvee_{j=1}^{d} \left\{\hat{F}_{n,j}(X_{i,j})\right\}^{1/w_j} - \bigvee_{j=1}^{d} \{F_j(X_j)\}^{1/w_j} \leq \sup_{j \in \{1,\ldots,d\}} \left|F_{n,j}(X_{i,j})^{1/w_j} - F_j(X_j)^{1/w_j}\right|.$$

Moreover, by symmetry of $\hat{F}_{n,j}$ and F_j, the second ones follows similarly. □

Proof of Lemma 3 By definition, we have for all $c > 0$

$$\ell(cx_1, \ldots, cx_d) = c\ell(x_1, \ldots, x_d).$$

The derivative with respect to x_j of the above expression yields

$$c\dot{\ell}_j(cx_1,\ldots,cx_d) = c\dot{\ell}(x_1,\ldots,x_d),$$

for every $j \in \{1,\ldots,d\}$. The result follows. $\square$

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