Interest Rate and Credit Models

8. Modeling dependence and copulas

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Spring 2019

Outline

Portfolio credit risk

- We now turn to the issues of modeling portfolios of credit risky assets.
- The central problem of portfolio credit risk modeling is understanding the impact of the dependence between credit events of the individual names on the portfolio as a whole.
- Exposure to portfolio credit risk is common in banking and insurance businesses.
- Various commonly traded structures such as *collateralized loan obligations* (CLOs) are exposed to portfolio credit risk.
- There is a class of credit derivatives, called *synthetic CDOs*, which are options on the portfolio losses in baskets of CDSs.

Portfolio loss function

- Let us consider portfolio consisting of risky N names.
- We fix a time horizon T, and let l_i and τ_i denote the *loss given default* (LGD) (defined as par less the recovery value) and the default time for name i, respectively.
- Let $L(T)$ denote the total portfolio loss over the time horizon T. Thus

$$L(T) = \sum_{i=1}^{N} 1_{\tau_i \leq T}\, l_i .$$

- The expected loss is thus given by

$$\begin{aligned} \mathrm{E}[L(T)] &= \sum_{i=1}^{N} \mathrm{E}[1_{\tau_i \leq T}] l_i \\ &= \sum_{i=1}^{N} Q_i(T)\, l_i , \end{aligned}$$

where $Q_i(T)$ is the default probability of name i.

Portfolio loss function

- The expected loss can often be estimated from CDS markets (which allows us to infer risk-neutral default probabilities) or from rating (using historical probabilities).
- The primary driver of loss distributions is the dependence among the defaults of the individual names.
- Intuitively, higher dependence among the credit events lead to more extreme events with multiple defaults.
- At the same time, higher dependence increases the likelihood of events with few defaults.
- As an illustration, consider $N = 10$, with $l_i = 1$ and $Q_i(T) = 0.1$, for all i.

Portfolio loss function

- If all names are completely independent:

$$P(L(T) = k) = \binom{N}{k} (0.1)^k (0.9)^{N-k}, \text{ where } n = 0, \ldots, 10.$$

In particular,

$$\begin{aligned} P(L(T) = 0) &= (0.9)^{10} = 0.349, \\ P(L(T) = N) &= (0.1)^{10} = 10^{-10}. \end{aligned}$$

- If all names are perfectly dependent (if one firm defaults, they all default):

$$\begin{aligned} P(L(T) = 0) &= 0.9, \\ P(L(T) = k) &= 0.0, \text{ for all } k = 1, \ldots, N-1, \\ P(L(T) = N) &= 0.1. \end{aligned}$$

- Consequently, more dependence implies higher probabilities of tail events.

Pearson correlation coefficient

- Consider N random variables $X_1, \ldots, X_N$ with joint distribution $H(X_1, \ldots, X_N)$. Their Pearson correlation matrix ρ is defined by

$$\rho_{ij} = \frac{\operatorname{Cov}(X_i, X_j)}{\sqrt{\operatorname{Var}(X_i)}\sqrt{\operatorname{Var}(X_j)}}\,.$$

- For example, if $X_i = 1_{\tau_i < T}$, then

$$\begin{aligned} \mathrm{E}[X_i^2] &= \mathrm{E}[X_i] \\ &= Q_i\,(T)\,, \end{aligned}$$

and so

$$\begin{aligned} \operatorname{Cov}(X_i, X_j) &= \mathrm{P}(\tau_i < T, \tau_j < T) - Q_i(T)Q_j(T), \\ \operatorname{Var}(X_i) &= Q_i(T)S_i(T). \end{aligned}$$

Correlation coefficient

- The Pearson correlation coefficient is a flawed measure of dependence:
  (i) It is not natural outside of Gaussian distributions.
  (ii) It only measures linear relationships.
  (iii) Perfectly dependent random variables do not necessarily have a correlation of 1.
  (iv) For example, if $X \sim N(0, 1)$, then X and $Y \triangleq X^2$ are perfectly dependent, but their correlation coefficient is 0. The correlation coefficient between X and $Z \triangleq X^3$ is $3/\sqrt{15} \approx 0.775$.
  (v) Correlation is not invariant under monotone transformations of the random variables.
- Some other measures include concordance measures such as Kendall's tau and Spearman's rho.

Kendall's tau

- Let $\{(x_1, y_1), \ldots, (x_n, y_n)\}$ be a sample of observations from a pair of random variables X and Y with joint distribution $H(X, Y)$.
- Of the $\binom{n}{2}$ distinct pairs (x_i, y_i), (x_j, y_j), let c be the number of *concordant* pairs (if $x_i < x_j$ and $y_i < y_j$, or $x_i > x_j$ and $y_i > y_j$), and let d be the number of *discordant* pairs (if $x_i < x_j$ and $y_i > y_j$, or $x_i > x_j$ and $y_i < y_j$).
- Then *Kendall's* tau is defined as

$$\widehat{\tau}_{X,Y} = \frac{c-d}{c+d}\,.$$

- The probabilistic version of this sample definition is

$$\tau_K(X, Y) = \mathrm{P}((X_1 - X_2)(Y_1 - Y_2) > 0) - \mathrm{P}((X_1 - X_2)(Y_1 - Y_2) < 0),$$

  where (X_1, Y_1) and (X_2, Y_2) are independent pairs of random variables drawn from H.

Spearman's rho

- We consider three pairs (X_1, Y_1), (X_2, Y_2) and (X_3, Y_3) of independent pairs of random variables drawn from the joint distribution H.
- Their Spearman' rho is defined by

$$\rho_S(X, Y) = 3\big(\mathrm{P}((X_1 - X_2)(Y_1 - Y_3) > 0) - \mathrm{P}((X_1 - X_2)(Y_1 - Y_3) < 0)\big).$$

- Spearman's rho is thus the difference of the probability of concordance and the probability of discordance for the vectors of random variables (X_1, Y_1) and (X_2, Y_3).
- These two pairs have the same margins, but the former has joint distribution H while the components of the latter are independent.

Definition of a copula

- Copulas are devices for constructing joint (multivariate) probability distributions out of marginal (univariate) probability distributions.
- To motivate the definition, we consider uniformly distributed random variables $U_i \in [0, 1]$, $i = 1, \ldots, N$.
- Their joint distribution is a function $C : [0, 1]^N \to [0, 1]$ such that

$$C(u_1, \ldots, u_N) = \mathrm{P}(U_1 \leq u_1, \ldots, U_N \leq u_N).$$

- Note that C satisfies the following conditions:
  (i)

$$\begin{aligned} C(u_1, \ldots, 0, \ldots, u_N) &= 0, \\ C(1, \ldots, 1, u_i, 1, \ldots, 1) &= u_i. \end{aligned}$$

  (ii) *Volume monotonicity condition*, which is elementary but somewhat cumbersome to write down.

Definition of a copula

- We shall formulate the volume monotonicity condition explicitly in the $N = 2$ case only, see [2] or [3] for the general case.
- Namely, if $N = 2$, it reads as follows: for $a_1 \leq b_1$ and $a_2 \leq b_2$,

$$C(b_1, b_2) - C(a_1, b_2) - C(b_1, a_2) + C(a_1, a_2) \geq 0.$$

- This is a consequence of the fact that $\mathrm{P}(a_1 \leq U_1 \leq b_1, a_2 \leq U_2 \leq b_2) \geq 0$, i.e.

$$\begin{aligned} 0 &\leq \int_{a_1}^{b_1} \int_{a_2}^{b_2} dC(u_1, u_2) \\ &= C(b_1, b_2) - C(a_1, b_2) - C(b_1, a_2) + C(a_1, a_2), \end{aligned}$$

where

$$dC(u_1, u_2) \triangleq \frac{\partial^2 C(u_1, u_2)}{\partial u_2 \partial u_2}\, du_1 du_2.$$

Definition of a copula

- *Definition*: Any function $C : [0, 1]^N \to [0, 1]$ satisfying conditions (i) and (ii) is called a *copula*.
- A copula with $N = 2$ is called a *bivariate copula*.

Examples of copulas

- The independence copula is defined by

$$C(u_1, \ldots, u_N) = \prod_{i=1}^{N} u_i .$$

- The dependence copula is defined by

$$C(u_1, \ldots, u_N) = \min_i u_i .$$

- The anti-dependence copula can be defined for $N = 2$:

$$C(u_1, u_2) = \max(u_1 + u_2 - 1, 0).$$

Joint probability distributions and copulas

- Consider N continuous random variables $X_1, \ldots, X_N$ with monotone increasing marginal probability distributions $F_1(x), \ldots, F_N(x)$, i.e. $F_i(x) = \mathrm{P}(X_i \leq x)$, for $i = 1, \ldots, N$.
- Let $H(X_1, \ldots, X_N)$ denote their joint probability distribution, i.e.

$$H(x_1, \ldots, x_N) = \mathrm{P}(X_1 \leq x_1, \ldots, X_N \leq x_N).$$

- For each i, consider the random variable $U_i = F_i(X_i)$. Clearly, $U_i \in [0, 1]$.
- Since

$$\begin{aligned} \mathrm{P}(U_i \leq u) &= \mathrm{P}(X_i \leq F_i^{-1}(u)) \\ &= F_i(F_i^{-1}(u)) \\ &= u, \end{aligned}$$

U_i is uniformly distributed on $[0, 1]$.

Sklar's theorem

- The function
$$C(u_1, \ldots, u_N) = H(F_1^{-1}(u_1), \ldots, F_N^{-1}(u_N))$$
defines a copula.
- Conversely, given a copula C, the function
$$H(x_1, \ldots, x_N) = C(F_1(x_1), \ldots, F_N(x_N))$$
defines a joint probability function with marginals $F_1, \ldots, F_N$.
- The last two statements form the content of *Sklar's theorem*.
- Actually, Sklar's theorem is a bit more general than what we formulated above.

Gaussian copula

- Consider an N-dimensional Gaussian distribution Φ_ρ with correlation matrix ρ.
- A random vector Z distributed according to Φ_ρ has zero mean and each of its components has variance one.
- The Gaussian copula is defined by

$$C_\rho(u_1, \ldots, u_N) = \Phi_\rho(N^{-1}(u_1), \ldots, N^{-1}(u_N)),$$

where $N(x)$ is the standard uniform Gaussian distribution function.

Gaussian copula

- Explicitly, in the bivariate case,

$$C_\rho(u_1, u_2) = \frac{1}{2\pi\sqrt{1-\rho_{12}^2}} \int_{-\infty}^{N^{-1}(u_1)} \int_{-\infty}^{N^{-1}(u_2)} \exp\Big\{ -\frac{s^2 - 2\rho_{12} su + u^2}{2(1-\rho_{12}^2)} \Big\} dsdu.$$

- Note that the correlation matrix ρ is the driver of dependence for the Gaussian copula.
- This is one of the reason's of the popularity of the Gaussian copula: its dependence parameters are the correlation coefficients between the random variables (which are not necessarily Gaussian).

Student t copula

- Let Z be a random vector distributed according to Φ_ρ, and let Y be a scalar random variable distributed according to the χ^2-distribution with ν degrees of freedom, $S \sim \chi^2_\nu$.
- The Student t copula $C_{\nu,\rho}$ with ν degrees of freedom is defined as the copula corresponding to the N-dimensional random variable $X = \sqrt{\nu/S}Z$,

$$C_{\nu,\rho}(u_1, \dots, u_n) = t_{\nu,\rho}(t_\nu^{-1}(u_1), \dots, t_\nu^{-1}(u_N)),$$

where $t_{\nu,\rho}$ is the distribution of $\sqrt{\nu/S}Z$, and t_ν is the distribution of $\sqrt{\nu/S}Z_1$.

Student t copula

- Explicitly, in the bivariate case,

$$C_{\nu,\rho}(u_1, u_2) = \frac{1}{2\pi\sqrt{1-\rho_{12}^2}} \int_{-\infty}^{t_\nu^{-1}(u_1)} \int_{-\infty}^{t_\nu^{-1}(u_2)} \Big(1 + \frac{s^2 - 2\rho_{12} su + u^2}{\nu(1-\rho_{12}^2)}\Big)^{-\frac{\nu+2}{2}} dsdu.$$

- The Student t copula has fatter tails than the Gaussian copula (the smaller ν, the fatter the tails).
- It is used to model situations where tail events are believed to play a role.

Archimedean copulas

- These are simple copulas that have interesting properties but (so far) little use in finance.
- A function $\phi : [0, 1] \to [0, \infty)$ is called a *copula generator* if it satisfies the properties:
  (i) ϕ is monotone decreasing,
  (ii) ϕ is convex,
  (iii) $\phi(0) = \infty$,
  (iv) $\phi(1) = 0$.
- Given a copula generator, an *Archimedean copula* is defined by

$$C(u_1, \ldots, u_N) = \phi^{-1}(\phi(u_1) + \ldots + \phi(u_N)).$$

- As expected, an Archimedean copula is indeed a copula.

Archimedean copulas

- Below are some of the more popular Archimedean copulas.
- *Independence copula*:
$$\phi(u) = -\log u.$$
- *Clayton copula*: for $\theta > 0$,
$$\phi(u) = u^{-\theta} - 1,$$
$$C_{Clayton}(u_1, \ldots, u_N) = (u_1^{-\theta} + \ldots u_N^{-\theta} - N + 1)^{-1/\theta}.$$

Archimedean copulas

- *Gumbel copula*: for $\theta > 1$,

$$\phi(u) = (-\log u)^\theta,$$
$$C_{Gumbel}(u_1, \ldots, u_N) = \exp\Big\{ -\big((-\log u_1)^\theta + \ldots + (-\log u_N)^\theta\big)^{1/\theta}\Big\}.$$

- *Frank copula*: for $\theta \in \mathbb{R}$,

$$\phi(u) = -\log \frac{e^{-\theta u} - 1}{e^{-\theta} - 1},$$
$$C_{Frank}(u_1, \ldots, u_N) = -\frac{1}{\theta} \log \Big(1 + \frac{(e^{-\theta u_1} - 1) \ldots (e^{-\theta_N u} - 1)}{(e^{-\theta} - 1)^{N-1}}\Big).$$

Copulas and dependence measures

- Let (X, Y) be a vector of continuous random variables with copula C. Then:
  (i) Kendall's tau is given by

$$\tau_K(X, Y) = 4 \iint_{[0,1]^2} C(u, v) dC(u, v) - 1.$$

  (ii) Spearman's rho is given by

$$\begin{aligned}\rho_S(X, Y) &= 12 \iint_{[0,1]^2} uv dC(u, v) - 3 \\ &= 12 \iint_{[0,1]^2} C(u, v) du dv - 3.\end{aligned}$$

- Note that these results do not depend on the marginals of X and Y.

Copulas and dependence measures

- For Clayton's copula,
$$\tau_K = \frac{\theta}{\theta + 2}\,.$$
- For Gumbel's copula,
$$\tau_K = 1 - \frac{1}{\theta}\,.$$
- For Gaussian and Student t copulas, the following relation holds:
$$\rho = 2\sin(\pi\rho_S/6)\,.$$

Tail dependence

- The concept of tail dependence relates to the amount of dependence in the upper right quadrant tail or lower left quadrant tail of a bivariate distribution.
- This concept is relevant for the study of dependence between tail ($\equiv$ extreme) events.
- One can prove that tail dependence between two continuous random variables X and Y is a copula property.
- As a result, the amount of tail dependence is invariant under strictly increasing transformations of X and Y.

Tail dependence

- Consider a bivariate copula is such that the limit

$$\lim_{u \to 1} (1 - 2u + C(u, u))/(1 - u) \triangleq \lambda_U$$

exists.

- Then C has *upper tail dependence* if $0 < \lambda_U \leq 1$, and no upper tail dependence if $\lambda_U = 0$
- Similarly, if

$$\lim_{u \to 0} C(u, u)/u \triangleq \lambda_L.$$

exists, then C has *lower tail dependence* if $0 < \lambda_L \leq 1$, and no lower tail dependence if $\lambda_L = 0$.

Tail dependence

- The definition is justified by the following calculation:

$$\begin{aligned}\lambda_U &= \lim_{u\to 1} \mathrm{P}(U_1 > u | U_2 > u)\\ &= \lim_{u\to 1} \mathrm{P}(U_2 > u | U_1 > u).\end{aligned}$$

  However,

$$\lim_{u\to 1} \mathrm{P}(U_1 > u | U_2 > u) = \lim_{x\to \infty} \mathrm{P}(X > x | Y > x).$$

- This shows that λ_U measures the co-dependence of X and Y at the right tail: $\lambda_U > 0$ if and only if the conditional probabilities $\mathrm{P}(X > x | Y > x)$ and $\mathrm{P}(Y > x | X > x)$ are positive for large values of x.
- A similar argument can be made for λ_L.

Tail dependence

- For the bivariate Gaussian copula, $|\rho_{12}| < 1$,

$$\lambda_U = 0,$$
$$\lambda_L = 0.$$

- For the bivariate Student t copula, $|\rho_{12}| < 1$,

$$\lambda_U = 2t_{\nu+1}(-\sqrt{\nu+1}\sqrt{(1-\rho_{12})/(1+\rho_{12})}),$$
$$\lambda_L = \lambda_U.$$

- For the bivariate Clayton copula, $\theta > 0$,

$$\lambda_U = 0,$$
$$\lambda_L = 2^{1/\theta}$$

- For the bivariate Gumbel copula, $\theta > 1$,

$$\lambda_U = 2 - 2^{1/\theta},$$
$$\lambda_L = 0.$$

Marshall-Olkin copula

- Consider a two-component system where the components are subject to shocks, which are fatal to one or both components.
- We assume that these shocks arrive at times T_1, T_2, and T_{12} as independent Poisson processes, with intensities of λ_1, λ_2, and λ_{12}, respectively.
- In credit applications, the components are credit names, and λ_1, λ_2, and λ_{12} are default intensities.
- The shared shock λ_{12} can be interpreted as global shock, that affects multiple names simultaneously.
- Let $\tau_1 = \min(T_1, T_{12})$ and $\tau_2 = \min(T_2, T_{12})$ denote the lifetimes of the two components.

Marshall-Olkin copula

- The joint survival probability is given by

$$\begin{aligned} \mathrm{P}(\tau_1 > t_1, \tau_2 > t_2) &= \mathrm{P}(T_1 > t_1)\mathrm{P}(T_2 > t_2)\mathrm{P}(T_{12} > \max(t_1, t_2)) \\ &= \exp(-\lambda_1 t_1 - \lambda_2 t_2 - \lambda_{12} \max(t_1, t_2)). \end{aligned}$$

- The marginal survival probabilities are

$$\begin{aligned} \mathrm{P}(\tau_1 > t_1) &= \exp(-(\lambda_1 + \lambda_{12})t_1), \\ \mathrm{P}(\tau_2 > t_1) &= \exp(-(\lambda_2 + \lambda_{12})t_2). \end{aligned}$$

- We now find the copula C_{MO} for this distribution.

Marshall-Olkin copula

- To this end, we express $\mathrm{P}(\tau_1 > t_1, \tau_2 > t_2)$ in terms of $\mathrm{P}(\tau_1 > t_1)$ and $\mathrm{P}(\tau_2 > t_2)$.
- Since

$$\max(t_1, t_2) = t_1 + t_2 - \min(t_1, t_2),$$

  we have

$$\mathrm{P}(\tau_1 > t_1, \tau_2 > t_2) = \mathrm{P}(\tau_1 > t_1)\mathrm{P}(\tau_2 > t_2)\min(\exp(\lambda_{12}t_1), \exp(\lambda_{12}t_2)).$$

- Set

$$\begin{aligned} u_1 &= \mathrm{P}(\tau_1 > t_1), \\ u_2 &= \mathrm{P}(\tau_2 > t_2), \end{aligned}$$

  and

$$\begin{aligned} \alpha_1 &= \lambda_{12}/(\lambda_1 + \lambda_{12}), \\ \alpha_2 &= \lambda_{12}/(\lambda_2 + \lambda_{12}). \end{aligned}$$

Marshall-Olkin copula

- Then

$$\begin{aligned}\exp(\lambda_{12} t_1) &= u_1^{-\alpha_1},\\ \exp(\lambda_{12} t_2) &= u_2^{-\alpha_2}.\end{aligned}$$

- This leads to the following copula:

$$\begin{aligned}C_{MO}(u_1, u_2) &= u_1 u_2 \min(u_1^{-\alpha_1}, u_2^{-\alpha_2})\\ &= \min(u_1^{1-\alpha_1} u_2, u_1 u_2^{1-\alpha_2}).\end{aligned}$$

- Note that the Marshall-Olkin copula is an example of a *survival copula*, which expresses the *joint survival probability* in terms of *marginal survival probabilities*.
- This is unlike the copulas discussed above, which express the joint event probabilities in terms of marginal event probabilities.

Marshall-Olkin copula

- The Marshall-Olkin copula can be extended to more than two names in a straightforward manner.
- However, its complexity increases with the number of components.
- There are different kinds of shared shocks: some will affect all names, some will affect only subsets (like those in a particular industry).
- In practice, the specification of these shocks and their intensities is impractical, as the combinatorics get complicated, and the Marshall-Olkin copula is not used often in practice.
- Elements of the MO copula approach, specifically the idea of shared shocks, are used in combination with other models.

Algorithm for simulating Gaussian copula

- Consider the N-dimensional Gaussian distribution $N(0, \rho)$ with mean 0 and correlation matrix ρ.
- Find the Cholesky decomposition of ρ, i.e. $\rho = LL^{\mathrm{T}}$, where L is an $N \times N$-dimensional lower triangular matrix.
- Then repeat the following steps a desired number of times:
  (i) *Step 1*. Simulate N independent samples $Z_1, \ldots, Z_N$ from $N(0, 1)$.
  (ii) *Step 2*. Calculate $X_1 = LZ_1, \ldots, X_N = LZ_N$.
  (iii) *Step 3*. Convert this sample to a correlated N-dimensional uniform vector $U_1 = N(X_1), \ldots, U_N = N(X_N)$.
- Then $(U_1, \ldots, U_N) \sim C_\rho$.

Algorithm for simulating Student t copula

- The algorithm is similar to the one above (Gaussian copula).
- Sampling from a χ^2-distribution can be done by standard acceptance-rejection techniques or by numerically inverting the cumulative distribution function
- Find the Cholesky decomposition L of ρ, and repeat the following steps:
  (i) *Step 1*. Simulate N independent samples $Z_1, \ldots, Z_N$ from from $N(0, 1)$.
  (ii) *Step 2*. Simulate a random variate S from χ^2_ν independent of $Z_1, \ldots, Z_N$.
  (iii) *Step 3*. Calculate $Y = LZ$.
  (iv) *Step 4*. Set $X = \sqrt{\nu/S}Y$.
  (v) *Step 5*. Set $U_i = t(X_i)$, for $i = 1, \ldots, N$.
- Then $(U_1, \ldots, U_N) \sim C_{\nu\rho}$.

References

- Embrechts, P., Lindskog, F., and McNeil, A.: Modeling dependence with copulas and applications to risk management, in *Handbook of Heavy Tailed Distributions in Finance*, Elsevier (2003).
- Joe, H.: *Dependence Modeling with Copulas*, Chapman & Hall (2014).
- Nelsen, R. B.: *An Introduction to Copulas*, Springer (1999).