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Modeling dependence between error components of the stochastic frontier model using copula: Application to intercrop coffee production in Northern Thailand

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ABSTRACT

In the standard stochastic frontier model, the two-sided error term V and the one-sided technical inefficiency error term W are assumed to be independent. In this paper, we relax this assumption by modeling the dependence between V and W using copulas. Nine copula families are considered and their parameters are estimated using maximum simulated likelihood. The best model is then selected using the AIC or BIC criteria. This methodology was applied to coffee production data from Northern Thailand. For these data, the best model was the one based on the Clayton copula. The main finding of this study is that the dependence between V and W is significant and cannot be ignored. In particular, the standard stochastic frontier model with independence assumption grossly overestimated the technical efficiency of coffee production. These results call for a reappraisal of previous production efficiency studies using the SFM with independence assumption, which may occasionally lead to overoptimistic conclusions.

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1. Introduction

The Stochastic frontier model (SFM) has proved very useful to assess technical efficiency of production units. The stochastic frontier production model for a cross-section of observations was independently proposed by Aigner et al. [1] and Meeusen and van den Broeck [20]. It is essentially a linear regression model with two independent error components: a two-sided term that captures random variation of the production frontier across firms and a one-sided term that measures inefficiency relative to the frontier. In recent decades, most studies about production, cost or profit efficiency have used the conventional SFM (see, e.g., [1,9,10,15,19,22–24,27–30,33–36]). In all these studies, it is assumed that the one-sided and two-sided error terms are independent. Based on this assumption, the parameters of the SFM can be estimated using the corrected ordinary least squares or maximum likelihood methods.

The impact of the independence assumption on technical efficiency estimation has long remained an open issue. This assumption can be relaxed by using a copula to fit the joint distribution of the two random error components more appropriately. Smith [26] first proposed an SFM allowing for dependence between the two error components using copula functions. Copula functions can be used to capture rank correlation and tail dependence between the two error components,

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thus making the stochastic frontier analysis much more flexible. However, the log-likelihood function in the copula-based SFM generally does not have a closed form, which makes its maximization numerically intricate.

In this paper, we propose to use the maximum simulated likelihood method, which has numerical and computational advantages over the numerical integration method used by Smith [26]. Furthermore, to explore the dependence structure of the error components in the SFM, we systematically consider several copula families including the Student-t, Clayton, Gumbel and Joe families as well as their relevant rotated versions. The model with the best fit-complexity trade-off is selected using the AIC or BIC criteria. This approach was applied to cross-sectional data about coffee production in Thailand. A comparison between technical efficiencies computed with and without the independence assumption (considering the best copula model) reveals that the standard approach grossly overestimates efficiency, which has important implication for production analysis using the SFM.

The remainder of this paper is organized as follows. Section 2 introduces the necessary background on the SFM and copula. Section 3 presents the copula-based stochastic frontier approach. Empirical results with this model applied to coffee production data are reported in Section 4. Finally, Section 5 concludes the paper.

2. Background and theory

The SFM is a regression-like model with a disturbance term that is asymmetric and distinctly non-normal. This model will first be briefly summarized in Section 2.1. Some background on copula will then be recalled in Section 2.2. These are the two building blocks of the copula-based model introduced in Section 3.

2.1. Stochastic frontier model

Classical models of production [13,19] consider ideal (i.e., highest achievable) production as a function $h(\boldsymbol{x}, \boldsymbol{\beta})$ of a vector $\boldsymbol{x}$ of inputs, where $\boldsymbol{\beta}$ is a vector of parameters. As real production Y can only be less than the ideal one, it can be written as

$$Y = h(\boldsymbol{x}, \boldsymbol{\beta}) \cdot TE, \tag{1}$$

where $TE < 1$, called technical efficiency, is the ratio of actual output y to maximum feasible output $h(\boldsymbol{x}, \boldsymbol{\beta})$. For instance, the Cobb–Douglas production model [37] can be written as

$$\ln Y = \boldsymbol{x}'\boldsymbol{\beta} - W, \tag{2}$$

where $\boldsymbol{\beta}$ is a vector of coefficients and $W = -\ln(TE)$ is a non-negative error term. However, a theoretical problem with this approach is that any measurement error on Y must be embedded in the disturbance W, making the estimation of $\boldsymbol{\beta}$ very sensitive to outliers. To solve this problem, Aigner et al. [1] proposed to add a symmetric random noise V to the right-hand side of (2), resulting in the following model,

$$\ln Y = \boldsymbol{x}'\boldsymbol{\beta} + \varepsilon, \tag{3a}$$

$$\varepsilon = V - W, \tag{3b}$$

where the two error components W and V are assumed to be independent. In this model, the frontier $\exp(\boldsymbol{x}'\boldsymbol{\beta} + V)$ is stochastic, hence the term “stochastic frontier”. The disturbances ε are now assumed to arise from two sources: (1) productive inefficiency, resulting in a non-negative error term W, and (2) firm-specific effects V, which can enter the model with either signs. The technical efficiency TE can then be written as

$$TE = \frac{\exp(\boldsymbol{x}_i'\boldsymbol{\beta} + V - W)}{\exp(\boldsymbol{x}_i'\boldsymbol{\beta} + V)} = \exp(-W). \tag{4}$$

The inefficiency error term W is usually assumed to have a gamma, exponential, or half-normal distribution (defined as the distribution of the absolute value of a normal variable) [11]. In contrast, the symmetric error term V is usually assumed to have a normal or logistic distribution.

2.2. Copula

A copula connects a given number of one-dimensional marginal distributions to form a joint multivariate distribution [21]. In the following, we will limit the presentation to bivariate copula, which will be used later. Sklar’s theorem [25] states that any cumulative distribution function (cdf) $F(x_1, x_2)$ of a two-dimensional random vector (X_1, X_2) can be expressed as

$$F(x_1, x_2) = C\left(F_1(x_1), F_2(x_2)\right), \tag{5}$$

where $F_1(\cdot)$ and $F_2(\cdot)$ are the marginal cdfs of X_1 and X_2, and C is a bivariate function, called a *copula*. If X_1 and X_2 are independent, then C is the product. A function $C : [0, 1]^2 \to [0, 1]$ is a copula if and only if it satisfies the following properties:

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