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CHANCE-CONSTRAINED PROGRAMMING WITH STOCHASTIC a_{ij}: AN APPLICATION

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Abstract

This work focuses on using chance-constrained stochastic programming technique to estimate revenue and profit after considering the problems of uncertainty resulting from damages incurred during production of rectangular building block products. Using this approach, some technical models were developed to determine production numbers achievable when certain level of uncertainty are considered. The study provides a distinct category of chance-constrained stochastic models where only the left-hand-sides of the general model are random. This work utilized block industry data from [5]. The Lingo solver software was used to obtain solutions for the aforementioned models.

Keywords: Chance-Constrained, Stochastic Programming, Nonlinear Models, Lingo Solver, Block Manufacturing Industry.

1. Introduction

Chance constraint stochastic programming problems are very challenging to solve in practice as they typically involve nonlinearities, non-convexities, discrete variables, and random variables. Earlier, in 1959, when the formulation of chance constraints was introduced, Charnes and Cooper [1], presented a model with a single chance constraints (where $m = 1$) and having a fixed left-hand side. Using these assumptions, they showed that the problem can be reformulated as a deterministic nonlinear programming problem equivalent by taking the inverse of the distribution of the random RHS. With known distributions, this transformation is linear and results in an efficiently solvable problem. For the case of single chance constraints and random left-hand sides, a convex problem was shown in [2] when the left-hand side is independently normally distributed and $\alpha \geq 0.5$. Miller et al. [3], introduced the joint chance-constraints problem ($m > 1$) with fixed technology matrices. Showing also that when the random right-hand side parameter distributions are independent, the logarithmic transforms of the products of the CDFs are convex and hence computationally tractable for a large class of probability distributions. In cases where the random right-hand sides are dependent, Prekopa [4], showed in 1971 that a convex deterministic equivalent problem can be formulated when the right-hand sides have log-concave distributions. This class includes such distributions as multivariate normal and multivariate beta.

1.1 Statement of Problem and Motivation

One of Nigeria's prominent building material is the rectangular building blocks made of cement added as an additive to sand (sharpsand or stonedusts or 3/8 granite stones) or even a mixture of all afore mentioned. The demand for rectangular block is huge in the capital city Abuja and this makes the industry lucrative as demand increases. This study collected data from one of the biggest rectangular block manufacturer in Abuja, Dunu Nigeria limited. The company manufactures seven (7) different brands of block products ranging from sandcrete block with sizes such as sandcrete 9" and sandcrete 6" which

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are products of the combination of cement, sharpsand and water. Another brand is the stonedust block with sizes such as stonedust 9”, stonedust 6” and stonedust 4” which are products of the combination of cement, coarsely crushed granite (stonedust) and water. Lastly, is the concrete block brand with sizes such as concrete 9” and 6” which are a product of the mixture of cement, 3/8 sized granite stones, water and a negligible quantity of sharpsand. The mixture of these materials makes it almost impossible for the industry to determine the various profit she makes from each block product considering also the damages incurred during production and as such making it difficult to determine the brand or product that accrues the largest profit. The damages recorded vary from truck to truck and as such, models have been developed to determine profits when only 15, 10, 5, and 0 damages are recorded.

1.2 Objective of the Study

a) To use the block industry data from Nwokike et al. [5] to obtain values for all the parameters of the model.
b) Create models that would deal with varying probability cases.
c) Determine products with better profit margins.

2. Relevant Literature

Nwokike et al. [5], applied the chance-constrained stochastic programming technique to a building block industry problem. The study focused more on when the resources (right-hand-side) are random quantities. The study just like this one was designed to maximize profit while considering the problems of uncertainty surrounding block production. An algorithm for solving multi-objective integer quadratic programming problems having random parameters in the objective functions and in the constraints was introduced in [6]. A chance-constrained programming model was developed to assist Queensland barley growers make varietal and agronomic decisions in the face of changing product demands and volatile production conditions [7]. Leguene et al. [8], proposes a new modeling and solution method for a class of multi-objective stochastic programming problems. The formulation includes a joint probabilistic constraint with a random technology matrix which requires a system of inequalities to hold with some probability level. A convex relations of chance constrained optimization problems in order to obtain lower bounds on the optimal value was developed in [9]. Using chance-constrained [10], discusses unmanned deep-sea and planetary vehicles operating in highly uncertain environments. More research have been conducted on chance-constrained [11 - 15]**.**

3. Methodology

The general chance-constrained stochastic programming model as stated [16]:

$$\left.\begin{array}{l} Maximize\ f(x) \\ subject\ to \\ \quad P\left\{\sum_{j=1}^{n} a_{ij}x_j \le b_i\right\} \ge \alpha_i, i = 1, 2, \dots\dots, m, \\ \quad where\ \ x_j \ge 0, for\ all\ j \end{array}\right\} \qquad (1)$$

The parameters a_{ij} and b_i are random variables and constraint i is realized with a minimum probability of $\alpha_i, 0 < \alpha_i < 1$.
$f(x)$ is the objective function with the largest possible total farm gross margin;
c_j is the profit from a unit of the jth activity;
x_j is the level of the ith resourse required to produce one unit of the jth activity;
a_{ij} is the quantity of ith resource required to produce one unit of the jth activity;
b_i is the level of the ith resource or constraint;
P is the probability that the ith constraint will be met;
α_i is the minimum probability of meeting the ith constraint;

3.1 Method of Data Collection

This study has used block industry data containing material weights, and costs generated and analyzed in [5].

3.2 Data Analysis

After the collection of data from the industry, Nwokike et al. [5], showed that the standard distribution of weights of all block products, the mean weight of all the raw material constituting a block product, calculation of the various cost of raw material in each block product and then the average cost of a block product was performed. This was followed by a subtraction of the results from the selling price of each block product to get the average profit accrued from a block product.

3.3 The General Chance-Constrained Stochastic Model for random a_{ij}

[1] When only a_{ij} are random variables: let only a_{ij} be normally distributed where $\bar{a}_{ij}$, $var\{a_{ij}\}$ and $cov\{a_{ij}, a_{i'j'}\}$ of a_{ij} and $a_{i'j'}$ denote mean, variance and covariance of the normal distribution respectively. The stochastic constraint analysis can be considered as

$$P\left\{\sum_{j=1}^{n} a_{ij}x_j \le b_i\right\} \ge 1 - \alpha_i \qquad (2)$$

where $\frac{h_i - E\{h_i\}}{\sqrt{var\{h_i\}}}$ is standard normally distributed mean with zero mean and unit variance. Which implies that

$$P\{h_i \le b_i\} = \Phi\left\{\frac{b_i - E\{h_i\}}{\sqrt{var\{h_i\}}}\right\} \qquad (3)$$

Where Φ represents the cumulative density function (CDF) of the standard normal distribution.
And below is the final model.
This is followed by some mathematics to produce the resultant chance-constrained stochastic model;

$$\left.\begin{array}{c} Maximize\ z = \sum_{j=1}^{n} c_j x_j \\ subject\ to: \\ \sum_{j=1}^{n} \bar{a}_{ij}x_j + K_i \sqrt{\sum_{j=1}^{n} var\{a_{ij}\}x_j^2} - b_i \le 0, \\ where\ \ x_j \ge 0, and\ \ j = 1, 2, ..n, i = 1, 2, ...m \end{array}\right\} \qquad (4)$$

z is the objective function with the largest possible total farm gross margin;
c_j is the profit from a unit of the jth activity;
x_j is the level of the ith resourse required to produce one unit of the jth activity;
a_{ij} is the quantity of ith resource required to produce one unit of the jth activity;
$\overline{b_i}$ is the mean level of the ith resource or constraint;
α_i is the minimum probability of meeting the ith constraint;
K_i is the value of the standard normal variate corresponding to the probability α_i

3.4 Data and Value Tables

The over-all mean number of blocks per truck was gotten by dividing the mean weight of material per truck by mean weight of blocks. Such that,

SCB 9" $= 882$, SCB 6" $= 1413$, SDB 9" $= 617$, SDB 6" $= 945$,
SDB 4" $= 1350$, CCB 9" $= 547$, CCB 6" $= 827$

Then, add all and divide by 7 (number of products), which implies

$$\frac{6581}{7} = 940\ blocks$$

Table 1
Material costs and profit per block brand

	Cement Cost (₦)	Cost of Sharpsand Stonedust & 3/8 Stone (₦)	Labour Cost (₦)	Average Production Cost (₦)	Selling Price (₦)	Average Profit (₦)
SCB 9"	35.38	28.43	15	78.81	155	76.19
SCB 6"	29.70	17.74	14	61.44	130	68.56
SDB 9"	36.31	84.89	18	139.20	200	60.78
SDB 6"	30.69	55.54	25	111.23	160	49.77
SDB 4"	25.50	38.79	14	78.29	120	40.71
CCB 9"	34.51	107.05	31	172.56	235	62.45
CCB 6"	31.84	93.77	29	154.61	205	50.39

4. Results

We start by stating the tabular representation of the problem.

Table 2

The problem represented in a table.

Required material	Materials required for block production														Available material
	SCB 9”		SCB 6”		SDB 9”		SDB 6”		SDB 4”		CCB 9”		CCB 6”		
	Mean $\bar{a}$	SD σ	Mean $\bar{a}$	SD σ	Mean $\bar{a}$	SD σ	Mean $\bar{a}$	SD σ	Mean $\bar{a}$	SD σ	Mean $\bar{a}$	SD σ	Mean $\bar{a}$	SD σ	
Cement	$\bar{a}_{11}$ 1.22	σ_{11} .052	$\bar{a}_{12}$ 1.024	σ_{12} .027	$\bar{a}_{13}$ 1.252	σ_{13} .044	$\bar{a}_{14}$ 1.056	σ_{14} .038	$\bar{a}_{15}$ .880	σ_{15} .022	$\bar{a}_{16}$ 1.190	σ_{16} .030	$\bar{a}_{17}$ .960	σ_{17} .016	2948
Sharpsand	$\bar{a}_{21}$ 22.56	σ_{21} 0.20	$\bar{a}_{22}$ 14.08	σ_{22} 0.34											19900
Stonedust					$\bar{a}_{33}$ 30.87	σ_{33} 0.27	$\bar{a}_{34}$ 20.16	σ_{34} 0.20	$\bar{a}_{35}$ 14.12	σ_{35} 0.34					19060
3/8 stones											$\bar{a}_{46}$ 35.33	σ_{46} 0.24	$\bar{a}_{47}$ 23.38	σ_{47} 0.23	19340
Labour	₦15		₦14		₦18		₦25		₦14		₦31		₦29		
Profit	₦76.19		₦68.56		₦60.78		₦49.77		₦40.71		₦62.45		₦50.39		

4.1 Denotation of the variables

We have identified the appropriate variables by associating each to a block product. Let,

Sandcrete block 9” x_1
Sandcrete block 6” x_2
Stonedust block 9” x_3
Stonedust block 6” x_4
Stonedust block 4” x_5
Concrete block 9” x_6
Concrete block 6” x_7

4.2 Formulation of the objective function

Since the mission is to maximize profit, the profit from the sale of each block product must be the objective function as follows:

$$\boldsymbol{Z} = 76.19x_1 + 68.56x_2 + 60.78x_3 + 49.77x_4 + 40.71x_5 + 62.45x_6 + 50.39x_7$$

4.3 Formulation of the constraint sets

Since there are various material required for the manufacture of each block, then, the quantity of these materials shall form the sets of constraints as follows:

$$\sum_{j=1}^{n} \bar{a}_{ij}x_j + K_i\sqrt{X^TV_iX} \leq b_i, \qquad i = 1, 2, 3 \dots m \tag{5}$$

The normally distributed random variables a_{ij} are independent, therefore, the covariance terms will be zero and reduces to a diagonal matrix as:

$$V_i = \begin{pmatrix} var\{a_{i1}\} & \dots & 0 \\ . & var\{a_{i2}\} & . \\ . & . & . \\ . & . & . \\ 0 & \dots & var\{a_{in}\} \end{pmatrix}$$

1. Cement constraint {kg}

Consider equation (5)

Where $j = 1, 2, 3 \dots, 7$ and $i = 1$ in (5)

We have,

$$\sum_{j=1}^{7} \bar{a}_{ij} x_j + K_i \sqrt{X^T V_i X} \leq b_i \, , i = 1 \qquad (6)$$

Then, equation (6) can further be written as

$$\bar{a}_{11}x_1 + \bar{a}_{12}x_2 + \bar{a}_{13}x_3 + \bar{a}_{14}x_4 + \bar{a}_{15}x_5 + \bar{a}_{16}x_6 + \bar{a}_{17}x_7 + K_i\sqrt{x_1^2\sigma_{a_{11}}^2 + x_2^2\sigma_{a_{12}}^2 + x_3^2\sigma_{a_{13}}^2 + x_4^2\sigma_{a_{14}}^2 + x_5^2\sigma_{a_{15}}^2 + x_6^2\sigma_{a_{16}}^2 + x_7^2\sigma_{a_{17}}^2} \leq b_i$$

Thus;

$$1.22x_1 + 1.024x_2 + 1.252x_3 + 1.056x_4 + 0.88x_5 + 1.19x_6 + 0.96x_7 + K_i\left[\sqrt{0.00264x_1^2 + 0.00073x_2^2 + 0.00194x_3^2 + 0.00144x_4^2 +} \atop \sqrt{+0.00049x_5^2 + 0.00090x_6^2 + 0.00026x_7^2}\right] \leq 2948 \qquad (7)$$

2. Sharpsand constraint {kg}

Considering equation (5)

Where $j = 1, 2$ and $i = 2$

Then,

$$\sum_{j=1}^{2} \bar{a}_{ij} x_j + K_i \sqrt{X^T V_i X} \leq b_i \, , i = 2$$

$$\bar{a}_{21}x_1 + \bar{a}_{22}x_2 + K_i\sqrt{x_1^2\sigma_{a_{21}}^2 + x_2^2\sigma_{a_{22}}^2} \leq b_i$$

Thus;

$$22.56x_1 + 14.08x_2 + K_i\sqrt{0.04x_1^2 + 0.12x_2^2} \leq 19900 \qquad (8)$$

3. Stonedust constraint {kg}

Considering equation (5)

Where $j = 3, 4, 5$ and $i = 3$

Then,

$$\sum_{j=3}^{5} \bar{a}_{ij} x_j + K_i \sqrt{X^T V_i X} \leq b_i \, , i = 3 \bar{a}_{33}x_3 + \bar{a}_{34}x_4 + \bar{a}_{35}x_5 + K_i\sqrt{x_3^2\sigma_{a_{33}}^2 + x_4^2\sigma_{a_{34}}^2 + x_5^2\sigma_{a_{35}}^2} \leq b_i$$

Thus;

$$30.87x_3 + 20.16x_4 + 14.12x_5 + K_i\sqrt{0.073x_3^2 + 0.04x_4^2 + 0.12x_5^2} \leq 19060 \qquad (9)$$

4. 3/8 stone constraint

Considering equation (5)

Where $j = 6, 7$ and $i = 4$

Then,

$$\sum_{j=6}^{7} \bar{a}_{ij} x_j + K_i \sqrt{X^T V_i X} \leq b_i \, , i = 4$$

$\bar{a}_{46}x_6 + \bar{a}_{47}x_7 + K_i\sqrt{x_6^2\sigma_{\bar{a}_{46}}^2 + x_7^2\sigma_{\bar{a}_{47}}^2} \le b_i$

Thus;

$$35.33x_6 + 23.38x_7 + K_i\sqrt{0.058x_6^2 + 0.053x_7^2} \le 19340 \qquad (10)$$

The general constraint becomes:

$$\left.\begin{array}{c} 1.22x_1 + 1.024x_2 + 1.252x_3 + 1.056x_4 + 0.88x_5 + 1.19x_6 + 0.96x_7 + \\ K_i\left[\sqrt{0.00264x_1^2 + 0.00073x_2^2 + 0.00194x_3^2 + 0.00144x_4^2} + \right. \\ \left. \sqrt{+0.00049x_5^2 + 0.00090x_6^2 + 0.00026x_7^2}\right] \le 2948 \\ 22.56x_1 + 14.08x_2 + K_i\sqrt{0.04x_1^2 + 0.12x_2^2} \le 19900 \\ 30.87x_3 + 20.16x_4 + 14.12x_5 + K_i\sqrt{0.073x_3^2 + 0.04x_4^2 + 0.12x_5^2} \le 19060 \\ 35.33x_6 + 23.38x_7 + K_i\sqrt{0.058x_6^2 + 0.053x_7^2} \le 19340 \end{array}\right\} \qquad (11)$$

[e] Formulation of the general chance-constrained stochastic programming model for this problem

$$\left.\begin{array}{l} Max\ \boldsymbol{Z} = 76.19x_1 + 68.56x_2 + 60.78x_3 + 49.77x_4 + 40.71x_5 + 62.45x_6 + 50.39x_7 \\ subject\ to: \\ \quad 1.22x_1 + 1.024x_2 + 1.252x_3 + 1.056x_4 + 0.88x_5 + 1.19x_6 + 0.96x_7 + \\ \quad K_i\left[\sqrt{0.00264x_1^2 + 0.00073x_2^2 + 0.00194x_3^2 + 0.00144x_4^2} + \right. \\ \quad \left. \sqrt{+0.00049x_5^2 + 0.00090x_6^2 + 0.00026x_7^2}\right] \le 2948 \\ \quad 22.56x_1 + 14.08x_2 + K_i\sqrt{0.04x_1^2 + 0.12x_2^2} \le 19900 \\ \quad 30.87x_3 + 20.16x_4 + 14.12x_5 + K_i\sqrt{0.073x_3^2 + 0.04x_4^2 + 0.12x_5^2} \le 19060 \\ \quad 35.33x_6 + 23.38x_7 + K_i\sqrt{0.058x_6^2 + 0.053x_7^2} \le 19340 \\ \quad where\ \ x_1, x_2, x_3, x_4, x_5, x_6, x_7 \ge 0 \end{array}\right\} \qquad (12)$$

For the K_i, when only 15 block damages are recorded per truck, we have:
$\frac{15}{940} \times 100\% = 1.595,\ which\ implies\ \ (100 - 1.595)\%\ success$**.** This represents a probability of 0.984. Therefore $K_1 = 0.984$. This is repeated for 10, 5, and 0 block damages.

$$
\left.\begin{aligned}
&Max\ \boldsymbol{Z} = 76.19x_1 + 68.56x_2 + 60.78x_3 + 49.77x_4 + 40.71x_5 + 62.45x_6 + 50.39x_7 \\
&subject\ to: \\
&\quad 1.22x_1 + 1.024x_2 + 1.252x_3 + 1.056x_4 + 0.88x_5 + 1.19x_6 + 0.96x_7 + \\
&\quad 0.984\left[\sqrt{0.00264x_1^2 + 0.00073x_2^2 + 0.00194x_3^2 + 0.00144x_4^2 +} \right. \\
&\quad \left. \sqrt{+0.00049x_5^2 + 0.00090x_6^2 + 0.00026x_7^2}\right] \le 2948 \\
&\quad 22.56x_1 + 14.08x_2 + 0.984\sqrt{0.04x_1^2 + 0.12x_2^2} \le 19900 \\
&\quad 30.87x_3 + 20.16x_4 + 14.12x_5 + 0.984\sqrt{0.073x_3^2 + 0.04x_4^2 + 0.12x_5^2} \le 19060 \\
&\quad 35.33x_6 + 23.38x_7 + 0.984\sqrt{0.058x_6^2 + 0.053x_7^2} \le 19340 \\
&\quad where\ \ x_1, x_2, x_3, x_4, x_5, x_6, x_7 \ge 0
\end{aligned}\right\} \quad (13)
$$

Table 3: Solution to the models provided using Lingo linear programming software

	15 block damages $K_1 = 0.984$	10 block damages $K_2 = 0.989$	5 block damages $K_3 = 0.995$	0 block damages $K_4 = 1.000$
x_1	468	469	469	470
x_2	196	194	193	191
x_3	165	165	165	165
x_4	375	376	375	374
x_5	123	122	122	122
x_6	222	220	217	219
x_7	321	323	326	323
Profit (₦)	112877.9	112759.3	112614.5	112494.0

5. Summary and Conclusion

5.1 Summary

The chance-constrained stochastic programming models developed in this work were designed to tackle the problem of uncertainty associated in production and a block industry problem used considered. The profit margins recorded in this work are based on the probability level in view and also the side of the equation considered as random. This research work presents a concrete research carried out to deal with various probability levels regarding block damages incurred in the rectangular building block industry and then a generally good, optimal solutions to the chance-constrained stochastic programs for the cases in which the random parameters are at the left-hand-side of the model. Table 3 shows the various profit as various damages are incurred during production.

5.2 Conclusion

This research work discusses chance-constrained stochastic programming with uncertainty as the basics for including probabilistic parameter when optimizing profit in a block manufacturing industry. This research introduces new models for chance-constrained stochastic programs with random left-hand side for block industry problem. The principal objective of this research is to expand on the set of tools available to mathematical programmers for solving this important kind of programming problems and also provide building block industries with solutions to some decision making problems.

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