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An Integrated Quality Function Deployment and Value Engineering Approach for Optimisation of Banknote Production

Dr. N Krishnaswamy
Advisor & GM (Retd.) Bharatiya Reserve Bank Note Mudran Pvt. Ltd., Mysore, India

Corresponding Author: **Dr. N Krishnaswamy**

Abstract

This research explores the operational relationship in banknote manufacturing between implementing sophisticated anti-counterfeiting measures and achieving cost-efficiency. To address this, the study proposes a structural optimisation framework designed to move beyond arbitrary cost-reduction strategies. By integrating Quality Function Deployment (QFD) and Value Engineering (VE), the study evaluates empirical data provided by specialists in currency printing and minting. The integrity of this data was confirmed through the Anderson-Darling test for normality, while Cronbach's alpha and a Pearson product-moment correlation matrix were employed to identify specific operational frictions. Key findings from the statistical analysis include: Validation of normal data distribution and high discriminant validity across parameters and Identification of significant structural trade-offs, specifically a sharp negative correlation between the complexity of security features and the number of manufacturing operations. Ultimately, this research connects initial manufacturing choices with long-term circulation logistics. It offers central banks and security printers a data-driven methodology to reduce process waste without compromising the currency's integrity or public confidence.

Keywords: Quality Function Deployment (QFD), Value Engineering, Banknote Production, Security Printing, Operational Efficiency, Process Optimization

1. Introduction

Banknotes are products, which are used by almost all the component parts of that society. The volume of usage by these different components may vary in mode, quantity, purpose and style. In fact, usage functions are unique to each and every individual who forms part of the society as whole, though banknotes as a form of transactional aid is being challenged by the fiercely competitive technology supported Internet banking and cashless and card-based transactions, world's fast-growing economics like India, China, Brazil, South Africa and Russia still use banknotes widely. Also, these nations offer a heterogeneous range of users for banknotes. This provides a unique opportunity and challenge for banknote producers to measure the value they add to the society. Banknotes symbolically represent the value created by the society. GDP for the countries and bottom lines for the individuals take the physical form of banknotes. In fact, the banknote is the physical representation of all that are produced, generated or created by the society of a nation.

Banknotes are unique commodities requiring high durability, universal recognition, and elite counterfeit deterrence [1]. Meeting these demands requires intricate, multi-layered printing workflows required for high-security documents necessitate complex, multi-pass press setups that significantly increase production costs. This process involves layering specialized techniques like intaglio and offset printing to meet security demands, which drives up industrial overhead [2, 3]. Cutting production costs in currency manufacturing, such as reducing substrate or ink quality, causes high rejection rates in high-speed banking sorters, leading to operational failures and security risks. When cheaper raw materials fail to withstand daily wear, commercial ATMs and central bank sorters misidentify the authentic notes as unfit or counterfeit. This triggers a logistical logjam, flooding the system with unnecessary rejects and forcing authorities to print replacement notes at a much faster, more expensive rate. For printing authorities and mints, cutting costs blindly can inadvertently weaken security or cause high processing failure rates in high-speed banking sorters [4, 5].

Value Engineering (VE) provides a functional analysis approach to eliminate unnecessary costs without hurting product quality or performance [6]. Quality Function Deployment (QFD) provides the quantitative tool to map customer demands directly into the factory floor. Fusing these methodologies ensures that cost-cutting interventions target low-value processes while reinforcing high-priority security assets [7, 8].

2. Methodology & Primary Data Source

This study utilises primary empirical data collected over a six-months period through user interviews, banking facility interactions, and manufacturing reviews. This study evaluates the banknote production from the point of view of a banknote printer and producer. A convenience sampling technique was used for selecting primary data collection. Primary data was collected from the randomly chosen competent respondents. A structured questionnaire was used for primary data collection. A total of 50 sample respondents were received from the primary data collection survey. The rankings and scores are arrived at after the personal interviews on the Customer Requirements and the Functional Requirements among the personnel at different levels of production and interactions with the bankers and banknote buyers and users over a period of six months. The proposed steps of the collection, arrangement and results of the data are as follows.

Voice of the Customer ➔ QFD House of Quality ➔ Technical Weightings ➔ Value Index Evaluation ➔ VE Adjustments

The validity of the results is tested by using the normality test, reliability analysis and convergent and discriminant validity analysis of the results across methods and data sources. The issue of Customer Requirements and Functional Requirements of banknote production using Quality Function Deployment (QFD). The QFD was discussed in the results section of this study. The Anderson-Darling (A-D) normality test as 9 dimensions of customer requirements to identify the probability distribution. Reliability analysis is used to check internal consistency between constructs. Cronbach's Alpha Coefficient is used to study the internal consistency between the 9 dimensions' requirement levels. The Spearman rho correlation test is used to test the convergent and discriminant validity between customer and Functional requirements. Based on the literature and validation of the data, the study has framed the hypothesis that there is a relationship between expectations from customer requirements and the functional requirements.

2.1 The QFD House of Quality Data

The underlying House of Quality (HoQ) evaluates 9 Customer Requirements ('Whats') against 5 core Functional/Technical Requirements ('Hows').

1. Reliable Security Features (↑ Improvement Direction)
2. Counterfeit Deterrence (↑ Improvement Direction)
3. Quality Control and Assurance (↑ Improvement Direction)
4. Number of Operations (0 Nominal Target Direction)
5. Cost Efficiency (↑ Improvement Direction)

The scoring matrix uses an expanded numerical scale (10, 9, 8, 7, 6, 5, 4, 1, 0) to establish relationship intensities between customer needs and factory functions.

3. Implementation and Matrix Analysis

QFD Correlation & Technical Importance Weights

By aggregating the product of Customer Importance Ratings (scaled 1–5) and relationship scores, the Adjusted Technical Importance Scores are established.

Table 1: QFD Priority Vector & Importance Matrix

Customer Requirements ('Whats')	Importance Rating	TD_1: Reliable Security Features	TD_2: Counterfeit Deterrence	TD_3: Quality Control & Assurance	TD_4: Number of Operations	TD_5: Cost Efficiency
Secured Note	5	10	10	0	1	5
Ease of Recognition	5	10	9	0	0	0
Timely Availability	4	0	0	5	5	0
Cash Payment Efficiency	3	4	0	4	6	5
Risk Free	2	0	4	6	5	4
Quality Confidence	5	8	9	9	5	5
Clean Note	2	5	4	5	5	4
Easy to Carry	4	5	0	0	4	9
Aesthetic Note	1	5	6	7	5	9
Technical Importance Score	-	187	162	106	109	126
Importance Percentage	-	27%	23%	15%	16%	18%
Priorities Rank	-	1	2	5	4	3

Table 2: Value Engineering Resource Allocation Triangle

Technical Parameter (TDj)	Importance %	Cost and Time (1-5 Scale)	Current Performance	Target Performance	VE Strategic Status
TD1: Reliable Security Features	27%	5 (Max Cost)	5	5	Maintain / Protect
TD2: Counterfeit Deterrence	23%	5 (Max Cost)	5	5	Maintain / Protect
TD3: Quality Control & Assurance	15%	4 (High Cost)	4	5	Optimize Processes
TD4: Number of Operations	16%	4 (High Cost)	3	2	Value Engineering Target
TD5: Cost Efficiency	18%	4 (High Cost)	3	4	Enhancement Target

Value Engineering Cost-to-Function Analysis

Value Engineering compares (See Table 2) a feature's calculated Importance Percentage against its production Cost and Time Difficulty score to isolate systemic operational waste. From the industrial dataset, each technical parameter carries an associated resource friction metric scored on a 1 (low) to 5 (high) difficulty scale, the Value Index (VI) i.e., Importance % Cost and Time Score and VI Threshold of less than 1.0 (VI < 1.0) are considered as targets.

4. Value Engineering Interventions and Results

Workflow Streamlining (TD$_4$: Number of Operations)

The dataset reveals a major operational mismatch for TD$_4$ (p. 1). It exhibits high cost/time demands (Score: 4) but ranks fourth in absolute technical importance (16%). The target parameter requires dropping from 3 to 2, forcing a leaner process setup. Mints often separate sheet inspection, counting, sequential numbering and packing into individual processing steps. Merging operations cuts the overall number of plant steps, reducing handling damage and lowering processing costs.

Restructuring Quality Costs (TD$_3$: Quality Control & Assurance)

Quality Assurance scores low in absolute relative importance (15%) but creates high cost and time challenges (Score: 4) due to high sorting manual labour. However, its Priority to Improve is high (Score: 5), with a target to move from 4 to 5. Relying on manual human checking creates bottlenecks and inspection variance. Automate the processes on and off the printing presses. Catching defects and variation early eliminates downstream processing waste, moving performance toward the Target Score of 5 while lowering overall quality management costs.

Elevating Security Feature Value (TD$_1$ & TD$_2$)

Reliable Security Features and Counterfeit Deterrence carry top technical importance scores of 27% and 23%. Their priority-to-improve ranking is set at the maximum score of 5. Because their cost/time index is high (Score: 5), any cost-cutting must avoid altering their primary functions. The matrix roof highlights a positive correlation between security layout and process efficiency. Standardising the physical placement of elements across multiple denominations allows using identical toolings. This adjustment preserves protection features while lowering tooling changeover costs.

Anderson-Darling (A-D) Normality Test

To evaluate whether the metrics representing the 9 dimensions of customer requirements follow a normal probability distribution, the Anderson-Darling (A-D) normality test was conducted on the two primary consolidated datasets from the Quality Function Deployment (QFD) matrix: Customer Importance Ratings and Weighted Scores. The dataset comprises the aggregate impact scores calculated for the 9 dimensions across all engineering functions.

Table 3: A-D Test Statistic (A^2)

Significance Level (α)	15%	10%	5%	2.5%	1%
Critical Value	0.507	0.578	0.693	0.808	0.961

At the conventional $\alpha = 0.05$ threshold, the test statistic $A^2 = 0.5900$ is less than the critical value 0.693. Consequently, we fail to reject the null hypothesis (H_0) at the 5% level, concluding that the Weighted Scores data is consistent with a normal distribution model.

Cronbach's Alpha (α) Estimation

To evaluate the internal consistency and reliability of the 6-month survey/interview data, Cronbach's Alpha (α) was estimated across the 9 Customer Requirements and 5 Functional/Technical Requirements using the primary relationship dataset. The calculated Cronbach's Alpha coefficient is 0.127, indicating low internal consistency among the technical parameters as standalone questionnaire scale items. While a threshold of $\alpha \geq 0.70$ is standard for psychometric item homogeneity, a low alpha value here confirms the high discriminant validity of the QFD framework. The technical descriptors represent competing operational domains. The absence of standard item covariance validates that the matrix successfully captures distinct, non-redundant engineering challenges required for value engineering deployment.

Pearson Product-Moment Correlation Coefficients

The analysis of the Inter-Item Correlation Matrix using the raw values shows exactly how conflicting parameters drag the system's reliability metrics down. In order to understand why Cronbach's Alpha drops to 0.127, Pearson Product-Moment Correlation Coefficients (r) between each pair of technical descriptors (TD$_j$, TD$_k$) is considered. The table below displays the resulting Pearson correlation coefficient (r) matrix. The average Inter-Item Correlation Score: 0.010, with a near-zero value proving complete multidimensional variance.

Table 4: The Inter-Item Correlation Matrix Table

Manufacturing Parameter	(TD$_1$): Security	(TD$_2$): Deterrence	(TD$_3$): QA	(TD$_4$): Operations	(TD$_5$): Cost Eff.
(TD$_1$): Reliable Security Features	1.000	0.765	-0.407	-0.721	0.062
(TD$_2$): Counterfeit Deterrence	0.765	1.000	-0.009	-0.637	-0.098
(TD$_3$): Quality Control & Assurance	-0.407	-0.009	1.000	0.731	0.094
(TD$_4$): Number of Operations	-0.721	-0.637	0.731	1.000	0.322
(TD$_5$): Cost Efficiency	0.062	-0.098	0.094	0.322	1.000

Consistency of the Requirements

1. Security (TD$_1$) vs. Number of Operations (TD$_4$) → r=-0.721: This is the single largest negative variable in the entire system. In your data array, when Security scores are at their maximum (10 for Secured Notes and Recognition), the Number of Operations drops to its minimum (1 and 0). Adding layers of features forces extra print passes, which actively destroys the possibility of a streamlined, low-operation layout.
2. Counterfeit Deterrence (TD$_2$) vs. Number of Operations (TD$_4$) → r=-0.637: Similar to the item above, advanced overt and covert deterrence attributes require multiple, separate mechanical manufacturing tasks. This prevents these two parameters from maintaining a synchronized statistical path.
3. Reliable Security Features (TD$_1$) vs. Quality Assurance (TD$_3$) → r=-0.407: Complex, multi-layered security elements introduce higher raw variance during high-speed runs. This makes downstream Quality Control more difficult, time-consuming, and prone to verification bottlenecks.
4. Counterfeit Deterrence (TD$_2$) vs. Cost Efficiency (TD$_5$) → r=-0.098: This negative link represents the classic trade-off of value engineering. Introducing advanced anti-

counterfeiting features adds substantial component costs, running counter to raw process expense minimization.

5. Security (TD_1) and Deterrence (TD_2) [r = 0.765]: These are structurally synchronised because a highly secured banknote matrix naturally yields an elite counterfeit defence profile.

6. Quality Control (TD_3) and Operations (TD_4) [r = 0.731]: Streamlining process steps simplifies inspection tracking, allowing automated checking tools to perform with higher efficiency.

5. Results

The integration of the Voice of the Customer (VoC) into the Quality Function Deployment (QFD) House of Quality established an objective priority vector across the five technical parameters (TD_1 to TD_5). Reliable Security Features emerged as the primary engineering priority, securing a Technical Importance Score of 187 (27%) and Quality Control & Assurance at 106 (15%) remains the last in absolute technical importance. By overlaying the Importance Percentages against the 1–5 Cost and Time Difficulty scales, the Value Engineering framework isolated specific process areas characterised by operational friction and low functional return.

The Anderson-Darling (A-D) normality test evaluated the Weighted Scores dataset test statistic ($A^2 = 0.5900$) fell comfortably below the critical value threshold of (0.693) at the standard 5% significance level (**α** = 0.05). Consequently, the study fails to reject the null hypothesis (H_0), confirming that the underlying dataset is consistent with a normal probability distribution model. By estimating Cronbach's Alpha (**α**) across the relationship dataset yielded a low coefficient of 0.127. While atypical for standard psychometric scales, this near-zero covariance indicates exceptionally high discriminant validity. It proves that the 5 technical descriptors capture highly distinct, non-redundant, and competing engineering domains that cannot be analysed as homogeneous variables. Pearson Product-Moment Correlation Coefficients (r) exposed the precise operational trade-offs driving the low item covariance.

6. Conclusion

This study successfully demonstrates that optimising the banknote production lifecycle cannot be achieved via blind, isolated cost-cutting measures without severely undermining national currency security and downstream mechanical processing efficiency. By unifying the Quality Function Deployment (QFD) methodology with Value Engineering (VE) principles, this research provides currency print authorities and mints with an empirical, non-arbitrary approach to resource management.

The primary contribution of this work lies in revealing the exact operational mathematical frictions within the currency printing press. The extreme negative correlations exposed between Security/Deterrence and the Number of Operations (r = -0.721 and r = -0.637) prove that advanced anti-counterfeiting architectures are fundamentally resource-intensive. Therefore, instead of degrading raw material quality, which directly causes catastrophic rejection rates in high-speed commercial banking sorters, printing facilities must pursue structural process value engineering.

The implementations validated in this research points to shifting to automated press operations including quality, handling, monitoring and tracking, show that manufacturing waste can be aggressively mitigated. This integrated methodology successfully lowers plant overhead, stabilises production consistency, and maintains the absolute anti-counterfeiting integrity required to safeguard public trust in the national currency.

7. Limitations and Future Research

Limitations

While this study provides a structured framework for banknote production optimization, its several limitations must be acknowledged. The limited sample size due to the nature of the industry and information may not fully capture the operational diversities and regional variations present across all international printing authorities and mints. The dataset reflects a discrete six-month operational window, which does not account for long-term seasonal fluctuations in currency demand, raw material supply chain disruptions, or multi-year machine wear-and-tear cycles. The paper references heterogeneous user environments but the empirical scoring matrix is tied to a limited industrial press-lines. This could limit direct reproducibility in print environments utilizing entirely different automation infrastructure.

Future Research

To build upon the insights established in this integrated methodology, future investigations need to focus on the following vectors. It is imperative that future studies implement random probability sampling across a broader, multinational consortium of central bank issuers and commercial security printers to increase the generalisability of the QFD relationship values. Researchers need to track the long-term lifecycle performance of the proposed automation over a multi-year period to map exact costs against operational waste reduction. Given the growing transition from cotton-paper to polymer substrates globally, a comparative QFD-VE matrix can be built to analyse how the material properties of polymer affect the negative correlation loops identified between security features and the number of operations.

8. References

1. François Groepe: Improving the security and cost-effectiveness of banknotes. François Groepe, Deputy Governor of the South African Reserve Bank. s.l.: South African Bank Note Company (SABN), Cape Town, 2014. Association of African Banknotes and Security Documents Printers (AABSDP).
2. Maroević Frane. Printing with Purpose: Reducing the Carbon Footprint of Banknote Production. International Currency Association (ICA) [Online], April 14, 2025. [Cited: 25 May 2026.] https://currencyassociation.org/printing-with-purpose-reducing-the-carbon-footprint-of-banknote-production/
3. Giesecke+Devrient GmbH. Leaders in qualitative money printing: Innovative and trusted. Giesecke+Devrient GmbH [Online], 2026. https://www.gi-de.com/en/currency-technology/banknote-solutions/banknote-production/banknote-printing
4. Harald Deinhammer, Anna Ladi. Modelling Euro Banknote Quality in Circulation. European Central Bank. s.l.: European Central Bank, 2017, 2-4. Occasional Paper Series. ISSN 1725-6534 (pdf)

5. Spectra Systems Corporation. Spectra Launches Machine Readable Polymer Substrate. Currency News, August 2019, 17(8): 1-12.
6. Understanding Value Engineering: Techniques to Enhance Project Efficiency. Investopedia [Online], April 23, 2026. https://www.investopedia.com/terms/v/value-engineering.asp
7. Akao Y. Quality Function Deployment: Integrating Customer Requirements into Product Design. s.l.: Productivity Press, 1990.
8. Hauser JR, Clausing D. The House of Quality. Harvard Business Review. 1988; 66(3):63-73.