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Decision-Making Model for Reliable Electronic Component Manufacturing in a Blockchain Environment

Sung Yong An, Guy Ngayo, Seng-Phil Hong*

Abstract: This study focuses on improving the efficiency of 5G ceramic antenna manufacturing through the application of blockchain and smart contract technologies. Using the Analytic Hierarchy Process (AHP), the relative importance of three key factors was assessed: 'Security', defined as the protection against unauthorized access and data integrity; 'Standards & Regulations', which refers to compliance with industry norms and legislative requirements; and 'Efficiency', highlighting process optimization and resource management. The findings indicate that 'Efficiency' is the most critical factor, with a weight of 0.545, followed by 'Security' (0.318) and 'Standards & Regulations' (0.137). Furthermore, the sub-factor analysis identifies 'Unit Gain', related to productivity improvements, and 'Integrity', concerning data veracity, as significant, with global weights of 0.309 and 0.111, respectively. These insights emphasize the critical role of chip efficiency in the manufacturing process. The study proposes an AHP-based decision model for effectively integrating blockchain technology in the 5G sector, offering strategies for optimizing antenna manufacturing. This approach not only delineates critical process elements but also promotes the advancement of blockchain applications in 5G technology, potentially catalysing substantial technological innovation.

Keywords: Analytic Hierarchy Process (AHP); blockchain; decision-making; Consistency Rate; smart contract; 5G ceramic antenna

1 INTRODUCTION

In the era of the Fourth Industrial Revolution, blockchain and smart contracts have emerged as transformative technologies, playing a crucial role in enhancing the reliability and security of enterprise manufacturing and supply chain management. Their implementation is particularly effective in addressing the logistical and security challenges posed by global business operations. This is especially pertinent given the recent surge in information leakage incidents, underscoring the need for the transparency, data integrity, and security that blockchain technology affords. Smart contract technology, in particular, is receiving increasing attention for its role in mitigating these concerns [1-6]. Parallel to these developments, 5G communication technology stands at the forefront of this industrial revolution. The advent of 5G ceramic antennas, developed as an advancement over traditional PCB-based antennas [7], marks a significant leap in communication efficiency. Recent initiatives are exploring the integration of blockchain and smart contracts to bolster the security and efficiency of these 5G ceramic antennas [8].

The progression of 5G technology is catalyzing innovations across various sectors, paving the way for new services and products. In the realm of 5G ceramic antenna manufacturing, there is a growing recognition of the need for enhanced security, compliance with standards and regulations, and operational efficiency. Adherence to regulatory standards enhances the credibility of antenna manufacturers, aligning them with international benchmarks. Furthermore, operational efficiency, a cornerstone in antenna production, necessitates a focus on streamlined processes, optimal resource allocation, and cost minimization [9, 10].

This research is dedicated to improving both the efficiency and reliability of the 5G ceramic antenna manufacturing process through the strategic application of the Analytic Hierarchy Process (AHP). Given the complex nature of antenna production, which is susceptible to defects that can necessitate expensive corrective measures, our approach integrates blockchain technology for meticulous tracking and smart contracts for streamlined issue resolution. AHP will be used to systematically prioritize aspects such as security, standards and regulations, and efficiency—focusing on key areas that significantly impact cost-effectiveness and performance.

Despite the advances in blockchain and smart contract applications within the 5G technology space, there remains a notable gap in systematic decision-making frameworks that leverage these technologies for optimizing manufacturing processes. Previous studies have predominantly focused on the theoretical potentials of blockchain in enhancing security and operational transparency but have not sufficiently explored its integration into practical manufacturing workflows, particularly in the context of ceramic antennas for 5G networks. This study seeks to fill this gap by developing an AHP-based decision model that not only prioritizes critical manufacturing factors but also integrates blockchain technology to enhance the efficiency and reliability of 5G ceramic antenna production.

2 LITERATURE REVIEW

2.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), developed by Professor T. L. Saaty in the 1970s, revolutionized decision-making in complex scenarios [11-16]. Initially designed to address decision-making challenges in the U.S. State Department, particularly in arms control and disarmament, AHP has since broadened its application, significantly impacting public sector investment projects. Its core aim is to manage subjective decision-making elements like intuition, emotion, and perception, traditionally challenging to quantify [17, 18].

AHP operates on the principle of pairwise comparisons to evaluate relative importance, making it particularly effective in complex scenarios involving multiple criteria or diverse stakeholders [19, 20]. This methodology provides a structured approach to decision-making, enhancing the clarity and robustness of choices made in intricate situations.

In public administration and policy analysis, AHP has been instrumental in evaluating infrastructure projects, including dams, airports, subways, and road construction [21, 22]. Its systematic process involves organizing decision-making factors hierarchically into main and sub-factors and determining their importance through pairwise comparisons. This process, supported by ratio scales, allows decision-makers to calculate weights and prioritize factors effectively, thereby simplifying complex decision-making processes [23, 24].

AHP is particularly valuable in situations where mathematical quantification of problems is challenging, such as in research and development (R&D) projects. It leverages expert judgment to assign weights to factors that are difficult to quantify objectively, aiding in the formulation of diverse and sometimes conflicting evaluation criteria [25, 26]. The methodology is underpinned by three foundational principles: building a hierarchical structure, determining relative importance through subjective pairwise comparisons, and maintaining logical consistency. Hierarchies help break down complex problems into simpler components, making them easier to analyse and solve. Pairwise comparisons involve subjective judgments to assess the relative significance of each element in the hierarchy. Logical consistency is assured using a consistency index, ensuring reliable and consistent decision-making [27].

2.2 Blockchain and Smart Contracts

2.2.1 Blockchain Technology: The Theoretical Foundation

Blockchain technology, a cornerstone of modern digital transactions, gained prominence with the introduction of Bitcoin by Satoshi Nakamoto [28]. Characterized by enhanced security and transparency, blockchain overcomes the limitations of traditional centralized systems through its use of distributed ledgers and cryptographic techniques. The technology's core is a distributed database, relying on a shared ledger that ensures transaction records are simultaneously distributed and validated across the network, thereby heightening security and reliability [29, 30].

The primary unit of blockchain is the "block," which contains multiple transaction records linked to previous blocks via cryptographic hashes. Each new block incorporates data from its predecessor, forming a chain and ensuring data immutability. Altering recorded data would require changes across all subsequent blocks, a feature that solidifies blockchain's security. Its applications span various sectors, from finance, where it is used in payments and smart contract-based financial products, to supply chain management, healthcare, intellectual property, and even voting systems [31-33].

In manufacturing, blockchain's decentralized nature promotes trust across production stages, addressing concerns like product quality and cost-efficiency. Unlike centralized systems, blockchain's distributed architecture supports transparent, direct peer-to-peer transactions, with all network participants verifying transactions. This structure guarantees data immutability and resistance to tampering, further bolstered by distributed computing that allows nodes to concurrently store and verify transactions, enhancing data security [29, 34]. Blockchain's potential extends to car sharing, medical in-formation exchange, and other industries, promising innovation and development. Its secure platform positions it as a catalyst for cross-industry advancements.

Incorporating AHP in blockchain, organizations can systematically evaluate and prioritize projects. By setting criteria and sub-criteria, decision-makers can objectively compare projects, considering aspects like security, cost, and expected profitability. AHP's methodology quantifies the relative importance of each aspect, aiding in informed project selection [35-39].

2.2.2 Smart Contracts: Automating Trust in Blockchain

Smart contracts, conceptualized by N. Szabo in 1994 [40], are automated digital protocols designed for executing contract terms autonomously, functioning as digital versions of traditional contracts on a blockchain. Encoded as software on a blockchain's distributed ledger, smart contracts autonomously manage and execute transactions based on predefined rules, negating the need for centralized intermediaries. The primary ad-vantages of smart contracts include heightened reliability due to their automatic operation, robust security stemming from the immutability and transparency of blockchain, and in-creased efficiency through automated execution, which streamlines the negotiation pro-cess.

Khan et al. [41] discussed blockchain's role in the financial industry, highlighting how it addresses trust issues in centralized systems. Smart contracts, as executable codes on blockchains, are pivotal in facilitating and automating agreements, especially between parties lacking mutual trust. Applications of smart contracts extend beyond finance into domains like smart city development. Ullah et al. [42] explored their use in managing real estate transactions in smart cities, proposing a framework for integrating blockchain and smart contracts in this sector. This approach facilitates more interactive and user-friendly contracting processes, potentially transforming traditional real estate into a model aligned with Industry 4.0 standards [3].

2.3 The theoretical Background of 5G Communication and Ceramic Antennas

2.3.1 5G Communication Technology: Unleashing the Next Era

5G, the fifth generation of mobile communication technology, marks a significant leap forward from its predecessors, 3G and 4G. It is characterized by substantially higher data speeds, reduced latency, and the ability to connect a vast array of devices simultaneously. These enhancements position 5G as a key driver of technological progress, particularly in areas requiring large-scale data transfer and Internet of Things (IoT) services.

A standout feature of 5G is its data transmission speed, reaching up to 20 Gbps. This speed is more than 20 times faster than 4G's 1 Gbps and significantly surpasses 3G's 384

Kbps. Such rapid data handling capabilities enable smooth streaming of high-definition and 4K videos, and support real-time applications like gaming, virtual reality (VR), and augmented reality (AR) with minimal latency [43, 44]. Another critical aspect of 5G is its ultra-low latency, which can be reduced to less than 1 millisecond. This improvement is crucial for applications requiring high precision and stability, such as autonomous vehicles and industrial robotics. Furthermore, 5G's extensive connectivity allows for the simultaneous connection of thousands of devices, making it integral to the development of smart cities and the broader IoT ecosystem. As 5G continues to roll out globally, it is set to transform a wide range of industries, heralding a new era of techno-logical innovation and connectivity [45, 46].

2.3.2 Evolution of 5G Antenna Technology: Key Challenges and Innovations

The progression of 5G communications is intrinsically linked to the advancements in 5G antenna technology. These antennas are pivotal for efficiently transmitting and receiving wireless signals, necessitating support for broader bandwidths and faster data rates. Unlike traditional antennas with fixed directional capabilities, 5G antennas require enhanced flexibility to manage signals from various directions. Current research efforts are geared towards developing antennas with improved tuning abilities to ensure precise signal directionality and strength.

A significant challenge in this arena is the need for 5G antennas to be compact and lightweight. Traditionally, high-performance antennas tended to be larger, but the emerging trend is to employ multiple smaller antennas to handle data transmission and reception in different directions. This shift has spurred technical research focused on creating more compact antenna designs. The physical length (L) of a 5G antenna, for instance, is determined by the eq. (1), which incorporates factors like effective wavelength (λ_{eff}) as shown in eq. (2) [7].

$$L = \frac{\lambda_{\text{eff}}}{2} \tag{1}$$

Where, λ_{eff} can be expressed as eq. (2) [47, 48].

$$\lambda_{\text{eff}} = \frac{\lambda_0}{\sqrt{\mu_r \cdot \varepsilon_r}} \tag{2}$$

Where, λ_0 is the wavelength in a vacuum, μ_r is the relative permeability, and ε_r is the relative permittivity. By utilizing ceramic materials with a higher dielectric constant, such as 9.45 compared to the 3.47 in current PCB antennas, the size of the antenna can be effectively reduced [7].

Fig. 1 illustrates a 5G ceramic antenna array, comprising low-band (24.25 GHz to 29.5 GHz) and high-band (37 GHz to 40 GHz) unit chips suitable for specific frequency ranges. This configuration is integral to the development of a comprehensive 5G antenna system. Research is underway to reduce power consumption through innovative antenna designs, contributing to the sustainable advancement of 5G communication technologies.

Figure 1 A 5G ceramic chip antenna array, displaying a module that combines a high-band unit and a low-band unit ceramic chip antenna, arranged in a 1 x 5 configuration.

3 RESEARCH METHODOLOGY

3.1 Research Design Description

This study's research design encompasses delineated in Fig. 2 presents the AHP research framework employed in our investigation. The study focuses on three fundamental factors: Security, Standard & Regulation, and Efficiency. The intent was to evaluate how these factors influence the stabilization and cost-effectiveness of the manufacturing processes for 5G ceramic antennas, particularly with the integration of blockchain technology and smart contracts. The selection of these pivotal factors and their respective sub-components stems from an extensive review of efficient manufacturing practices for 5G ceramic antennas, as detailed in our previous work [8]. We conducted a thorough pairwise comparison to ascertain the relative importance of each primary and secondary factor, thus quantifying their impact within the AHP model. This methodological approach enabled a structured analysis of how each element contributes to the overall manufacturing goals.

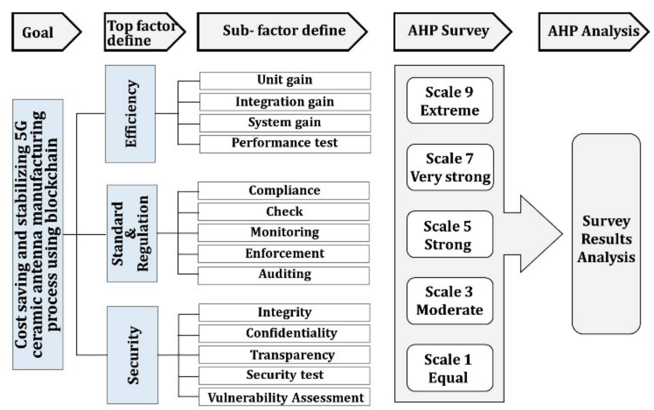

Figure 2 AHP research framework for evaluating key factors in 5G ceramic antenna manufacturing.

3.2 AHP analysis

AHP methodology was employed to facilitate decision-making in evaluating security, standard & law regulation, and efficiency in the blockchain-based 5G ceramic antenna manufacturing process. Data were gathered using a standardized questionnaire based on Saaty's 9-point scale [13], detailed in Tab. 1. This scale ranges from 1, representing equal importance between two factors, to 9, indicating a strong preference for one factor over another.

Table 1 The scoring system and meanings for Saaty's 9-point scale [13] used in the AHP analysis.

Scale	Definition	Explanation
9	Extreme	The evidence favouring one activity over another is of the highest possible order of affirmation
7	Very strong	An activity is favoured very strongly over another; its dominance demonstrated in practice
5	Strong	Experience and judgement strongly favour one activity over another
3	Moderate	Experience and judgement slightly favour one activity over another
1	Equal	Two activities contribute equally to the objective

The collected data underwent AHP analysis, leading to the development of a pair-wise comparison matrix (Eq. (3)). This approach is advantageous as it simplifies the evaluation process by allowing for direct comparisons between two factors at a time, which is generally more manageable for evaluators than multiple simultaneous comparisons.

Consistency in responses is crucial for the validity of AHP analysis. The significance of each response is determined by combining the results of individual evaluators, focusing on those with consistency ratio values (derived from the pairwise comparison matrix and geometric mean calculations) of less than 0.1. Responses with consistency ratios above this threshold are excluded to ensure the reliability of the analysis.

The pairwise comparison matrix $\boldsymbol{A}$, generated through the AHP process, reflects the relative importance of 'n' elements compared within each layer. For elements (A_1, A_2, ..., A_n), the result of pairwise comparisons between A_i and A_j is denoted as a_{ij}, forming the matrix $\boldsymbol{A} = (a_{ij})$. If the importance of each element is w_i (i = 1, 2, …, n), the matrix $\boldsymbol{A} = (a_{ij})$ is used to calculate these weights, ensuring the accuracy and relevance of the derived values.

$$\boldsymbol{A} = (a_{ij}) = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \cdots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \quad (3)$$

In the AHP framework, each element's relative importance is represented as a ratio. For instance, w_1/w_1 compares A_1 with itself, naturally yielding a value of 1. Similarly, w_1/w_2 represents the relative importance of A_1 compared to A_2, and w_1/w_n for A_1 compared to A_n. Multiplying eq. (3) by the column vector $w = [w_1, w_2, \ldots, w_n]$, which represents the approximate values of relative importance between evaluation items, results in eq. (4).

$$\begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \cdots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ nw_2 \\ \vdots \\ nw_n \end{bmatrix} \quad (4)$$

Using the eigenvalue calculation method, it can be expressed as follows.

$$\boldsymbol{A} \cdot w = \lambda_{\max} \cdot w \quad (5)$$

The maximum eigenvalue of the pairwise comparison matrix $\boldsymbol{A}$, denoted as $\lambda_{\max}$, is critical for determining the weights. It is found by solving the characteristic equation, which provides a non-zero solution in a system of n simultaneous equations, thereby determining the $\lambda_{\max}$ value that satisfies Eq. (6).

$$\left|\boldsymbol{A} - \lambda I\right| = 0 \quad (6)$$

The $\lambda_{\max}$ value is always greater than or equal to the number of elements, n. The closer the $\lambda_{\max}$ value is to n, the more consistent the pairwise comparison matrix A is considered. The consistency of these comparisons is quantified using the Consistency Index (CI) and the Consistency Ratio (CR), calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{(n-1)} \quad (7)$$

$$CR = \frac{CI}{RI} \quad (8)$$

Where, n denotes the dimension of the matrix, and RI represents the Saaty Random Index [14], which varies with the matrix dimension. The RI is an average consistency index obtained from randomly generated reciprocal matrices, serving as a benchmark for acceptable consistency levels. The RI values are listed in Tab. 2. A CR of 0.1 or less indicates acceptable consistency in the survey responses, validating the reliability of the AHP analysis. For each survey item, the weights (w) were determined using the eigenvalue method, and then the overall weights were calculated using the geometric mean method. The values of the CI, CR, and the $\lambda_{\max}$ were determined by taking the arithmetic mean of the values obtained from each survey item to calculate the overall values.

Table 2 The Saaty Random Index (RI) values [14], which are used in the AHP to evaluate the consistency of pairwise comparisons.

n	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.3 Research Process and Data Collection

For this study, an AHP questionnaire was developed based on the established model. The data collection phase spanned six weeks, from November 6 to December 15, 2023, targeting experts in the fields of blockchain and 5G ceramic antennas. The survey was disseminated through online platforms, email, and in-person visits, accompanied by comprehensive guidelines explaining the survey's objectives and key factors. Regarding the mix of in-person and email data collection, this approach was chosen to enhance the accessibility and response rate from experts in diverse locations, ensuring a comprehensive representation of opinions. Our sampling method was purposeful, targeting individuals with specific qualifications (minimum master's degree and 10 years of experience) to gather informed perspectives into blockchain and 5G antenna technology. The survey questionnaire is detailed in the Appendix. From the 42 questionnaires collected, 30 were deemed suitable for analysis after excluding 8 due to non-response and 4 due to inconsistency, as determined by their consistency ratios. A threshold consistency ratio of 0.1 was applied to ensure the reliability of the responses.

Tab. 3 presents the demographics of the respondents. The majority (76.7 %) were male, with the largest age group being those in their 50s (53.3 %), followed by respondents in their 40s (33.3 %), and those in their 30s (13.3 %). Regarding professional experience, 64.5 % of the experts had at least 10 years in their field, 25.8 % had 15 years, and 9.7 % had over 20 years of experience. This distribution reflects the relatively recent development of blockchain and 5G technologies, resulting in a higher concentration of experts with 10 to 15 years of experience. The respondent pool comprised an equal split of 15 experts in blockchain and 15 in 5G antennas, maintaining a balanced representation of both fields.

Table 3 Demographic data of the respondents involved in the study. It includes information such as the distribution of gender, age groups, and professional experience.

Section	Characters	Frequency	Ratio
Gender	Male	23	76.7
	Female	7	23.3
	Total	30	100
Age	30s	4	13.3
	40s	10	33.3
	50s	16	53.4
	Total	30	100
Work experience in the related field	10-15years	20	64.5
	15-20years	8	25.8
	Over 20years	3	9.7
	Total	30	100
Professional area	Blockchain	15	50.0
	5G antenna	15	50.0
	Total	30	100

4 RESULTS AND DISCUSSION

Using AHP, we integrated blockchain and smart contracts to identify the relative importance of key factors affecting the 5G ceramic antenna manufacturing process, including 'security', 'standards and regulations', and 'efficiency' based on previous research [8]. It was decided as the top factor. The results of this comprehensive analysis are showcased in Tab. 4 and depicted in the visual format as Fig. 4. Among the trio of critical factors identified— 'Security', 'Standard & Regulation', and 'Efficiency'— 'Efficiency' emerged as the most significant, with a relative weight of 0.545. This dominant weight of 'Efficiency' underscores the potential for substantial cost savings and heightened production effective-ness in the manufacturing of 5G ceramic antennas.

Following 'Efficiency' in terms of importance, 'Security' received a considerable weight of 0.318, illustrating its vital role in the overall manufacturing framework. Despite being less influential than 'Efficiency' and 'Security', 'Standard & Regulation' held its ground with a weight of 0.137, indicating its necessary, albeit less prioritized, role in the production process. The pie chart in Fig. 4 provides a clear and concise visual representation of these weights, effectively communicating the hierarchy of factors in the decision-making process. The chart shows 'Efficiency' as the largest segment, colored in grey, denoting its predominant impact. The blue segment, representing 'Security', occupies a significant portion but is noticeably smaller than 'Efficiency'. The smallest slice, in orange, corresponds to 'Standard & Regulation', suggesting it has the least weight among the top factors. The precision of our AHP analysis is further supported by the calculated λ_{max} value of 3.035, with a *CI* of 0.017 and a *CR* of 0.033, against a *RI* of 0.58 for *n* equals 3. The *CR* value, being lower than 0.1, indicates that the expert opinions gathered for the study are consistent [49].

The strategic application of AHP, as evidenced by the detailed results in Tab. 4 and the illustrative Fig. 3, offers valuable perspectives into prioritizing efforts within the manufacturing sector. It highlights 'Efficiency' as a crucial lever in optimizing the production of 5G ceramic antennas, indicating that investments and improvements in this area are likely to yield the most significant returns in terms of cost-effectiveness and production capacity. This data-driven approach, enhanced by blockchain and smart contract technologies, paves the way for informed decision-making and strategic planning in the rapidly evolving telecommunications industry.

Table 4 The AHP results for the primary dimensions or top-level factors in the context of 5G ceramic antenna manufacturing. It ranks and assigns weights to each top-level factor, such as 'Security', 'Standard & Regulation', and 'Efficiency', demonstrating their relative importance.

Top factor	Rank	Weight
Security	2	0.318
Standard & Regulation	3	0.137
Efficiency	1	0.545
Sum		1.000
CI		0.017
CR		0.033
λ_{max}		3.035

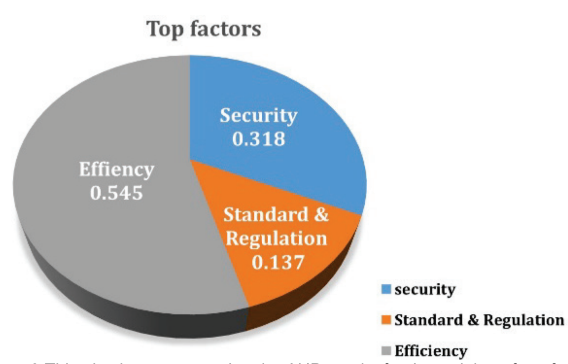

Figure 3 This pie chart representing the AHP results for the weights of top factors in the evaluation of 5G antenna manufacturing processes: 'Security', 'Standard & Regulation', and 'Efficiency'.

The AHP was employed to determine the weights of various sub-factors under the primary factor of 'Security', as detailed in Tab. 5. This process involved a comprehensive evaluation of the relative importance of these sub-factors. Notably, within the hierarchy of ‘Security’-related sub-factors, ‘Integrity,’ with a weight of 0.349, surfaced as the most crucial element. This high weighting underscores its significant role in the overall security framework for 5G antenna manufacturing. In contrast, ‘Security Test’ was assigned a comparatively lower weight of 0.126. This indicates that, while still important, it holds less significance relative to other sub-factors in the context of ‘Security’. Such differentiation in the weights illustrates the varying levels of importance assigned to each sub-factor and their impact on the overall security of the manufacturing process.

Further validating the reliability and consistency of this AHP analysis are the calculated metrics: the λ_{max} value stood at 5.194, the *CI* was 0.049, and the *CR* was 0.044. These figures are significant because the *CR* is below the 0.1 threshold, implying a high degree of consensus among the expert opinions surveyed. Additionally, the *RI* value for a matrix of dimension 5 (n = 5) was 1.12 [14], further supporting the consistency and reliability of the findings. This thorough AHP approach not only quantifies the importance of various security aspects but also ensures the methodological robustness of the analysis.

Table 5 The AHP calculated weights for sub-factors under the top-level factor of ‘Security’ in the context of 5G ceramic antenna manufacturing. It ranks each sub-factor and assigns a weight to it, which cumulatively sum to 1.000. Additionally, it includes the λ_{max} value, *CI*, and *CR* to demonstrate the level of agreement among the surveyed experts' opinions, indicating a high level of consistency with a *CR* below 0.1.

Sub-factor	Rank	Weight
Integrity	1	0.349
Confidentiality	2	0.216
Transparency	4	0.143
Security test	5	0.126
Vulnerability assessment	3	0.167
Sum		1.000
CI		0.049
CR		0.044
λ_{max}		5.194

In conducting our study, we applied the AHP to meticulously evaluate the relative importance of various sub-factors falling under the overarching category of ‘Standard & Regulation’ within the context of 5G antenna manufacturing, as comprehensively delineated in Tab. 6. Our analysis brought to the forefront the sub-factor ‘Compliance,’ which conspicuously stood out as the most pivotal, evidenced by its highest weight value of 0.456. This prominence underscores ‘Compliance’s integral role in maintaining stringent standards and regulations in the manufacturing process. Further in the hierarchy of importance, ‘Auditing’ was assigned a notable weight of 0.174, reflecting its substantial role in ensuring adherence to established protocols and regulations. Closely following were the sub-factors ‘Check’ and ‘Enforcement,’ each with respective weights of 0.138 and 0.128. The nearly identical weights of these two sub-factors signify their parallel significance in the regulatory framework, highlighting the need for effective implementation and continuous oversight of standards and practices.

In contrast, the sub-factor ’Monitoring’ was ascribed the lowest weight at 0.104. This lower weighting indicates its comparatively reduced priority in the spectrum of ‘Standard & Regulation’ sub-factors, albeit its relevance remains non-negligible in the overall regulatory landscape of antenna manufacturing. Crucially, the robustness of our AHP analysis is evidenced by the calculated λ_{max} value of 5.202, alongside a *CI* of 0.068 and a *CR* of 0.046. The *RI* value, calculated for an n of 5, stood at 1.12 [14]. The *CR*’s positioning well below the 0.1 benchmark is indicative of a high level of agreement among the expert responses, affirming the methodological soundness and reliability of our analysis. This meticulous assessment and quantification of the sub-factors under ‘Standard & Regulation’ provide a nuanced understanding of their hierarchical importance. It serves as a guiding framework for decision-makers in the 5G antenna manufacturing industry, enabling them to strategically prioritize and allocate resources to areas that are critical for maintaining high standards and regulatory compliance.

Table 6 The weights and ranks for the sub-factors within the top-level factor of ‘Standard & Regulation’ as determined by the AHP.

Sub-factor	Rank	Weight
Compliance	1	0.456
Check	3	0.138
Monitoring	5	0.104
Enforcement	4	0.128
Auditing	2	0.174
Sum		1.000
CI		0.068
CR		0.046
λ_{max}		5.202

In our detailed assessment encapsulated in Tab. 7, we meticulously computed the weights by evaluating the relative significance of various sub-factors associated with the top factor, ‘Efficiency’, in the realm of 5G ceramic antenna manufacturing. This evaluation led to revealing perspectives about the hierarchy of these sub-factors in terms of their influence on manufacturing efficiency. The sub-factor ‘Unit Gain’ distinctly stood out as the most influential, with a dominant weight of 0.568. This finding underscores the criticality of achieving high efficiency in the unit chip of 5G ceramic antennas, as ‘Unit Gain’ is a direct measure of an antenna's efficiency in its operational environment. The substantial weight of this sub-factor illuminates its pivotal role in the overall efficiency of the antenna manufacturing process.

Following ‘Unit Gain’ in terms of importance were ‘Integration Gain and Performance Test,’ with respective weights of 0.177 and 0.133. These sub-factors highlight the significance of integrating various system components effectively and the necessity of rigorous performance testing to ensure optimal antenna functionality. ‘System Gain,’ with a weight of 0.123, though ranked lower, still plays an integral role in the efficiency equation, reflecting the benefits accrued from system-level enhancements in the antenna design and manufacturing process.

The analytical robustness of this assessment is further corroborated by key AHP metrics: the λ_{max} value was determined to be 4.144, the *CI* stood at 0.048, and the *CR* was calculated as 0.054. The *RI* for a matrix size of $n = 4$ was 0.9 [14], as noted in Tab. 2. Importantly, with the *CR* being well below the 0.1 threshold, the survey's findings are validated as consistent, reinforcing the reliability of our AHP analysis. In essence, this comprehensive evaluation, as reflected in Tab. 7, not only delineates the relative weights of the Efficiency sub-factors but also provides a clear and consistent framework for prioritizing enhancements in the manufacturing process of 5G ceramic antennas, with a particular emphasis on unit chip efficiency.

Table 7 The AHP calculated weights for sub-factors within the top-level factor of 'Efficiency' in the con-text of 5G ceramic antenna manufacturing.

Sub-factor	Rank	Weight
Unit gain	1	0.568
Integration gain	2	0.177
System gain	4	0.123
Performance test	3	0.133
Sum		1.000
CI		0.048
CR		0.054
λ_{max}		4.144

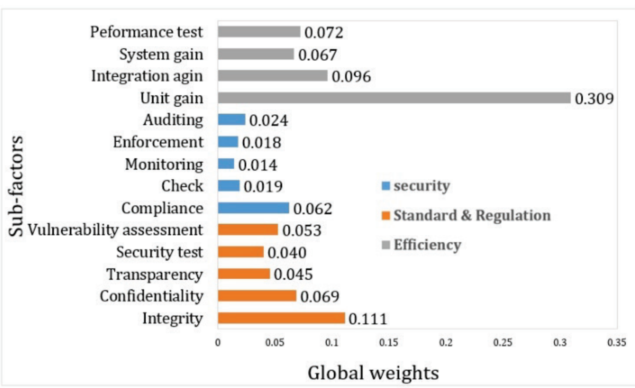

Figure 4 The global weights for various sub-factors as determined by the AHP in the context of 5G ceramic antenna manufacturing. These sub-factors are likely categorized under the main factors of 'Security', 'Standard & Regulation', and 'Efficiency'. The figure provides a visual representation of the relative importance or global weight of each sub-factor, highlighting how they contribute to the overall efficiency and effectiveness of the manufacturing process. This includes a focus on key aspects such as unit gain, integration gain, system gain, and performance test, thereby offering understanding into the areas that are most impactful for optimizing the manufacturing process.

Fig. 4 presents a comprehensive bar chart resulting from the AHP used to deter-mine the global weights of various sub-factors in the manufacturing process of 5G ceramic antennas, focusing on three main categories: 'Security', 'Standard & Regulation', and 'Efficiency'. According to the AHP results depicted in Fig. 4, 'Unit gain' emerges as the most influential sub-factor across all evaluated domains, holding the highest global weight value of 0.309, as detailed in Tab. 8. This sub-factor's prominence underscores its pivotal role in driving cost efficiencies within the antenna manufacturing industry. 'Integrity' follows in significance with a global weight of 0.111, occupying a central position in maintaining robust security protocols. Following in importance are 'Integration gain' and 'Performance test, with global weights of 0.0.096 and 0.0.072 respectively, ranking third and fourth. These factors underscore the pivotal role of effective integration and thorough performance testing in enhancing the efficiency of 5G ceramic antenna production.

Moreover, three sub-factors tied in the fifth rank, all falling under the 'Efficiency' category, reflect the highest weight observed in the top factor, 'Unit gain.' This conveys the significant impact that efficiency improvements in the unit chip of 5G ceramic antennas have on the cost-effectiveness and overall performance of the manufacturing process. These results are instrumental in highlighting the areas where strategic investments and improvements could optimize 5G antenna production, particularly emphasizing the substantial gains in cost reduction that can be achieved by enhancing efficiency in specific areas such as unit chip production, integration processes, and performance testing. The chart serves as a decision-making guide, illustrating the comparative importance of each sub-factor and their collective impact on advancing the manufacturing of 5G antennas.

Table 8 The AHP results, showing the weights of top factors and their associated sub-factors, along with the global weights and global ranks determined from the AHP analysis.

Top factor	Weight	Sub-factor	Local weight	Global weight	Global rank
Security	0.318	Integrity	0.349	0.111	2
		Confidentiality	0.216	0.069	5
		Transparency	0.143	0.045	9
		Security test	0.126	0.040	10
		Vulnerability assessment	0.167	0.053	8
Standard & Regulation	0.137	Compliance	0.456	0.062	7
		Check	0.138	0.019	12
		Monitoring	0.104	0.014	14
		Enforcement	0.128	0.018	13
		Auditing	0.174	0.024	11
Efficiency	0.545	Unit gain	0.568	0.309	1
		Integration gain	0.177	0.096	3
		System gain	0.123	0.067	6
		Performance test	0.133	0.072	4

5 CONCLUSIONS

This study focused on enhancing the efficiency of 5G ceramic antenna manufacturing through the integration of smart contracts and blockchain technology. Employing the AHP, we systematically prioritized key factors— 'Security', 'Standard & Regulation', and 'Efficiency'—in the manufacturing process. Our findings reveal that 'Efficiency is the most crucial factor, with a weight of 0.545, followed by 'Security' (0.318) and 'Standard & Regulation' (0.137). This underscores the importance of focusing on antenna efficiency to drive cost savings in the manufacturing process.

The AHP model identified 'Unit gain' as having the highest global weight, highlighting its critical role in the efficiency of 5G ceramic antenna manufacturing. Additionally, the use of blockchain and smart contracts was found to offer significant benefits in terms of trust enhancement, data integrity, and automation of contractual conditions. The detailed AHP analysis provided a quantitative understanding of the impact of 'Security', 'Standard & Regulation', and 'Efficiency' on manufacturing costs. The in-depth evaluation of sub-factors within these top categories further refined our understanding of the priorities within each domain.

The consistency of the expert opinions, as evidenced by the λ_{max} values, *CI*, and *CR*, validates the reliability of the AHP methodology used in this study. These findings offer strategic implications for the application of blockchain technology in 5G antenna manufacturing, potentially fostering innovation and development within this sector.

Despite its contributions, this study is not without limitations. The specificity of the research context may limit the generalizability of the findings to different times or manufacturing environments. Variations in expert opinions in the AHP analysis could affect the consistency of the results across diverse expert groups. The AHP model's assumptions may not perfectly align with real-world scenarios, particularly concerning weight estimation and consistency evaluations. Additionally, the practical application of blockchain and smart contract technology may face technical challenges that impact the stability and reliability of these solutions. A drawback of AHP is the absence of an independent accuracy evaluation, meaning the results could be flawed due to the subjective assessments of the user.

External factors such as legal changes and technological advancements could also influence the outcomes, and controlling these variables is challenging. Recognizing these limitations is crucial for expanding the study's scope in future research. Future research will aim for a more nuanced understanding of the technical feasibility of implementing blockchain and smart contracts. We plan to explore solutions to realistic challenges and consider a wider range of technical aspects in 5G ceramic antenna manufacturing and blockchain integration. To validate the effectiveness of our model, empirical field research will be conducted to assess its practical applicability and efficacy.

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Authors' contacts:

Sung Yong An, PhD
Seoul Business School, aSSIST University,
46 Ewhayeodae 2-gil, Fintower, Sinchon-ro, Seodaemun-gu, Seoul, 03767, Korea
sung.an@stud.assist.ac.kr

Guy Ngayo, Prof.
School of Management Fribourg,
The University of Applied Sciences and Arts Western Switzerland,
1700 Fribourg, Switzerland
guyngayo@hotmail.com

Seng-Phil Hong, Prof.
(Corresponding author)
School of Computing and AI, HanShin University,
137 Hanshindae-gil, Osan-si, Gyenggi-Do, 18101, Korea
sphong@hs.ac.kr