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Applying Blockchain, Causal Loop Diagrams, and the Analytical Hierarchy Process to Enhance Fifth-Generation Ceramic Antenna Manufacturing: A Technology–Organization–Environment Framework Approach

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Abstract: This study used a technology–organization–environment (TOE) framework as the primary analytical tool to explore the burgeoning capabilities of blockchain technology in the area of 5G ceramic antenna development. A causal loop diagram (CLD) analysis is used to further clarify the complex dynamics and feedback mechanisms, and the impact of blockchain on the design, production, and deployment phases of ceramic antennas, which play a pivotal role in the development of 5G communications, is studied. We found that blockchain's unique features, including its immutable ledger and decentralized architecture, have the potential to significantly improve the transparency, security, and efficiency of the ceramic antenna manufacturing process. Technology (T), organization (O), and environment (E) were used as the top factors, and the subfactors of TOE were selected and analyzed using the Analytic Hierarchy Process (AHP) by CLD. The AHP analysis was used to evaluate the relative importance of various internal and external factors affecting the adoption of blockchain technology. The integration of the TOE framework with AHP and CLD provides a comprehensive analytical tool that enhances the understanding of the complex dynamics in the 5G ceramic antenna manufacturing process. This methodological approach not only clarifies the interactions between technological, organizational, and environmental factors but also facilitates strategic decision-making through a structured evaluation of these factors. The AHP analysis showed that technical factors are the most important in the TOE analysis of 5G ceramic antenna manufacturing, with a weight of 0.427, which indicates the important role of technical factors in the development of ceramic antenna production. In addition, environmental and organizational factors were given weights of 0.302 and 0.271, respectively, confirming the importance of technological innovation and internal process optimization. In the subfactor of Technology (T), 'Blockchain Technology' has the highest ranking among the subfactors, with a global weight value of 0.129, emphasizing the importance of blockchain technology. This study explored the technical and organizational complexities of introducing blockchain technology into the 5G ceramic antenna manufacturing industry and, through an in-depth investigation of the potential benefits of such integration, it aims to propose new approaches to improve quality control and manufacturing efficiency. The research findings aim to contribute to the sustainable growth of the telecommunications industry by providing strategic recommendations for the application of blockchain technology in the production of 5G ceramic antennas.

Keywords: blockchain; smart contract; 5G antenna; analytic hierarchy process (AHP); causal loop diagram (CLD); technology–organization–environment (TOE)

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1. Introduction

1.1. Research Background

The rapid development of 5G technology necessitates significant advancements in the manufacturing processes of critical components such as ceramic antennas. Along with these technological advances, there is an imperative need to develop 5G antennas, especially high-performance ceramic antennas that can manage smaller sizes while meeting the demanding specifications of the new networks. These antennas are not just a component, but a fundamental building block of the 5G infrastructure, playing an essential role in achieving the high speeds and reliability required for next-generation networks. The growing importance of antenna performance as we enter the 5G era calls for revolutionary advancements in antenna manufacturing. This study aims to fill this gap by exploring how blockchain's immutable ledger and decentralized architecture can enhance the transparency, security, and efficiency of the manufacturing process [1–3].

The evolution of 5G ceramic antennas has been characterized by breakthroughs in materials science and engineering. The use of ceramics, known for their dielectric properties, enables the production of antennas that are not only smaller but also more efficient than their predecessors. This is critical in an environment where data demand is skyrocketing and space on devices is becoming scarce [4,5]. In addition, the sophisticated design of these antennas and their ability to operate in multiple bands embodies a complex interplay between form and function. The transition from the laboratory to the real world is a tremendous challenge, as they must not only fit into increasingly smaller and more complex devices, but also perform with unparalleled efficiency [6,7]. This transition is fraught with obstacles that are more challenging than ever before. The precision required to manufacture these antennas cannot be overstated: a difference of one millimeter can mean the difference between optimal performance and poor network performance. This precision requires not only advanced manufacturing techniques, but also an environment that minimizes the potential for error [4,8]. In addition, the quality control measures required to ensure each antenna meets the stringent standards of 5G require thoroughness and attention to detail. Each step from design to deployment must be executed flawlessly to maintain the integrity of the 5G network [9].

Moreover, securing the supply chain for these critical components is paramount. In a globalized economy, the supply chain for 5G antennas spans multiple continents and can be vulnerable to a myriad of risks, from geopolitical tensions to natural disasters. Ensuring the resilience of these supply chains is not just about protecting a set of components, it is about protecting the future of connectivity itself, which emphasizes the need for innovative logistics solutions and strategic partnerships to build robust supply chains that can respond to the demands of a rapidly evolving technology landscape [10].

Overcoming these challenges and moving forward is fraught with obstacles and opportunities. Paving the way for the successful deployment of 5G ceramic antennas will require a concerted effort by industry leaders, policymakers, and researchers. This effort is not just about overcoming technical hurdles, but about unlocking the full potential of 5G to create a future that transforms our society and economy [11]. The stakes are high, but the rewards—a world of unprecedented connectivity and opportunity—are undoubtedly worth it. In this environment, blockchain technology is emerging as a disruptor, providing a new framework to revolutionize the antenna manufacturing paradigm. With its immutable ledger, decentralized architecture, and superior security features, blockchain's resurgence offers a disruptive approach to overcome the numerous obstacles surrounding the ceramic antenna space. By leveraging the blockchain, stakeholders within the 5G ecosystem can significantly improve the integrity, transparency, and efficiency of the antenna manufacturing process, increasing product quality and reliability while ensuring a more secure supply chain [12].

Our prior research [4], proposed an innovative architecture to mitigate the complexities inherent in the 5G ceramic antenna manufacturing process. This architecture aimed to bolster transparency, security, and efficiency via a blockchain-based framework and smart contracts. Further expanding on this theme, our recent paper [7] delved into integrating blockchain and smart contract technologies, underpinned by a thorough Analytic Hierarchy Process (AHP) analysis. The advent of blockchain technology and the development of 5G ceramic antennas are poised to revolutionize not only telecommunications but also the landscape of electronic commerce. By enhancing the security, reliability, and speed of online transactions, these technological advancements promise to address current e-commerce challenges, offering a seamless, secure shopping experience.

This study extends the application of the technology–organization–environment (TOE) framework [13–15] in the domain of ceramic antenna development and deployment to examine the innovative adoption of blockchain technology in this context. We meticulously analyze the various factors that influence the design and manufacturing process of ceramic antennas to optimize their performance and cost-effectiveness. Focusing on the intersection of blockchain technology and the manufacturing process of ceramic antennas, the study emphasizes enhancing security and efficiency through increased transparency. After examining each dimension of the TOE model, we used causal loop diagrams (CLDs) [16,17] to visualize the dynamic interactions between technological, organizational, and environmental factors and their cumulative impact on the system. To determine the relative importance of these factors, we also utilized an analytic hierarchy process (AHP) analysis to enable a quantitative assessment of strategic priorities. Through this investigation, we aim to uncover the potentially transformative impact of the integration of blockchain technology and 5G ceramic antennas on the telecommunications industry and, in doing so, to explore directions for sustainable evolution. The results of this study will provide new insights to experts and practitioners in the field, laying the foundation for future research directions and practical applications.

1.2. Literature Gap and Research Questions

Despite the recognized benefits of blockchain in various industries, its application in 5G ceramic antenna manufacturing remains underexplored. This study addresses this gap by investigating the potential improvements in transparency, security, and efficiency when integrating blockchain technology into this manufacturing process. The key research questions are as follows:

Q1. How does blockchain technology enhance the transparency of the 5G ceramic antenna manufacturing process?

Q2. What are the security benefits of adopting blockchain technology in this context?

Q3. How does blockchain integration impact the overall efficiency of ceramic antenna production?

1.3. Hypotheses

To guide our research, we have formulated the following hypotheses:

H1: *Blockchain technology significantly improves the transparency of the 5G ceramic antenna manufacturing process.*

H2: *The adoption of blockchain technology enhances the security of the manufacturing process.*

H3: *Integrating blockchain technology increases the overall efficiency of the ceramic antenna production.*

H4: *Technological factors (T) are more critical than organizational (O) and environmental (E) factors in the adoption of blockchain technology for 5G ceramic antenna manufacturing.*

H5: *Among the technological factors, blockchain technology is the most influential subfactor in enhancing the manufacturing process.*

These hypotheses provide a clear framework for our study, aligning the methodology and results sections with the overall goals of the research.

1.4. Novelty and Contributions

This study is novel in its comprehensive integration of the technology–organization–environment (TOE) framework with Causal Loop Diagram (CLD) analysis and the Analytic Hierarchy Process (AHP) to examine the impact of blockchain technology on 5G ceramic antenna manufacturing. Unlike previous studies that have examined 5G and blockchain independently, our research uniquely combines these technologies to explore their synergistic effects on manufacturing processes. Specifically, this study:

(1) Demonstrates how blockchain technology can be leveraged to enhance transparency, security, and efficiency in 5G ceramic antenna manufacturing.
(2) Provides a detailed analysis of the relative importance of technological, organizational, and environmental factors in this integration.
(3) Offers strategic recommendations for stakeholders in the telecommunications industry based on empirical data and rigorous analytical methods.

2. Theoretical Background and Literature Review

2.1. Blockchain and Smart Contracts

Blockchain technology, initially popularized by Bitcoin, offers enhanced security and transparency compared to traditional centralized systems. It utilizes a distributed ledger and cryptographic techniques, with a distributed database at its core. Each 'block' in the blockchain contains transaction records linked via cryptographic hashes, forming an immutable chain. This security aspect is crucial, as altering any recorded data requires changes across all subsequent blocks [18–20]. Blockchain's applications are diverse, including finance, supply chain management, healthcare, and more. In manufacturing, it fosters trust and efficiency, supporting transparent peer-to-peer transactions and ensuring data immutability and security. Its decentralized nature has extended to industries like car-sharing and medical information exchanges, showcasing its potential as a cross-industry catalyst [21–26].

Smart contracts, introduced by N. Szabo [27] in 1994, are self-executing digital protocols on a blockchain. They autonomously manage transactions based on predefined rules, eliminating the need for central intermediaries. Smart contracts enhance reliability, security, and efficiency, particularly in automating and streamlining negotiation processes. In sectors like finance, blockchain and smart contracts address trust issues, facilitating automated agreements in environments lacking mutual trust. Their applications in areas such as smart city development and real estate transactions illustrate their transformative potential [28–34].

2.2. The Theoretical Framework of 5G Communications and Ceramic Antennas

2.2.1. 5G Communication Technology: Catalyzing a New Epoch

Fifth-generation technology is at the forefront of mobile communications evolution, representing a monumental leap beyond its predecessors, 3G and 4G. Distinguished by dramatically elevated data transmission speeds, diminished latency, and an enhanced capacity for simultaneous device connectivity, 5G emerges as a pivotal force in propelling technological advancement. It finds particular resonance in scenarios demanding extensive data transfer and seamless Internet of Things (IoT) integration [35–37].

A defining attribute of 5G technology is its remarkable data transmission capability, attaining speeds of up to 20 Gbps. This represents a quantum leap, being over twentyfold faster than 4G's peak of 1 Gbps and vastly outpacing 3G's 384 Kbps. Such an exponential enhancement in data throughput facilitates the seamless streaming of ultra-high-definition and 4K content, while underpinning real-time applications—ranging from gaming to virtual reality (VR) and augmented reality (AR)—with negligible latency. Moreover, 5G's ultra-low latency, reducible to sub-millisecond levels, is critical for applications necessitating the utmost precision and reliability, such as autonomous vehicular operations and sophisticated industrial robotics. The expansive connectivity potential of 5G, capable of linking innumerable devices concurrently, is instrumental in fostering smart urban ecosystems and enriching the IoT landscape [38]. With the ongoing global deployment of 5G, its influence is poised to redefine a multitude of sectors, ushering in an unparalleled era of technological innovation and interconnectedness [39,40].

2.2.2. The Advancement of 5G Antenna Technology: Challenges and Breakthroughs

The evolution of 5G communication technology is deeply entwined with the progressive developments in antenna technology specific to 5G. These antennas are critical in the efficient transmission and reception of wireless signals, necessitating an architecture that supports expanded bandwidths and accelerated data rates. Distinct from conventional antennas, which typically possess fixed directional capabilities, 5G antennas are required to exhibit a higher degree of adaptability, managing signal transmission across multiple trajectories. Contemporary research is intensely focused on engineering antennas with superior tuning mechanisms, aimed at optimizing signal directionality and amplification [41–43].

One of the foremost challenges in this domain is the imperative for 5G antennas to be both diminutive and lightweight. Historical paradigms have seen high-performance antennas that were relatively large, yet the emerging paradigm shift demands the integration of multiple smaller antennas, orchestrated to manage the transmission and reception of data across diverse orientations. This transition has ignited a wave of technical exploration aimed at devising antenna architectures that are not only compact but also efficient. The physical dimensions (L) of a 5G antenna, as an example, are determined by Equation (1), incorporating variables such as the effective wavelength (λ_{eff}), as depicted in Equation (2). This mathematical approach underscores the intricate relationship between antenna size and operational wavelength, facilitating the design of antennas that are both spatially efficient and functionally robust, marking a significant milestone in the technological evolution towards achieving the full potential of 5G connectivity [44–46].

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

where λ_{eff} can be expressed as Equation (2):

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

In this context, λ_0 represents the wavelength in a vacuum, μ_r denotes the relative permeability, and ε_{r} symbolizes the relative permittivity. The strategic use of ceramic materials, characterized by a higher dielectric constant—for instance, 9.45 as opposed to the 3.47 found in contemporary PCB antennas—enables a significant reduction in antenna size. This optimization leverages the intrinsic properties of ceramics to achieve compact yet efficient antenna designs, which are crucial for the spatial demands of modern 5G technology [9].

Figure 1 shows a sophisticated 5G ceramic chip antenna array designed for integration within the slender confines of a mobile device's form factor. The array includes specialized low-band unit chips (24.25 GHz to 29.5 GHz) and high-band unit chips (37 GHz to 40 GHz), each engineered for specific frequency ranges to ensure comprehensive 5G coverage. The configuration is meticulously optimized to not only fit within the minimal thickness of contemporary mobile phones but also to address the imperative of energy-efficient design in 5G antenna technology. The research continues to focus on reducing power consumption, promoting the sustainable advancement of 5G communication technologies.

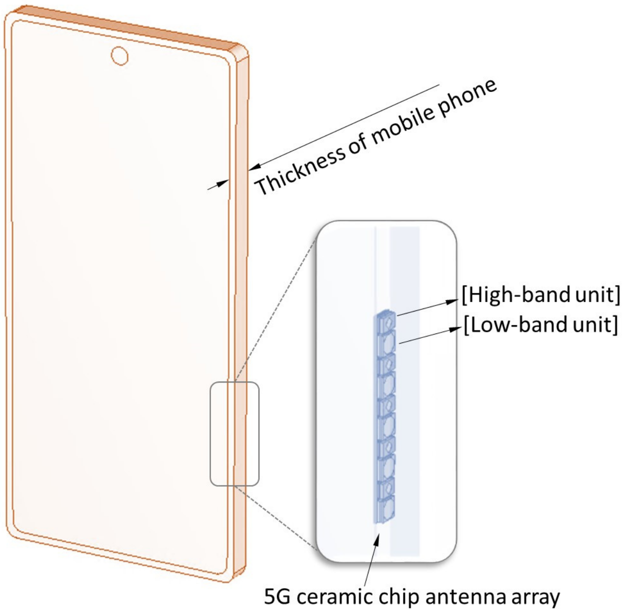

Figure 1. A schematic representation of a mobile phone highlighting the integration of a 5G ceramic chip antenna array, featuring distinct high-band and low-band units within the phone's thickness profile [9].

2.3. *Technology–Organization–Environment (TOE) Model*

The TOE model, originally designed by Tornatzky and Fleischer in 1990, describes the organizational components that influence the decision to adopt various technological innovations (see Figure 2). This model categorizes the influencing factors into three primary dimensions—technology, organization, and environment—and explains how these dimensions impact the decision to adopt innovations in a corporate context. These dimensions play a crucial role in how organizations identify the need to explore and adopt new technologies [14].

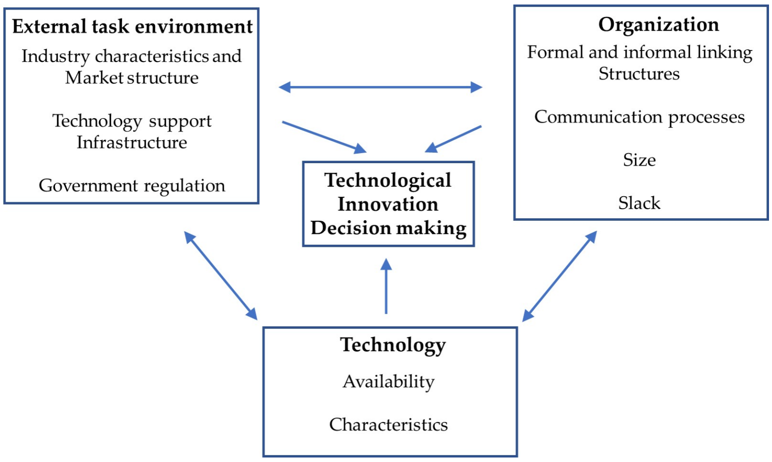

Figure 2. The TOE framework [14].

While the TOE model provides a comprehensive framework for analyzing the factors influencing technological innovation decisions, it is also widely recognized as one of the traditional theories for examining the implementation of new technologies at the organizational level. It offers a solid foundation and a broad perspective for research into organizational behavior concerning technological changes. Specific applications of the TOE model, such as its use in analyzing the continuity of corporate information security management, as discussed by Kim and Kim [47], highlight its relevance and adaptability to various contexts. Similarly, the study by Cho et al. [48] applies the TOE framework in the context of a global electronic components company's overseas market expansion strategy, illustrating the model's utility in strategic business decisions. These particular studies demonstrate how the TOE framework can be employed to understand significant factors that influence the adoption and implementation of innovations within organizations.

The technological dimension represents the characteristics of the technology that the organization is considering adopting. This dimension includes the technology's maturity, standardization level, compatibility, and relative advantage, among others. The technological dimension is essential for assessing how effectively the new technology can be applied within the organization. The organizational dimension includes the internal structure, leadership, corporate culture, and resources of the organization. It reflects the organization's ability and readiness to adopt and integrate new technologies quickly and efficiently. The organizational dimension emphasizes the internal factors that can facilitate or hinder technology adoption. The environmental dimension encompasses external factors like market trends, competitive landscape, regulatory environment, and technological advancements. These environmental factors can significantly impact the organization's technology adoption decisions and help to assess how the organization responds and adapts to these external factors [49,50].

In this study, we aim to analyze how blockchain technology integrated into the 5G ceramic antenna manufacturing process can improve efficiency and transparency by using the TOE model. Specifically, by applying this model, we can understand the complex interactions between the various technological, organizational, and environmental factors that can occur in the manufacturing process and identify their impact on process performance. Additionally, it provides insights into how the application of blockchain technology can improve data management and analysis in the manufacturing process, how the organizational culture and structure can support or hinder technology adoption and utilization, and how the external environment influences the organization's technology adoption strategy. Through this, we conduct an analysis of the technological, organizational, and environmental dimensions in the blockchain-applied 5G ceramic antenna manufacturing process.

2.4. Causal Loop Diagram (CLD)

The CLD is a tool for understanding the dynamic interactions within complex systems, developed as a core element of the system dynamics methodology by Professor Jay Wright Forrester at the Massachusetts Institute of Technology (MIT) in the mid-20th century [17,51]. This methodology uses feedback loops and time delays to understand the behavior of systems over time. A CLD visualizes the causal relationships between the components of a system, showing how each component affects the others and how these relationships form loops that either reinforce or balance the system's behavior. The elements of a CLD include variables, arrows, polarities, and loops. Variables are elements within the system that change over time, such as inventory levels, the number of employees, or the rate of technology adoption. Arrows represent connections between variables, indicating the direction of influence. An arrow from A to B means that A causes a change in B. Each connection is assigned a positive (+) or negative (−) polarity. A positive connection means that an increase in A causes an increase in B, while a negative connection indicates the opposite relationship. Changes in variables can form pathways that directly or indirectly affect themselves, creating reinforcing loops (R) that represent exponential growth or decline, or balancing loops (B) that tend to stabilize the system [16].

Figure 3 illustrates two causal loop diagrams marked with R and B, representing reinforcing and balancing loops, respectively. Reinforcing loops describe situations within the system where a change amplifies itself, such as when an increase in a population boosts the resources it produces, which, in turn, promotes further population growth. These loops have a self-promoting characteristic, indicated by 'R'. On the other hand, balancing loops describe changes within the system that suppress themselves or maintain a certain goal or equilibrium state. For example, an increase in the number of predators in an ecosystem could lead to a decrease in their prey, eventually reducing the predator population as well. Loops marked 'B' represent this equilibrium. The arrows in the diagram indicate causal relationships between variables within the system, with symbols ('+', '−') indicating the nature of these relationships. A positive symbol ('+') shows a direct correlation where an increase in one variable leads to an increase in another, while a negative symbol ('−') represents an inverse correlation. These causal loop diagrams provide a theoretical background for understanding dynamic interactions within systems and enable predictions about system changes. By clearly visualizing the complex relationships between various system variables, policymakers or researchers can develop more effective intervention strategies [52].

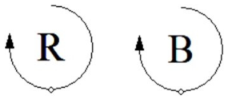

Figure 3. Reinforcing and balancing loops [16].

In this study, we construct a CLD through the TOE model to enhance process transparency and decision-making in the blockchain-applied 5G ceramic antenna manufacturing process. The technological elements include the characteristics of blockchain, manufacturing technologies, data analysis capabilities, and the integration of 5G technology. The organizational elements examine the structural, cultural, and human resource aspects that facilitate or hinder the adoption and effective utilization of technology. The environmental elements reflect external factors such as market trends, regulatory frameworks, and economic conditions.

2.5. Analytic Hierarchy Process (AHP)

The AHP, conceived by Professor T. L. Saaty in the 1970s, has profoundly transformed the landscape of decision-making within complex environments. Originally developed to tackle intricate decision-making challenges faced by the U.S. State Department, notably in the realms of arms control and disarmament, AHP's utility has since expanded across a myriad of domains, markedly influencing investment decisions in the public sector. Its primary objective is to navigate the intricate terrain of subjective decision-making factors—such as intuition, emotion, and perception—which are inherently difficult to quantify [53,54].

Operating on the foundational principle of using pairwise comparisons to assess relative importance, AHP excels in multifaceted scenarios characterized by numerous criteria or a diverse array of stakeholders. The methodology offers a systematic and structured approach to decision-making, significantly enhancing the clarity and integrity of decisions in complex contexts. Within the spheres of public administration and policy analysis, AHP has played a pivotal role in the evaluation of infrastructure projects, encompassing dams, airports, subway systems, and road constructions. It meticulously organizes decision-making factors into a hierarchical structure of main and subfactors, determining their significance through pairwise comparisons. Supported by ratio scales, this hierarchical evaluation process enables decision-makers to ascertain weights and prioritize factors effectively, streamlining the decision-making process in intricate scenarios [55–57].

AHP is exceptionally beneficial in contexts where the mathematical quantification of problems presents challenges, such as in research and development (R&D) endeavors. It capitalizes on expert judgment to allocate weights to factors that are otherwise challenging to objectively quantify, facilitating the development of comprehensive and occasionally conflicting evaluation criteria. The methodology is anchored in three core principles: the construction of a hierarchical structure, the determination of relative importance via subjective pairwise comparisons, and the maintenance of logical consistency. These hierarchies simplify complex problems into more manageable components, easing the analytical and resolution process. Pairwise comparisons leverage subjective evaluations to gauge the relative importance of each hierarchical element, while logical consistency is ensured through a consistency index, promoting reliable and consistent decision-making outcomes [58,59].

3. Research Design and Methodology

3.1. Methodological Framework for Analyzing TOE and Blockchain Integration in 5G Ceramic Antenna Manufacturing

The primary objective of this study is to analyze the influence of TOE factors on the adoption of 5G ceramic antennas and to explore how blockchain technology can enhance this adoption process by improving transparency and decision-making. In this research, 'transparency' specifically refers to the clarity and immediacy of data regarding manufacturing processes, which is essential for better quality control and timely decision-making. To achieve these goals, the study employs a methodological framework that systematically integrates the TOE framework with blockchain technology, focusing particularly on the nuanced interactions that these technologies facilitate within the manufacturing sector.

The TOE framework is applied to systematically identify and analyze factors across three key domains: technological factors include the capabilities of emerging 5G technology; organizational factors include the infrastructure of the company and the skills of its employees; and environmental factors include market demand and regulatory policies. Each of these domains is crucial for understanding the broader landscape of the adoption of 5G antennas and how blockchain can play a transformative role.

The AHP is utilized to prioritize these factors based on their significance and the impact they have on the adoption of 5G antennas. AHP assists in quantifying the preferences and importance of each TOE factor, thereby facilitating strategic decision-making (see Figure 4). This integration of AHP within the TOE framework allows for a structured evaluation of how each factor influences the adoption process, and how blockchain can be effectively integrated to address the most critical identified aspects. Through a series of pairwise comparisons, AHP guides the strategic deployment of blockchain technology to robustly address these factors.

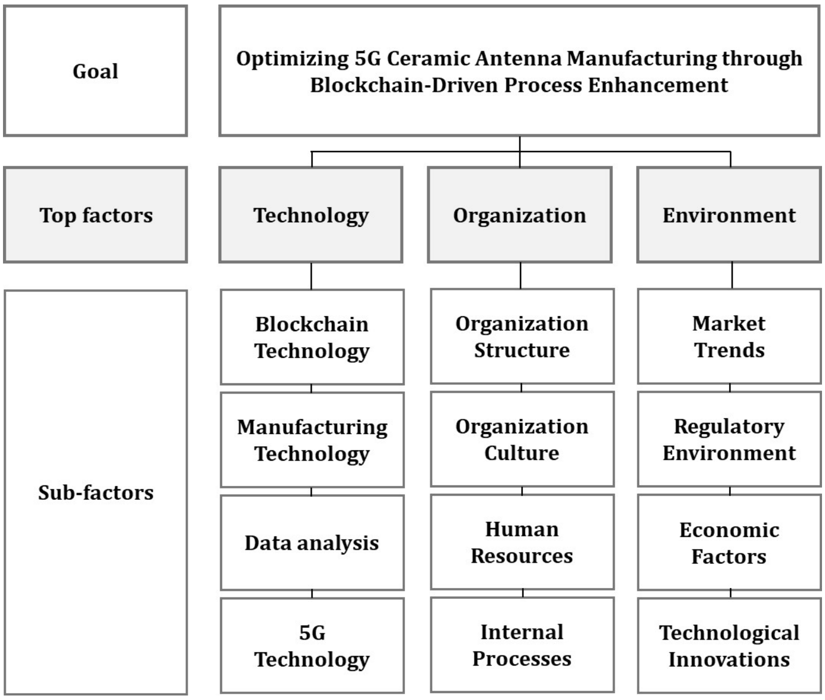

Figure 4. Research model of AHP methodology for 5G ceramic antenna manufacturing enhancement.

In the technological domain, the study highlights critical elements such as blockchain technology, manufacturing technology, data analysis, and 5G technology. These components are crucial as they represent the technological tools and methodologies employed not only in the production processes but also in managing and analyzing manufacturing data. In terms of organization, the research explores factors like organizational structure, culture, human resources, and internal processes. This examination delves into the internal workings and dynamics of the manufacturing entity, assessing how its structure and cultural environment impact overall efficiency and effectiveness. The environmental aspect of the research considers market trends, regulatory environment, economic factors, and technological innovations, providing a broad context for the manufacturing operations by highlighting the external pressures and trends that influence strategic decision-making and operational adaptations.

The core aim of this structured methodological approach is to enhance decision-making and increase transparency in the manufacturing processes by leveraging the capabilities of blockchain technology. This integration seeks to provide a real-time, transparent view of the manufacturing data, essential for improving quality control and operational efficiency. By systematically analyzing these factors within the integrated TOE and AHP framework, the study aims to identify how blockchain technology can be embedded within the manufacturing framework to drive process optimization and cost efficiency, ultimately leading to more stable and innovative production outcomes.

3.2. Constructing the System Dynamics Model: The Integration of Causal Loop Diagrams and Expert Insights

In our study, we embarked on the construction of a detailed System Dynamics Model to encapsulate the multifaceted interactions within 5G ceramic antenna manufacturing. The development of this model was anchored in a mixed-methods approach, which combined empirical evidence, theoretical frameworks, and expert insights to ensure accuracy and comprehensiveness. The initial phase involved a thorough review of the existing literature to establish a foundational understanding of the relevant technological applications. We specifically drew upon the findings from Somoza-Tornos et al. [60], who explored electrochemical CO_2 reduction processes. Their research provided valuable insights into complex system interactions, which we found to be analogous to those in ceramic antenna manufacturing. This literature review guided our preliminary hypotheses about the key factors and their interrelations within the manufacturing process.

To refine these initial hypotheses, we organized a series of consultations with a panel of industry specialists, each possessing over 15 years of experience in telecommunications technology. These sessions were designed to facilitate an iterative feedback mechanism, allowing for dynamic adjustments to the CLD. The experts were presented with the initial model and asked to critique and suggest modifications based on their practical experience and technical knowledge. This iterative process ensured that the model not only reflected theoretical assumptions but was also grounded in industry realities.

Following the expert consultations, the CLD underwent a validation process through a pilot test in a simulated manufacturing environment. This testing phase was crucial to confirming the practical relevance and applicability of the relationships depicted in the model. The validation helped to confirm that the model accurately represents the operational intricacies of 5G ceramic antenna manufacturing and is robust enough to support further analysis of the potential integration of blockchain technology.

The insights gained from both the literature review and the expert panels were integrated into the final version of the CLD. This comprehensive model serves as a crucial tool in our methodology, providing a systemic view of the interactions and dependencies within the manufacturing process. It enables us to simulate various scenarios and predict outcomes, thereby offering a strategic framework for decision-making and further research.

This section not only underlines the methodological rigor of our study but also elucidates the complex dynamics influencing the innovative integration of blockchain technology into ceramic antenna production. By detailing each step in the construction of our system dynamics model, we aim to provide a clear and replicable methodological pathway for future research in similar technological fields.

3.3. AHP Analysis

In this investigation, the AHP methodology was utilized to streamline the decision-making process regarding the assessment of security, regulatory standards, and efficiency within the context of a blockchain-enabled 5G ceramic antenna manufacturing framework. Data collection was facilitated through a meticulously structured questionnaire, adhering to Saaty's renowned 9-point scale [61], as elaborated in Table 1. This scale progresses from a value of 1, symbolizing a parity in importance between two factors, to a value of 9, denoting a pronounced preference for one factor over the other.

Table 1. The scoring system and meanings for Saaty's 9-point scale [61], used in the AHP analysis. The scale ranges from 1, indicating equal importance between two factors, to 9, signifying a strong preference for one factor over another. Each score on the scale is accompanied by a definition and an explanation, clarifying how scores such as 'Extreme' (9), 'Very strong' (7), 'Strong' (5), and 'Moderate' (3) relate to the comparative importance of different factors in the context of 5G ceramic antenna manufacturing. This table is crucial for understanding the basis on which the AHP analysis was conducted and how the pairwise comparisons between factors were quantitatively assessed.

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

Subsequent to data collection, an AHP analytical procedure was executed, culminating in the construction of a pairwise comparison matrix. This methodological approach offers a distinct advantage by distilling the evaluation process to pairwise comparisons between two factors at any given instance, thus rendering the task more comprehensible and manageable for evaluators than an attempt to compare multiple factors simultaneously.

For the effectiveness and accuracy of AHP analysis, the consistency of the questionnaire responses is paramount. While the methodology appraises the significance of each response by consolidating the judgments of individual evaluators, it is crucial to monitor the consistency ratio values. Although responses with consistency ratio values under 0.1 are typically sought to ensure the dependability of the evaluative process, it is the analyst's responsibility, in consultation with the decision-maker, to scrutinize any values above this threshold. Rather than the AHP method filtering out inconsistent responses automatically, it is the analysts who must critically assess and decide how to handle these instances to preserve the integrity and reliability of the analysis. This critical evaluation is a fundamental aspect of maintaining the analytical rigor of the AHP framework.

The construction of the pairwise comparison matrix A is a central aspect of the AHP method. It captures the relative importance of 'n' elements being assessed within each hierarchical layer. In this matrix, elements A_1, A_2,. . . A_n, are compared to each other, and the outcome of the comparison between any two elements, A_i and A_j, is denoted by a_{ij}. This systematic approach yields the matrix $A = (a_{ij})$, which is a structured representation of the comparative judgments. Utilizing the matrix $A = (a_{ij})$, the AHP method calculates the weights w_i (for i = 1,2,. . .n) that signify the importance of each element. These weights are derived through a mathematical process that ensures the accuracy and relevance of the resulting values. The weights offer quantifiable measures that guide decision-making, reflecting the relative priorities of the elements under consideration. This quantitative foundation enables decision-makers to discern the most critical factors within complex scenarios, facilitating informed and objective decision-making.

Furthermore, the AHP methodology incorporates a rigorous validation process to assess the consistency of the evaluators' judgments. This process involves calculating consistency ratios (CR) for the responses, a step that distinguishes AHP from less structured decision-making frameworks. A CR value of less than 0.1 is deemed acceptable, indicating a reasonable level of consistency in evaluators' judgments. This threshold is pivotal, as it ensures that the decision-making process is based on reliable and coherent evaluations. By systematically excluding responses that exceed this threshold, the AHP methodology upholds the quality and trustworthiness of the analysis, making it a powerful tool for addressing complex decision-making challenges.

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

In the AHP framework, the relative importance of each element is quantified as a ratio. For example, w_1/w_1, which compares element A_1 with itself, naturally results in a value of 1, reflecting the principle of identity in comparisons. Similarly, w_1/w_2 represents the relative importance of A_1 compared to A_2, and w_1/w_n represents the relative importance of A_1 compared to A_n, indicating how each element is evaluated in relation to others within the hierarchy. When these ratios are applied across the board, they form the basis for constructing the pairwise comparison matrix. This matrix is a structured representation of all possible pairwise comparisons within a set of elements, encapsulating the essence of the evaluative process in AHP. Each entry in the matrix, denoted as a_ij, is a direct manifestation of the relative importance or preference of element A_i over A_j calculated as $w_\mathrm{i}/w_\mathrm{j}$. By multiplying Equation (3)—which represents a mathematical formulation of these concepts—by the column vector w = [w_1, w_2,. . .,w_n], we arrive at Equation (4). This column vector w embodies the approximate values of relative importance among the evaluation items, essentially serving as a summary of the evaluative judgments made in the pairwise comparison process. This multiplication helps in consolidating these individual judgments into a coherent framework that supports the derivation of weights or priorities among the elements being analyzed. This procedure highlights the analytical strength of AHP in distilling complex, subjective judgments into quantifiable, comparable weights that guide decision-making. The resulting values facilitate a structured comparison of elements based on their relative importance, ensuring that decision-makers can prioritize actions or choices in a manner that is both systematic and reflective of their underlying preferences and values.

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

The calculation of the maximum eigenvalue, $\lambda_{\max}$, from the pairwise comparison matrix A is a crucial step in the AHP for determining the relative weights of the elements under consideration. This process is elucidated through the eigenvalue calculation method, which involves solving the characteristic equations derived from matrix A. These equations are set to find non-zero solutions in n simultaneous equations, leading to the determination of $\lambda_{\max}$. The equation can be expressed symbolically as Equation (5), setting the stage for a deeper mathematical exploration.

$$A \cdot w = \lambda_{\max} \cdot w \tag{5}$$

The significance of $\lambda_{\max}$ extends beyond mere numerical value; it serves as a benchmark for assessing the consistency of the pairwise comparisons made within the matrix A. By definition, $\lambda_{\max}$ should always be greater than or equal to the number of elements, n, being compared. A $\lambda_{\max}$ value that closely aligns with n signals a high level of consistency within the matrix A, indicative of coherent and reliable evaluative judgments. This relationship is formalized and further scrutinized in Equation (6), which aims to identify the precise value of $\lambda_{\max}$ that satisfies the mathematical and logical constraints of the AHP methodology.

$$|A - \lambda I| = 0 \tag{6}$$

In the AHP, the consistency of the judgment matrix is assessed by first calculating the maximum eigenvalue ($\lambda_{\max}$), which is derived from the eigenvector corresponding to the largest eigenvalue of the pairwise comparison matrix. The consistency index (*CI*) is then computed using the following formula:

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

where n represents the dimension of the matrix. This formula encapsulates the essence of the consistency assessment, translating the abstract concept of judgment coherence into a tangible metric. The consistency ratio (*CR*) is subsequently determined by comparing the *CI* against the random index (*RI*), a value that varies with the dimension of the matrix and is sourced from Saaty's standard tables of random indices [62–64]. The *RI* serves as a benchmark, representing the average *CI* value expected from a matrix of randomly generated judgments. The *CR* is computed as follows:

$$CR = \frac{CI}{RI} \tag{8}$$

A *CR* value of 0.1 or less is generally accepted as indicating a satisfactory level of consistency, signifying that the judgments within the pairwise comparison matrix are sufficiently coherent to be considered reliable. For each item in the survey, weights (w) were ascertained using the eigenvalue method. Subsequently, the overall weights were computed employing the geometric mean method, rather than calculating the arithmetic mean of the values from each survey item to determine overall *CI*, *CR*, and $\lambda_{\max}$. This comprehensive approach integrates the eigenvalue method with geometric mean calculations for weights, ensuring a thorough and accurate determination of consistency measures, thereby reinforcing the methodological integrity of the AHP analysis. The values for *RI* are provided in Table 2.

Table 2. The Saaty *RI* values [61], which are used in the AHP to evaluate the consistency of pairwise comparisons. The *RI* values are essential for calculating the *CR* of AHP matrices.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.4. Data Collection and Questionnaire Design

For this study, an AHP questionnaire was developed based on the established model and disseminated over a four-week period from 5 February to 2 March 2024. The data for this study were collected through a structured questionnaire that was distributed to experts in the fields of blockchain technology, 5G technology, and manufacturing. The questionnaire was meticulously designed to gather respondents' insights into the integration of blockchain technology into the manufacturing process of 5G ceramic antennas. It included several key components.

Firstly, the demographic information section contained questions about the respondents' backgrounds, including their experience and expertise in relevant fields. This section aimed to provide context for the responses and ensure that the insights were drawn from knowledgeable and experienced individuals.

Secondly, the technological factors section included items that assessed the perceived impact of blockchain technology on the transparency, security, and efficiency of manufacturing processes. This part of the questionnaire was crucial for understanding how experts view the role of blockchain in enhancing these specific aspects of manufacturing.

Thirdly, the organizational factors section contained questions that evaluated the role of the organizational structure, culture, and resources in the adoption of blockchain technology. This section aimed to explore how internal organizational dynamics could influence the integration of blockchain into manufacturing processes.

Lastly, the environmental factors section included items that measured the influence of market trends, regulatory conditions, and economic factors on the integration process. This section was designed to capture the external factors that might affect the adoption of blockchain technology in manufacturing.

Out of the initial 45 questionnaires received, multiple rounds of discussion were held with respondents who provided inconsistent answers (consistency ratios above 0.1). These interactions aimed to clarify and, if possible, refine their judgments to enhance the consistency and reliability of the data. Despite these efforts, 15 responses were ultimately excluded due to persistently high inconsistency ratios, leaving 30 questionnaires that met the stringent criteria for inclusion in the analysis.

Table 3 provides a demographic breakdown of the 30 participants, detailing their gender, age distribution, and professional experience in the areas relevant to the study. The sample consisted predominantly of male experts, accounting for 66.7% of respondents, while female experts represented 33.3%. Age-wise, the largest group was those in their 40s, comprising 46.7% of the participants, followed by those in their 50s, at 30%, and those in their 30s, at 20%. A small fraction, 3.3%, were in their 60s. The professional experience within the related fields varied, with those having 15–20 years of experience forming the largest group, at 40%, followed by those with 20–25 years, at 33.3%. The cohort also included professionals with 10–15 years (13.3%) and over 25 years (16.7%) of experience. The areas of expertise were evenly distributed among blockchain (33.3%), 5G antenna technology (30.0%), and manufacturing (36.7%), ensuring a well-rounded perspective on the integration of blockchain technology in the 5G antenna manufacturing process.

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

Section	Characters	Frequency	Ratio (%)
Gender	Male	20	66.7
	Female	10	33.3
	Total	30	100
Age	30 s	6	20.0
	40 s	14	46.7
	50 s	9	30.0
	60 s	1	3.3
	Total	30	100
Work experience in the related field	10–15 years	4	13.3
	15–20 years	12	40.0
	20–25 years	9	30.0
	Over 25 years	5	16.7
	Total	30	100
Professional area	Blockchain	10	33.3
	5G antenna	9	30.0
	Manufacturing	11	36.7
	Total	30	100

To optimize the decision-making process, the study employed a structured methodology to assign weights to each expert's judgment, directly correlating with their area of specialization and demographic characteristics, such as years of experience and professional background. Weights were determined using a predefined scale that quantifies the relevance and depth of each expert's experience in relation to the specific aspects under study. This ensured that experts with more pertinent experience had a proportionately greater influence on the outcomes relevant to their field of expertise. Additionally, a systematic consensus-building technique was utilized to address and harmonize differing viewpoints among the experts. This method involved iterative rounds of feedback and adjustment, where experts were encouraged to discuss and refine their assessments based on collective insights. This collaborative approach not only validated the significance of each expert's contribution but also promoted a comprehensive evaluation of the factors influencing technology adoption. This rigorous methodology ensured that each expert's input was not only considered according to their professional relevance but also integrated in a way that enhanced the multidimensional analysis of the organizational, technological, and manufacturing dimensions influencing the study. By doing so, the research provided a holistic view that reflects a balanced interplay of diverse expert insights, thereby enhancing the reliability and applicability of the findings in real-world settings.

4. Results and Discussion

4.1. TOE Model and CLD Analysis

This section aims to elucidate how the TOE model, augmented by CLD analysis, provides a comprehensive framework for understanding the systemic impact of blockchain technology on 5G ceramic antenna manufacturing, thereby aligning with the broader objectives of enhancing industry-wide technological integration and efficiency. In the context of the TOE model, this study conducted a CLD analysis, focusing on the 'Technology' dimension to enhance process transparency and informed decision-making within the blockchain-enabled 5G ceramic antenna manufacturing sector. The application of CLD, as depicted in Figure 5, is pivotal in demonstrating the dynamic interconnections and mutual reinforcement among technological advancements in this domain. This analysis highlights how innovations are not standalone but part of a complex system where each component influences and is influenced by others in a continuous feedback loop [47].

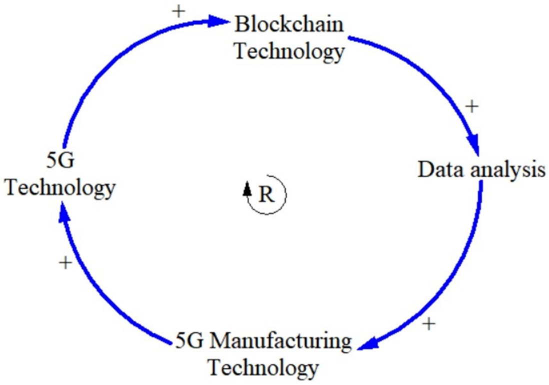

Figure 5. Reinforcing loop of technological advancements in 5G antenna manufacturing: This causal loop diagram illustrates a positive feedback loop where advancements in blockchain technology enhance data analysis capabilities, which in turn improve 5G manufacturing technology, leading to further developments in 5G technology itself.

Within the 'technology' dimension of the TOE model, the study emphasizes critical components such as blockchain echnology, data analysis, 5G manufacturing technology, and broader 5G technology. Blockchain technology is particularly noted for its potential to significantly enhance data analysis capabilities, which are crucial for the precision and optimization of 5G manufacturing technology. These improved processes, in turn, lead to further advancements in 5G technology, creating a positive, self-reinforcing cycle that fosters continuous innovation and efficiency. The importance of this interconnected loop is that enhancements in blockchain technology not only contribute to more sophisticated data analysis methods but also elevate the manufacturing technology, which ultimately advances 5G technology as a whole. Such interconnectivity underscores the critical role of each identified element within the technological spectrum of the TOE model, illustrating that improvements in one area can catalyze growth across the entire system. To further substantiate these observations, the study integrates findings from the recent literature that discuss similar feedback loops in technology adoption and innovation. For instance, research by Pihlajamaa et al. [65] and Gliem et al. [66] provides empirical evidence of how technological advancements, especially in high-tech sectors, are often the result of compounded enhancements across different but related technologies. These references support the claim that blockchain's integration into manufacturing processes not only has more isolated benefits but also triggers broader technological advancements within the industry.

Figure 5 illustrates a CLD that represents a reinforcing loop of technological advancement in the manufacturing of 5G antennas. This diagram captures the positive feedback loop, where each component in the loop influences the next in a way that promotes the continuation and strengthening of the cycle. It begins with advancements in blockchain technology, which are posited to enhance the capabilities of data analysis. As data analysis becomes more refined and effective, it positively impacts 5G manufacturing technology, leading to improvements in the processes and techniques used in producing 5G antennas. These improvements in manufacturing technology then contribute to further developments in 5G technology as a whole. The diagram denotes each step in the loop with a positive sign (+), indicating that an increase or enhancement in one element leads to an increase or improvement in the next. The presence of the 'R' symbolizes that this is a reinforcing loop, suggesting that this cyclical process is self-sustaining and can lead to exponential growth or advancement within the system of 5G antenna manufacturing.

The relationships within the causal loop diagram depicted in Figure 5 can be formalized through a set of mathematical equations that provide a quantitative framework for understanding and simulating the dynamic interactions within the technological advancement loop of 5G antenna manufacturing. The relationships, as per the CLD, can be described by the following system of equations:

Equation (9) encapsulates the influence of advancements in 5G technology on the evolution of blockchain technology at any given time t, expressed as B_{t}:

$$B_t = a \cdot T_{t-1} \tag{9}$$

where a is a constant that quantifies the degree to which enhancements in the previous period's 5G technology ($T_{\mathrm{t}-1}$) boost blockchain technology in the subsequent period. Equation (10) demonstrates how blockchain technology progression bolsters the capabilities of data analysis (D_t):

$$D_t = b \cdot B_t \tag{10}$$

with b being a constant that signifies the extent to which blockchain technology advances (B_{t}) improve data analysis capabilities. Equation (11) delineates the relationship between the enriched data analysis capabilities and the progression of 5G manufacturing technology (M_{t}):

$$M_t = c \cdot D_t \tag{11}$$

where c is a constant that reflects how data analysis enhancements (D_{t}) contribute to advancing 5G manufacturing technology. Equation (12) connects the advancements in 5G manufacturing technology with subsequent developments in 5G technology (T_{t}):

$$T_t = d \cdot M_t \tag{12}$$

In this case, d quantifies the impact of manufacturing technology improvements (M_t) on the future evolution of 5G technology. This system of equations represents a reinforcing loop wherein the output from one aspect positively influences the subsequent one, fostering a continual cycle of technological evolution. Each variable is influenced by the performance of the preceding factor, and the constants a, b, c, and d symbolize the intensities of these positive feedback mechanisms. Although the linear approach simplifies the illustration of the feedback loop, it captures the core dynamics governing the reinforcing interactions in the technological progression of 5G antenna manufacturing. Extending this model may require adjustments based on empirical data to incorporate non-linear dynamics, time delays, and additional complexities that mirror the intricacies of technological development processes.

Figure 6 presents a CLD that encapsulates the reinforcing dynamics within an organization's structure as it pertains to the production of 5G antennas. This diagram, as a part of the organizational component of the TOE model, illustrates how the different aspects of an organization interact to create a feedback loop that reinforces the efficacy and innovation of 5G antenna manufacturing processes. At the outset of the loop, an effective organizational structure is established as a fundamental backbone. This structure is instrumental in fostering a strong organizational culture, characterized by shared values, beliefs, and practices that define the workplace environment. A robust organizational culture, in turn, exerts a positive influence on the organization's capacity to attract and retain skilled human resources. These skilled individuals are crucial assets, bringing expertise and creativity, which are critical for innovation and process improvement. The presence of competent human resources enhances the internal processes, which include the methodologies and routines through which work is accomplished. As these internal processes become more streamlined and proficient, they reinforce the organizational structure by providing feedback that can lead to the refinement of organizational hierarchies, communication flows, and decision-making protocols [67].

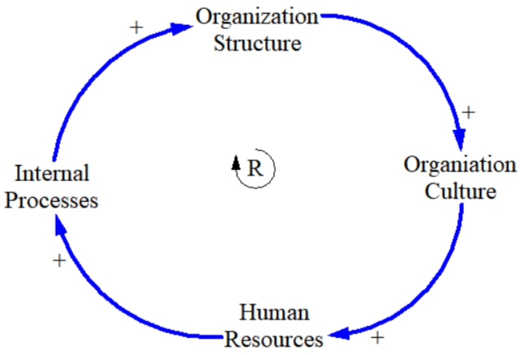

Figure 6. Reinforcing loop of organizational dynamics in 5G antenna production: This diagram depicts the reinforcing relationship between an organization's structure, culture, human resources, and internal processes. An effective organizational structure supports a strong organizational culture, which in turn attracts and retains skilled human resources, thereby enhancing internal processes that contribute to organizational efficiency and innovation in 5G antenna production.

This reinforcing loop, denoted by the 'R' in the center, suggests that improvements in any one of these areas—structure, culture, human resources, or internal processes—will positively influence the others, leading to a cycle of continuous improvement. Such a loop indicates a self-sustaining mechanism where organizational elements synergize to promote an environment conducive to continuous learning, adaptation, and advancement in the realm of 5G antenna production. The positive signs (+) in the diagram signify that there is a compounding effect where enhancements in one area amplify benefits in others. This concept is central to understanding how organizational dynamics can be optimized to support the complex and evolving field of 5G technology and contribute to a competitive edge in the telecommunications industry.

Drawing a parallel with the reinforcing feedback loop illustrated in Figure 5, which pertains to the technological domain, Figure 6 can be expounded upon within the organizational context of 5G antenna production. Just as advancements in one technological sector fuel progress in the next, the same principle applies to the organizational dynamics, where the quality of one organizational component amplifies the performance of the subsequent one. For instance, taking the established relationships from Figure 5 and applying them to the organizational components in Figure 6, a mathematical model can be constructed to represent the reinforcing loop. The equations below demonstrate how each element within an organization's framework—structure, culture, human resources, and internal processes—serves as a catalyst for the subsequent element, thereby creating a cycle that propels organizational efficiency and innovation in 5G antenna production.

Starting with the organizational structure, which is akin to the role of 5G technology in the previous figure, we establish that an effective organizational structure (S_{t}) fosters a strong organizational culture (C_{t}). This can be modeled by the following equation:

$$C_t = \alpha \cdot S_t \tag{13}$$

where α symbolizes the influence strength of structure on culture, paralleling the impact of 5G technology on blockchain technology. The organizational culture then plays a role similar to that of blockchain technology by enhancing the organization's human resources (H_{t}):

$$H_t = \beta \cdot C_t \tag{14}$$

with β quantifying the extent to which culture influences the acquisition and development of human resources. These human resources are the organization's equivalent of data analysis capabilities, boosting the effectiveness of internal processes (P_{t}):

$$P_t = \gamma \cdot H_t \tag{15}$$

where γ reflects the impact of human capital on the optimization of internal processes. Finally, just as improvements in data analysis lead to improvements in 5G manufacturing technology, the enhanced internal processes complete the loop by reinforcing the organizational structure:

$$S_{t+1} = \delta \cdot P_t \tag{16}$$

In Equation (16), δ represents the feedback from process efficiencies back into the organizational structure for the next period. Each step in this cycle mirrors the technological progression depicted in Figure 5, emphasizing how improvements in one area have a ripple effect, leading to enhancements throughout the organization. This cyclical process suggests a strategy whereby reinforcing one component of the organizational loop will lead to cumulative benefits across the entire organization, analogous to a reinforcing loop in a technological system that leads to continuous advancement.

Figure 7 offers a visual representation of a CLD that analyzes the environmental aspect of the TOE model, specifically within the 5G technological ecosystem. The CLD captures the intricate relationships and feedback mechanisms among various environmental factors: market trends, technological innovations, economic factors, and regulatory environments. The diagram identifies two reinforcing loops (R1 and R2), which illustrate the self-amplifying cycles within the system. The first reinforcing loop (R1) illustrates how market trends and technological innovations positively feed into each other. As market trends indicate the demand for more advanced technology, this stimulates technological innovations. In turn, new technological breakthroughs can drive market trends by introducing novel products or services that reshape consumer demand and open new markets. The second reinforcing loop (R2) further emphasizes the synergistic relationship between technological innovations and economic factors. Technological advancements can lead to economic growth, as new technologies often streamline operations, reduce costs, or create new economic opportunities. This economic growth can then reinvest in research and development, spurring further technological innovations.

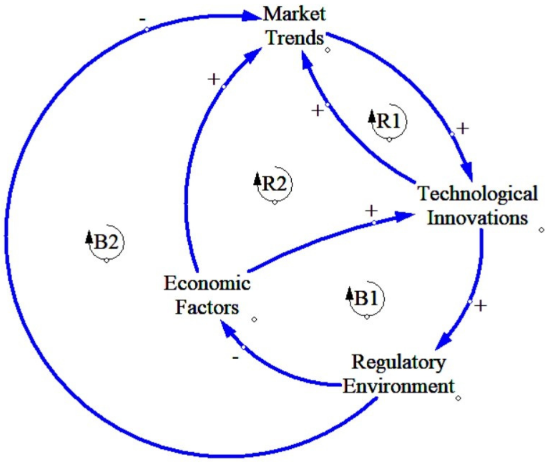

Figure 7. Dynamic interplay of environmental factors in 5G technological ecosystem: This CLD illustrates the complex interactions between market trends, technological innovations, economic factors, and regulatory environments. The diagram showcases two reinforcing loops (R1 and R2) that depict the positive feedback mechanisms where market trends and technological innovations fuel each other. Additionally, it presents a balancing loop (B1) where the regulatory environment influences economic factors, which, in turn, can temper the pace of technological innovation. Another balancing loop (B2) indicates the moderating effect of economic factors on market trends, stabilizing the system.

In contrast, the CLD also presents two balancing loops (B1 and B2), which serve to moderate the system and maintain equilibrium. The first balancing loop (B1) indicates how the regulatory environment can influence economic factors. Regulations can either encourage technological advancement through incentives or hinder it with restrictions, thus potentially tempering the pace of technological innovation. The regulatory environment's impact on economic factors can create a feedback loop that either accelerates or slows down innovation, depending on the nature of the regulations. The second balancing loop (B2) shows the moderating effect of economic factors on market trends. Economic downturns or financial constraints may reduce consumer demand or investment in new technologies, while economic prosperity may boost demand and investment. This loop helps to stabilize the system by adjusting market trends in response to economic fluctuations. Together, these loops offer a comprehensive view of the environmental factors affecting the 5G technological ecosystem. The understanding of these loops is crucial for stakeholders in the 5G sector, as it aids in navigating the complex and dynamic landscape where external factors, such as market forces, regulatory policies, and economic conditions, interact and shape the trajectory of technological progress.

The dynamic interactions within the 5G technological ecosystem, as depicted in Figure 7, are governed by a set of complex relationships among environmental factors. These relationships are mathematically articulated to reflect the interplay of reinforcing and balancing feedback loops. Technological innovations at any given time t are influenced by the market trends of the previous period. This is modeled by the function f, which illustrates the push of market demand on the development of new technologies:

$$TI_t = f(MT_{t-1}) \tag{17}$$

In a reciprocal manner, technological innovations feed back into and shape market trends, represented by the function g, indicating a future where today's innovations redefine tomorrow's market demands:

$$MT_{t+1} = g(TI_t) \tag{18}$$

Simultaneously, the regulatory environment exerts an influence on economic factors, captured by the function h, which can either facilitate or inhibit economic stability and, by extension, technological progression:

$$EF_t = h(RE_t) \tag{19}$$

Economic factors then feedback into both technological innovations and market trends, with the function i depicting their effect on the innovation rate and j on market behavior:

$$TI_{t+1} = i(EF_t) \tag{20}$$

$$MT_{t+1} = j(EF_t) \tag{21}$$

By formulating these equations, a quantitative framework is established, allowing for an analysis of how shifts in policy, economy, and market trends might converge to shape the trajectory of 5G technology development. This framework aids in anticipating the effects of various environmental factors and in crafting strategies that can navigate the complex system of influences affecting the technological landscape.

In Figure 8, the interconnectedness of the technology, organization, and environment aspects of 5G antenna manufacturing is meticulously encapsulated. This figure serves as a macroscopic lens, offering a sweeping survey of how these three facets coalesce and influence one another through a series of feedback loops, which are either reinforcing or balancing in nature. The diagram visually articulates the reinforcing loops within the technological domain, highlighting the cyclical boost that blockchain technology provides to data analysis, which, in turn, propels the advancement of 5G manufacturing technology. This feedback is critical as it indicates that improvements in blockchain implementation could substantially elevate the precision and utility of data analytics, thereby driving forward the capabilities of 5G manufacturing technologies. The interconnectivity showcases how advancements in one area, like blockchain, can precipitate improvements across the technology spectrum, culminating in a more robust and innovative 5G technology landscape.

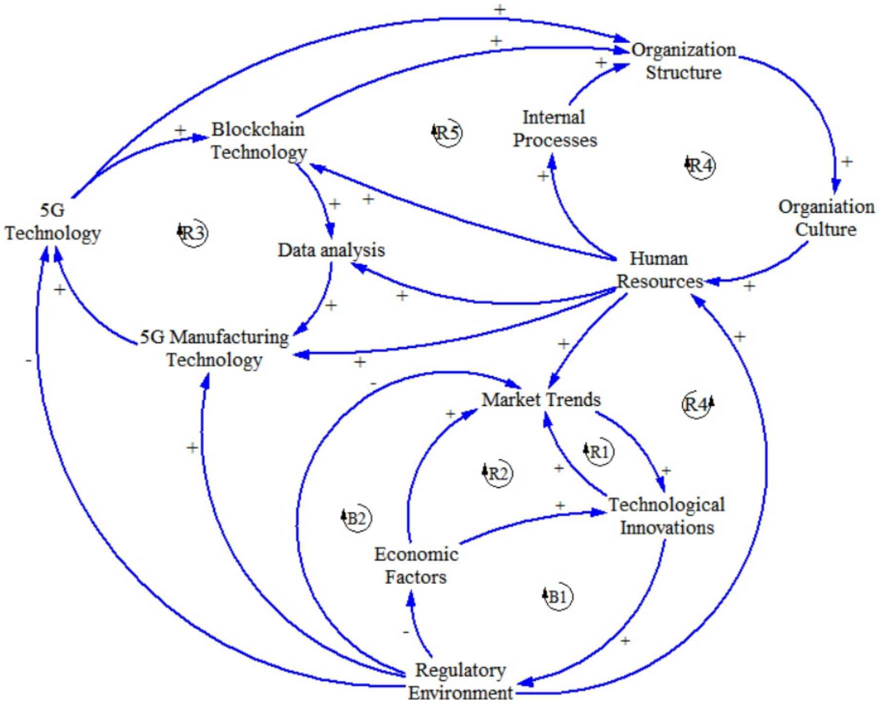

Figure 8. Integrated CLD of the TOE framework in 5G antenna manufacturing: This diagram presents a comprehensive view of the interdependencies and feedback loops within the technology, organization, and environment aspects of 5G antenna manufacturing.

On the organizational front, the reinforcing loop illuminates the synergy between an organization's structure and culture, which collectively nurtures human resources and internal processes. A well-designed organizational structure, underpinned by a resonant culture, magnetizes and retains top-tier talent, which is instrumental in refining internal processes. These processes, in turn, feed back into strengthening the organizational framework, crafting a self-sustaining loop of organizational excellence that can significantly influence the success of 5G antenna manufacturing endeavors.

The environmental dimension is dissected to reveal both reinforcing and balancing loops. Market trends and technological innovations mutually fuel each other, creating a reinforcing loop that underscores the bidirectional relationship between market demands and technological advancements. Conversely, the balancing loops demonstrate the regulatory environment's impact on economic factors, which can either temper or stimulate technological innovation. These loops capture the nuanced dance between external regulatory pressures and the economic realities that can moderate the pace of market trends and technological advancements.

Figure 8 presents a sophisticated network of the various systems influencing 5G antenna manufacturing, moving beyond the individual causal loop diagrams of Figures 5–7 to portray a comprehensive interplay of technological innovation, organizational dynamics, and environmental factors. This complex framework transcends the sum of its parts, emphasizing the need for an integrated analysis to fully grasp the interactive effects within the manufacturing landscape. It reveals a nuanced matrix where technological strides, organizational changes, and environmental shifts dynamically influence each other.

The diagram is a visual representation of an ecosystem where no single factor operates in isolation; instead, each is a thread in a broader tapestry. Technological advances in 5G and blockchain technologies initiate developments that ripple through organizational structures, influencing and being influenced by market trends and economic factors. This interconnection suggests that changes in any one area can propagate through the entire ecosystem, impacting aspects far beyond their origin.

The mathematical principles derived from Figures 5–7 offer a quantitative lens through which these intricate relationships can be examined. While Figure 8 might not present a distinct mathematical model, it embodies the cumulative interactions of the previously detailed models. Technological advancements are not merely a series of isolated innovations but are deeply woven into the fabric of the organization and its place within the broader economic and regulatory environment. This intricate connection can be mathematically expressed through a set of integrated equations that encapsulate the reinforcing and balancing loops between these domains:

$$T_t = d \cdot M_t + k_1 \cdot MT_t \tag{22}$$

$$S_{t+1} = \delta \cdot P_t + k_2 \cdot EF_t \tag{23}$$

$$MT_{t+1} = j(EF_t) + k_3 \cdot P_t \tag{24}$$

In these expressions, variables and constants from the separate models are harmonized to reflect the system's multifaceted nature, highlighting how an intervention in one aspect can have cascading effects across the spectrum of 5G antenna manufacturing. By adopting this integrated approach, stakeholders are equipped with a strategic framework for navigating the complexities of incorporating blockchain technology into 5G antenna production. This framework not only acknowledges the intricate web of the manufacturing ecosystem but also enables a prioritization of efforts, channeling resources into areas with the most significant potential impact. It lays the groundwork for future research to delve deeper into these interdependencies and provides a methodological pathway for understanding the practical implications of each subsystem's interactions. The holistic understanding gleaned from this model ensures that strategic decisions are made with a full appreciation of their potential effects throughout the entire ecosystem.

4.2. AHP Results

When exploring complex system dynamics within 5G ceramic antenna manufacturing, the integration of CLDs with AHPs offers a robust methodology for assessing and prioritizing influential factors. For instance, Prihantoro and Husin [68] demonstrated the efficacy of this approach in enhancing project value through system dynamics, which facilitated a comprehensive understanding of project complexities and aided in decision-making by utilizing AHP to prioritize inputs from CLD analyses. Similarly, Kodrat et al. [69] applied CLD in conjunction with AHP to study supply chain performance in the agro-industry. In their research, the insights generated by CLD were quantitatively assessed using AHP, ensuring that strategic decisions were underpinned by both qualitative and quantitative analyses. These instances underscore the benefits of combining CLD and AHP to deepen analytical rigor and enhance operational precision in complex systems evaluations, thus supporting its application in research aimed at integrating blockchain technology into ceramic antenna manufacturing.

In this study, the AHP was utilized to integrate blockchain and smart contracts in order to determine the relative significance of principal factors impacting the manufacturing process of 5G ceramic antennas. The findings from this comprehensive AHP analysis are summarized in Table 4 and visually represented in Figure 9. The analysis identified 'technology' as the most critical factor, holding the greatest relative weight of 0.427 in the decision-making process for 5G ceramic antenna manufacturing. This highlights the pivotal role that technological advancements and innovations play in driving efficiencies and potential cost reductions in production.

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 'technology', 'organization', and 'environment', demonstrating their relative importance. The table also likely includes AHP metrics like $\lambda_{\max}$ value, *CI*, and *CR* to validate the consistency of the expert opinions used in the analysis, further emphasizing the significance of efficiency in the manufacturing process.

Top Factor	Rank	Weight
Technology	1	0.427
Organization	3	0.271
Environment	2	0.302
SUM		1.000
CI		0.011
CR		0.020
$\lambda_{\max}$		3.021

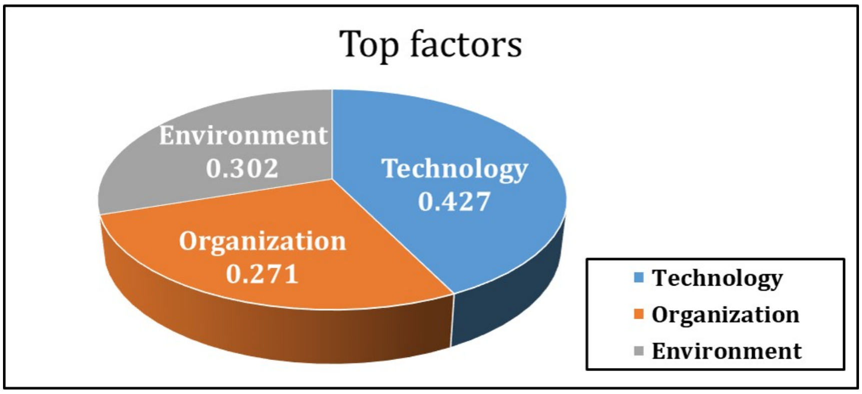

Figure 9. Pie chart analysis of AHP weights for evaluating 5G ceramic antenna manufacturing factors, showcasing 'technology' as the predominant influence, with 'environment' and 'organization' also playing crucial roles.

'organization' and 'environment' follow in significance, with 'organization' assigned a substantial weight of 0.271, which emphasizes its essential role in supporting the manufacturing process. Although 'organization' is less influential compared to 'technology', it is still a significant factor that influences the efficiency and effectiveness of the manufacturing framework. 'Environment', receiving a weight of 0.302, also plays a crucial role in the manufacturing landscape by encompassing external factors, such as market trends, regulatory requirements, and economic conditions, that can influence manufacturing processes and outcomes.

The pie chart in Figure 9 graphically delineates the distribution of these weights, offering a succinct depiction of the hierarchical importance of these factors. The chart visually differentiates the impact of each factor: 'technology' is the largest segment, in blue, 'environment' is in grey, and 'organization' is in orange, sequentially representing their weights and indicating their relative importance in the manufacturing of 5G antennas. The reliability of the AHP analysis is underpinned by the calculated $\lambda_{\max}$ value, CI, and CR, which validate the consistency of the expert opinions collated for the study. The CR value falling well below the acceptability threshold signifies the dependability of the findings. This methodical application of AHP, as evidenced by the detailed results and the illustrative pie chart, provides valuable insights for prioritizing initiatives within the manufacturing sector. It underscores the importance of focusing on 'Technology' as a key driver for optimizing the production process, suggesting that enhancements in technological aspects are likely to deliver the most significant benefits in terms of cost efficiency and production capability. This analytical approach, augmented by the capabilities of blockchain and smart contracts, facilitates informed strategic decision-making in the dynamic field of telecommunications.

Table 5 systematically compiles the results from employing the AHP to assess the factors impacting the adoption of blockchain technology in the production of 5G ceramic antennas. This analytical exercise is rooted in the TOE framework, distinguishing itself through its focus on the multifaceted dynamics that drive technological integration in manufacturing settings. The significance of this table extends beyond mere numerical representation; it articulates a nuanced understanding of how the blockchain, as a pioneering technological force, interfaces with organizational and environmental dimensions to sculpt the future of manufacturing in the telecommunications sector.

Table 5. The AHP analysis summary for blockchain integration in 5G ceramic antenna manufacturing.

Main Factor	Weight	Description of Relevance to Blockchain Adoption
Technology	0.427	Dominant factor, underscoring the pivotal role of technological advancements, including blockchain, in enhancing the manufacturing process.
Organization	0.271	Reflects the significance of the internal structure, leadership, and culture in supporting or hindering the adoption of blockchain technology.
Environment	0.302	Encompasses market trends, regulatory landscape, and economic factors influencing the broader adoption of blockchain in manufacturing.

In the realm of technology, assigned the most substantial weight at 0.427, the emphasis is placed on the transformative capacity of blockchain to revolutionize manufacturing processes. This factor underscores the crucial role of technological innovation, particularly the unique attributes of blockchain, such as its immutable ledger and decentralized nature, in advancing manufacturing efficiencies and security protocols. The preeminent weight of technology signals the paramount importance of continuous innovation and development in blockchain applications, urging stakeholders to foster a culture of research and experimentation to leverage its full spectrum of benefits.

The organization factor, though weighted slightly less at 0.271, encapsulates critical internal dynamics including the structure, culture, leadership, and resource allocation within manufacturing entities. This dimension highlights the internal prerequisites for blockchain adoption, pointing to the necessity of an organizational milieu that is conducive to technological innovation. This indicates that the successful integration of blockchain technology is not merely a technological endeavor but also an organizational strategy that demands an adaptive culture, visionary leadership, and strategic resource management.

On the environmental front, the factor is allocated a weight of 0.302, illustrating the significant influence of external forces such as market demands, regulatory landscapes, and economic conditions on the adoption process. This weight reveals the critical role of the external operating environment in shaping the adoption and implementation strategies for blockchain technology. It accentuates the need for organizations to pay close attention to market trends, regulatory compliance, and economic factors, which collectively constitute the broader ecosystem within which blockchain technology must be considered.

Table 5 is not merely a tabulation of factors and weights; it is a strategic artifact that distills complex analytical insights into actionable intelligence. It serves as a compass for decision-makers in the telecommunications industry, guiding strategic focus and resource allocation towards the areas of greatest impact on the blockchain adoption journey. By elucidating the nuanced interplay between the factors of technology, organization, and environment, Table 5 provides a comprehensive overview that aids stakeholders in crafting informed strategies to embrace the challenges and opportunities presented by blockchain technology in the innovative realm of 5G ceramic antenna manufacturing. This synthesis not only facilitates a deeper comprehension of the blockchain adoption landscape but also propels forward-thinking approaches to navigating this evolving technological frontier.

Table 6 delineates the AHP-calculated weights for the subfactors within the 'technology' domain for 5G ceramic antenna manufacturing. The AHP methodology quantifies the importance of each subfactor, providing a structured way to prioritize technological considerations in the manufacturing process. The subfactor 'blockchain technology' emerges as the most influential, with the highest weight of 0.303. This prominence reflects the transformative potential of blockchain in enhancing the transparency, traceability, and security of manufacturing processes. The ability of blockchain to underpin data integrity and to streamline operations through smart contracts is acknowledged as paramount in advancing manufacturing efficacy. 'Manufacturing technology' follows closely with a weight of 0.288, ranking second in importance. This emphasizes the critical nature of manufacturing innovations and the adoption of cutting-edge production technologies in improving product quality and manufacturing throughput, which are essential for maintaining competitiveness in the dynamic 5G market. The concept of '5G technology' itself is also a significant subfactor, weighted at 0.272, underscoring the continual need for advancements in the core technology that is being manufactured. This suggests that ongoing investment in 5G technology development is essential for meeting the evolving demands of the market and enabling new functionalities. The 'data analysis' subfactor, while ranked fourth with a weight of 0.138, remains an important aspect. It underlines the role of sophisticated data analytics in optimizing production processes, predicting maintenance needs, and enhancing decision-making through insights derived from manufacturing data.

The sum of the weights equals 1.000, indicating that these subfactors collectively encompass the entirety of the 'technology' factor's influence within the TOE framework for this context. The AHP analysis further validates the importance of these subfactors, with a CR of 0.043, well below the 0.1 threshold, indicating a reliable set of comparisons. The $\lambda_{\max}$ value of 4.115 and a CI of 0.038 contribute to confirming the methodological robustness of the AHP analysis. These calculated weights and ranks provide a strategic viewpoint for decision-makers in the 5G antenna manufacturing sector, pointing to where technological investments and improvements should be directed for optimal impact. The insights garnered from this AHP analysis inform a targeted approach towards technology adoption and development, which is essential for advancing the manufacturing capabilities and product offerings in the 5G antenna industry.

Table 6. The AHP-calculated weights for subfactors under the top-level factor of ‘Technology’ in the context of 5G ceramic antenna manufacturing.

Subfactor	Rank	Weight
Blockchain Technology	1	0.303
Manufacturing Technology	2	0.288
Data Analysis	4	0.138
5G Technology	3	0.272
SUM		1.000
CI		0.038
CR		0.043
$\lambda_{\max}$		4.115

Table 7 of the study presents the AHP-derived weights and ranks for the subfactors within the ‘organization’ dimension, a crucial top-level factor in the manufacturing of 5G ceramic antennas. These subfactors are essential in determining the efficiency and effectiveness of the organizational contribution to the manufacturing process. The subfactor ‘internal processes’ is identified as the most significant within the organizational context, with the highest weight of 0.355, signifying its primary role in driving organizational productivity. Efficient internal processes are critical for streamlining operations, reducing waste, and enhancing the agility of the organization in responding to manufacturing challenges. ‘Human resources’ follows closely, weighted at 0.332, highlighting the importance of skilled and knowledgeable personnel in the manufacturing industry. This reflects an understanding that the expertise and innovation brought forth by human capital are indispensable in achieving a high performance and maintaining a competitive advantage. ‘Organization culture’, with a weight of 0.178, is ranked third among the subfactors. This indicates that the shared values, beliefs, and behaviors within the organization significantly impact the overall morale, collaboration, and motivation of the workforce, which in turn influences productivity and innovation. The subfactor ‘organization structure’ is assigned the lowest weight of 0.135, ranking fourth, yet it remains an influential component. It underscores the need for a well-designed organizational hierarchy and communication framework to effectively manage operations and support strategic decision-making.

Table 7. The weights and ranks for the subfactors within the top-level factor of ‘organization’ as determined by the AHP.

Subfactor	Rank	Weight
Organization Structure	4	0.135
Organization Culture	3	0.178
Human Resources	2	0.332
Internal Processes	1	0.355
SUM		1.000
CI		0.031
CR		0.035
$\lambda_{\max}$		4.093

The sum of the weights for all subfactors is 1.000, ensuring that the full scope of the ‘organization’ factor’s influence is accounted for. The AHP method’s reliability is confirmed by the consistency measures: a CI of 0.031 and a CR of 0.035, with a $\lambda_{\max}$ value of 4.093. These values attest to the methodological precision of the AHP analysis, with the CR being significantly below the threshold of 0.1, validating the consistency of the expert assessments incorporated into the study. This detailed weighting and ranking of organizational subfactors affords a nuanced perspective of managerial decision-making in the 5G antenna manufacturing sector. It underscores the need for a balanced focus on refining internal processes and investing in human resources as foundational strategies for enhancing organizational performance. Moreover, nurturing a conducive organizational culture and establishing a robust structure are also recognized as vital for supporting the overarching goals of innovation and efficiency in manufacturing operations.

Table 8 presents the results from the AHP concerning the 'environment' factor in the manufacturing of 5G ceramic antennas, presenting the calculated weights for each subfactor. This factor encapsulates the external elements that influence the manufacturing process. The AHP results indicate that 'technological innovations' hold the highest weight at 0.353, ranking as the most impactful environmental subfactor. This suggests that breakthroughs in technology and the adoption of new technical methodologies are crucial drivers for the sector, potentially dictating the pace and direction of manufacturing advancements in the 5G antenna industry.

Table 8. The AHP calculated weights for subfactors within the top-level factor of 'environment' in the context of 5G ceramic antenna manufacturing.

Subfactor	Rank	Weight
Market Trends	2	0.327
Regulatory Environment	4	0.108
Economic Factors	3	0.212
Technological Innovations	1	0.353
SUM		1.000
CI		0.030
CR		0.033
$\lambda_{\max}$		4.089

'Market trends' are the second most influential subfactor, with a weight of 0.327. The prominence of market trends underscores the need for manufacturers to stay attuned to the shifting demands and preferences within the market to ensure that production aligns with current and future consumer and industry needs. 'Economic factors' hold a significant weight of 0.212, ranking third. This weight reflects the substantial influence of economic conditions, such as investment levels, cost structures, and financial market dynamics, on the manufacturing environment. The 'regulatory environment' is ascribed the lowest weight at 0.108, placing it fourth in terms of impact. While regulatory frameworks are less weighted compared to other factors, they nonetheless represent an important aspect of the environmental context, encompassing compliance with the laws, standards, and guidelines that can shape manufacturing practices.

The sum of all subfactor weights equals 1.000, confirming that these factors collectively encompass the full scope of the 'environment' factor's influence within the study's AHP framework. The methodological rigor of the AHP is validated by consistency metrics: a $\lambda_{\max}$ value of 4.089, a CI of 0.030, and a CR of 0.033. These metrics fall well within acceptable ranges, confirming the reliability of the AHP calculations and the coherence of the expert evaluations used in the analysis. The findings from Table 8 offer strategic insight into the environmental variables that must be navigated in the 5G antenna manufacturing sector. Understanding the weight of each subfactor can help organizations prioritize their strategic responses to external forces, positioning themselves to capitalize on technological trends, adapt to economic shifts, and adhere to regulatory demands, all of which are pivotal for success in the dynamic landscape of 5G antenna manufacturing.

Figure 10 shows the global weights of various subfactors as determined through the AHP within the context of 5G ceramic antenna manufacturing. The AHP analysis provides a nuanced understanding of how different subfactors, categorized under the overarching themes of 'technology', 'organization', and 'environment', contribute to the manufacturing process. The subfactors under 'technology' include blockchain technology, manufacturing technology, data analysis, and 5G technology. Blockchain technology has been identified as the most significant within this category, with a weight of 0.303, indicating its transformative impact on the manufacturing process through enhanced security and process efficiency. Manufacturing technology follows with a weight of 0.288, highlighting the importance of advanced production techniques and equipment in the manufacturing process. Fifth-generation technology, with a weight of 0.272, underscores the continuous need for development in the core technology of the products. Data analysis is also critical but is given a lesser weight of 0.138, reflecting its supportive role in the process. In the 'organization' category, internal processes is deemed the most influential, with a weight of 0.355, reflecting the pivotal role of streamlined operations in achieving manufacturing excellence. Human resources, weighted at 0.332, emphasizes the importance of skilled personnel in driving innovation and productivity. Organization culture, with a weight of 0.178, affects the collaborative and innovative capabilities of the workforce, while organization structure has the lowest weight, at 0.135, yet is still vital for defining the hierarchical and communication channels within the company. Environmental subfactors include market trends, regulatory environment, economic factors, and technological innovations. Technological innovations carry the highest weight of 0.362, suggesting the significant influence of emerging technologies on the manufacturing landscape. Market trends, with a weight of 0.322, highlight the need to align manufacturing strategies with market demands. Economic factors weigh in at 0.209, pointing to the broader economic context that can influence manufacturing costs and investment decisions. The regulatory environment, at 0.107, although having the lowest weight, is crucial for ensuring compliance and navigating the legal aspects of manufacturing.

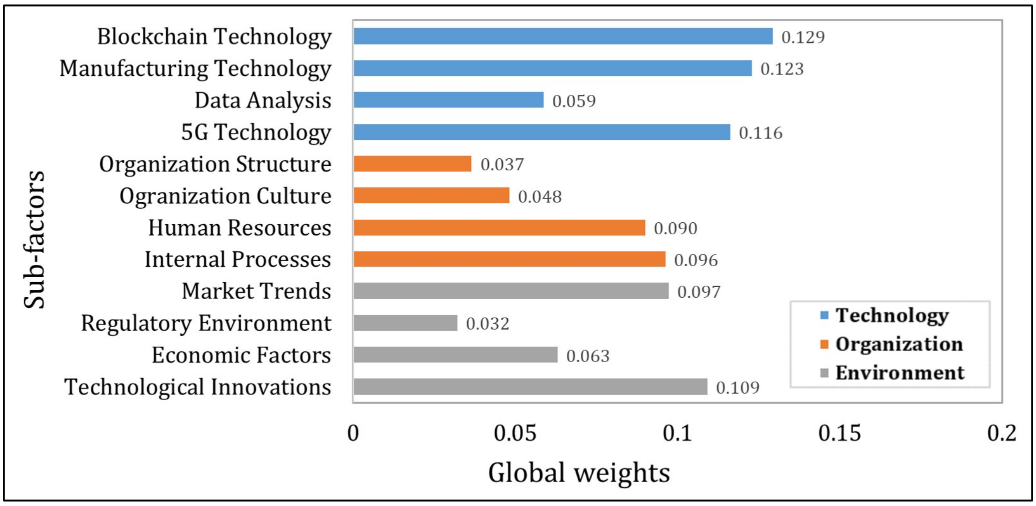

Figure 10. The global weights for various subfactors as determined by the AHP in the context of 5G ceramic antenna manufacturing. These subfactors are likely categorized under the main factors of 'technology', 'organization', and 'environment'.

The bar graph in Figure 10 provides a clear visual representation of these weights, demonstrating the relative importance of each subfactor within their respective categories. The weights are depicted along a scale from 0 to 0.6, allowing for an immediate visual comparison of their influence on the manufacturing process. The analysis embodied in Figure 10 is crucial for strategic decision-making within the 5G ceramic antenna manufacturing sector. It informs managers and stakeholders where to focus their efforts and resources to optimize production, navigate the organizational landscape, and respond effectively to external environmental pressures. This holistic view, grounded in quantitative analysis, empowers decision-makers to enact evidence-based strategies that align with the intricate dynamics of 5G antenna manufacturing.

Table 9 provides a detailed overview of the AHP results, which rank and weigh the primary factors and their associated subfactors within the manufacturing process of 5G ceramic antennas. The top-level factors assessed in the AHP analysis are ‘technology’, ‘organization’, and ‘environment’. ‘Technology’ emerged as the most significant factor with a weight of 0.427, while ‘blockchain technology’ was identified as the most impactful subfactor, followed by ‘manufacturing technology’, ‘5G technology’, and ‘data analysis’, with respective local weights of 0.303, 0.288, 0.272, and 0.138. Their global weights, which reflect their overall impact across all factors, were 0.129, 0.123, 0.116, and 0.059, with global ranks from first to ninth. ‘Organization’ was weighted at 0.271 and included subfactors such as ‘human resources’ and ‘internal processes’, which were more influential than ‘organization culture’ and ‘organization structure’, with local weights of 0.332 and 0.355 compared to 0.178 and 0.135, respectively. The global ranks of these subfactors ranged from sixth to eleventh. The ‘environment’ factor, with a weight of 0.302, highlighted ‘technological innovations’ and ‘market trends’ as the most substantial subfactors, with local weights of 0.353 and 0.327, and global ranks of fourth and fifth, respectively. ‘Economic factors’ and the ‘regulatory environment’ were also recognized but had a lower weight and ranked eighth and twelfth globally. This table indicates the relative importance of each factor and subfactor in the context of the overall manufacturing process, as determined by the AHP methodology. It offers a hierarchical perspective of where strategic efforts in the manufacturing process may yield the most significant impact.

Table 9. The AHP results showing the weights of the top factors and their associated subfactors, along with the global weights and global ranks determined from the AHP analysis.

Top Factor	Weight	Subfactor	Local Weight	Global Weight	Global Rank
Technology	0.427	Blockchain Technology	0.303	0.129	1
		Manufacturing Technology	0.288	0.123	2
		Data Analysis	0.138	0.059	9
		5G Technology	0.272	0.116	3
Organization	0.271	Organization Structure	0.135	0.037	11
		Organization Culture	0.178	0.048	10
		Human Resources	0.332	0.090	7
		Internal Processes	0.355	0.096	6
Environment	0.302	Market Trends	0.327	0.099	5
		Regulatory Environment	0.108	0.033	12
		Economic Factors	0.212	0.064	8
		Technological Innovations	0.353	0.106	4

5. Conclusions

5.1. Key Insights and Implications

This study leveraged the TOE model and CLD analysis to meticulously dissect the complex dynamics of 5G ceramic antenna manufacturing. The application of the TOE framework provided a structured approach to understand how technological, organizational, and environmental factors collectively influence this process. Utilizing the AHP, the study not only integrated insights on blockchain and smart contracts but also quantified the relative importance of the principal factors impacting the manufacturing process.

The integration of blockchain technology notably enhances the transparency, security, and operational efficiency of the manufacturing processes. This technology not only improves quality control but also provides a robust framework for managing the complexities inherent in a globalized supply chain. The systematic prioritization of key factors—technology, organization, and environment—through the AHP methodology has facilitated a nuanced understanding of their relative impacts. Moreover, the methodological consistency, validated by AHP’s $\lambda_{\max}$ values, *CI*, and *CR*, underscores the robustness of our findings. These results suggest that strategic applications of blockchain technology could serve as a catalyst for fostering innovation and enhancing the development process in 5G antenna manufacturing.

In conclusion, the study offers crucial insights for decision-makers in the telecommunications industry, presenting a strategic blueprint for the adoption of blockchain technology. By systematically understanding and addressing the key TOE factors, industry leaders can significantly optimize the efficiency and cost-effectiveness of 5G ceramic antenna manufacturing, paving the way for more innovative and competitive manufacturing practices in the high-tech sector.

5.2. Research Limitation and Future Plans

In recognizing the limitations of our research, it is important to note the context-specific nature of this study, which may limit the generalizability of our conclusions to different temporal and manufacturing contexts. The variability inherent in the diversity of expert opinions, a fundamental aspect of the AHP analysis, could introduce variations that affect the uniformity of the results across different expert cohorts. Additionally, the theoretical constructs employed by AHP, while robust, may not fully capture all the nuances of real-world manufacturing dynamics, particularly in terms of weight estimations and consistency evaluations.

The practical implementation of blockchain and smart contract technologies in manufacturing is not without challenges. These technologies could present technical issues that might impact the stability and reliability of manufacturing processes. However, integrating the TOE model with CLD analysis has provided a comprehensive understanding of the complex elements influencing 5G antenna manufacturing. This synthesis lays both quantitative and qualitative foundations for informed strategic decision-making. The consistency in expert opinions throughout our analysis reinforces the validity of this research and sets a robust platform for future inquiries aimed at overcoming the technical challenges associated with the implementation of blockchain and smart contracts in the 5G antenna manufacturing industry.

Future research should focus on validating the practical applicability of the proposed blockchain integration strategies through empirical studies and pilot projects in real-world manufacturing settings. This validation is crucial for confirming the efficacy and adaptability of the strategies in practical scenarios. Additionally, it is imperative to explore the synergies between blockchain technology and other emerging technologies such as AI and the IoT. These technologies hold significant promise for further revolutionizing the manufacturing processes of 5G ceramic antennas.

Given the nascent stage of blockchain technology adoption in the manufacturing sector, conducting longitudinal studies would also be valuable. Such studies could provide deeper insights into the long-term impacts and challenges associated with this technological integration, offering a clearer picture of the evolutionary trends in manufacturing technologies. Moreover, considering the interdependencies among various factors identified in our study, future research could explore the Analytic Network Process (ANP) for a more interconnected analysis. ANP would allow for a deeper investigation into the complex interactions and feedback loops that were visually depicted through CLD, enhancing the robustness and applicability of the findings to inform more dynamic and integrated strategic decisions.

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