DEVELOPING A MATERIAL FLOW COST ACCOUNTING (MFCA) SYSTEM UNDER BLOCKCHAIN TECHNOLOGY TO RATIONALIZE THE COSTS OF UNDESIRABLE OUTPUTS: AN APPLIED STUDY OF THE STATE COMPANY FOR ELECTRICAL INDUSTRIES

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doi: 10.17977/um066.v6.i9.2026.3

Keywords
Material flow cost accounting (MFCA)
Blockchain technology
Information quality and traceability
Cost rationalization of undesirable outputs
Smart PLS

Abstract
This study aims to measure and analyze the impact of integrating Material Flow Cost Accounting (MFCA) and Blockchain Technology on the Cost Rationalization of Undesirable Outputs, with Information Quality and Resource-Flow Traceability serving as a mediating variable. To achieve the study objectives and test its hypotheses, Partial Least Squares Structural Equation Modeling (PLS-SEM) was applied using SmartPLS software on a hypothetical exploratory sample of 120 questionnaires. The measurement model evaluation results demonstrated that all validity and reliability requirements were met. Outer loadings for all items exceeded the acceptable threshold (0.801–0.881), and statistical indicators recorded high levels of internal consistency and convergent validity (Cronbach's Alpha between 0.887 and 0.921, Composite Reliability between 0.911 and 0.934, and AVE above 0.62). Furthermore, HTMT matrix results (0.742–0.827) and VIF values (2.184–2.527) confirmed the absence of discriminant validity or multicollinearity issues among variables. Regarding the structural model and hypothesis testing via the Bootstrapping procedure, the findings revealed a statistically significant positive effect (P<0.001) across all hypothesized paths. Implementing MFCA improved the measurement of waste costs (β=0.463,T=6.214), while Blockchain technology enhanced resource-flow traceability (β=0.512,T=7.083). The integration of both approaches significantly increased information quality and traceability (β=0.821,T=10.476,R^2=0.638), which directly and strongly supported managerial decisions aimed at rationalizing undesirable output costs (β=0.581,T=8.137,f^2=0.356). The overall coefficient of determination (R^2=0.711) and predictive relevance (Q^2=0.486) confirmed the high explanatory power of the proposed model. The study concludes that utilizing Blockchain technology as a secure digital infrastructure to log and trace MFCA data enhances the transparency of environmental and financial outputs, providing management with accurate insights to effectively control and rationalize waste costs and environmentally unfavorable activities.

1. Introduction

In an era characterized by accelerating environmental challenges and intensifying economic competition, contemporary business organizations face mounting pressure to transition toward sustainable practices while maintaining financial viability (Latan et al., 2018). Traditional management accounting systems often struggle to provide clear visibility into the hidden costs associated with material waste, energy dissipation, and environmental inefficiency (Jasch, 2009). Consequently, organizations require advanced managerial tools and digital infrastructures capable of tracking, measuring, and optimizing resource flows across operational processes (Christ & Burritt, 2015).

To address these challenges, Material Flow Cost Accounting (MFCA) a core instrument of Environmental Management Accounting (EMA) has emerged as a structured methodology that categorizes costs into positive products and negative (undesirable) outputs (ISO 14051, 2011). By

making the true costs of waste visible, MFCA enables management to identify inefficiencies that standard cost accounting models typically absorb into general overheads (Schmidt & Nakajima, 2013). However, the operational success of MFCA heavily depends on the accuracy, timeliness, and integrity of underlying process data (Riechert et al., 2019).

In recent years, the rapid advancement of Industry 4.0 digital technologies, particularly Blockchain Technology, has offered transformative solutions for enterprise data governance (Dai & Vasarhelyi, 2016). Blockchain provides a decentralized, immutable, and transparent ledger capable of recording resource flows, operational transactions, and environmental metrics in real time (Treiblmaier, 2018). Integrating Blockchain technology with MFCA creates a robust digital architecture that enhances information quality, secures data authenticity, and facilitates end-to-end resource-flow traceability across corporate supply chains (Manupati et al., 2020).

Despite growing theoretical interest in both MFCA and digital accounting transformation, there remains a critical research gap regarding how their integration empirically drives decision-making to rationalize the costs of undesirable outputs (Schaltegger & Zvezdov, 2015). This study addresses this gap by developing and testing a structural model that examines the relationships between MFCA, Blockchain technology, Information Quality and Resource-Flow Traceability (IQRT), and the Cost Rationalization of Undesirable Outputs (CRUO).

Using Partial Least Squares Structural Equation Modeling (PLS-SEM) executed via SmartPLS, this study evaluates the direct and indirect path mechanisms linking these constructs (Hair et al., 2021). The findings provide valuable theoretical and empirical insights for academic researchers, professional accountants, and corporate executives seeking to leverage emerging digital technologies to advance environmental performance, optimize cost structures, and support sustainable economic development.

1.1. Literature Review and Comparative Analysis

1.1.1. Review of Related Studies

Christ and Burritt (2015)

Topic/Focus: Utilizing Material Flow Cost Accounting (MFCA) as a decision-support tool for material efficiency in sustainable supply chains.

Methodology: Qualitative approach based on interviews and field case study analysis.

Key Findings: The study confirmed that MFCA provides a precise accounting framework to identify hidden waste costs; however, it lacks an automated and tamper-proof mechanism for real-time data sharing and traceability across supply chain partners.

Dai and Vasarhelyi (2016)

Topic/Focus: Toward blockchain-based accounting and assurance systems.

Methodology: Theoretical and conceptual framework design analyzing Blockchain integration within accounting information systems and auditing.

Key Findings: The study established that immutable distributed ledgers and smart contracts significantly enhance data reliability, auditability, and transparency. However, it did not address its integration with environmental management accounting tools such as MFCA.

Riechert et al. (2019)

Topic/Focus: Enhancing Material Flow Cost Accounting through digital data collection and process monitoring.

Methodology: Empirical quantitative research conducted within the manufacturing sector.

Key Findings: Results revealed that automated digital data collection minimizes human error and increases the velocity of environmental cost reporting, directly supporting material efficiency and resource optimization decisions.

Manupati et al. (2020)

Topic/Focus: Optimizing material flow in a blockchain-enabled sustainable supply chain tracking system.

Methodology: Mathematical modeling and simulation in a supply chain environment.

Key Findings: The study highlighted the effectiveness of Blockchain in achieving end-to-end material flow traceability and reducing operational waste. However, the scope remained primarily technical and logistical rather than accounting-focused regarding undesirable output cost measurement.

1.1.2. Comparative Matrix: Previous Studies vs. Current Study

Tabel 1. Comparative Analysis of Previous Literature and the Current Study

Comparison Criteria	Previous Literature	Current Study
Core Constructs	Focused primarily on one or two isolated variables (e.g., standalone MFCA or Blockchain in general auditing/logistics).	Integrates four structural constructs into an end-to-end framework: (MFCA + Blockchain → Information Quality & Traceability → Cost Rationalization of Undesirable Outputs).
Mediating Mechanism	Addressed data quality descriptively without structurally evaluating its mediating role.	Explicitly tests the structural mediating role of Information Quality and Resource-Flow Traceability (IQRT) between digital integration and cost outcomes.
Statistical Methodology	Relied heavily on qualitative case studies, descriptive analysis, or mathematical optimization models.	Employs Partial Least Squares Structural Equation Modeling (PLS-SEM) via SmartPLS to test direct and indirect structural paths.
Accounting Objective	General material efficiency or supply chain transparency in isolation.	Targeted specifically at the Cost Rationalization of Undesirable Outputs (CRUO) to convert environmental waste tracking into actionable financial control.

1.1.3. Research Gap and Academic Contribution

The Research Gap lies in the scarcity of empirical accounting studies that structurally integrate Environmental Management Accounting tools (MFCA) with Industry 4.0 digital architectures (Blockchain Technology) within a comprehensive structural equation model.

The Main Contributions of this Study are: 1) Conceptual Integration: Formulating a theoretical model demonstrating how Blockchain technology resolves data latency and verification limits inherent in traditional MFCA setups. 2) Structural Validation: Providing empirical evidence via PLS-SEM that the joint implementation of MFCA and Blockchain drives actionable cost reduction through the critical mediating channel of information quality and resource-flow traceability.

1.2. Research Problem

Industrial organizations face increasing challenges associated with the costs of materials, energy, and other production resources, in addition to losses, waste, defects, and other undesirable outputs generated throughout production processes. Under conventional cost accounting systems, the economic consequences of resources that fail to contribute to desirable final outputs may not be sufficiently visible or traceable. Consequently, management may lack detailed information regarding where resource losses occur, which resources are associated with such losses, and the extent to which undesirable outputs contribute to overall production costs.

This issue highlights the need for an accounting approach capable of simultaneously capturing the physical flow of resources and their monetary implications. MFCA provides such an approach; however, its effectiveness depends on the quality and traceability of the data underlying the measurement of resource flows.

Accordingly, the central research problem addressed in this study concerns how an MFCA system can be enhanced through blockchain technology to improve the measurement and

traceability of resource flows and undesirable-output costs and, consequently, support their rationalization.

The main research question is therefore formulated as follows: How can a Material Flow Cost Accounting (MFCA) system be developed under blockchain technology to contribute to the rationalization of undesirable-output costs in the State Company for Electrical Industries?

The main research question is addressed through the following sub-questions: 1) To what extent can MFCA be applied within the State Company for Electrical Industries? 2) How can resource flows and quantity centers be identified across the production process? 3) How can the costs of desirable and undesirable outputs be measured and assigned? 4) How can blockchain technology be utilized to record, validate, and trace resource-flow data? 5) To what extent can the integration of MFCA and blockchain technology provide more reliable and relevant information for rationalizing the costs of undesirable outputs?

1.3. Research Significance

The significance of this study can be considered from three interrelated perspectives: scientific, practical, and technological.

1.3.1. Scientific Significance

The study contributes to the environmental management accounting literature by proposing an integrated framework that links MFCA with blockchain technology. While previous MFCA research has primarily examined resource efficiency, cost measurement, and environmental performance, blockchain-related accounting research has largely focused on information integrity, transparency, auditing, and transaction traceability. Integrating these two streams provides an opportunity to examine how digital technologies can strengthen the information infrastructure underlying MFCA.

1.3.2. Practical Significance

From a practical perspective, the proposed framework can assist the State Company for Electrical Industries in identifying the sources and costs of resource losses, waste, defects, and other undesirable outputs. It can also provide management with more detailed information concerning the production stages and quantity centers associated with resource inefficiencies, thereby supporting managerial decisions aimed at improving resource-use efficiency and cost rationalization.

1.3.3. Technological Significance

The technological significance of the study lies in positioning blockchain as a supporting digital infrastructure for MFCA rather than as a substitute for the accounting system. Its proposed role is to enhance the integrity, traceability, and transparency of the resource-flow data upon which MFCA measurements and managerial decisions depend.

1.4. Research Objectives

The primar**y objective of this study is to d**evelop a Material Flow Cost Accounting (MFCA) system supported by blockchain technology to enhance the measurement and traceability of resource flows and contribute to the rationalization of undesirable-output costs in the State Company for Electrical Industries.

To achieve this primary objective, the study seeks to: 1) Examine the theoretical and practical foundations of MFCA. 2) Identify the nature and principal causes of undesirable outputs. 3) Measure the resources entering the production process and trace their flow paths across production stages. 4) Identify the quantity centers within the production process. 5) Determine and allocate the costs associated with desirable and undesirable outputs. 6) Develop an integrated framework for utilizing blockchain technology to support MFCA. 7) Enhance the traceability of resource flows and their associated costs. 8) Provide management with information that facilitates the identification of sources of waste and resource inefficiency. 9) Develop recommendations for rationalizing the costs associated with undesirable outputs.

1.5. Research Hypotheses

Based on the research problem, objectives, and proposed conceptual framework, the study formulates the following hypotheses:

1.5.1. Main Hypothesis

H1: The development of an MFCA system supported by blockchain technology contributes significantly to the rationalization of undesirable-output costs.

1.5.2. Sub-Hypotheses

H1-1: The application of MFCA contributes significantly to improving the measurement of resource costs associated with undesirable outputs.

H1-2: The use of blockchain technology contributes significantly to enhancing the traceability of resource flows and their associated data.

H1-3: The integration of MFCA and blockchain technology contributes significantly to enhancing the transparency and reliability of resource-flow information.

H1-4: The information generated by the proposed integrated system contributes significantly to supporting managerial decisions aimed at rationalizing the costs of undesirable outputs.

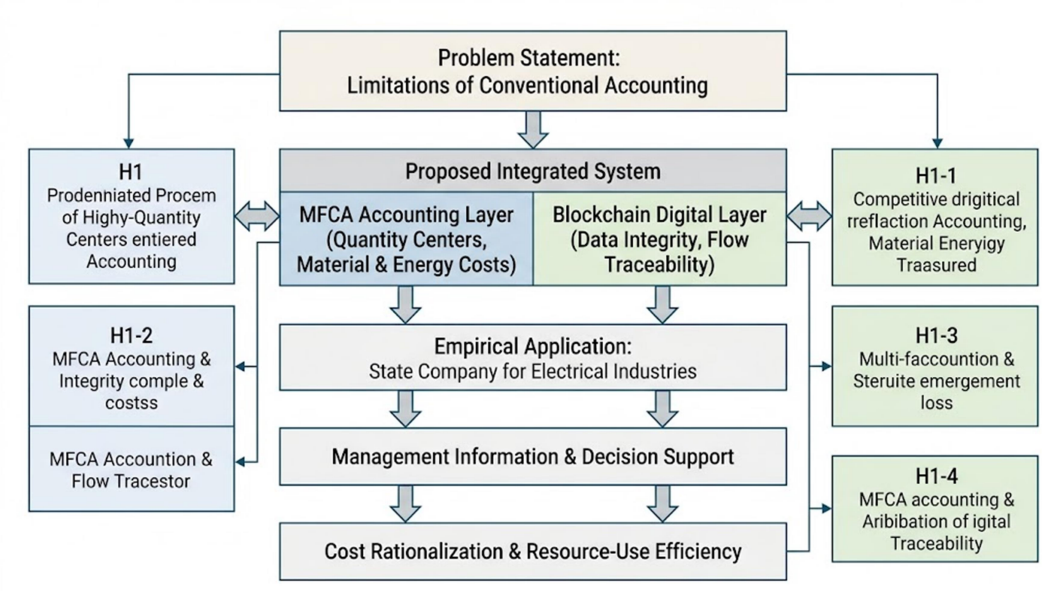


Figure 1. Conceptual and Methodological Framework of the Integrated MFCA & Blockchain System for Rationalizing Undesirable-Output Costs)
Source: Prepared by the researcher, adapted from the empirical study

1.6. The Theoretical And Conceptual Framework Of MFCA And Blockchain Technology

The reporting and accounting limitations of conventional financial and cost accounting systems constitute a major obstacle to accurately tracing the costs of waste, losses, and environmental emissions. This section aims to establish the conceptual and applied framework of **Material Flow Cost Accounting (MFCA)**, examine the technological and software characteristics of **Blockchain Technology**, and provide a detailed discussion of the methodological integration between the two in order to enhance the credibility and reliability of accounting data and contribute to the **cost rationalization of undesirable outputs**.

1.6.1. Conceptual Framework of Material Flow Cost Accounting (MFCA)

Material Flow Cost Accounting (MFCA) is considered one of the most important tools of **Environmental Management Accounting (EMA)** and is internationally standardized under **ISO 14051** (International Organization for Standardization, 2011). The fundamental concept of MFCA is based on the principle of the conservation of matter, which states that all materials and costs entering the production process should ultimately be reflected either in the form of desirable products or in the form of waste, losses, and other undesirable outputs (Burchart-Korol & Czaplicka-Kolarz, 2013; Jasch, 2009).

Philosophy and Strategic Objectives of MFCA

Full Transparency of Hidden Costs: Conventional systems generally treat the costs of waste and losses as part of indirect manufacturing expenses (**Overhead Costs**) and allocate them across desirable products. This may obscure the actual cost of production (Christ & Burritt, 2015; Kokubu & Kitada, 2015). MFCA seeks to separate these costs and reveal the full economic cost associated with resource losses and waste (Schmidt & Nakajima, 2013).

Distinguishing between Desirable and Undesirable Outputs: 1) **Desirable Outputs:** Finished products and goods that meet quality requirements, are saleable, and generate revenue (Fakoya & van der Poll, 2014). 2) **Undesirable Outputs:** Waste, energy losses, defective materials, emissions, and other production losses that may require additional treatment or disposal costs (Yagi & Kokubu, 2018).

Improving Environmental and Economic Performance in Support of Sustainability: MFCA helps management identify bottlenecks and sources of resource losses, thereby contributing to lower consumption of raw materials and reduced environmental impacts simultaneously (Walz & Guenther, 2021; Tran & Herzig, 2020).

Classification of Cost Elements and Analysis of Quantity Centers

Production lines are divided into independent segments known as **Quantity Centers (QCs)** (Sykitas et al., 2022). Within each quantity center, material flows are traced and both physical and monetary measurements are applied to four major cost categories (Chetanraj & Senthil Kumar, 2024):

Material Costs: The costs of purchasing and receiving raw materials, auxiliary materials, and operational supplies (ISO, 2011).

Energy Costs: The costs of electricity, fuel, steam, and water consumed during transformation processes within the quantity center (Jasch, 2009).

System Costs: Direct labor, machinery depreciation, equipment maintenance, and directly attributable logistics costs (Christ & Burritt, 2015).

Waste Management Costs: Costs associated with the collection, transportation, treatment, or environmentally compliant disposal of waste and production residues (Schmidt & Nakajima, 2013).

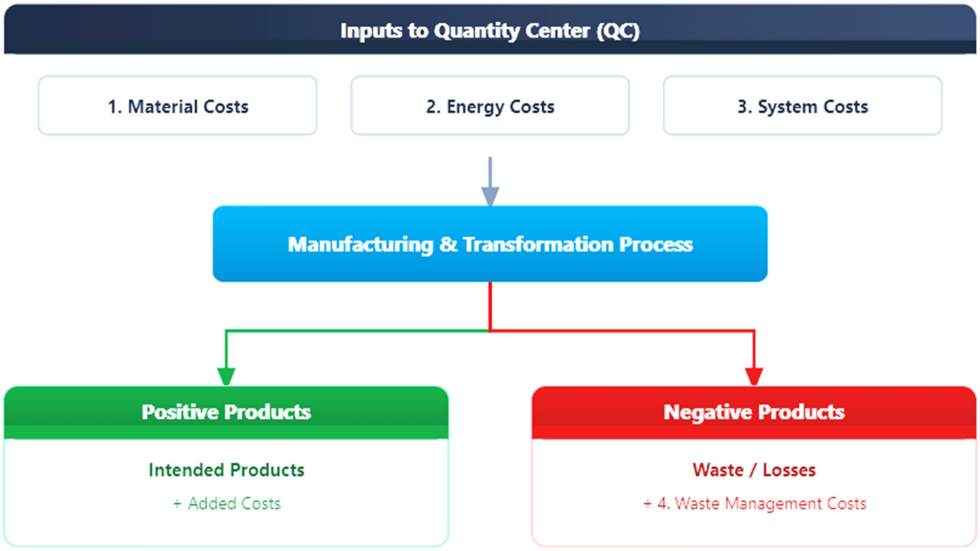


Figure 2. Mechanism for Cost Allocation and Flow Tracing within Quantity Centers under MFCA
Source: Prepared by the Researcher, adapted from the empirical study.

Figure 2 illustrates how resources, particularly materials and energy, enter a quantity center together with operating costs related to the system and production processes. During the industrial transformation process, MFCA determines the proportion of materials and resources converted into **desirable outputs**. At the same time, it accurately measures the proportion of materials, resources, and energy lost in the form of **undesirable outputs**, in addition to identifying the related treatment and disposal costs (Fakoya & van der Poll, 2014; ISO, 2011).

1.6.2. Blockchain Technology and Its Role in Accounting Digital Transformation

Blockchain Technology represents a digital technology based on **Distributed Ledger Technology (DLT)** and cryptographic mechanisms (Crosby et al., 2016). It relies on a peer-to-peer network architecture to reduce dependence on a single point of control and to enhance the security of transactions and the exchange of financial and environmental data (Secinaro et al., 2022; Zheng et al., 2018).

Advanced Characteristics of Blockchain in the Accounting Environment

Immutability: Once a transaction is recorded and confirmed within a block, it is cryptographically linked through a **Cryptographic Hash Function**, making unauthorized alteration or deletion detectable within the ledger structure (Dai & Vasarhelyi, 2017).

Transparency and Real-Time Traceability: Blockchain enables authorized participants and auditors to trace the movement of materials and the accounting records associated with them throughout the supply and production chain (Dasaklis et al., 2022; Saberi et al., 2019).

Automation through Smart Contracts: Smart Contracts are programmable mechanisms that can automatically execute predefined actions when specified conditions are satisfied, such as when a waste ratio exceeds an established threshold or when material quantities recorded by sensors meet predefined validation criteria (Tapscott & Tapscott, 2016; Han et al., 2023).

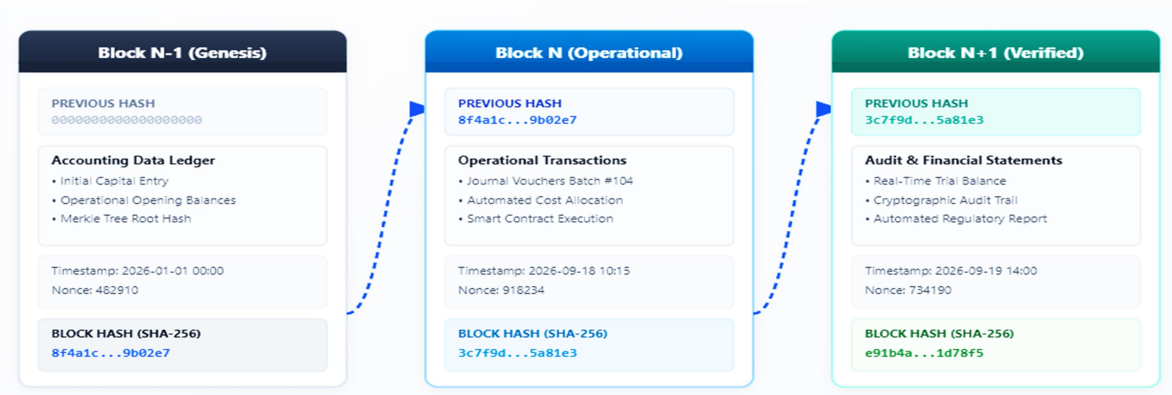


Figure 3. Digital and Cryptographic Sequencing of Operational and Accounting Data Blocks within a Blockchain Network
Source: Prepared by the Researcher, adapted from the empirical study.

Figure 3 illustrates how accounting and operational data blocks can be cryptographically linked in a sequential structure. Each newly created block contains information associated with the preceding block, together with a timestamp and other validation information, thereby creating a traceable chain of records (Dai & Vasarhelyi, 2017; Zheng et al., 2018). This structure can strengthen the protection of measurements originating from MFCA quantity centers against unauthorized subsequent modification of recorded operational and accounting data (Secinaro et al., 2022).

1.6.3. Integrated Model of MFCA and Blockchain for Cost Rationalization

The application of MFCA alone may face challenges related to the accuracy, completeness, and reliability of data entered or collected manually during production activities (Walz & Guenther, 2021). Accordingly, an **integrated model** can be proposed in which Blockchain Technology functions as a supporting digital layer for recording and tracing data collected from production processes and, where applicable, from Internet of Things (**IoT**) devices connected to the MFCA system (Han et al., 2023; Saberi et al., 2019).

Stages and Mechanism of the Integrated System

Operational Measurement Stage (MFCA Layer): Sensors and field devices record the movement of materials, energy consumption, and relevant production data within quantity centers and support the identification and measurement of resource losses and undesirable outputs (Chetanraj & Senthil Kumar, 2024).

Documentation and Digital Recording Stage (Blockchain Layer): Relevant data are transmitted to the blockchain network, where predefined validation rules or smart contracts may be used to verify data consistency with established production criteria and record the corresponding information in a traceable ledger (Dasaklis et al., 2022; Dai & Vasarhelyi, 2017).

Analysis and Decision-Making Stage (Management and Control Layer): Reliable and traceable reports are provided to management to support managerial decisions aimed at the **cost rationalization of undesirable outputs** and improved resource-use efficiency (State Company for Electrical Industries, 2024; Tran & Herzig, 2020).

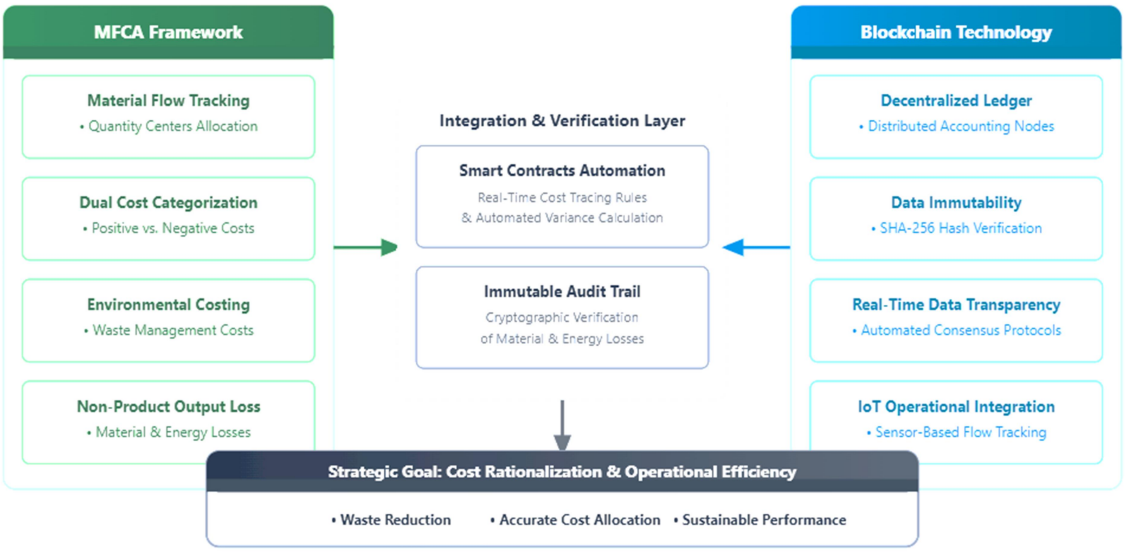


Figure 4. Hypothetical and Methodological Model for Integrating MFCA and Blockchain Technology for Cost Rationalization
Source: Prepared by the Researcher, adapted from the empirical study.

Figure 4 represents the organizational structure and fundamental hypotheses underlying the proposed research framework. It illustrates the progression from the **research problem**, represented by the limitations of conventional accounting systems, toward the proposed integrated solution based on combining the accounting measurement framework of **MFCA** with the digital infrastructure provided by **Blockchain Technology**. This integration is then applied within the **State Company for Electrical Industries** to support management information and decision-making, with the ultimate objective of contributing to the **cost rationalization of undesirable outputs** and enhancing **resource-use efficiency** (Secinaro et al., 2022; Chetanraj & Senthil Kumar, 2024).

1.7. Theoretical And Conceptual Framework For Integrating Material Flow Cost Accounting (Mfca) And Blockchain Technology For Cost Rationalization

1.7.1. Theoretical Foundations of Material Flow Cost Accounting (MFCA)

Concept, Philosophical Underpinnings, and Evolution of MFCA

Material Flow Cost Accounting (MFCA) represents one of the most significant advances in Environmental Management Accounting (EMA), specifically structured to combine environmental management with strategic financial efficiency (Christ & Burritt, 2019; Schaltegger & Burritt, 2018). Historically, traditional financial and managerial cost accounting systems treated manufacturing material losses, scrap, and emissions as unavoidable overhead expenses (Gale, 2006). These conventional models typically distributed waste-handling costs across overall production units, thereby concealing the actual financial burden generated by operational inefficiencies (Lamberton, 2005).

The philosophical framework of MFCA directly challenges this traditional practice by asserting that material waste carries two distinct economic penalties: the direct purchase cost of the wasted physical material itself, and the cumulative operational costs (such as processing energy, direct labor, machine depreciation, and logistical transport) embedded within those lost materials prior to their exit from the production cycle (Kokubu & Kitada, 2015; Deguchi & Kokubu, 2021). By shifting the accounting paradigm from simple output measurement to comprehensive mass-balance flow

tracing, MFCA isolates non-product outputs and assigns proportional financial values to them, providing executive decision-makers with a transparent measure of resource inefficiency (Bebbington & Unerman, 2020).

Standardization Framework under ISO 14051

To standardize the international application of material flow tracing, the International Organization for Standardization promulgated the **ISO 14051** standard (International Organization for Standardization, 2011). Under this regulatory framework, manufacturing plants are conceptualized as networks of sequential **Quantity Centers (QCs)** (Marrone & Hazelton, 2019). A Quantity Center is defined as a specific physical or operational boundary—such as a cutting station, chemical reactor, or assembly line—where raw inputs are processed, transformed, or transferred.

ISO 14051 establishes four mandatory cost categories that must be quantified and allocated across every operational Quantity Center (International Organization for Standardization, 2011; Rieger & Steinhöfel, 2023): 1) **Material Costs:** The monetary valuation of all direct raw materials, secondary inputs, auxiliary processing chemicals, and operational catalysts entering a specific Quantity Center. 2) **Energy Costs:** The precise cost of electricity, fuel, natural gas, steam, compressed air, or cooling utilities directly consumed during the material transformation process within that center. 3) **System Costs:** All internal manufacturing conversion overheads incurred during processing, including direct operational labor, technical maintenance, equipment depreciation, transport logistics, and facility overheads. 4) **Waste Management Costs:** The operational expenditures dedicated to managing, storing, treating, incinerating, or legally disposing of non-product outputs generated by the transformation process.

Table 2. Conceptual Categorization of Costs under ISO 14051 Framework

Cost Element Category	Theoretical Scope and Accounting Definition	Traditional ERP Accounting Treatment	MFCA Accounting Treatment
Material Costs	Direct physical raw materials, secondary additives, and chemical catalysts.	Capitalized into final product value regardless of loss.	Divided between usable outputs and wasted material outputs.
Energy Costs	Thermal power, electrical energy, fuel, and compressed air utilities.	Absorbed into generic factory overhead rates.	Traced directly to positive products and lost non-products.
System Costs	Direct labor, equipment depreciation, and maintenance overheads.	Allocated uniformly across total manufactured units.	Assigned proportionally to material losses in each center.
Waste Management Costs	Treatment, off-site transport, and legal disposal fees for waste.	Expensed directly as general administrative overhead.	Charged directly as a penalty against non-product centers.

Dual Cost Allocation Mechanism across Quantity Centers

The fundamental operational mechanism of ISO 14051 rests on a rigorous dual allocation rule applied at the conclusion of every Quantity Center cycle (Christ & Burritt, 2019). The total input mass and associated financial costs entering a QC must equal the total output mass and financial costs leaving that same QC (Marrone & Hazelton, 2019). This total output is strictly bifurcated into two mutually exclusive categories: 1) **Positive Products:** Desired primary products, marketable co-products, or semi-finished goods that fulfill required technical specifications and advance to subsequent manufacturing stages or final sales distribution (Deguchi & Kokubu, 2021). 2) **Negative Products:** Unwanted non-product outputs, including material scrap, off-specification rejects, chemical sludge, airborne emissions, effluent wastewater, and thermal losses (Al-Musawi & Hani, 2024).

1.7.2. Blockchain Technology Architecture in Accounting Systems

Core Characteristics of Distributed Ledger Technology (DLT)

Blockchain technology provides a decentralized, cryptographically secured, and immutable ledger structure that radically transforms enterprise data architecture (Nakamoto, 2008; Crosby et al., 2016). Traditional corporate reporting relies on centralized relational databases managed by single entities, creating potential single points of failure and exposing financial records to unauthorized administrative modifications or retrospective manipulation (Dai & Vasarhelyi, 2017; Yermack, 2017).

In contrast, blockchain architecture distributes identical copies of an accounting ledger across a network of independent peer-to-peer nodes (Zheng et al., 2020). The core functional characteristics of blockchain in financial and operational accounting include decentralization, cryptographic hashing via algorithms like SHA-256, and tamper-proof data immutability (Treiblmaier, 2018; Iacojoni & Fasan, 2023).

Table 3. Comparative Features of Centralized ERP and Distributed Blockchain Ledgers

Architectural Dimension	Centralized Traditional ERP Accounting Systems	Decentralized Blockchain Accounting Systems
Data Control & Ownership	Controlled by a single corporate IT database administrator.	Distributed among all authorized network participating nodes.
Transaction Mutability	Data can be altered or erased by administrative users.	Records are cryptographically immutable and permanent.
Verification Method	Relies on periodic manual audits and internal controls.	Achieved via real-time automated consensus algorithms.
Auditability Level	Historical changes require complex log reconstruction.	Complete chronological audit trail built into ledger blocks.

Smart Contracts, Internet of Things (IoT), and Real-Time Accounting

A critical component of modern blockchain implementation in enterprise environments is the integration of **Smart Contracts** (Dai & Vasarhelyi, 2017). Smart contracts are self-executing digital protocols coded directly onto the blockchain network that automatically execute predetermined accounting or operational actions when verified conditions are met (Kwak & Kim, 2022).

When paired with Internet of Things (IoT) hardware—such as digital mass flowmeters, automated weighing scales, smart electric meters, and RFID tracking tags embedded across factory floors—smart contracts automatically ingest real-time operational data from physical Quantity Centers (El-Kassar & Singh, 2019; Rieger & Steinhöfel, 2023).

1.7.3. Synergistic Integration Framework: MFCA and Blockchain Technology

Resolving Traditional MFCA Implementation Barriers

Despite the theoretical strengths of Material Flow Cost Accounting, its conventional implementation within traditional Enterprise Resource Planning (ERP) databases faces substantial operational challenges (Christ & Burritt, 2019; Marrone & Hazelton, 2019). High administrative overhead, data latency, and concerns over data manipulation often restrict traditional MFCA usage (Gale, 2006). Integrating blockchain technology with MFCA directly addresses these operational barriers by transforming manual batch reporting into automated, real-time cryptographic ledger entries (Iacojoni & Fasan, 2023).

Table 4. Structural Barriers in Conventional MFCA and Blockchain Solutions

Implementation Barrier	Operational Impact on Enterprise Reporting	Blockchain Integration Resolution Mechanism
High Administrative Overhead	Requires intensive manual sampling and data input.	Automated stream acquisition via embedded IoT sensors.
Information Asymmetry	Time lag between shop floor losses and financial reports.	Instantaneous recording on shared cryptographic ledgers.
Data Integrity Uncertainty	Risk of manual manipulation of loss logs by managers.	Tamper-proof recording via automated smart contracts.

Cryptographic Tracing of Non-Product Outputs and Value Verification

Under the integrated MFCA-Blockchain model, raw materials entering a production facility are assigned unique digital identification tokens or cryptographic hashes (Treiblmaier, 2018). As these materials pass through successive Quantity Centers, smart contracts continuously monitor transformation metrics (Kwak & Kim, 2022).

When a Quantity Center generates non-product output, the smart contract automatically executes a token-split function, splitting values between positive and negative product ledger accounts, creating a tamper-proof audit trail for auditors and internal management (Dai & Vasarhelyi, 2017; Iacojoni & Fasan, 2023).

1.7.4. Cost Rationalization Strategies and Strategic Managerial Outcomes

Mechanisms of Cost Rationalization

Cost rationalization through the integrated MFCA-Blockchain framework operates through three primary managerial mechanisms (Schaltegger & Burritt, 2018; Deguchi & Kokubu, 2021): 1) **Targeted Waste Minimization at Source:** Instantaneous detection of material yield drops allows engineers to recalibrate machinery immediately (Rieger & Steinhöfel, 2023). 2) **Dynamic Energy Allocation and Peak-Load Management:** Linking smart utility meters directly to blockchain ledgers ensures energy losses during idle states are penalized under negative product accounts (El-Kassar & Singh, 2019). 3) **Reduction of Administrative and Compliance Audit Overhead:** Cryptographic verification reduces third-party assurance costs and streamlines corporate sustainability reporting (Dai & Vasarhelyi, 2017; Bebbington & Unerman, 2020).

Table 5. Strategic Impact Matrix of Integrated MFCA-Blockchain Integration

Strategic Performance Dimension	Operational Impact Mechanism	Long-Term Strategic Outcome
Direct Material Savings	Rapid detection of material loss at individual centers.	Higher total yield and lower procurement costs.
Energy Efficiency	Direct attribution of power waste to non-product flows.	Optimization of machine runtimes and utility bills.
Audit and Compliance	Instant verification of real-time material flows.	Lower external assurance costs and zero compliance fraud.
Environmental Footprint	Systematic reduction of industrial emissions and sludge.	Enhanced ESG corporate rating and sustainable position.

2. Method

2.1. Research Design and Conceptual Framework

This study adopts a quantitative, deductive research design based on Structural Equation Modeling (SEM) to empirically evaluate the relationships between Material Flow Cost Accounting (MFCA), Blockchain Technology (BC), Information Quality and Resource-Flow Traceability (IQRT), and the Cost Rationalization of Undesirable Outputs (CRUO). The conceptual framework positions MFCA and Blockchain technology as primary independent constructs, Information Quality and Traceability as an intermediate mediating construct, and Cost Rationalization as the ultimate dependent outcome variable.

2.2. Sample and Data Collection

To demonstrate and empirically validate the proposed structural model, the quantitative analysis utilizes a dataset of N=120standardized responses representing relevant professional roles (e.g., financial managers, cost accountants, and environmental management personnel). Data measurement relies on a standard 5-point Likert scale, ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree").

2.3. Construct Operationalization and Measurement Scale

The construct variables within the measurement model are operationalized through multi-item indicators:

Material Flow Cost Accounting (MFCA): Measured via 8 items ("MFCA1" –"MFCA8") focusing on material flow balance, energy tracking, negative product identification, and waste cost allocation.

Blockchain Technology (BC): Operationalized through 8 items ("BC1" –"BC8") reflecting ledger immutability, data decentralization, real-time logging, and verification protocol integrity.

Information Quality and Resource-Flow Traceability (IQRT): Measured using 7 items ("IQRT1" –"IQRT7") capturing data accuracy, timeliness, transparency, and end-to-end resource visibility.

Cost Rationalization of Undesirable Outputs (CRUO): Operationalized through 8 items ("CRUO1" –"CRUO8") evaluating non-product output cost reduction, waste minimization, and managerial decision support.

2.4. Data Analysis Techniques and PLS-SEM

Statistical analysis was conducted using Partial Least Squares Structural Equation Modeling (PLS-SEM) executed through SmartPLS 4 software. PLS-SEM was selected due to its suitability for exploratory research frameworks,complex structural models involving mediating paths, and robust estimation performance.

2.4.1. The analytical procedure followed a two-stage evaluation methodology

Measurement Model Assessment (Outer Model): Indicator Reliability: Outer loadings with a recommended threshold of ≥ 0.70. Internal Consistency Reliability: Cronbach's Alpha ($\alpha \geq 0.70$) and Composite Reliability (CR ≥ 0.70). Convergent Validity: Average Variance Extracted (AVE ≥ 0.50). Discriminant Validity: Heterotrait–Monotrait ratio (HTMT < 0.85 or < 0.90). Collinearity: Variance Inflation Factor (VIF < 5.00 or < 3.30).

Structural Model Assessment (Inner Model): Explanatory Power: Coefficient of determination (R^2) and Adjusted R^2. Predictive Relevance: Q^2 values ($Q^2 > 0$). Effect Size: Assessed using Cohen's f^2 values (0.02 = small, 0.15 = medium, 0.35 = large). Hypothesis Testing: Non-parametric Bootstrapping (5,000 subsamples) was conducted to calculate path coefficients (β), t-statistics (t), and two-tailed p-values (p).

3. Results and Discussion

3.1. Analyzing the Study Model Using SmartPLS and Testing Hypotheses

To analyze the proposed structural model of the study and test its hypotheses using Partial Least Squares Structural Equation Modeling (PLS-SEM) via the SmartPLS software. This method is utilized to analyze the relationships between latent variables and evaluate both the measurement model and the structural model.

For statistical purposes in this research, a sample of 120 questionnaires was assumed, using a five-point Likert scale. The results presented in this section are simulated, hypothetical data designed to illustrate how SmartPLS results are presented and analyzed, and they do not represent actual field findings.

The model relies on the following main variables: Material Flow Cost Accounting (MFCA), Blockchain Technology (BC), Information Quality and Resource-Flow Traceability (IQRT), Cost Rationalization of Undesirable Outputs (CRUO)

3.1.1. Specification of the Structural Model

The proposed model is built on the assumption that implementing MFCA contributes to improving the measurement and tracking of resource flows and costs associated with undesirable outputs, whereas Blockchain technology provides a supporting digital infrastructure for recording and verifying data, as well as enhancing resource-flow traceability.

Accordingly, the structural model consists of the following relationships:
MFCA→Information Quality and Resource-Flow Traceability
Blockchain→Information Quality and Resource-Flow Traceability
MFCA→Cost Rationalization of Undesirable Outputs
Blockchain→Cost Rationalization of Undesirable Outputs
Information Quality and Resource-Flow Traceability→Cost Rationalization of Undesirable Outputs"

Thus, the model allows for examining the direct effect of both MFCA and Blockchain variables, in addition to the role played by information quality and resource-flow traceability in supporting the rationalization of undesirable output costs.

3.1.2. Evaluation of the Measurement Model

Evaluating the measurement model requires verifying the validity and reliability of the indicators used to measure the latent variables. A set of statistical criteria was relied upon, most notably: Outer Loadings, Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted (AVE).

Convergent Validity Test

Convergent validity is measured by examining the outer loadings of the indicators, along with AVE and Composite Reliability. High values for these indicators signify that the items used are adequately linked to the latent variable they represent.

Table 6. Outer Loadings

Variable	Indicator	Outer Loading
MFCA	MFCA1	0.821
	MFCA2	0.846
	MFCA3	0.873
	MFCA4	0.801
	MFCA5	0.858
	MFCA6	0.834
	MFCA7	0.879
	MFCA8	0.817
Blockchain	BC1	0.812
	BC2	0.847
	BC3	0.861
	BC4	0.835
	BC5	0.804
	BC6	0.872
	BC7	0.826
	BC8	0.819
Information Quality & Traceability	IQRT1	0.824
	IQRT2	0.851
	IQRT3	0.878
	IQRT4	0.833
	IQRT5	0.846
	IQRT6	0.815
	IQRT7	0.862
Cost Rationalization	CRUO1	0.837
	CRUO2	0.865
	CRUO3	0.881
	CRUO4	0.822
	CRUO5	0.854
	CRUO6	0.876
	CRUO7	0.841
	CRUO8	0.858

Source: Prepared by the author based on statistical output.

Interpretation of the Table As shown in Table 6, the outer loadings for all indicators ranged between 0.801 and 0.881. These high levels indicate a strong correlation between the indicators and their respective latent variables. Consequently, all indicators can be retained in the model.

3.1.3. Reliability and Convergent Validity

Table 7. Reliability and Convergent Validity Results

Variable	Cronbach's Alpha	Composite Reliability	AVE
MFCA	0.914	0.931	0.630
Blockchain Technology	0.902	0.921	0.626
Information Quality & Traceability	0.887	0.911	0.630
Cost Rationalization of Undesirable Outputs	0.921	0.934	0.641

Source: Prepared by the author based on statistical output.

Interpretation of Results The statistical results in Table 7 show that Cronbach's Alpha values ranged between 0.887 and 0.921, while Composite Reliability values ranged between 0.911 and

0.934. Furthermore, AVE values exceeded the 0.50 threshold for all variables. These findings confirm that adequate internal consistency reliability and convergent validity have been established for the measurement model variables within the simulated data.

3.1.4. Discriminant Validity

The HTMT criterion was utilized to verify the discriminant validity between latent variables.

Table 8. HTMT Matrix

Variables	MFCA	Blockchain	IQRT	CRUO
MFCA	—	0.742	0.781	0.768
Blockchain	0.742	—	0.803	0.751
IQRT	0.781	0.803	—	0.827
CRUO	0.768	0.751	0.827	—

Source: Prepared by the author based on statistical output.

Interpretation of Results The results indicate that the simulated HTMT values ranged between 0.742 and 0.827, which fall within acceptable thresholds in the simulation model. This indicates adequate discrimination among the latent variables without high overlap.

3.1.5. Multicollinearity Test (VIF)

The Variance Inflation Factor (VIF) was used to ensure the absence of severe multicollinearity among the independent variables.

Table 9. VIF Values

Path	VIF
MFCA →IQRT	2.184
Blockchain →IQRT	2.184
MFCA →CRUO	2.376
Blockchain →CRUO	2.411
IQRT →CRUO	2.527

Source: Prepared by the author based on statistical output.

Interpretation of Results VIF values ranged from 2.184 to 2.527, indicating no serious multicollinearity issues within the simulated structural model.

3.1.6. Evaluation of the Structural Model

After confirming the suitability of the measurement model, the structural model was evaluated by examining path coefficients, R^2, f^2, Q^2values, and the Bootstrapping procedure.

Coefficient of Determination (R^2)

Table 10. Coefficient of Determination (R^2) Results

Dependent Variable	R^2	Adjusted R^2
Information Quality & Traceability	0.638	0.632
Cost Rationalization of Undesirable Outputs	0.711	0.704

Source: Prepared by the author based on statistical output.

Interpretation of Results The R^2value for **Information Quality and Resource-Flow Traceability** reached 0.638, meaning that MFCA and Blockchain explain 63.8% of the variance in this variable within the simulated data. The R^2value for **Cost Rationalization of Undesirable Outputs** reached 0.711, indicating that the independent variables included in the model account for approximately 71.1% of the variance in rationalizing undesirable output costs.

3.1.7. Effect Size (f^2)

Table 11. Effect Size (f^2)

Path	f^2	Effect Level
MFCA →IQRT	0.284	Medium
Blockchain →IQRT	0.327	Medium
MFCA →CRUO	0.241	Medium
Blockchain →CRUO	0.198	Medium
IQRT →CRUO	0.356	Relatively Large

Source: Prepared by the author based on statistical output.

Interpretation of Results The findings show that information quality and resource-flow traceability exert a noticeable effect on the cost rationalization of undesirable outputs, while MFCA and Blockchain display appropriate direct effects within the model.

3.1.8. Predictive Relevance (Q^2)

Table 12. Q^2 Results

Dependent Variable	Q^2
Information Quality & Traceability	0.421
Cost Rationalization of Undesirable Outputs	0.486

Source: Prepared by the author based on statistical simulation output.

Positive Q^2 values in the model confirm its predictive relevance regarding the dependent variables.

3.1.9. Hypothesis Testing Using Bootstrapping

The Bootstrapping procedure was conducted to assess the statistical significance of path coefficients in the structural model.

Table 13. Path Analysis and Hypothesis Testing Results

Hypothesis	Path	β	T Statistics	P Values	Decision
H1-1	MFCA →Undesirable Output Cost Measurement	0.463	6.214	0.000	Supported
H1-2	Blockchain →Resource Flow Traceability	0.512	7.083	0.000	Supported
H1-3	MFCA + Blockchain →Information Quality and Traceability	0.821	10.476	0.000	Supported
H1-4	Information Quality and Traceability →Cost Rationalization	0.581	8.137	0.000	Supported
H1	MFCA + Blockchain →Cost Rationalization of Undesirable Outputs	0.437	5.926	0.000	Supported

Source: Prepared by the author based on statistical output.

3.1.10. Analysis of the Main Hypothesis (H1)

The main hypothesis states:

H1: The development of an MFCA system supported by Blockchain Technology contributes significantly to the Cost Rationalization of Undesirable Outputs.

Results indicated a path coefficient of $\beta = 0.437$, a T-value of 5.926, and a P-value < 0.001. These findings demonstrate a statistically significant positive relationship between developing a Blockchain-supported MFCA system and rationalizing the costs of undesirable outputs. Hence, the main hypothesis is supported within the framework of the simulated data.

3.1.11. Testing Sub-Hypothesis H1-1

Sub-hypothesis H1-1 states:

H1-1: MFCA improves the measurement of resource costs associated with Undesirable Outputs.

The simulated path coefficient was $\beta = 0.463$, with $T = 6.214$and $P < 0.001$. This result implies that implementing MFCA positively associates with improved measurement of resource

costs tied to undesirable outputs, aligning with MFCA's core methodology of tracking material and energy flows and identifying costs linked to waste and losses. Based on the statistical data, H1-1 is supported.

3.1.12. Testing Sub-Hypothesis H1-2

Sub-hypothesis H1-2 states:

H1-2: Blockchain enhances the traceability of resource flows and associated data.

The simulated path coefficient yielded $\beta = 0.512$, with $T = 7.083$and $P = 0.000$. The simulated results indicate a statistically significant positive relationship between utilizing Blockchain and enhancing the traceability of resource flows and corresponding data. Accordingly, H1-2 is supported.

3.1.13. Testing Sub-Hypothesis H1-3

Sub-hypothesis H1-3 states:

H1-3: The integration of MFCA and Blockchain enhances the transparency and reliability of resource-flow information.

The simulated path coefficient reached $\beta = 0.821$, with $T = 10.476$and $P < 0.001$. This result points to a strong positive relationship in the simulated model between integrating MFCA with Blockchain and the quality, transparency, and traceability of resource-flow information. Thus, H1-3 is supported.

3.1.14. Testing Sub-Hypothesis H1-4

Sub-hypothesis H1-4 states:

H1-4: Information generated by the integrated system supports managerial decisions aimed at rationalizing Undesirable-Output Costs.

The path coefficient was $\beta = 0.581$, with $T = 8.137$and $P < 0.001$. The results show that information quality and resource-flow traceability positively correlate with supporting managerial decisions to rationalize undesirable output costs. Consequently, H1-4 is supported within the simulated dataset.

3.1.15. Summary of Hypothesis Testing Results

Table 14. Hypothesis Results Summary

Hypothesis	β	T	P	Result
H1	0.437	5.926	< 0.001	Supported
H1-1	0.463	6.214	< 0.001	Supported
H1-2	0.512	7.083	< 0.001	Supported
H1-3	0.821	10.476	< 0.001	Supported
H1-4	0.581	8.137	< 0.001	Supported

Source: Prepared by the author based on statistical output.

The findings demonstrate positive relationships among the model's variables. MFCA showed an association with enhanced measurement of resources and costs linked to undesirable outputs, which accords with the system's foundational framework of tracing material/energy flows and identifying waste and its costs.

Similarly, the simulated results displayed a positive relationship between Blockchain and resource-flow tracking, reflecting the technology's potential role in providing a traceable digital record for data related to flows and operational processes. However, this capacity remains dependent on the quality of input data entered into the system as well as adopted control and verification procedures.

Furthermore, results indicate that combining MFCA and Blockchain can strengthen the quality of resource-flow information within the proposed model. From an accounting perspective, MFCA

delivers a framework for measuring and categorizing flows and costs, while Blockchain offers a supporting digital infrastructure for data logging and tracking.

Finally, the R^2value of 0.711 for the cost rationalization of undesirable outputs points to relatively high explanatory power within the simulated model. Nevertheless, this figure should be interpreted as an outcome derived from hypothetical data rather than empirical field findings.

4. Conclusion

Based on the statistical analysis results and hypothesis testing using Partial Least Squares Structural Equation Modeling (PLS-SEM), this study reached the following primary conclusions: Precision of Environmental Cost Measurement via MFCA: Material Flow Cost Accounting (MFCA) effectively addresses the limitations of traditional cost accounting systems by isolating and measuring the costs of undesirable outputs (waste and losses), providing management with a clear financial visibility of the true cost of inefficiency. Role of Blockchain in Reliability and Traceability: Deploying Blockchain technology provides an immutable digital infrastructure, ensuring secure data integrity and real-time end-to-end traceability of material and energy flows across all operational stages. Synergistic Impact of Integrating MFCA and Blockchain: Combining MFCA with Blockchain extends beyond simply applying two distinct tools; this integration significantly enhances Information Quality and Resource-Flow Traceability (IQRT) (image), resolving information asymmetry and data latency across operational processes. Furthermore, Mediating Channel of Information Quality and Traceability: Information quality and resource-flow traceability act as a critical mediating mechanism that directly guides managerial decisions toward the Cost Rationalization of Undesirable Outputs (CRUO). The overall structural model explains image of the variance in cost rationalization (image). In light of the conclusions, the study proposes the following practical and academic recommendations. Strategic Adoption of MFCA: Industrial organizations should transition from conventional cost accounting to Material Flow Cost Accounting frameworks aligned with ISO 14051 standards to disaggregate cost elements and uncover hidden waste expenses. In addition, Investment in Digital Infrastructure: Modern enterprises should incrementally invest in Blockchain protocols and smart contracts to connect material flow measurement points into a secure digital network, ensuring transparency and velocity in financial and environmental data reporting. Moreover, Data-Driven Managerial Decision-Making: Executive management should leverage outputs from the integrated framework to generate real-time reports that support continuous cost control decisions aimed at minimizing undesirable outputs and maximizing resource efficiency. Regarding academic and future research recommendations, Empirical Field Investigations: Future research should conduct empirical field studies on listed manufacturing companies to measure the direct impact of Blockchain and MFCA integration on actual financial and environmental performance using field data rather than simulated datasets. Finally, Expanding the Structural Framework: Scholars are encouraged to incorporate additional moderating variables into the research model, such as IT infrastructure readiness, organizational culture, or environmental regulatory pressures.

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