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BLOCKCHAIN INTEGRATION IN SUSTAINABLE SUPPLY CHAINS: MEASURING ITS CONTRIBUTION TO CIRCULAR ECONOMY GOALS

Mateusz Zaczyk, PhD Eng.
Silesian University of Technology
Gliwice, Poland

Presentation plan

RECENT PUBLICATIONS IN THE FIELD

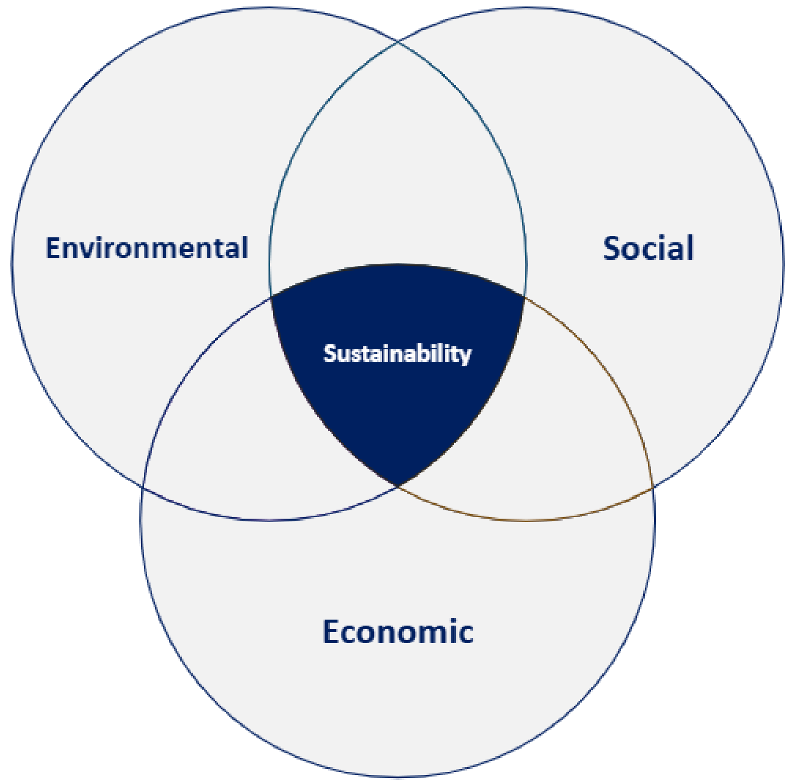
Mateusz Zaczyk, PhD Eng.

1) „Conditions for the use of the blockchain technology in logistics - a review"
2) „Key areas of blockchain technology application in Logistics"
3) „Distributed ledger technology for supply chain and public governance as a response for sustainability issues"
4) „The concept of a decentralized autonomous organization as an innovative organizational structure"
5) „Blockchain technology for supply chain management in the context of AI-based solutions"
6) „Areas of blockchain technology application in modern cities – Part I"
7) „Areas of blockchain technology application in modern cities – Part II"
8) „Building supply chain resilience: how blockchain technology addresses vulnerabilities and strengthens capabilities"

Context: Blockchain and Sustainable Supply Chains

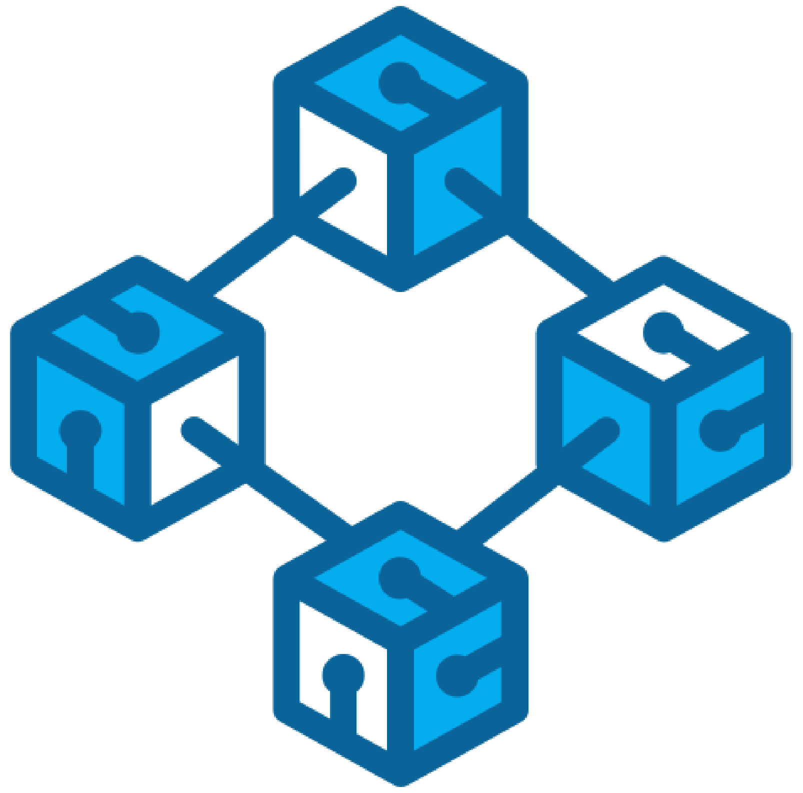
- The role of supply chains in the global economy is multifaceted, encompassing **efficiency**, **sustainability**, and the **integration** of diverse economic activities.
- Supply chains facilitate **the movement of goods and services** across borders, creating interdependencies among nations and industries.
- This interconnectedness not only enhances **economic growth** but also shapes **cultural exchanges** and influences **local economies**.

A sustainable supply chain is defined as a system that integrates environmental, social, and economic considerations into supply chain management, aiming to minimize negative impacts while maximizing benefits for all stakeholders.



- Environmental Responsibility
- Social Equity
- Economic Viability

Does blockchain adress those elements?



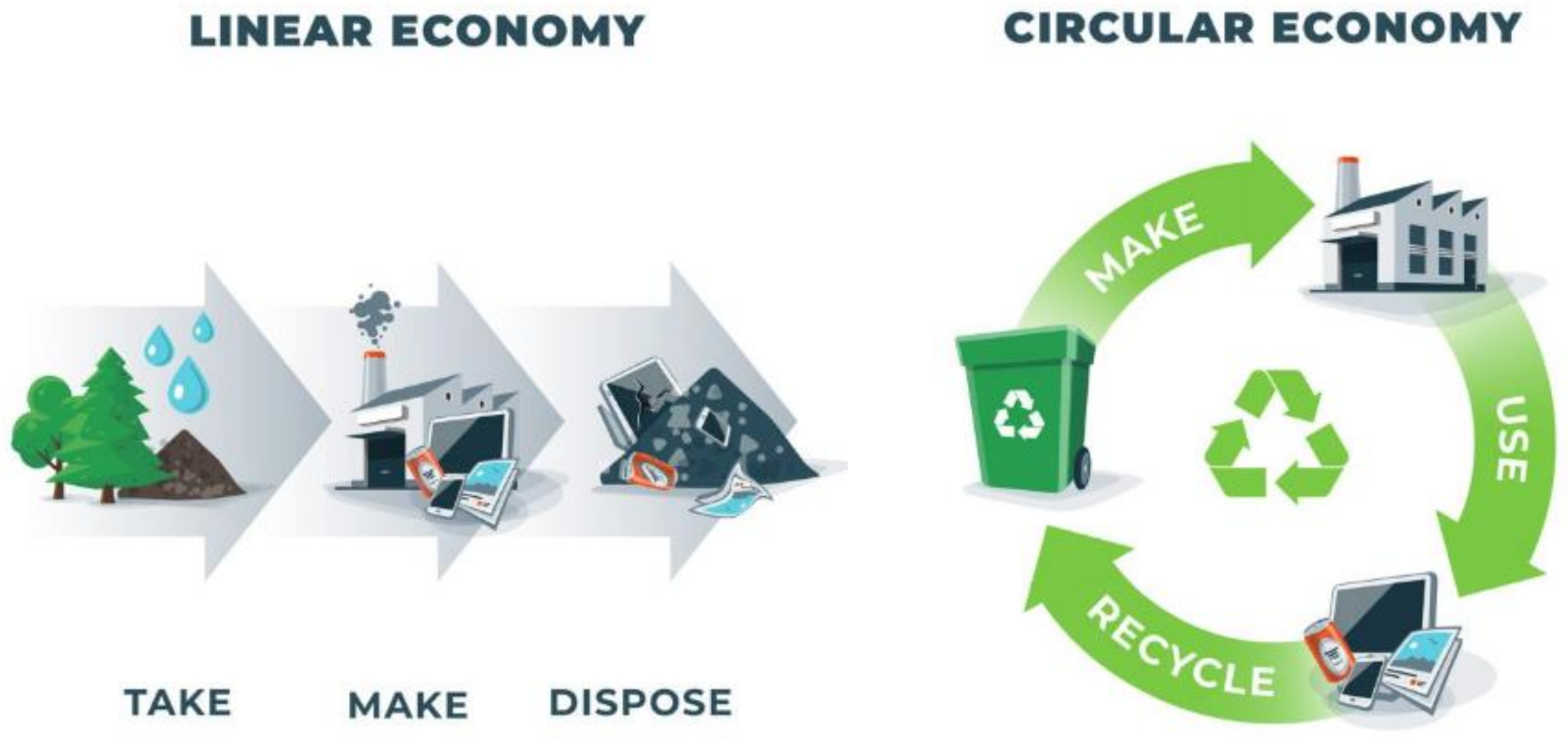
Definition of Circular Economy (CE)

An alternative economic model that seeks to minimize waste and make the most of resources.

- **It contrasts with the traditional linear economy, which follows a "take-make-dispose" approach.**
- **The circular economy emphasizes restorative and regenerative practices, aiming to create a sustainable system that benefits the environment, economy, and society.**

Key Principles of Circular Economy

- Reduce, Reuse, Recycle
- Value Retention Options
- Sustainable Design
- Systems Thinking



Source: www.aandapackaging.co.uk

How to support those with blockchain?

Key CE Goals and Their Link to Logistics

Objectives of Circular Economy

- Sustainability
- Resource Efficiency
- Economic Value Creation

Logistics Implications

- Closed-Loop Supply Chains
- Facility and Network Design
- Product Recovery Management

Challenges for Circular Economy

- **Governance and Ethics**
  - Governance processes automation
  - Smart contracts for transparent agreements
- **Information Sharing and Traceability**
- **Financial and Infrastructural Barriers**
  - Lower transaction costs
  - Improved ROI
  - Intermediaries reduction
- **Greenwashing avoidance**

Blockchain can enhance transparency, traceability, and efficiency in CE systems, addressing key issues that hinder effective adoption

Lack of transparency in traditional supply chains

Problems:

1) Complexity and Hidden Suppliers (Tiered suppliers)
2) Data management challenges (Incomplete and Innacurate Data, Inconsistent Reporting)
3) Compliance and Ethical Concerns
4) Operational Risks (Disruptions, Reputation, Trust)

Hidden or Incomplete Information:

1) Suplier Details
2) Material Sourcing
3) Operational Practises
4) Lack of access to full product history for consumers

Greenwashing practices

The practice of making false or misleading claims about the environmental benefits or sustainability of a product, service, or company

- Manipulation Techniques
- Vague Language and Misleading Labels
- Irrevelant Claims and Hidden Trade-offs
- Exaggerated Claims

The Dieselgate scandal (Volkswagen emissions scandal)

- Involved Volkswagen's deliberate manipulation of emissions tests for their diesel vehicles.
- The company installed software known as "defeat devices" in their cars, which activated emissions controls only during laboratory tests, making the vehicles appear more environmentally friendly than they actually were.

Affected Vehicles:Approximately 11 million vehicles worldwide.

Emissions Impact: Vehicles emitted up to 40 times more nitrogen oxides (NOx) than allowed by regulations.

Consequences: Severe legal and financial repercussions, including billions of dollars in fines and settlements.

The Importance of Transparency and Trust in Supply Chains

- **Combining transparency and trust creates a powerful synergy that drives progress towards sustainability.**
- **This synergy enhances reputations, contributes to a more ethical and environmentally friendly market, and supports long-term business success.**

Transparency is a key

- Consumer trust and brand loyalty
- Risk management and compliance
- Competitive advantage
- Environmental impact reduction

Trust is a key

- Foundation for sustainable practises
- Stakeholder confidence
- Long-term value creation
- Reputation and accountability

How Is Blockchain Changing the Data Management Paradigm?

By its main features:

- Decentralization and transparency
- Data integrity and security
- Interoperability and scalability
- Regulatory compliance
- Integration with other emerging technologies

Blockchain as a Solution to CE Problems

1. Plastic Waste Recycling

- **IBM Blockchain Platform and Plastic Bank**: The collaboration using blockchain to track plastic waste collection and recycling, ensuring transparency and accountability in the process
- **Augoraa Tech Lab and Ethereum Foundation**: The work on a complementary currency system for plastic waste, incentivizing recycling through blockchain-based rewards.

2. Resource Tracking and Efficiency

- **Circularise**: A Dutch company that uses blockchain to track waste electronic devices, enhancing transparency and trust in resource management
- **Troventum Limited**: Focuses on tracking solid recyclable household waste using blockchain, improving waste management efficiency

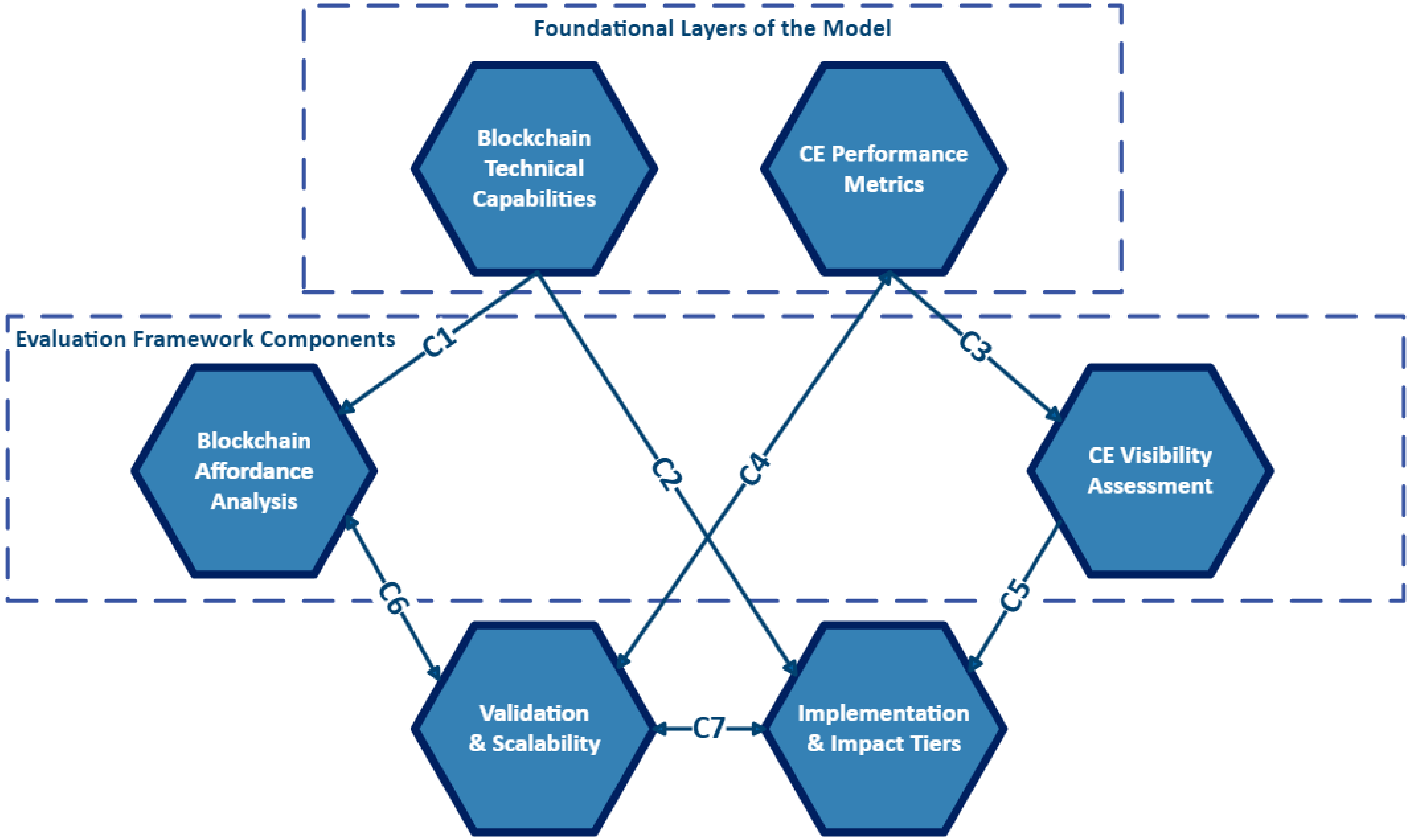
3. Smart Contracts for Sustainable Practices

4. Complementary Currencies for Waste Management

- **Cycled and Zafeplace Blockchain Platform**: These platforms use blockchain to manage household waste and end-of-life plastics, respectively, by creating systems that incentivize recycling through digital currencies or tokens

But how to measure the blockchain contribution to CE goals?

Measuring Blockchain's Contribution to Circular Economy Goals – The Model Proposal



Measuring Blockchain’s Contribution to Circular Economy Goals – The Model Proposal

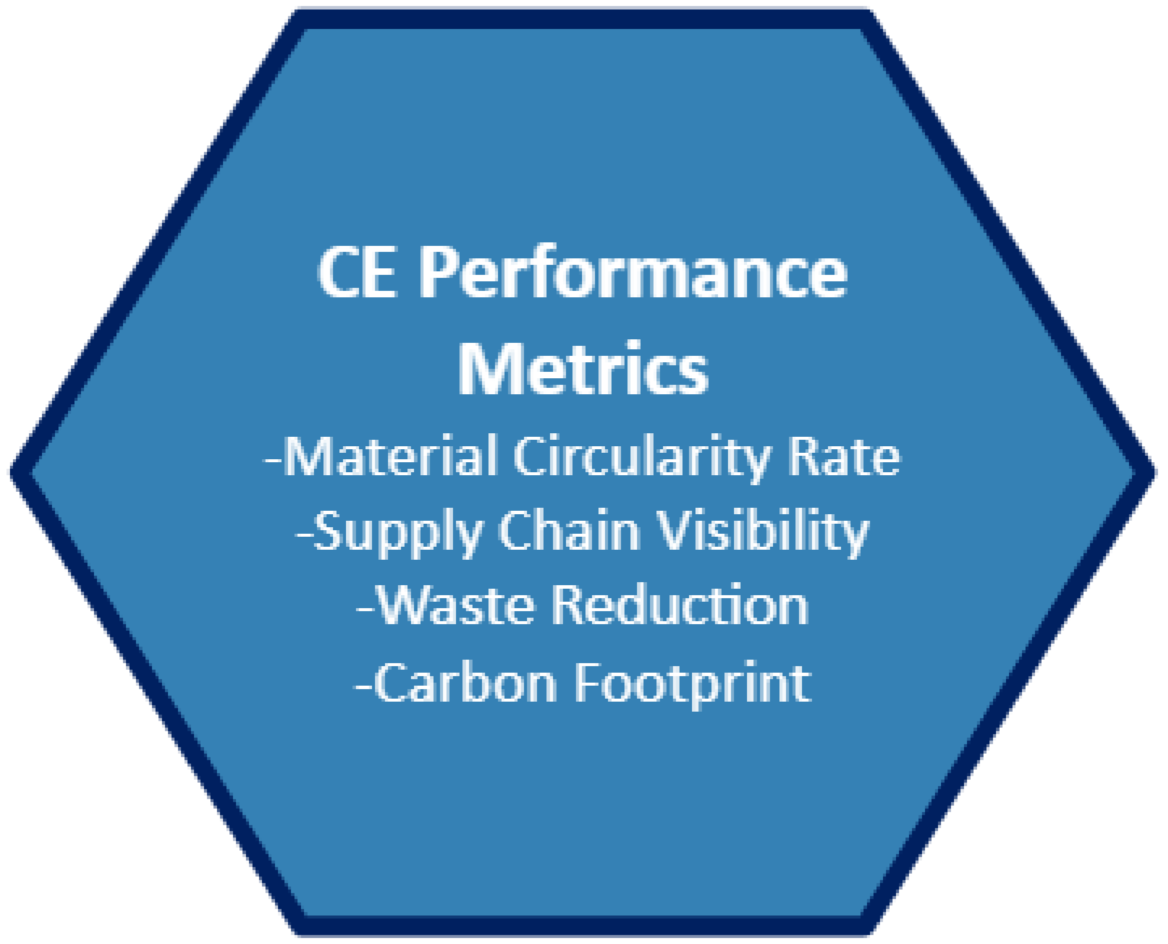
1. Foundational Layers of the Model

A. Blockchain Technical Capabilities (Core blockchain features that enable CE outcomes)

- Transparency and Traceability
- Smart Contracts
- Decentralized Verification
- Tokenization

B. CE Performance Metrics (Key indicators to measure blockchain’s impact)

- Materials Circularity Rate
- Supply Chain Visibility
- Waste reduction
- Carbon Footprint



Measuring Blockchain’s Contribution to Circular Economy Goals – The Model Proposal

2. Evaluation Framework Components

A. Circular Economy Visibility Assessment

(Evaluates blockchain’s ability to):

- **Track Supply Chain Entities**
- **Capture Condition Data**
- **Integrate Multi-Stakeholder Data**

B. Blockchain Affordance Analysis

(Assesses how blockchain capabilities align with CE goals):

Blockchain Capability	CE Impact	Example Metric
Transparency & Traceability	Reduces greenwashing	% of recycled content verified
Smart Contracts	Automates circular incentives	Volume of materials recovered via tokenized rewards
Decentralized Collaboration	Enables peer-to-peer exchanges	Growth in waste-to-resource marketplaces

Measuring Blockchain’s Contribution to Circular Economy Goals – The Model Proposal

2. Evaluation Framework Components

CE Visibility Assessment

-Track Supply Chain Entities
-Capture Condition Data
-Integrate Multi-Stakeholder Data

Blockchain Affordance Analysis

-Transparency & Traceability -> Reduces Greenwashing
-Smart Contracts -> Automates Circular Incentives
-Decentralized Collaboration -> Enables Peer-to-Peer Exchange

Measuring Blockchain's Contribution to Circular Economy Goals – The Model Proposal

3. Implementation & Impact Tiers

A. Operational Efficiency

- **Short-term: Focus on material traceability and waste reduction**
- **Medium-term: Integrate smart contracts for automated resource recovery**

B. Systemic Transformation

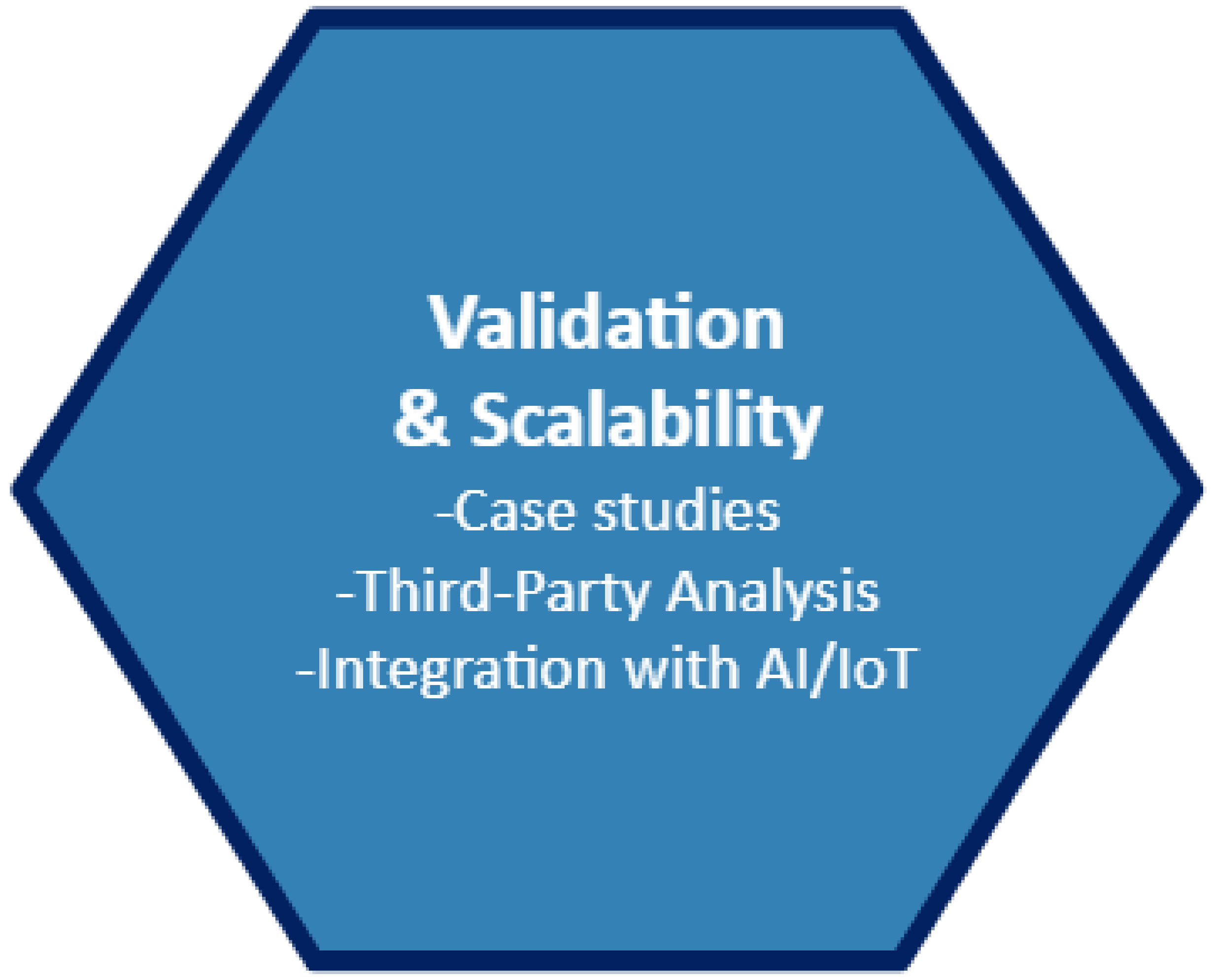
- **Long-term:**
  - **Chain of Responsibility: Blockchain-driven accountability for product lifecycles**
  - **Decentralized Marketplaces: Peer-to-peer platforms for secondary materials**

Implementation & Impact Tiers
-Operational Efficiency (Short-Term)
-Systemic Transformation (Long-Term)

Measuring Blockchain’s Contribution to Circular Economy Goals – The Model Proposal

4. Validation and Scalability

- Case studies: Use real-world pilots to refine metrics
- Third-Party Audits: Leverage blockchain’s tamper-proof records for certification
- Integration with AI/IoT: Enhance predictive analytics for material rocevery and lifecycle management



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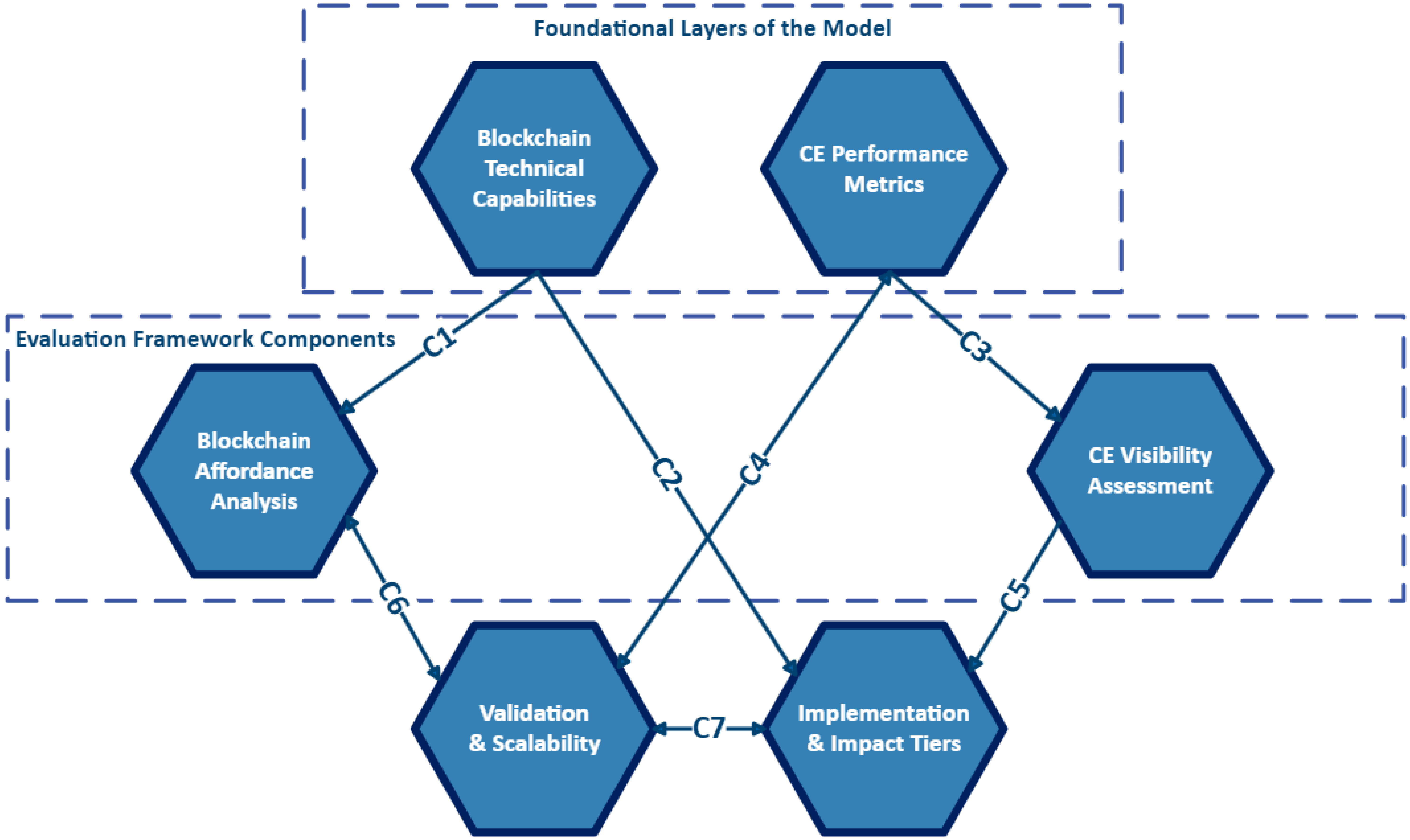

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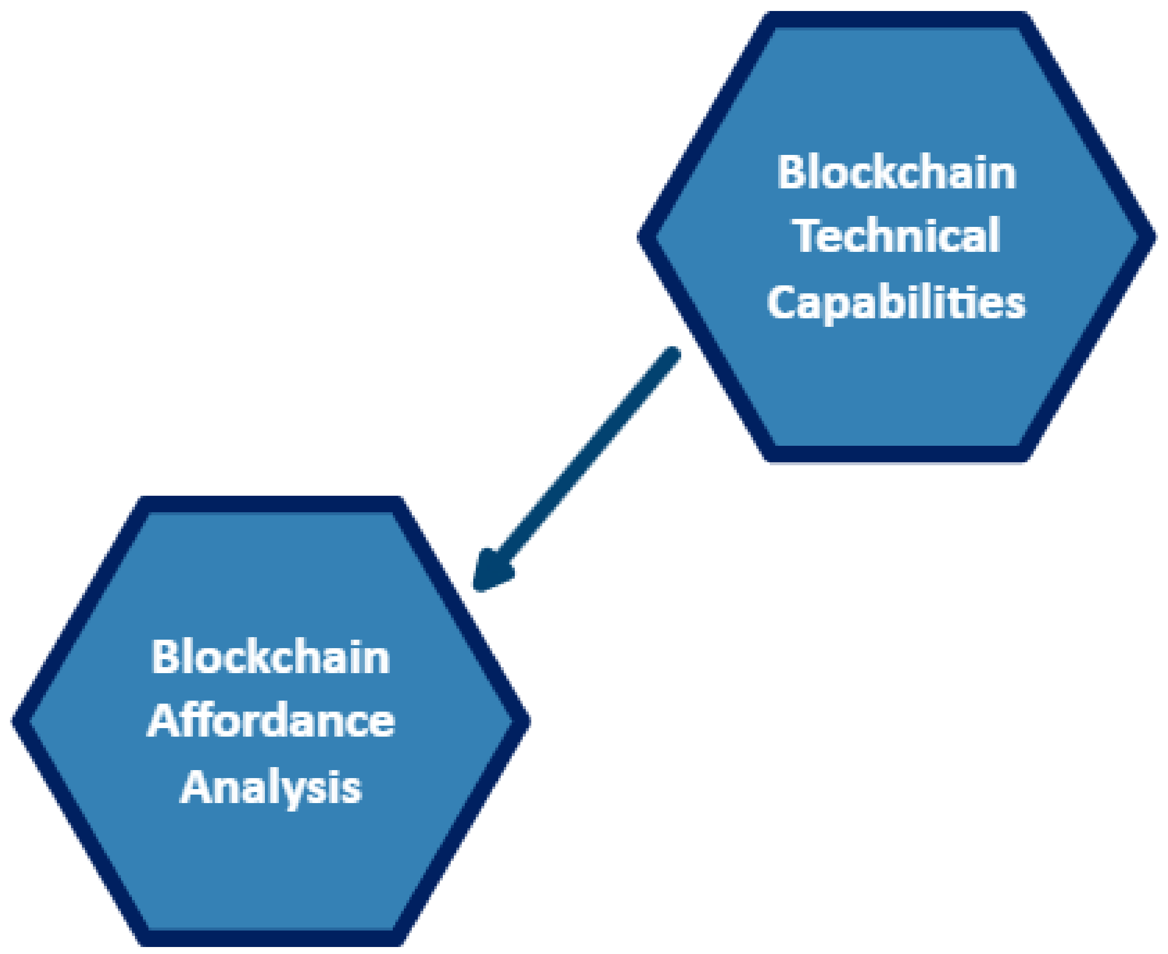
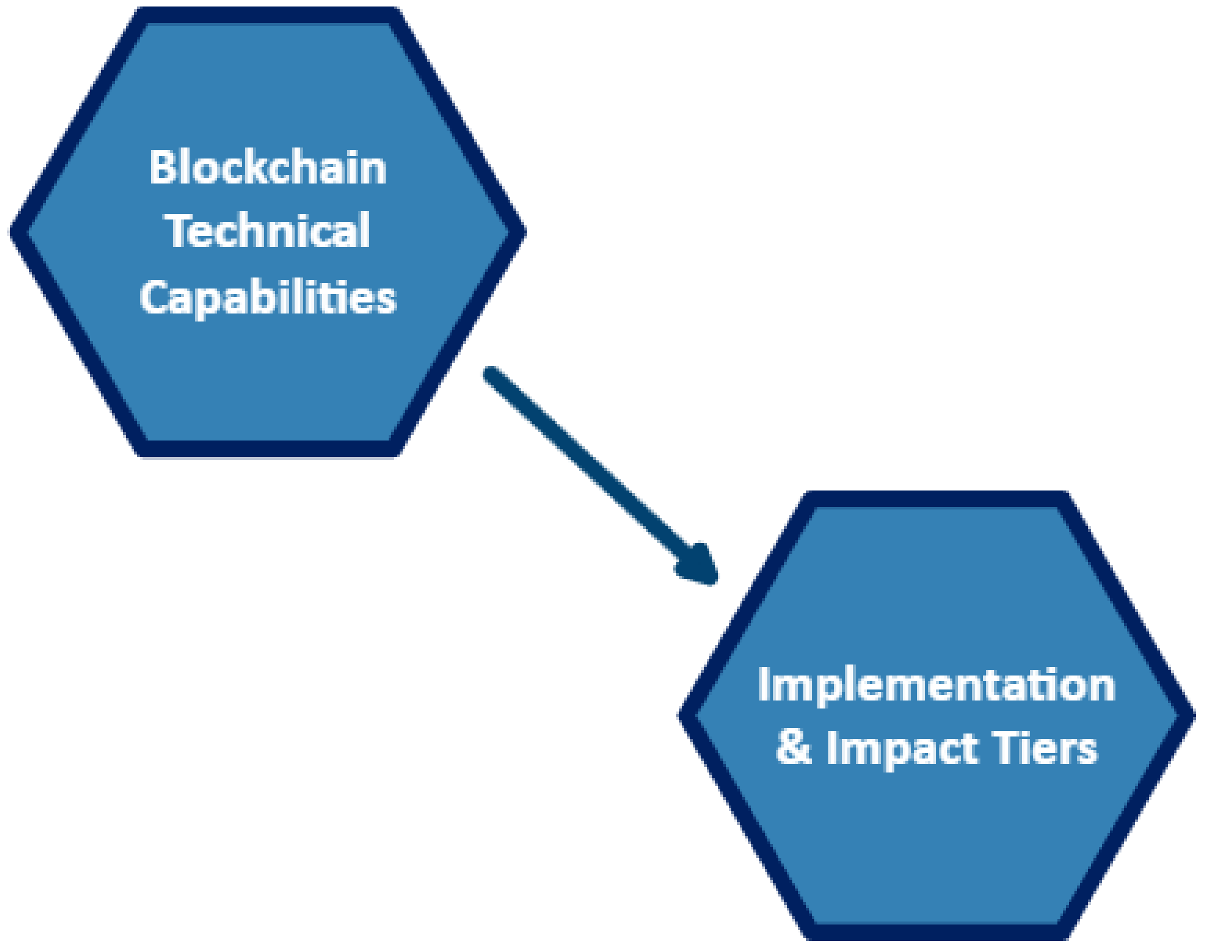
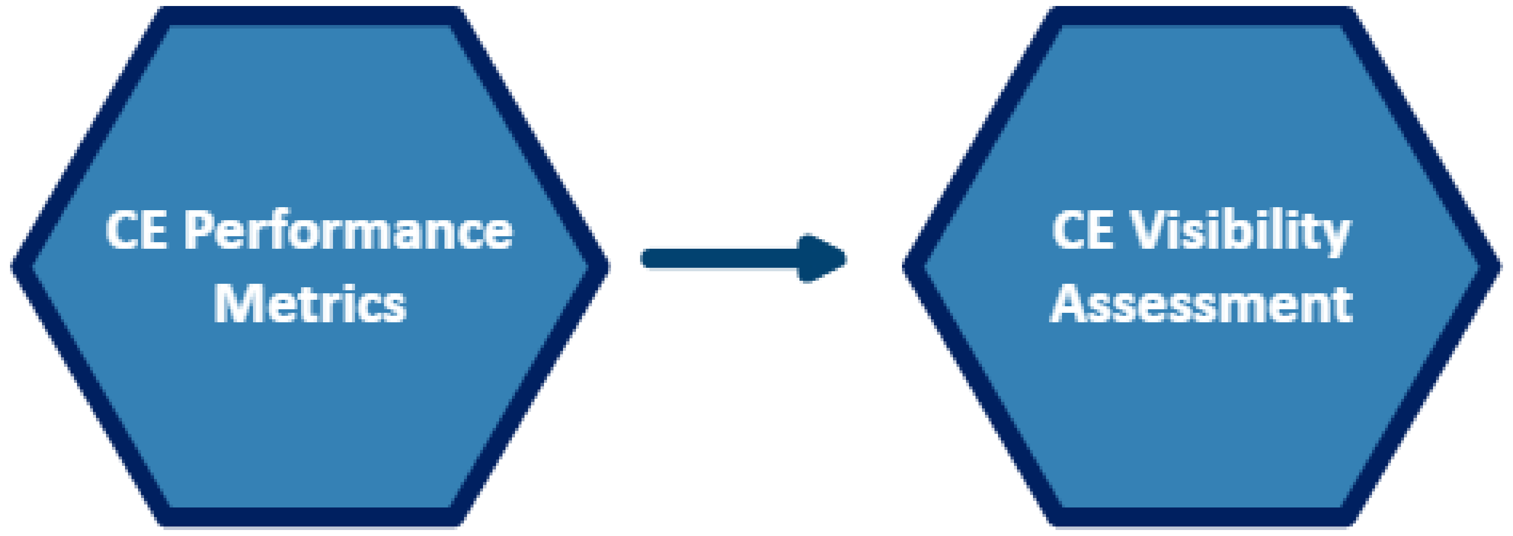


Purpose of the connection:
Demonstrates how technical features of blockchain (e.g., transparency, smart contracts, tokenization) enable specific circular economy (CE) outcomes.
Explanation:
This link highlights the functional translation of blockchain tools into CE affordances. For example, transparency enables verification of recycled content, while tokenization supports user engagement in take-back schemes.
Example:
Blockchain transparency allows Coca-Cola’s reward system to verify the return of plastic bottles by waste collectors.



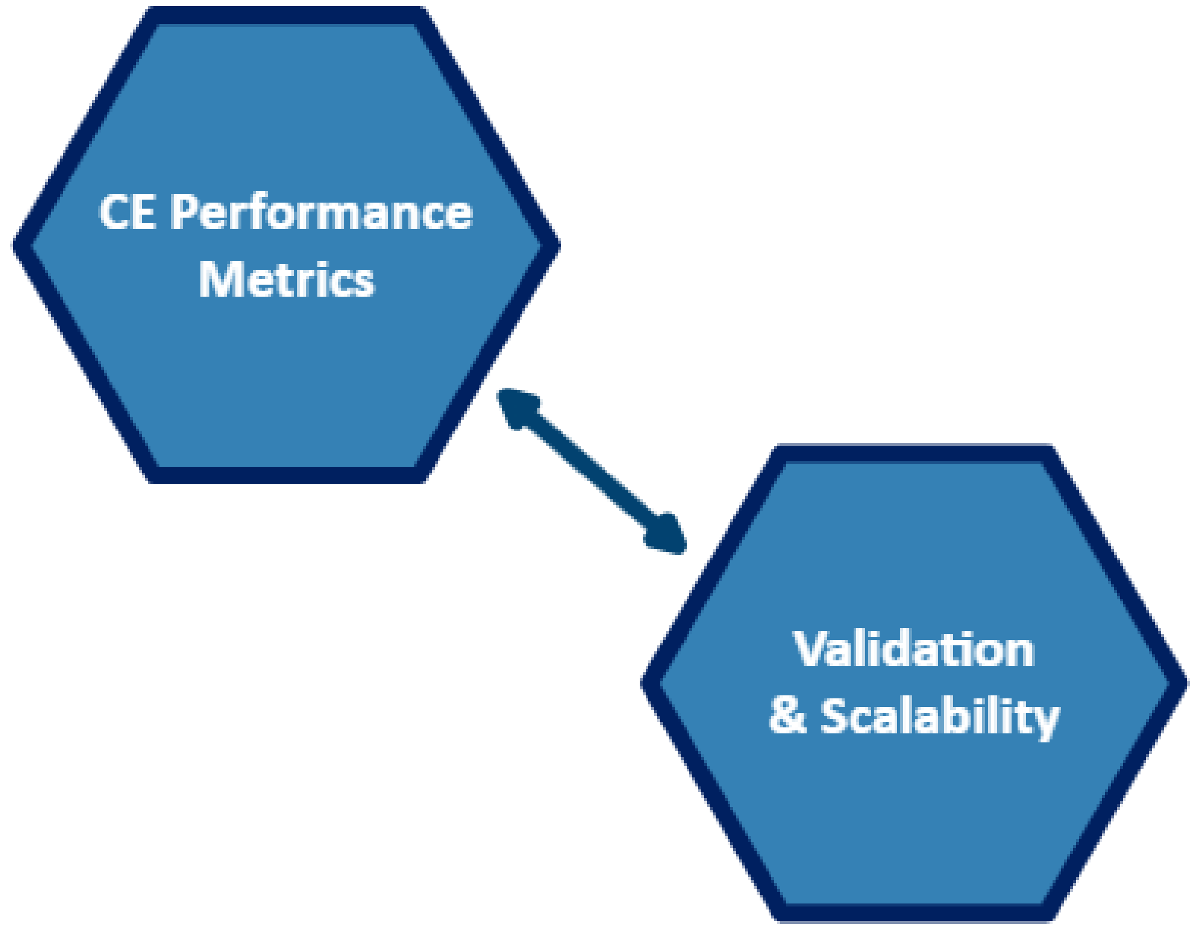
Purpose of the connection:
Shows how practical CE implementations rely on the technical foundation provided by blockchain.
Explanation:
As impact tiers evolve (e.g., from operational efficiency to systemic change), blockchain capabilities such as decentralized verification or smart contracts become critical enablers. This link reinforces the cyclical nature of innovation and capability development.
Example:
A decentralized marketplace for secondary materials relies on blockchain to ensure trust, quality control, and transaction traceability.

Measuring Blockchain's Contribution to Circular Economy Goals – The Model Proposal



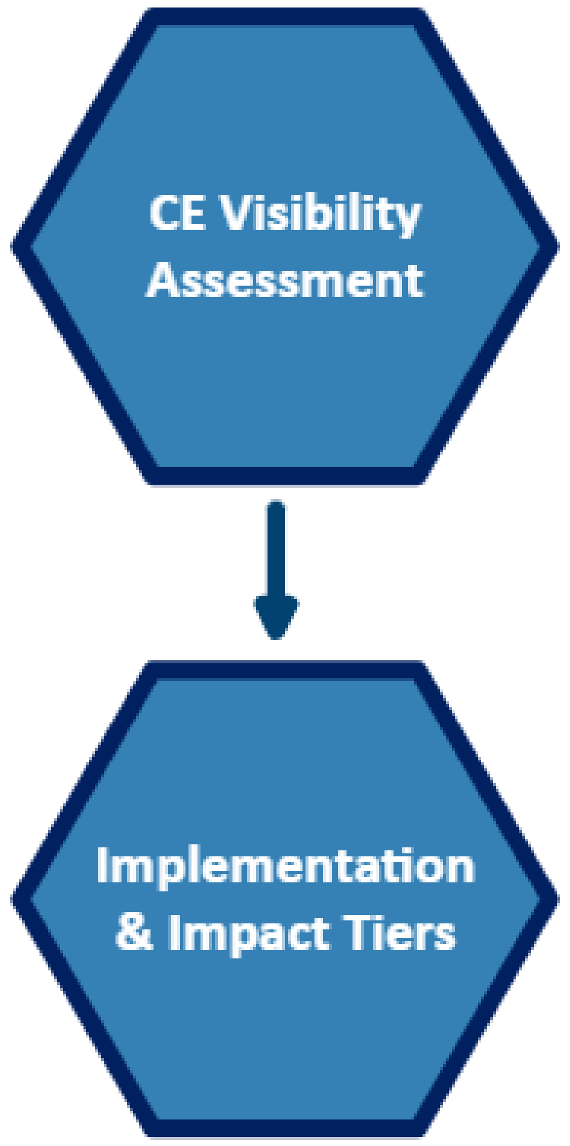
21

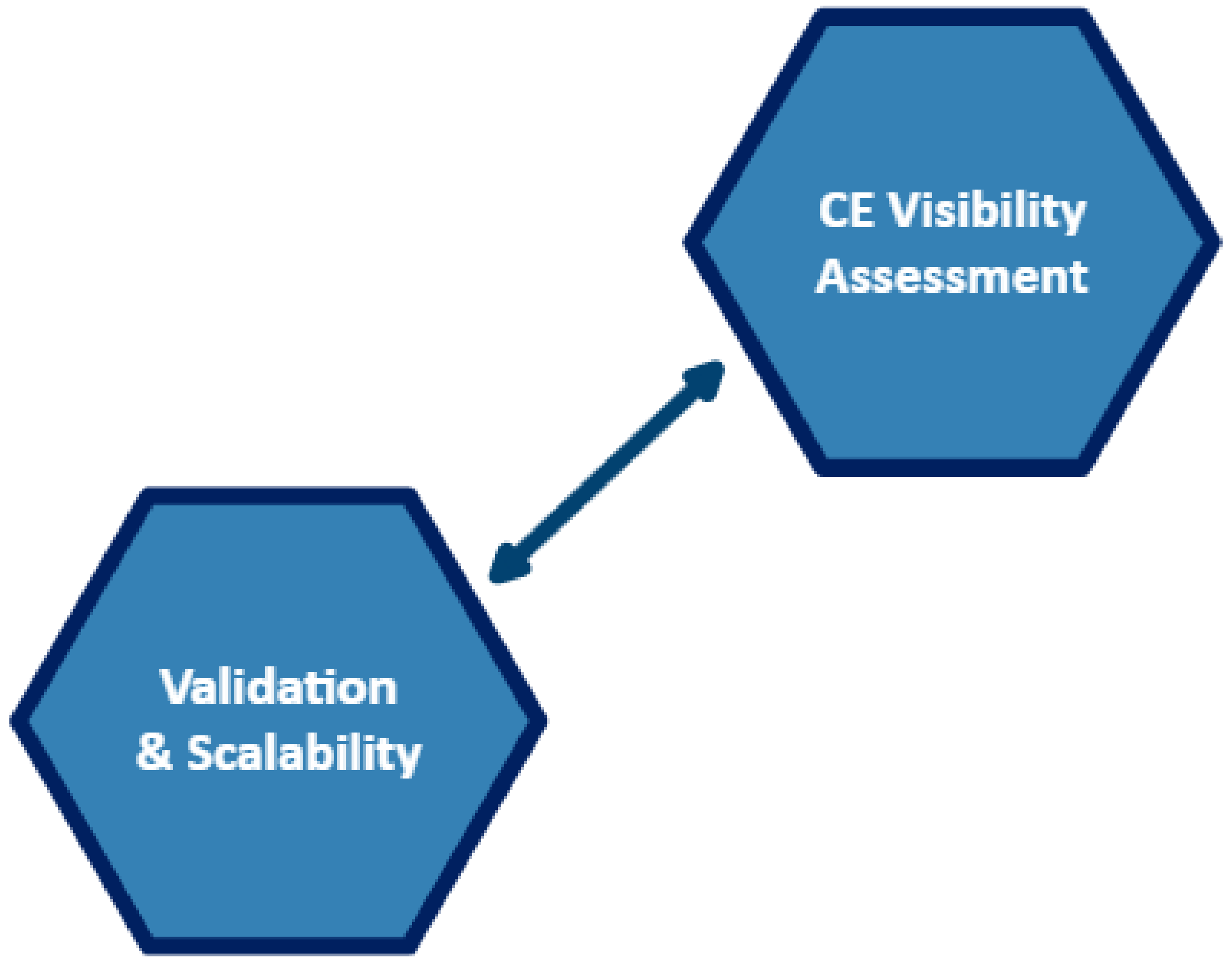
Purpose of the connection:
Illustrates how performance indicators are dependent on robust visibility mechanisms to ensure accurate measurement and monitoring.
Explanation:
Without visibility (e.g., sensor data, IoT integration), performance metrics such as the material circularity rate or carbon reduction cannot be credibly validated. Visibility ensures traceability across the value chain, enabling real-time tracking and reporting.
Example:
Everledger's diamond traceability platform demonstrates how CE metrics like ethical sourcing can be tracked across multiple stakeholders



Purpose of the connection:
Ensures that performance metrics are backed by credible, auditable, and standardized data sources.
Explanation:
Validated and scalable systems allow metrics to be recognized across industries and regulatory systems. Blockchain's immutability and auditability increase the reliability of CE indicators.
Example:
Blockchain-based verification enables emission reduction claims to be accepted in ESG reporting frameworks.

Measuring Blockchain's Contribution to Circular Economy Goals – The Model Proposal

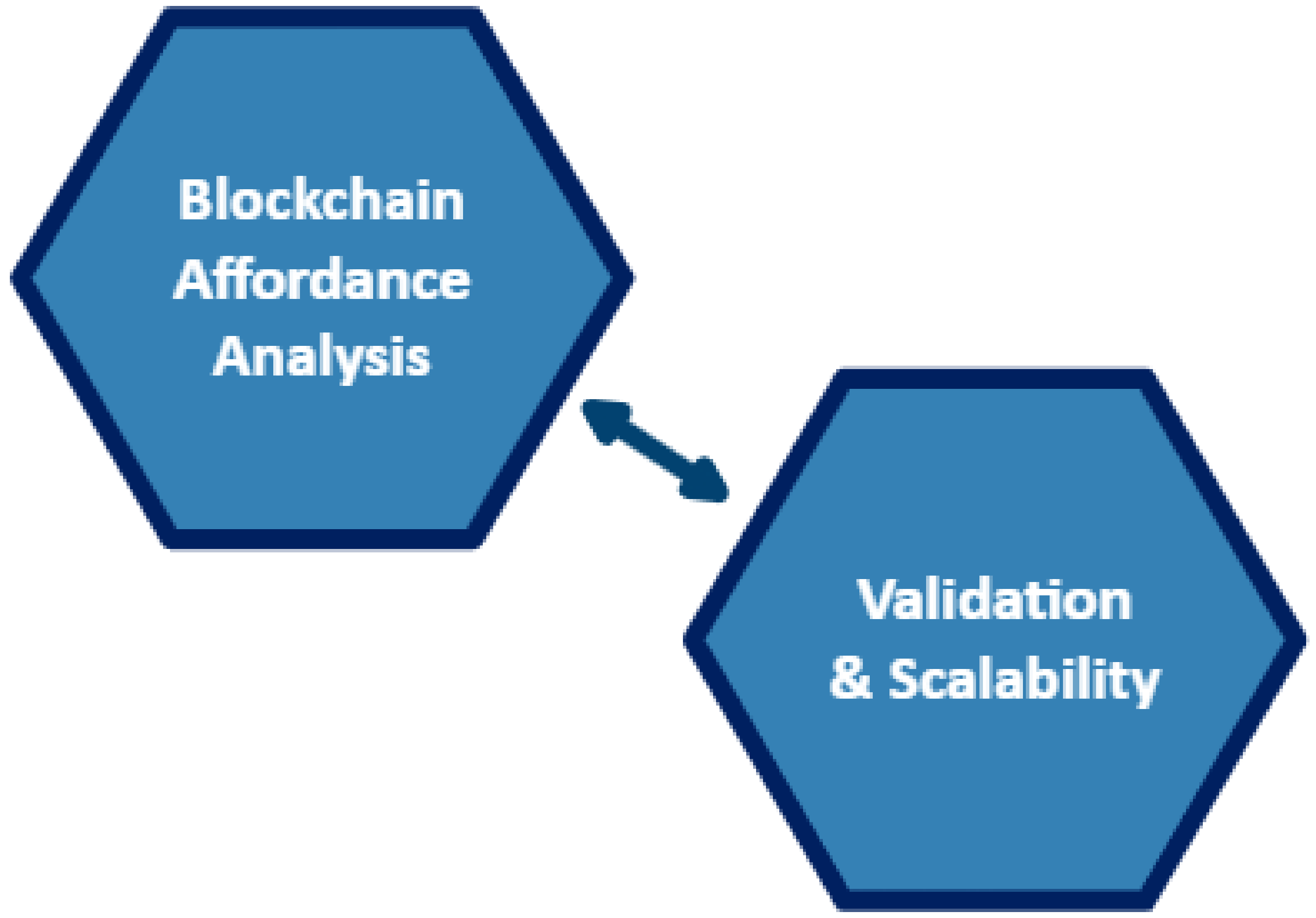




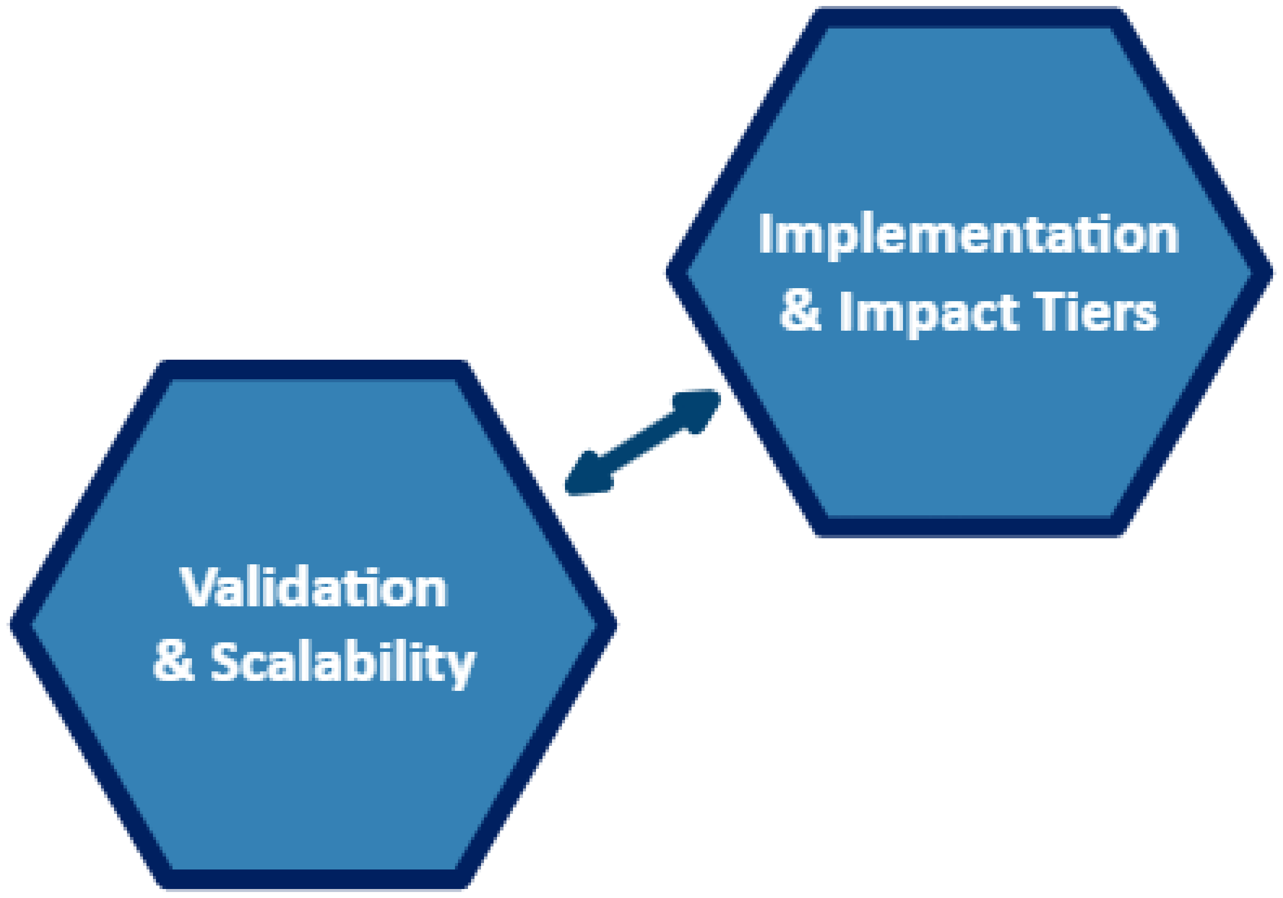
Purpose of the connection:
Represents how visibility supports implementation stages and helps scale CE initiatives by identifying process bottlenecks and material flows.
Explanation:
Visibility tools (e.g., digital twins, condition monitoring) provide the necessary infrastructure to gradually implement CE solutions, from short-term traceability to long-term product lifecycle accountability.
Example:
A recycling initiative using IoT sensors and QR codes provides material data used to trigger automated return processes through smart contracts

Purpose of the connection:
Indicates that visibility-driven data must be verifiable and scalable to be useful in broader CE validation and certification frameworks.
Explanation:
IoT, RFID, and sensor-generated data used for CE visibility should be integrated into validation protocols, certification processes, and scalable information infrastructures.
Example:
Real-time tracking of reused components feeds into ESG dashboards and third-party certification systems using blockchain standards (e.g., GS1).

Measuring Blockchain's Contribution to Circular Economy Goals – The Model Proposal



Purpose of the connection:
Emphasizes the importance of validating how blockchain-enabled CE capabilities perform in real-world contexts and can be scaled sustainably.
Explanation:
Each affordance (e.g., peer-to-peer exchanges, incentive systems) needs to be tested for impact, audited for credibility, and proven scalable across industries. This includes considering energy use, transaction costs, and data standardization.
Example:
A pilot project offering tokenized recycling incentives must demonstrate cost-effectiveness and regulatory compliance before nationwide deployment.



Purpose of the connection:
Highlights the need to evaluate and validate CE implementations before scaling them across industries or regions.
Explanation:
Each implementation (e.g., P2P secondary material platforms) must be assessed for actual impact and replicability. Case studies, verified indicators, and interoperability tests are critical to moving from pilot to scaled solutions.
Example:
A smart contract-enabled buy-back scheme is piloted in one city, then scaled nationally after successful audit and integration into standard frameworks.

Measuring Blockchain's Contribution to Circular Economy Goals – The Model Proposal

Challenges & Adaptability

- **Data Standardization**: Ensuring interoperability between blockchain platforms.
- **Scalability Limits**: Addressing energy consumption and transaction speeds for global supply chains.
- **Regulatory Alignment**: Evolving policies to recognize blockchain-verified CE claims

Proposed model positions blockchain as a **catalyst for CE transition**, transforming supply chains into regenerative systems through verifiable accountability. By aligning technical capabilities with CE metrics, stakeholders can quantify progress toward eliminating waste and fostering resource resilience.

Proposed model's usage

- The model serves a diagnostic and analytical function
- It enables a systematic examination of the extent to which the implementation of blockchain technology supports the achievement of key circular economy goals

The model usage procedure – step by step

Step 1. Identification of Applied Blockchain Functions (Blockchain Capabilities)

To identify which blockchain functions are being used in the analyzed solution:

- Does it ensure transparency of material flows?
- Does it use smart contracts to automate circular economy processes?
- Does it build trust among participants (e.g., through decentralized verification)?
- Does it introduce tokenization mechanisms to incentivize circular actions?

Blockchain Technical Capabilities
-Transparency & Traceability
-Smart Contracts
-Decentralized Verification
-Tokenization

To conclude this step - mark the active functions in the evaluated project

Proposed model's usage

Blockchain Affordance Analysis
-Transparency & Traceability -> Reduces Greenwashing
-Smart Contracts -> Automates Circular Incentives
-Decentralized Collaboration -> Enables Peer-to-Peer Exchange

The model usage procedure – step by step

Step 2. Linking Capabilities to Impact on the CE (Blockchain Affordance Analysis)

At this stage, the focus is on assessing how specific blockchain functions translate into circular economy goals.

For example:

- Transparency can help reduce greenwashing.
- Smart contracts may support automated packaging return programs.

This allows for understanding the potential impact of the technology on circular practices.

Blockchain Capability	Potential CE Impact	Present?
Transparency & Traceability	Reduction of greenwashing	[ ] Yes [ ] No
Smart Contracts	Automation of returns and recovery	[ ] Yes [ ] No
Decentralized Collaboration	Peer-to-peer resource exchange	[ ] Yes [ ] No
Tokenization	Motivation for circular actions	[ ] Yes [ ] No
...	...	[ ] Yes [ ] No

<u>**To conclude this step - mark and comment on the impact of each function**</u>

Proposed model's usage

The model usage procedure – step by step

Step 3. Measurement of Effects (CE Performance Metrics)

Next, an analysis is made of which metrics are available and being measured:

- What is the material circularity rate?
- How much waste has been reduced?
- Are there visible reductions in waste or use of virgin materials?
- Is the carbon footprint (CO_2) reported?
- How does blockchain contribute to reducing the carbon footprint?
- Are the metrics based on blockchain-verified data?

If the data is based on immutable blockchain records, its credibility increases.

CE Performance Metrics
-Material Circularity Rate
-Supply Chain Visibility
-Waste Reduction
-Carbon Footprint

<u>To conclude this step - note the available metrics and their source of validation</u>

Proposed model's usage

The model usage procedure – step by step

Step 4. Tracking and Visibility Assessment (CE Visibility Assessment)

The model enables evaluation of whether the blockchain system provides precise tracking of:

- Where materials are at each stage of the product lifecycle?
- What condition and quality the resources have?

This is crucial for reliable closed-loop material management.

CE Visibility Assessment
-Track Supply Chain Entities
-Capture Condition Data
-Integrate Multi-Stakeholder Data

<u>To conclude this step - indicate the level of visibility: low / medium / high</u>

Proposed model’s usage

The model usage procedure – step by step

Step 5. Implementation and Impact Analysis (Implementation & Impact Tiers)

The model also enables an assessment of the implementation maturity stage:
- Does blockchain only support current operations (e.g., recycling)?
- Or is it moving toward more advanced forms — such as decentralized secondary markets?

This helps measure the degree of systemic transformation

To determine the stage of maturity:
- Operational use: tracking and recycling
- Automation: conditional contracts, returns
- Systemic transformation: CE-oriented design, secondary markets

Implementation & Impact Tiers
-Operational Efficiency (Short-Term)
-Systemic Transformation (Long-Term)

<u>To conclude this step - mark the appropriate level and give an example of the action</u>

Proposed model's usage

The model usage procedure – step by step

Step 6. Validation and Scalability (Validation & Scalability)

Investigate:

- Are the data auditable?
- Has the system undergone a pilot or external audit?
- Is the technology scalable (in terms of cost, energy, integration)?
- Are there regulatory constraints?

These are necessary conditions for the technology to realistically support sustainable development goals.

To conclude this step - formulate conclusions on readiness for broader deployment

Proposed model's usage

Not to overcomplicate – A proposition of summary table:

Model Element	Qualitative Evaluation	Criteria	Examples / Evidence	Comments / Recommendations
1. Blockchain Capabilities	High / Medium / Low	Number and relevance of functions used (e.g. traceability, smart contracts, tokenization)	E.g., Smart contracts used for return logistics	Consider expanding tokenization mechanisms
2. CE Impact (Affordance)	High / Medium / Low	Expected contribution to CE goals (reuse, recovery, waste reduction, material efficiency)	E.g., Traceability reduces overproduction	Strong potential, but dependent on partner uptake
3. CE Performance Metrics	Strong / Moderate / None	Availability, relevance, and credibility of CE-related KPIs and indicators	E.g., CO_2 reduction metrics based on blockchain data	Needs third-party verification
4. CE Visibility	High / Medium / Low	Life cycle transparency, integration of multi-source data, accessibility to stakeholders	E.g., QR code traceability on packaging	Medium: no quality/status data for reused parts
5. Implementation & Impact	Short-term / Intermediate / Systemic	Level of adoption and integration in operations or business models	E.g., Smart contracts operational in return logistics	Could evolve toward systemic design in next phase
6. Validation & Scalability	Strong / Limited / None	External audits, pilots, ability to scale across processes and locations	E.g., EU-funded pilot project completed in 2023	Limited scalability due to energy costs

Note:

- You can use other rating scales (e.g. a point scale), other ways of describing elements, etc.
- This is one of the suggestions for using the model.

Proposed model's usage

Practical Applications of the Model:

- Evaluation of specific blockchain-based pilot projects in logistics, industry, or waste management.
- Comparison of alternative solutions — which blockchain implementation better supports CE goals?
- Verification of technological maturity — does a given blockchain solution translate into measurable environmental benefits?
- Decision-making support for public and private stakeholders looking to invest in technologies that promote circularity.

Blockchain Integration in Sustainable Supply Chains…

SUMMARY

- Does the Circular Economy really matter?
- Is Blockchain the right tool to support Circular Economy?
- How can we know it really works?

- That’s why **we need to measure impact, analyze data, and build evaluation models**.
- **Blockchain can support CE goals** – but only when its implementation is thoughtful and justified.

BLOCKCHAIN INTEGRATION IN SUSTAINABLE SUPPLY CHAINS: MEASURING ITS CONTRIBUTION TO CIRCULAR ECONOMY GOALS

THANK YOU FOR ATTENTION!

UCZELNIA BADAWCZA
INICJATYWA DOSKONAŁOŚCI

POLITECHNIKA ŚLĄSKA
WYDZIAŁ ORGANIZACJI I ZARZĄDZANIA

80 LAT Politechniki Śląskiej

Mateusz Zaczyk, PhD Eng.

(mateusz.zaczyk@polsl.pl)

Silesian University of Technology

Faculty of Organization and Management