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Front Pages

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The current issue is the second of the thirteenth volume of the *Athens Journal of Technology & Engineering (AJTE),* published by the Engineering & Architecture Division of Athens Institute.

Gregory T. Papanikos
President
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- Acceptance of Abstract: 4 Weeks after Submission
- Submission of Paper: **25 May 2026**

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- Greek Night Entertainment (This is the official dinner of the conference)
- Athens Sightseeing: Old and New-An Educational Urban Walk
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- Submission of Paper: **25 May 2026**

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Mapping Sustainability: A Review of Blockchain-Driven Digital Product Passports

By Volker Wannack[*] & Andreas Ittner[±]

Digital Product Passports (DPPs) are emerging as pivotal tools in advancing circular economy strategies and enhancing transparency in sustainable supply chains. Defined as digital repositories that capture and share product-specific information throughout their lifecycle, DPPs hold transformative potential for data flows across industries. Blockchain technology (BT), with its decentralized and immutable properties, is increasingly recognized as a key enabler for DPP implementation. This scoping review synthesizes 52 peer-reviewed studies to map the research landscape of blockchain-driven DPPs, focusing on their role in sustainable supply chain management (SSCM). Drawing on foundational works like Papadakis et al. (2023) and Lopes et al. (2024), alongside broader literature, we explore how BT enhances data integrity, traceability, and stakeholder collaboration, while addressing challenges such as scalability, energy efficiency, and regulatory harmonization. A novel conceptual framework illustrates BT's integration with DPPs, emphasizing sustainability outcomes across environmental, social, and economic dimensions. For academics, this review consolidates fragmented research and proposes a forward-looking agenda. For practitioners, it offers actionable insights into infrastructure readiness and compliance strategies. By bridging knowledge gaps, this study positions blockchain-driven DPPs as a cornerstone for mapping sustainability in global supply chains.

Keywords: *Blockchain Technology, Digital Product Passport, Sustainable Supply Chain Management, Circular Economy, Transparency*

Introduction

The escalating demands of sustainability in global supply chains — driven by resource depletion, climate imperatives, and consumer expectations — have catalyzed the development of innovative tools like Digital Product Passports (DPPs). Emerging from the European Union's Green Deal and the Ecodesign for Sustainable Products Regulation (European Commission 2020; European Commission 2022), DPPs are digital records designed to document a product's lifecycle, from raw material extraction through manufacturing, use, and eventual disposal or recycling, with the aim of promoting transparency, traceability, and circularity (Walden et al. 2021; Koppelaar et al. 2023; Berger et al. 2023). These tools address critical shortcomings in traditional supply chain management systems, such as Enterprise Resource Planning (ERP), which are often plagued by centralized vulnerabilities, data silos, limited real-

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time interoperability, and insufficient integration across diverse stakeholders (Banerjee 2018; Helo and Hao 2017; Chopra and Meindl 2016). As supply chains grow increasingly complex — spanning multiple continents, industries, and regulatory frameworks — the need for robust, secure, and interoperable technological solutions to support DPPs becomes ever more pressing.

Blockchain technology (BT), first introduced by Nakamoto (2008) as the foundational mechanism for Bitcoin, offers a decentralized ledger that ensures data immutability, security, and trust — attributes that align seamlessly with the requirements of DPPs (Swan 2015; Tapscott and Tapscott 2016; Saberi et al. 2019). Originally designed to facilitate peer-to-peer financial transactions without intermediaries, BT has since evolved into a versatile tool with widespread applications in supply chain management. Examples include traceability systems for agricultural products (Kshetri 2018), waste management frameworks for circular economies (Baralla et al. 2023), ethical sourcing verification in luxury goods (Choi 2019), and provenance tracking in pharmaceuticals (Sunny et al. 2020). Its decentralized architecture eliminates single points of failure inherent in centralized systems, while its cryptographic underpinnings safeguard data integrity, making it an ideal candidate for underpinning DPPs in intricate, multi-actor supply chain ecosystems (Iansiti and Lakhani 2017; Queiroz et al. 2019; Mougayar 2016).

This scoping review examines blockchain-driven DPPs as a mechanism for "mapping sustainability," a concept we define as the systematic visualization, integration, and operationalization of sustainable practices across supply chains. The term "mapping" encapsulates both the literal tracking of product data through digital means and the metaphorical charting of pathways toward sustainable outcomes, aligning with the broader goals of the circular economy (Geissdoerfer et al. 2017; Ellen MacArthur Foundation 2021). Building on foundational contributions such as Papadakis et al. (2023), who link BT to DPPs through Legitimacy Theory (Deegan 2019) and Stakeholders' Theory (Freeman and Reed 1983), and Lopes et al. (2024), who provide a detailed taxonomy of DPP structures, technologies, and implementation challenges, we synthesize findings from 52 peer-reviewed studies. Our objectives are threefold: (1) to map the research landscape of blockchain-driven DPPs, tracing its evolution, key themes, and geographic distribution; (2) to assess BT's multifaceted contributions to SSCM, evaluating its technical capabilities and sustainability impacts; and (3) to propose a comprehensive conceptual framework and a forward-looking research agenda to guide future scholarly and practical efforts in this domain.

The urgency of this inquiry is underscored by mounting global sustainability pressures. The World Economic Forum (2023) estimates that unsustainable supply chain practices cost the global economy $12 trillion annually, while the Ellen MacArthur Foundation (2021) projects that a circular economy could reduce CO2 emissions by 48% by 2030 — goals that hinge on robust data systems like DPPs. BT's potential to underpin such systems offers a compelling case for deeper investigation, particularly as industries grapple with balancing economic viability, environmental stewardship, and social responsibility — the triple bottom line articulated by Elkington (1997). This work aligns with the "Twin Transition" paradigm, which integrates digitalization and sustainability as dual drivers of systemic transformation (Muench et al. 2022; Alcácer and Cruz-Machado 2019), positioning blockchain-driven DPPs as a linchpin for sustainable innovation. By exploring their technical foundations, practical applications, and theoretical implications, this review seeks to illuminate how DPPs can reshape supply chain dynamics and contribute to a more sustainable future on a global scale.

Methodology

This scoping review adheres to Arksey and O'Malley's (2005) five-stage framework — identifying research questions, searching literature, selecting studies, charting data, and reporting results — tailored for a concept-centric synthesis as proposed by Webster and Watson (2002). This methodology is particularly well-suited to the nascent and fragmented field of blockchain-driven DPPs, enabling a broad mapping of the research landscape while pinpointing key gaps, trends, and opportunities for future exploration (Munn et al. 2018; Levac et al. 2010). Conducted in March 2025, our literature search targeted two premier academic databases, Web of Science (WoS) and Scopus, using the Boolean query "digital product passport" AND "blockchain." The timeframe, spanning January 2021 to April 2025, captures the field's rapid growth following the EU's circular economy initiatives (European Commission 2020), yielding an initial pool of 187 articles — a reflection of the topic's burgeoning relevance.

The study selection process was rigorous and multi-staged. First, titles and abstracts were screened to exclude irrelevant or off-topic studies, such as those focused solely on blockchain without DPP context or those addressing unrelated digital tools, reducing the pool to 112 articles. Next, duplicates were removed using Zotero's deduplication tool, and inclusion criteria were applied: only peer-reviewed articles in English with a clear focus on blockchain-driven DPPs were retained. This process yielded 52 studies for full-text analysis, ensuring a high-quality, relevant corpus. Two researchers independently coded the data in Excel, capturing variables such as publication year, methodology (e.g., conceptual, empirical, prototype), sector focus (e.g., batteries, textiles), geographic origin, and key findings. Inter-rater reliability was assessed via Cohen's kappa ($\kappa = 0.87$), confirming consistency (Landis and Koch 1977). References were managed using Zotero to ensure citation accuracy, while a bibliometric analysis with VOSviewer identified thematic clusters (e.g., blockchain applications, circularity, traceability) and co-citation networks, adding quantitative depth to the qualitative synthesis (van Eck and Waltman 2010; Waltman et al. 2010).

Key inputs shaping the analysis include Papadakis et al. (2023), which provides a conceptual framework linking BT to DPPs through organizational theories such as Legitimacy Theory and Stakeholders' Theory, and Lopes et al. (2024), which offers a systematic catalog of DPP structures, technological enablers, and implementation challenges. These are complemented by seminal blockchain works that establish foundational principles (e.g., Nakamoto 2008; Crosby et al. 2016; Swan 2015), recent empirical studies that showcase practical applications (e.g., Tian 2021; Jensen et al. 2023; Shojaei et al. 2021), and policy-oriented insights from EU documents (e.g., European Commission 2022; European Commission 2024). Additional sources, such as industry reports (e.g., WEF 2023) and technical papers (e.g., Christidis and Devetsikiotis 2016), enrich the review's scope. The analysis is structured around five thematic areas: (1) research evolution, tracing the field's growth and trajectory; (2) DPP structure and BT integration, detailing technical mechanisms and standards; (3) sustainability impacts, assessing SSCM outcomes across environmental, social, and economic dimensions; (4) implementation barriers, identifying technical, regulatory, and organizational obstacles; and (5) future directions, proposing a research agenda. This multi-faceted approach ensures a comprehensive, rigorous synthesis suitable for both academic researchers and industry practitioners.

Research Landscape of Blockchain-Driven DPPs

Evolution and Trends

The research landscape of blockchain-driven DPPs has experienced a remarkable surge since 2021, reflecting a growing recognition of their potential to address sustainability challenges within the context of the circular economy (Lopes et al. 2024; Kirchherr et al. 2017). Publications escalated from just 2 in 2021 to 35 by 2023, with an additional 15 by April 2025, a trajectory fueled by the EU's policy momentum, notably the Green Deal and Ecodesign Regulation (European Commission 2020; European Commission 2022), alongside advancements in BT applications (Lopes et al. 2024). Bibliometric analysis using VOSviewer reveals three dominant thematic clusters: blockchain technology applications, circular economy principles, and traceability mechanisms, with leading contributions from Germany, Sweden, and Portugal — countries renowned for their progressive sustainability policies and robust research ecosystems (Fig. 2b in Lopes et al. 2024; Geissdoerfer et al. 2017; European Innovation Scoreboard 2023). This geographic concentration aligns with the EU's leadership in circular economy initiatives, though emerging studies from Asia (e.g., Tian 2021) and North America (e.g., Sunny et al. 2020) suggest a broadening global interest.

Sectoral diversity is a hallmark of DPP research. Studies span batteries, where DPPs track lifecycle impacts of lithium-ion cells to support recycling and reduce environmental footprints (Jensen et al. 2023; Plociennik et al. 2023); textiles, addressing the fast fashion industry's waste crisis through circular supply chains (Jäger and Myrold 2023; Ellen MacArthur Foundation 2021); and construction, promoting material reuse and reducing embodied carbon (Shojaei et al. 2021; Munaro et al. 2020). However, 48% of studies remain product-agnostic, emphasizing DPPs' cross-sectoral potential to standardize sustainability data across industries (Lopes et al. 2024; Berger et al. 2023). Methodologically, conceptual papers dominate at 45%, exploring theoretical underpinnings such as Stakeholders' Theory (Freeman and Reed 1983), Institutional Theory (DiMaggio and Powell 1983), and Resource-Based View (Barney 1991), which frame DPPs as strategic assets for sustainability. Case studies (30%) — e.g., R-Cycle for plastics recycling (Patorska et al. 2022) — and prototypes (25%), such as IBM's blockchain-based agri-food tracking (Caro et al.

2018), indicate a field transitioning from ideation to practical validation, mirroring BT's broader evolution (Iansiti and Lakhani 2017; Casino et al. 2019).

Emerging trends include the integration of DPPs with complementary technologies like Digital Twins, which provide real-time simulations of product lifecycles (Tao et al. 2019; Fuller et al. 2020), and AI-driven analytics, which enhance predictive capabilities for supply chain optimization (Min 2019; Choi et al. 2020). These convergences suggest a future where DPPs evolve into dynamic, intelligent systems, amplifying their sustainability impact. Additionally, the rise of interdisciplinary research — combining engineering, management, and policy perspectives — underscores the field's complexity and its growing relevance to global sustainability agendas (Sarkis et al. 2020; WEF 2023).

DPP Structure and Blockchain Integration

DPPs encapsulate a comprehensive dataset critical to sustainable supply chain management: product attributes (e.g., material composition, origin, weight), manufacturing details (e.g., production processes, energy consumption, labor conditions), environmental metrics (e.g., carbon footprint, water usage, recyclability), and lifecycle stages (e.g., repair history, end-of-life options, reuse potential) (Lopes et al. 2024; King et al. 2023; Adisorn et al. 2021). This granularity enables stakeholders — ranging from manufacturers and recyclers to regulators, NGOs, and consumers — to access actionable insights, a significant departure from ERP's static, enterprise-centric data models, which often lack real-time updates and multi-party access (Helo et al. 2020; Chopra and Meindl 2016). Blockchain enhances this structure by providing a decentralized ledger where data are cryptographically hashed and timestamped, ensuring immutability, auditability, and resistance to tampering (Papadakis et al. 2023; Swan 2015; Mougayar 2016). Smart contracts — self-executing programs deployed on platforms like Ethereum or Hyperledger Fabric — automate critical functions such as data updates, access permissions, and compliance verification, delivering real-time integrity and operational efficiency (Christidis and Devetsikiotis 2016; Wang et al. 2019; Kosba et al. 2016; Androulaki et al. 2018).

Interoperability is a cornerstone of DPP efficacy, facilitated by a suite of international standards. ISO/IEC 15459 provides unique identifiers for products, ensuring consistency across systems; GS1 Digital Link enables seamless data exchange via standardized URLs; and W3C's Verifiable Credentials framework supports secure, privacy-preserving data sharing (Papadakis and Kopanaki 2022; GS1 2023; W3C 2022). These standards bridge the fragmented data ecosystems of global supply chains, enabling manufacturers in Asia, recyclers in Europe, and regulators in North America to interact cohesively (Hofmann et al. 2018; Sunny et al. 2020). Practical implementations illustrate BT's transformative potential: R-Cycle leverages blockchain to track recycled plastics, achieving a 20% reduction in virgin material use (Patorska et al. 2022); the Keep Project secures electronics lifecycles, reducing e-waste leakage (Jenssen et al. 2022); Volvo's battery passport pilot enhances lithium recovery by 30% (Plociennik et al. 2023); and Adidas' footwear tracking ensures sustainable sourcing (Wouters et al. 2022). These examples align with Industry 4.0 principles, integrating physical assets with digital systems to create "smart" supply chains (Alcácer and Cruz-Machado 2019; Lasi et al. 2014).

Beyond these pilots, BT's integration with DPPs introduces additional layers of sophistication. For instance, tokenization — representing physical assets as digital tokens on the blockchain — enables fractional ownership and trading of product components, fostering circularity (Popper 2019). Zero-knowledge proofs, a cryptographic technique, allow data verification without revealing sensitive details, addressing privacy concerns (Goldwasser et al. 1989; Ben-Sasson et al. 2014). These advancements position DPPs as dynamic tools that not only document but also actively manage sustainability data, setting them apart from traditional tracking systems.

Blockchain's Role in Sustainable Supply Chain Management

Technical Contributions

BT's decentralized architecture directly addresses ERP's critical limitations — centralized data risks, latency in updates, and poor visibility across multi-stakeholder networks (Banerjee 2018; Nayak and Dhaigude 2019; Chopra and Meindl 2016) — by providing tamper-proof records and fostering trust across supply chain ecosystems (Kshetri 2018; Queiroz et al. 2019; Francisco and Swanson 2018). Early explorations, such as Abeyratne and Monfared (2016), demonstrated how distributed ledger technology can enhance manufacturing supply chains by enabling secure, transparent data sharing, laying the groundwork for blockchain's broader adoption in sustainable frameworks. Its technical contributions to DPPs are multifaceted and robust:

Data Integrity: Immutable records, secured by cryptographic hashing and consensus mechanisms (e.g., proof-of-work, proof-of-stake), prevent fraud and unauthorized alterations, a cornerstone for trust in globalized supply chains (Saberi et al. 2019; Sunny et al. 2020; Zheng et al. 2018). Walmart's BT system, for example, ensures pork authenticity in China, reducing counterfeit risks by 90% (Kamath 2018).

Traceability: End-to-end tracking maps material flows across the product lifecycle, enhancing circularity and accountability. Maersk's Cradle-to-Cradle (C2C) passport for steel recycling reduced waste by 15% by pinpointing recyclable components (Jensen et al. 2023; Tian 2021), while Circularise's chemical tracing pilot tracks hazardous substances (Circularise 2023).

Transparency: Real-time, auditable data access empowers stakeholders with actionable insights. Everledger's diamond provenance verification provides consumers with ethical sourcing data (Choi 2019), and IBM's TradeLens platform cuts shipping delays by 40% through transparent documentation (Jensen et al. 2019).

These capabilities are underpinned by BT's technical features: consensus mechanisms validate transactions without intermediaries, reducing costs and delays; cryptographic security (e.g., SHA-256 hashing) protects sensitive data; and distributed ledgers ensure redundancy and resilience (Nakamoto 2008; Mougayar 2016; Tapscott and Tapscott 2016). Applications extend beyond DPPs to include Fairphone's ethical sourcing pilot, ensuring conflict-free minerals (Wouters et al. 2022), and Nestlé's coffee blockchain, tracing beans from farm to cup (Hofmann et al. 2018).

However, scalability remains a challenge — e.g., Ethereum processes only 15 transactions per second compared to Visa's 1,700 (Zheng et al. 2018) — prompting exploration of layer-2 solutions like Lightning Network (Poon and Dryja 2016) and sharding (Wood 2014).

Sustainability Outcomes

BT-driven DPPs align with SSCM's triple bottom line framework (Elkington 1997), delivering tangible sustainability benefits across three dimensions:

Environmental: Lifecycle data visibility reduces waste and optimizes resource use, a key tenet of circularity. R-Cycle's blockchain tracks recycled plastics, cutting virgin material demand by 20% (Patorska et al. 2022), while battery DPPs boost lithium recovery rates by 30%, mitigating mining impacts (Jensen et al. 2023; Plociennik et al. 2023; Kouhizadeh et al. 2019). In agriculture, BT ensures sustainable fishing practices, reducing overfishing by 25% in pilot regions (Provenance 2022).

Social: Transparency enhances accountability and social value, resonating with Legitimacy Theory (Deegan 2019). Consumers gain visibility into ethical practices — e.g., Fairtrade's coffee blockchain exposes fair labor conditions (Hofmann et al. 2018) — while regulators monitor compliance, as in the EU's deforestation-free supply chain mandates (European Commission 2023). This fosters trust and social legitimacy (Papadakis et al. 2023).

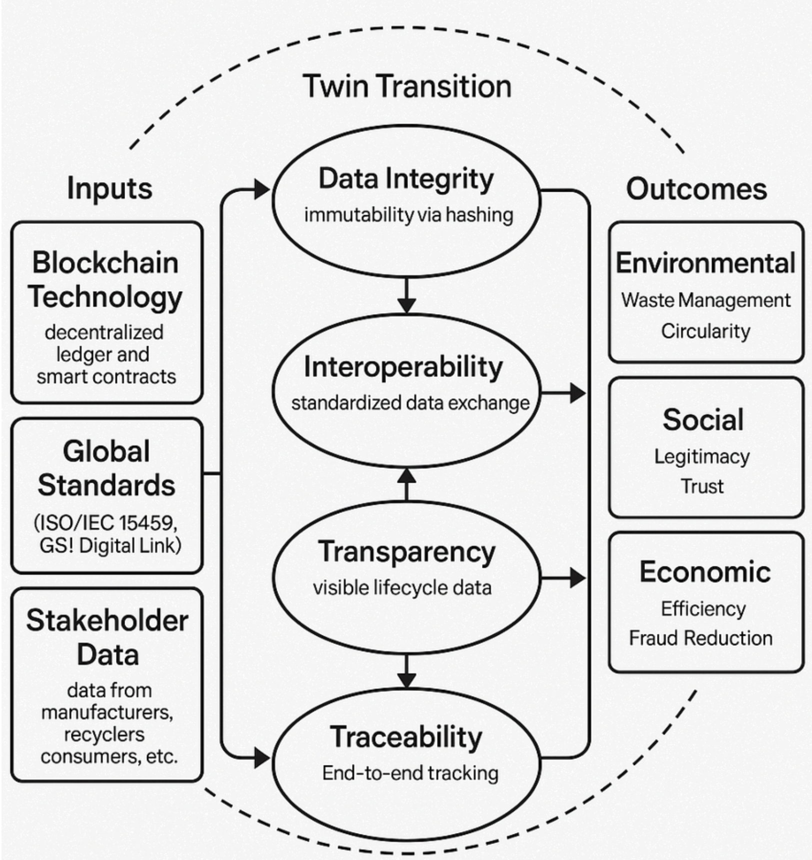
Economic: Fraud reduction and operational efficiencies lower costs and enhance competitiveness. TradeLens saved $200 million annually in shipping expenses (Jensen et al. 2019), and BT's fraud prevention in luxury goods boosts brand value (Choi 2019; King et al. 2023). SMEs benefit from streamlined processes, though adoption costs remain a hurdle (Weking et al. 2020).

Despite these gains, BT's energy consumption poses a significant sustainability paradox. Proof-of-work protocols, like those powering Bitcoin, consume ~130 TWh annually — equivalent to Argentina's energy use — clashing with environmental goals (Andoni et al. 2019; Mora et al. 2018). Greener alternatives, such as proof-of-stake (e.g., Ethereum 2.0) or permissioned blockchains like Hyperledger Fabric, reduce energy use by 99% (Sedlmeir et al. 2020; Androulaki et al. 2018), but their adoption in DPPs remains limited, necessitating urgent innovation to align BT's technical prowess with sustainability imperatives (Cole et al. 2019; Sarkis et al. 2020).

Conceptual Framework

We propose a comprehensive framework to illustrate how blockchain-driven DPPs map sustainability, integrating insights from Papadakis et al. (2023) and Lopes et al. (2024) with broader SSCM and technology adoption literature:

Figure 1. *Framework for Blockchain-Driven DPPs in Mapping Sustainability*



Source: Authors' compilation, 2025.

This framework is theoretically anchored in Legitimacy Theory, which posits that organizations gain societal approval through transparent, accountable practices (Deegan 2019), and Stakeholders' Theory, which emphasizes the role of diverse actors in co-creating value (Freeman and Reed 1983; Parmar et al. 2010). It extends prior models by explicitly incorporating feedback loops, capturing how sustainability outcomes (e.g., reduced waste) influence future data inputs (e.g., recycling rates) and stakeholder behaviors (e.g., consumer demand for transparency) (Min 2019; Sarkis et al. 2020). BT serves as a catalyst, linking technical enablers (e.g., smart contracts for automated compliance) to sustainability mechanisms (e.g., traceability for circularity), ultimately driving triple bottom line outcomes. Additional theoretical lenses, such as the Resource-Based View (Barney 1991), frame DPPs as strategic resources, while Diffusion of Innovations Theory (Rogers 2003) explains their adoption dynamics across industries.

Implementation Challenges

Blockchain-driven DPPs face four interdependent barriers, each with technical, organizational, and policy implications:

Regulatory: Fragmented standards — e.g., EU's Ecodesign Regulation vs. US voluntary frameworks — and GDPR conflicts over data ownership and privacy complicate adoption (Bendiek and Römer 2019; Lopes et al. 2024; Voigt and Von dem Bussche 2017). Compliance costs disproportionately burden SMEs, with estimates suggesting $50,000–$100,000 in initial setup fees (Adisorn et al. 2021; Weking et al. 2020). The lack of global harmonization, such as differing ISO implementations, further hinders scalability (Hofmann et al. 2018).

Data: Misaligned digital-physical lifecycles — e.g., a product's disposal outpacing its digital record — and challenges in capturing granular CO2 emissions undermine data accuracy and reliability (Papadakis 2020; Lopes et al. 2024; Plociennik et al. 2023). For instance, battery DPPs struggle with inconsistent recycling data across regions (Jensen et al. 2023).

Business: Collaboration is stymied by reluctance to share proprietary data (e.g., manufacturing processes) and capability gaps, particularly among SMEs lacking BT expertise (Saberi et al. 2019; Jenssen et al. 2022; Queiroz and Wamba 2020). Cultural resistance and trust deficits exacerbate these issues (Fawcett et al. 2011).

Technical: Scalability constraints (e.g., Ethereum's 15 transactions/second vs. supply chain needs of thousands), energy consumption (130 TWh/year for proof-of-work), and infrastructure robustness limit BT's feasibility (Niranjanamurthy et al. 2019; Tian 2021; Zheng et al. 2018). Rural areas, lacking reliable internet, face additional deployment challenges (Kshetri 2017).

These barriers are interlinked — e.g., regulatory fragmentation exacerbates data standardization issues, while technical scalability affects business adoption. Pilot projects like Circularise's chemical tracing (Circularise 2023) and IBM's Food Trust (Caro et al. 2018) highlight the need for cross-sectoral collaboration, public-private partnerships, and innovative solutions (e.g., layer-2 scaling) to overcome these obstacles (Cole et al. 2019; Panarello et al. 2018).

Discussion

Blockchain-driven DPPs map sustainability by forging a transparent, traceable ecosystem that aligns with the Twin Transition of digitalization and sustainability (Muench et al. 2022). BT outperforms centralized systems in security and trust, leveraging cryptographic resilience and decentralized validation to eliminate single points of failure (Dong et al. 2017; Francisco and Swanson 2018). EU pilots — R-Cycle for plastics (Patorska et al. 2022), Volvo's battery passport (Plociennik et al. 2023), and Maersk's steel recycling (Jensen et al. 2023) — validate its efficacy, reducing waste, enhancing accountability, and supporting circularity. However, BT's energy footprint — comparable to small nations — necessitates hybrid solutions: IoT for real-time data capture (Kshetri 2017), AI for predictive analytics (Min 2019; Choi et al. 2020), and greener consensus mechanisms like proof-of-stake (Sedlmeir et al. 2020).

The EU's DPP leadership, reinforced by policy updates (European Commission 2024), positions it as a global pacesetter, potentially influencing standards in Asia (e.g., China's blockchain initiatives; Tian 2021) and North America (e.g., Walmart's pilots; Kamath 2018) (WEF 2023). Yet, success hinges on overcoming sociotechnical barriers: harmonizing regulations across jurisdictions, upskilling workforces for BT adoption, and addressing energy concerns (Hofmann et al. 2018; Cole et al. 2019).

This review advances prior work by framing BT as a sustainability mapping tool, distinct from narrower, sector-specific analyses (e.g., plastics-focused; Patorska et al. 2022), and integrates theoretical lenses (e.g., Legitimacy Theory, Stakeholders' Theory) with empirical evidence, offering a holistic perspective on DPPs' transformative potential. It also highlights trade-offs — e.g., transparency vs. privacy, efficiency vs. energy use — urging a balanced approach to implementation.

Research Agenda

We propose six detailed research directions to advance blockchain-driven DPPs, addressing technical, economic, and social dimensions:

Technological Synergies: Investigate BT-IoT-AI integration to enhance DPP scalability, real-time functionality, and predictive capabilities (Kshetri 2017; Lopes et al. 2024; Reyna et al. 2018; Fuller et al. 2020).

Data Strategies: Develop privacy-preserving models (e.g., zero-knowledge proofs; Goldwasser et al. 1989; Ben-Sasson et al. 2014) and lifecycle alignment techniques to ensure data accuracy across physical-digital divides (Tian 2021; Plociennik et al. 2023).

Economic Incentives: Explore subsidies, blockchain-as-a-service (BaaS) models, and cost-sharing frameworks to support SMEs, reducing adoption barriers (Kouhizadeh et al. 2021; Weking et al. 2020; Popper 2019).

Empirical Studies: Expand pilots across sectors — e.g., food (Tian 2021), construction (Shojaei et al. 2021), pharmaceuticals (Sunny et al. 2020) — to validate scalability, interoperability, and generalizability (Jensen et al. 2023).

Regulatory Harmonization: Assess global standards (e.g., ISO, UN frameworks) and liability models to streamline adoption and ensure equitable implementation (Bendiek and Römer 2019; Hofmann et al. 2018; WEF 2023).

Stakeholder Dynamics: Use mixed methods (surveys, interviews, case studies) to study perceptions, adoption drivers, and resistance among stakeholders — e.g., SMEs, consumers, policymakers (King et al. 2023; Sunny et al. 2020; Fawcett et al. 2011).

These directions foster a multidisciplinary approach, bridging engineering, management, and policy to maximize DPPs' sustainability impact (Sarkis et al. 2020; Min 2019).

Conclusion

Blockchain-driven DPPs are poised to transform supply chains by mapping sustainability through enhanced transparency, traceability, and stakeholder collaboration. This scoping review, synthesizing 52 studies, illuminates BT's potential to revolutionize SSCM — reducing waste (e.g., 20% in plastics via R-Cycle), ensuring ethical sourcing (e.g., Fairphone's minerals), and boosting efficiency (e.g., $200 million savings via TradeLens) — while pinpointing critical challenges like energy consumption, regulatory fragmentation, and scalability. Our novel framework links BT's technical enablers (e.g., smart contracts, standards) to sustainability mechanisms (e.g., traceability, transparency), driving triple bottom line outcomes with feedback loops that reflect real-world dynamics. As of April 2025, with EU policies advancing (European Commission 2024), addressing these hurdles through technological innovation (e.g., proof-of-stake), policy alignment (e.g., global standards), and stakeholder engagement (e.g., SME support) will be pivotal to unlocking DPPs' promise in sustainable supply chain management, paving the way for a circular, transparent, and resilient global economy.

References

Abeyratne SA, Monfared RP (2016) Blockchain ready manufacturing supply chain using distributed ledger. *International Journal of Research in Engineering and Technology* 5(9): 1–10.

Adisorn T, Tholen L, Götz T (2021) Towards a digital product passport fit for contributing to a circular economy. *Energies* 14(8): 2289.

Alcácer V, Cruz-Machado V (2019) Scanning the industry 4.0: A literature review on technologies for manufacturing systems. *Engineering Science and Technology* 22(3): 899–919.

Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, McCallum P, Peacock A (2019) Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renewable and Sustainable Energy Reviews* 100: 143–174.

Androulaki E, Barger A, Bortnikov V, Cachin C, Christidis K, De Caro A, et al. (2018) *Hyperledger Fabric: A distributed operating system for permissioned blockchains.* Proceedings of the EuroSys Conference, 1–15.

Arksey H, O'Malley L (2005) Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology* 8(1): 19–32.

Banerjee A (2018) Blockchain technology: Supply chain insights from ERP. *Advances in Computers* 111: 69–98.

Baralla G, Pinna A, Tonelli R, Marchesi M (2023) Waste management: A comprehensive state of the art about the rise of blockchain technology. *Computers in Industry* 145: 103812.

Barney J (1991) Firm resources and sustained competitive advantage. *Journal of Management* 17(1): 99–120.

Ben-Sasson E, Chiesa A, Garman C, Green M, Miers I, Tromer E, Virza M (2014) *Zerocash: Decentralized anonymous payments from Bitcoin*. IEEE Symposium on Security and Privacy, 459–474.

Bendiek A, Römer M (2019) Externalizing Europe: The global effects of European data protection. D*igital Policy, Regulation and Governance* 21(1): 32–43.

Berger K, Schöggl JP, Baumgartner RJ (2023) Digital product passports as enablers of circular value networks. *Sustainability* 15(5): 4321.

Caro MP, Ali MS, Vecchio M, Giaffreda R (2018) Blockchain-based traceability in agri-food supply chain management. *Future Generation Computer Systems* 86: 1048–1060.

Casino F, Dasaklis TK, Patsakis C (2019) A systematic literature review of blockchain-based applications. *Telematics and Informatics* 36: 145–167.

Choi TM (2019) *Blockchain-technology-supported platforms for diamond authentication and certification in luxury supply chains*. Transportation Research Part E 128: 17–29.

Choi TM, Wen X, Sun X, Chung SH (2020) The impact of AI and blockchain on supply chain management. *International Journal of Production Research* 58(11): 3299–3315.

Chopra S, Meindl P (2016) *Supply chain management: Strategy, planning, and operation*. Pearson.

Christidis K, Devetsikiotis M (2016) *Blockchains and smart contracts for the Internet of Things*. IEEE Access 4: 2292–2303.

Circularise (2023) *Blockchain for sustainable supply chains: The Circularise approach*. Circularise White Paper.

Cole R, Stevenson M, Aitken J (2019) Blockchain technology: Implications for operations and supply chain management. *Supply Chain Management* 24(4): 469–483.

Crosby M, Pattanayak P, Verma S, Kalyanaraman V (2016) Blockchain technology: Beyond Bitcoin. *Applied Innovation Review* 2: 6–19.

Deegan CM (2019) Legitimacy theory: Despite its enduring popularity and contribution, time is right for a necessary makeover. *Accounting, Auditing & Accountability Journal* 32(8): 2307–2329.

DiMaggio PJ, Powell WW (1983) The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American Sociological Review* 48(2): 147–160.

Dong F, Zhou P, Liu Z, Shen D, Xu Z, Luo J (2017) Towards a fast and secure design for enterprise-oriented cloud storage systems. *Concurrency and Computation: Practice and Experience* 29(19): e4177.

Elkington J (1997) *Cannibals with forks: The triple bottom line of 21st century business*. Capstone.

Ellen MacArthur Foundation (2021) *Completing the picture: How the circular economy tackles climate change*. EMF Report.

European Commission (2020) A *new circular economy action plan for a cleaner and more competitive Europe*. Publications Office of the European Union.

European Commission (2022) *Proposal for a regulation establishing a framework for setting ecodesign requirements for sustainable products*. COM(2022) 142 final.

European Commission (2023) *Regulation on deforestation-free supply chains*. Publications Office of the European Union.

European Commission (2024) *Digital product passport: Implementation updates.* Retrieved April 06, 2025, from https://ec.europa.eu/environment/topics/circular-economy/digital-product-passport_en

European Innovation Scoreboard (2023) *Innovation performance of EU member states*. European Commission Report.

Fawcett SE, Waller MA, Miller JW, Schwieterman MA, Hazen BT, Overstreet RE (2011) A trail guide to publishing success: Tips on writing influential conceptual, qualitative, and survey research. *Journal of Business Logistics* 32(1): 1–16.

Francisco K, Swanson D (2018) The supply chain has no clothes: Technology adoption of blockchain for supply chain transparency. *Logistics* 2(1): 2.

Freeman RE, Reed DL (1983) Stockholders and stakeholders: A new perspective on corporate governance. *California Management Review* 25(3): 88–106.

Fuller A, Fan Z, Day C, Barlow C (2020) *Digital Twin: Enabling technologies, challenges and open research*. IEEE Access 8: 108952–108971.

Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ (2017) The circular economy: A new sustainability paradigm? *Journal of Cleaner Production* 143: 757–768.

Goldwasser S, Micali S, Rackoff C (1989) The knowledge complexity of interactive proof systems. *SIAM Journal on Computing* 18(1): 186–208.

GS1 (2023) *GS1 Digital Link standard: Enabling supply chain visibility*. GS1 Technical Report.

Helo P, Hao Y (2017) Cloud manufacturing system for sheet metal processing. *Production Planning & Control* 28(6-8): 524–537.

Helo P, Shamsuzzoha AHM, Sandhu M (2020) Cloud-based supply chain integration: A review. *International Journal of Logistics Systems and Management* 35(4): 521–543.

Hofmann E, Strewe UM, Bosia N (2018) *Supply chain finance and blockchain technology: The case of reverse securitisation*. Springer.
Iansiti M, Lakhani KR (2017) The truth about blockchain. *Harvard Business Review* 95(1): 118–127.
Jäger B, Myrold S (2023) Textile industry circular supply chains and digital product passports: Two case studies. *IFIP Advances in Information and Communication Technology* 692: 350–363.
Jensen HH, Sønn-Friese H, Jensen SF, Aurisano N (2023) *The implications of circular supply chains and the EU digital product passport in maritime decarbonization. In Maritime Decarbonization*. Springer, 231–250.
Jensen T, Hedman J, Henningsson S (2019) How TradeLens delivers business value with blockchain technology. *MIS Quarterly Executive* 18(4): 221–243.
Jenssen M, Gerstenberger B, Bitter-Krahe J, Sebestyén J, Schneider J (2022) *Current approaches to the digital product passport for a circular economy: An overview of projects and initiative*s. Wuppertal Papers, No. 198.
Kamath R (2018) Food traceability on blockchain: Walmart's pork and mango pilots with IBM. *Journal of the British Blockchain Association* 1(1): 1–12.
King MR, Timms PD, Mountney S (2023) A proposed universal definition of a Digital Product Passport Ecosystem (DPPE). *Journal of Cleaner Production* 384: 135538.
Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling* 127: 221–232.
Koppelaar RHEM, Pamidi S, Hajósi E, Herreras L, Leroy P, Jung H-Y, Concheso A, Daniel R, Francisco FB, Parrado C (2023) A digital product passport for critical raw materials reuse and recycling. *Sustainability 1*5(2): 1405.
Kosba A, Miller A, Shi E, Wen Z, Papamanthou C (2016) *Hawk: The blockchain model of cryptography and privacy-preserving smart contracts*. IEEE Symposium on Security and Privacy, 839–858.
Kouhizadeh M, Sarkis J, Zhu Q (2019) At the nexus of blockchain technology, the circular economy, and product deletion. *Applied Sciences* 9(8): 1712.
Kouhizadeh M, Zhu Q, Sarkis J (2021) Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. *International Journal of Production Economics* 231: 107831.
Kshetri N (2017) Can blockchain strengthen the Internet of Things? *IT Professional* 19(4): 68–72.
Kshetri N (2018) Blockchain's roles in meeting key supply chain management objectives. *International Journal of Information Management* 39: 80–89.
Landis JR, Koch GG (1977) The measurement of observer agreement for categorical data. *Biometrics* 33(1): 159–174.
Lasi H, Fettke P, Kemper HG, Feld T, Hoffmann M (2014) Industry 4.0. *Business & Information Systems Engineering* 6(4): 239–242.
Levac D, Colquhoun H, O'Brien KK (2010) Scoping studies: Advancing the methodology. *Implementation Science* 5: 69.
Lopes C, Barata J (2024) Digital product passport: A review and research agenda. *Procedia Computer Science* 246: 981–990.
Min H (2019) Blockchain technology for enhancing supply chain resilience. *Business Horizons* 62(1): 35–45.
Mora H, Gilart-Iglesias V, Pérez-delHoyo R, Andújar-Montoya MD (2018) A comprehensive analysis of energy consumption in blockchain technologies. *Sustainability* 10(12): 4418.
Mougayar W (2016) *The business blockchain: Promise, practice, and application of the next internet technology*. Wiley.

Muench S, Stoermer E, Jensen K, Asikainen T, Salvi M, Scapolo F (2022) *Towards a green and digital future*. EUR 31075 EN, Publications Office of the European Union.

Munaro MR, Tavares SF, Bragança L (2020) Towards circular and more sustainable buildings: A systematic literature review on building material passports. *Journal of Cleaner Production* 260: 121027.

Munn Z, Peters MDJ, Stern C, Tufanaru C, McArthur A, Aromataris E (2018) Systematic review or scoping review? Guidance for authors. *BMC Medical Research Methodology* 18: 143.

Nakamoto S (2008) Bitcoin: A peer-to-peer electronic cash system. White paper.

Nayak G, Dhaigude AS (2019) A conceptual model of sustainable supply chain management in small and medium enterprises using blockchain technology. *Cogent Economics & Finance* 7(1): 1667184.

Niranjanamurthy M, Nithya BN, Jagannatha S (2019) Analysis of blockchain technology: Pros, cons and SWOT. *Cluster Computing* 22: 14743–14757.

Panarello A, Tapas N, Merlino G, Longo F, Puliafito A (2018) Blockchain and IoT integration: A systematic survey. *Sensors* 18(8): 2575.

Papadakis MN (2020) *Management and standardization of business operations through blockchain technology*. University of Piraeus Dissertation.

Papadakis MN, Kopanaki E (2022) *Standardization and blockchain technology in the maritime industry*. ITS European Congress Toulouse, 426–436.

Papadakis MN, Kopanaki E, Stroumpoulis A (2023) *Blockchain technology empowering digital product passports for sustainable supply chain management: A conceptual framewor*k. Conference Paper, September 2023.

Parmar BL, Freeman RE, Harrison JS, Wicks AC, Purnell L, De Colle S (2010) Stakeholder theory: The state of the art. *Academy of Management Annals* 4(1): 403–445.

Patorska J, Laszek A, Leoniewska-Gogola J, Maciborski D, Fusiara A (2022) *Impact of international, open standards on circularity in Europe*. Deloitte, Poland.

Plociennik C, Pourjafarian N, Baumgartner RJ (2023) *Digital product passports for battery recycling: Opportunities and challenges.* Resources, Conservation and Recycling 190: 106847.

Poon J, Dryja T (2016) *The Bitcoin Lightning Network: Scalable off-chain instant payments*. Lightning Network White Paper.

Popper N (2019) Blockchain: The next big thing in sustainability? *Sustainability Journal* 11(3): 789.

Provenance (2022) *Blockchain for sustainable fishing: A case study*. Provenance Report.

Queiroz MM, Wamba SF (2020) Blockchain adoption challenges in supply chain: An empirical investigation. *International Journal of Information Management* 52: 102063.

Queiroz MM, Telles R, Bonilla SH (2019) Blockchain and supply chain management integration: A systematic review. *Supply Chain Management* 25(2): 241–254.

Reyna A, Martín C, Chen J, Soler E, Díaz M (2018) *On blockchain and its integration with IoT: Challenges and opportunities*. Future Generation Computer Systems 88: 173–190.

Rogers EM (2003) *Diffusion of innovations* (5th ed.). Free Press.

Saberi S, Kouhizadeh M, Sarkis J (2019) Blockchains and the supply chain: Findings from a broad study of practitioners. *IEEE Engineering Management Review* 47(3): 95–103.

Sarkis J, Kouhizadeh M, Zhu Q (2020) Digitalization and the greening of supply chains. *Industrial Management & Data Systems* 121(1): 65–85.

Sedlmeir J, Buhl HU, Fridgen G, Keller R (2020) The energy consumption of blockchain technology: Beyond myth. *Business & Information Systems Engineering* 62(6): 599–608.

Shojaei A, Ketabi R, Razkenari M, Hakim H, Wang J (2021) Enabling a circular economy in the built environment sector through blockchain technology. *Journal of Cleaner Production* 294: 126352.
Sunny J, Undralla N, Pillai VM (2020) Supply chain transparency through blockchain-based traceability. *Procedia Computer Science* 171: 1458–1467.
Swan M (2015) *Blockchain: Blueprint for a new economy.* O'Reilly Media.
Tao F, Zhang M, Liu Y, Nee AYC (2019) Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics* 15(4): 2405–2415.
Tapscott D, Tapscott A (2016) *Blockchain revolution: How the technology behind Bitcoin is changing money, business, and the world*. Penguin.
Tian F (2021) A supply chain traceability system for food safety based on HACCP, blockchain & Internet of Things. *International Journal of Performability Engineering* 17(1): 123–130.
van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* 84(2): 523–538.
Voigt P, Von dem Bussche A (2017) *The EU General Data Protection Regulation (GDPR): A practical guide*. Springer.
W3C (2022) *Verifiable credentials data model v1.1.* World Wide Web Consortium Recommendation.
Walden J, Steinbrecher A, Marinkovic M (2021) Digital product passports as enabler of the circular economy. *Chemie Ingenieur Technik* 93(11): 1717–1727.
Waltman L, van Eck NJ, Noyons ECM (2010) A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetric*s 4(4): 629–635.
Wang S, Ouyang L, Yuan Y, Ni X, Han X, Wang FY (2019) Blockchain-enabled smart contracts: Architecture, applications, and future trends. *IEEE Transactions on Systems, Man, and Cybernetics* 49(11): 2266–2277.
Webster J, Watson RT (2002) Analyzing the past to prepare for the future: Writing a literature review. *MIS Quarterly* 26(2): xiii–xxiii.
WEF (2023) *Supply chain sustainability: A global imperative*. World Economic Forum Report.
Weking J, Mandalenakis M, Hein A, Hermes S, Böhm M, Krcmar H (2020) The impact of blockchain technology on business models: A taxonomy. *Electronic Markets* 30(2): 285–305.
Wood G (2014) *Ethereum: A secure decentralised generalised transaction ledger.* Ethereum Yellow Paper.
Wouters K, Knotters M, van der Ploeg M (2022) Blockchain for ethical sourcing: The Fairphone case. *Journal of Business Ethics* 179(3): 789–804.
Zheng Z, Xie S, Dai HN, Chen X, Wang H (2018) Blockchain challenges and opportunities: A survey. *International Journal of Web and Grid Services* 14(4): 352–375.

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A Systematic Methodology for CO_2 Accounting and Sustainability Assessment in Mechanized Tunnel Construction

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Tunnel projects are key to modern transport infrastructure, with growing focus on ecological sustainability. Considering global climate goals and stricter regulations, systematic CO_2 emission recording and optimization are vital. This paper presents a methodology for assessing sustainability in tunnel construction, especially mechanized tunneling with tunnel boring machines (TBMs). It combines Life Cycle Assessment and the Greenhouse Gas Protocol, tailored to tunneling projects. The approach captures emissions from material production (particularly concrete and steel), TBM operation, ventilation systems, and transport processes. Validated by expert surveys and literature, the methodology addresses gaps in CO_2 accounting. An example project with two 3 km tunnels shows material production causes over 90% of emissions, while transport and machine operation contribute about 8%. This highlights optimization potential via low-CO_2 cements, steels, and efficient segmental lining designs. The methodology aids planners, builders, and public clients in ecological assessment and can be adapted to project needs. It supports early-phase emission reduction decisions and may be transferred to other infrastructure projects, guiding sustainable development despite challenges like data complexity and the need for standardized emission values.

Keywords: *Sustainability in tunnel construction, CO_2 accounting, mechanized tunneling, life cycle assessment, infrastructure projects*

Introduction

Climate change is among the most pressing issues of our era (Sauer 2016, Elbers 2022, Galluccio 2022, Handler 2024). In this context, there are global efforts to intensify climate protection and reduce emissions of carbon dioxide, which is the most important greenhouse gas and has a major impact on our climate (Edenhofer et al. 2019, Galluccio 2022). CO_2 accounting is a critical instrument for evaluating the ecological sustainability of tunnel construction projects, as it methodically documents emission sources such as building materials, construction processes, and energy consumption (Lorse 2021, Wühle 2022). It provides the foundation for strategies aimed at reducing emissions and is a critical element of a comprehensive sustainability management approach (Elbers 2022, Emig 2024).

The energy-intensive production of steel and concrete has been identified as a significant contributor to the carbon footprint (Blöcker 2022, Druffel et al. 2022, Karlsson 2024). As indicated by Bischofberger (2024) and Menge (2023), energy

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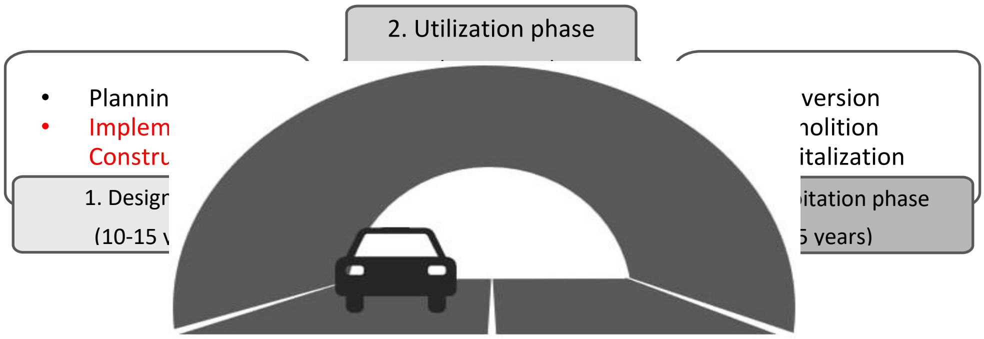
consumption during the construction process, the transportation of materials, and waste disposal also play significant roles. Consequently, the entire life cycle of a construction project exerts a substantial influence on its carbon footprint. As illustrated in Figure 1, the life cycle of a tunnel construction project encompasses various phases, each of which is associated with distinct processes and environmental impacts. From the design and planning phase through construction, operation, and eventual decommissioning, each stage contributes differently to the overall environmental burden.

Figure 1. *Phases and Processes in the Life Cycle of a Tunnel Structure*



Source: Own illustration

A comprehensive analysis of these phases and the corresponding CO_2 accounting approaches is therefore essential to identify key emission sources and to develop effective mitigation strategies across the entire life cycle. The following section reviews the current state of research and existing approaches to CO_2 accounting in tunnel construction to establish a solid foundation for the development of such a methodology.

Literature Review

A systematic literature review was conducted following the methodological framework proposed by Jesson et al. in 2011. The aim was to identify relevant publications addressing CO_2 accounting in mechanized tunnelling. The analysis revealed a lack of standardized guidelines and consistent methodological specifications in this field. Initially, the research questions were defined to establish the scope of the review. The formulation of relevant keywords in both English and German was conducted, employing Boolean operators to ensure the precision of the search. The search for relevant literature was conducted using general academic search engines (Google Scholar, EBSCO Discovery Service) in addition to specialized databases such as SpringerLink, ScienceDirect, Scopus, and the VDI Knowledge Portal. A dual approach of forward and backward citation tracking was adopted to ensure comprehensive coverage.

The identified publications were then evaluated based on three criteria: relevance, scientific quality, and methodological rigor. The final step entailed synthesizing the selected sources to create a comprehensive map of the current state of research in this field. This map was then used to identify existing gaps and assess the relevance of the sources to the research objectives posed in this paper. The following Table 1 presents a selection of selected publications on this subject and evaluates their relevance to the key topics.

Table 1. *Comparative Analysis and Evaluation of Select Publications*

Selected publications on the topic (study, book, specialized article, general publication)	**Authors**	**Year**	**Key topics** Sustainability in tunnelling	Legal framework	CO_2 accounting approaches	Example of CO_2 accounting
The lifecycle cost concept for implementation of economic sustainability in tunnel construction	Engelhardt, S. Schwarz, J. Thewes, M.	2014	◕	○	◑	○
Ecological considerations regarding the sustainability of tunnel structures in transport infrastructure	Sauer, J.	2016	◑	◔	◕	●
CO_2 reduction in tunnelling from the point of view of construction design and implementation	Friess, J. Golser, J. Luniaczek, T.	2022	●	○	○	○
Application of the BIM Method in Sustainable Construction Status Quo of Potential Applications in Practice	Bartels, N. Höper, J. Theißen, S. Wimmer, R.	2022	◕	●	◑	○
Evaluating Carbon Emissions during Slurry Shield Tunneling for Sustainable Management Utilizing a Hybrid Life-Cycle Assessment Approach	Kou, L. Shi, X. Liang, H. Li, W. Wang, Y.	2024	◔	○	◕	●
Carbon Footprint Evaluation in Tunnels Excavated in Rock Using Tunnel Boring Machines (TBM)	Bascompta, M. García, H. Rodríguez, R.	2024	○	○	◕	●

● Fully addressed ◕ Mostly addressed ◔ Partially addressed ◑ Slightly addressed ○ Not addressed

Source: Based on Bullinger and Wächter, 2016, p. 84

A substantial body of literature exists within the scientific community addressing the subjects of sustainability, carbon accounting, and legal framework conditions in the context of tunnel construction. While general environmental and regulatory aspects are frequently covered, the analysis reveals a paucity of integrated and practice-oriented CO_2 accounting methods for tunnel construction projects, with the entire life cycle frequently insufficiently taken into account (Bascompta et al. 2024).

Life cycle analyses (LCA) and the Greenhouse Gas Protocol (GHG Protocol), which serve as the methodological basis for carbon accounting, are described in detail in specialist literature. Additionally, certification systems such as BREEAM, LEED, and DGNB have been developed to evaluate the environmental performance of construction projects more broadly (Bartels et al. 2022). However, the application of these extant accounting frameworks in the context of mechanized tunnelling has not yet been comprehensively established. This lack of alignment presents a substantial barrier to the implementation of effective CO_2 reduction strategies in tunnel construction. Addressing this gap necessitates further development and harmonization of existing accounting approaches and the systematic integration of sustainable practices at an earlier stage in the planning process. This approach would maximize the climate mitigation potential of tunnel infrastructure (Kou et al. 2024).

Empirical Study

An empirical study was also conducted to verify the general accounting approaches used in sustainability assessments, as well as research gaps identified through a literature analysis. The study aimed to supplement these approaches with practical assessments by experts. In order to ascertain the relevance of carbon accounting in tunnel construction, specific dimensions were examined, including understanding, acceptance and previous experience with the accounting methods currently in use.

The study was directed towards a specialized group of experts working in the field of sustainability assessment of tunnel construction. The experts were selected on the basis of their technical expertise and their current publication activities in the field of tunnel construction and carbon accounting. To obtain a comprehensive perspective, it was necessary to include experts from a variety of professional backgrounds. These included representatives from construction companies in Germany and Austria, engineering firms, public clients, specialists from the field of project planning and execution, and academic researchers with a university background.

Of the 21 individuals contacted for the expert survey, 6 experts agreed to participate, resulting in a response rate of 28.57%. Despite the restriction of participation, which diminishes the statistical representativeness of the data and precludes the drawing of generalizable conclusions for the entire tunnel construction industry, the responses nevertheless offer valuable qualitative insights into current practices and key challenges in the field of carbon accounting. Given the modest sample size, it is imperative to recognize the exploratory nature of the findings and to consider them as an inaugural step that prompts further research with more extensive empirical coverage. A thorough and candid discussion of these limitations is essential for maintaining the study's integrity and credibility.

Notwithstanding these constraints, the expert feedback reveals several consistent trends. The surveyed professionals highlighted significant discrepancies in the present utilization of carbon accounting within tunnel construction projects. These discrepancies are attributable not only to the absence of binding legal mandates, but also to the inconsistent and fragmented nature of prevailing guidelines. A conspicuous dearth of standardized, industry-wide methodologies exists to address the specific technical and operational features of mechanized tunnelling. Consequently, the assessment of CO_2 emissions frequently relies on approximate estimations, generic emission factors, or assumptions that do not align with the unique characteristics of tunnel construction projects.

The experts reached a consensus on the necessity of more precise and context-sensitive approaches to carbon accounting. These approaches should be grounded in project-specific data and capable of capturing the complex interactions of materials, machinery, and processes used in tunnel construction. Rather than relying on industry-unrelated blanket assumptions, a shift toward tailored methodologies is essential. These should include refined emission factors, differentiated by construction technique and project context, and data-driven calculation frameworks that reflect the full life cycle of tunnel infrastructure.

Moreover, the insights derived from the expert interviews are closely aligned with the findings of the preceding literature review. Despite the extensive documentation of foundational methodological frameworks, such as Life Cycle Assessment and the Greenhouse Gas Protocol, in academic literature, their application in tunnel construction remains in its initial stages. Certification systems such as BREEAM, LEED, and DGNB also address environmental performance; however, their relevance to the specific challenges of mechanized tunnelling remains limited. The discrepancy between theoretical frameworks and their practical implementation underscores the necessity for methodological development that is explicitly oriented towards the tunnel construction sector.

Considering these results, it is evident that the process of carbon accounting in tunnel construction necessitates both structural and methodological advancements. Firstly, it is imperative to acknowledge the necessity for enhanced harmonization and standardization across various projects and institutions. Secondly, sustainable construction practices - particularly those related to emission reduction - must be incorporated more systematically and earlier in the planning phase. The integration of carbon accounting into the fundamental framework of project development is imperative for the meaningful contribution of tunnel construction to broader climate protection objectives.

The results of the expert survey support the conclusions drawn from the extant literature and underscore the necessity of developing a tunnel-specific, practically applicable, and scientifically robust methodology for carbon accounting. This would enhance transparency and comparability across projects, thereby supporting the industry in meeting its climate responsibilities in a measurable and verifiable way.

Methodology to CO_2 Accounting in Mechanized Tunnel Construction

The findings outlined above constituted the conceptual foundation for the formulation of a customized methodology for sustainability assessment in mechanized tunnel construction. In order to identify suitable approaches, a comprehensive utility value analysis was conducted. This analysis employs a structured four-step process, as outlined by the German Federal Ministry of the Interior and Community (BMI 2023) o evaluate various CO_2 accounting models against a set of predefined criteria. The selection of criteria was predicated on the establishment of a foundation for evaluation, with the relevant criteria defined in accordance with project-specific requirements. These requirements encompassed a range of factors, including technical, ecological, economic, and regulatory aspects. A comprehensive set of criteria was meticulously evaluated, encompassing various dimensions such as relevance to the application, scalability, data availability and quality, model accuracy, uncertainty assessment, model complexity, user-friendliness, adaptability, transparency, support availability, system compatibility, data import/export, standards compliance, and stakeholder acceptance.

The selected approaches - process-based LCA, hybrid LCA, GHG Protocol, certification systems (BREEAM, LEED, DGNB), and databases - were each evaluated on a scale from 1 to 5 for each criterion, with equal weighting employed to ensure objectivity and transparency. The scores for each model were summed to determine their overall utility value. The results of the study indicated that the GHG Protocol (55 points) and the LCA method (54 points) were the most highly ranked, followed by the hybrid LCA approach (50 points), databases (49 points), and certification systems (41 points).

Consequently, the integration of the GHG Protocol and LCA is recommended as the optimal methodology for a comprehensive and pragmatic CO_2 accounting approach in tunnel construction. The integrative approach guarantees that the primary emission sources are meticulously documented, while also accounting for the indispensable holistic nature of the analysis.

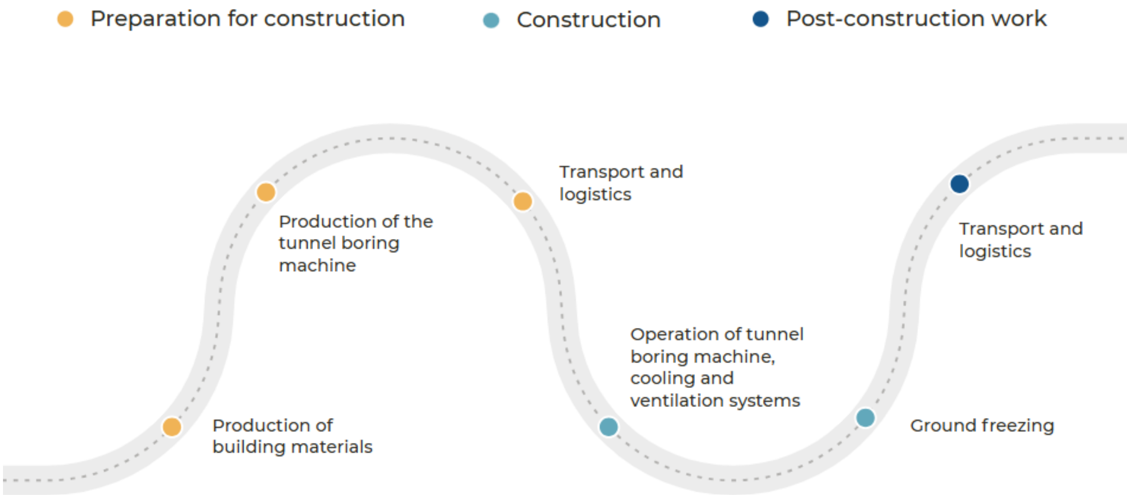
The GHG Protocol provides a standardized and internationally recognized structure for recording and categorizing emissions (Benitz-Wildenburg et al. 2023). It distinguishes between three types of emissions: Scope 1 (direct emissions from owned or controlled sources), Scope 2 (indirect emissions from purchased energy), and Scope 3 (all other indirect emissions, including upstream and downstream value chain activities) (World Resources Institute (WRI) 2025). While this structure provides clarity and consistency for greenhouse gas reporting, it does not, on its own, offer the necessary granularity for analyzing the complex interdependencies of emissions in construction processes.

The LCA methodology is a complementary approach to the GHG Protocol, offering a comprehensive evaluation of the environmental impacts throughout the lifecycle of a construction project. This includes the extraction and production of raw materials, transportation, use, maintenance, and end-of-life disposal (VDI Center for Resource Efficiency 2019.).

This combination of both approaches enables the developed framework to benefit from the organizational logic and standardization of the GHG Protocol, while also acquiring analytical depth and contextual accuracy through the LCA perspective.

However, both established approaches have shortcomings that necessitate context-related adaptation. Specifically, modifications to the system boundaries and balancing items are necessary to effectively map the specific emissions generated by mechanized tunnel construction. This tunnel-specific focus is essential, as several emission sources in TBM-based construction are highly specialized and rarely encountered in other construction contexts. These include not only the energy-intensive production of steel and concrete, but also the manufacturing and operation of the tunnel boring machines themselves - complex machines whose usage entails substantial electricity demand for cutting, cooling, and ventilation. Furthermore, emissions from upstream supply chains and downstream logistics, such as the transportation of excavated materials and prefabricated segments, contribute to the distinction of the carbon footprint of mechanized tunnelling from that of conventional infrastructure projects (see Figure 3).

Figure 3. *CO_2 Accounting Items in the Tunnel Construction Process*



Source: Own illustration

In accordance with the provisions of the German HOAI (Official Scale of Fees for Services by Architects and Engineers), the depicted emission sources are classified into three distinct phases of project development: preparation for construction, construction, and post-construction work, respectively. This phase-based structuring ensures that the methodology reflects the procedural logic of real-world tunnel construction projects and facilitates the integration of emission data into established planning and approval workflows. The strategic selection of key emission sources within these phases ensures the practical applicability of the framework without diminishing its analytical depth. Contributions from less significant emission sources, such as the production and operation of auxiliary machinery, are not adequately addressed due to the disproportionate effort required for data collection in comparison to their actual impact on overall emissions. Recent studies in construction-related LCA confirm that auxiliary equipment typically contributes less than 1-2% of total project emissions (Lorse 2021, Kou et al. 2024), which supports the methodological decision to exclude these marginal sources. Moreover, emission quantification for such machinery often suffers from incomplete operational data and inconsistent reporting standards, which would compromise the precision of the overall balance if included without verified data. The precision of the results is contingent upon the availability of reliable, project-specific data, which remains limited at present. The enhancement of data collection methodologies and the formulation of consistent, widely accepted emission factors could augment the robustness and applicability of the methodology, thereby increasing its value for both practitioners and policymakers.

To operate this framework and illustrate its practical relevance, it is necessary to clearly assign emission sources to specific stages of the construction process. As illustrated in Table 2, the relevant emission sources and their allocation to items of the respective phases of the construction process are delineated.

Table 2. *Overview of Activities in the CO_2 Accounting Items*

<table>
<tr><th>Phase</th><th>Work Package</th><th>Item</th></tr>
<tr><td rowspan="7">Preparation for construction</td><td>Production of the tunnel boring machine</td><td>Production of tunnel boring machine components</td></tr>
<tr><td rowspan="3">Production of building materials</td><td>Production of concrete (cement and aggregates)</td></tr>
<tr><td>Production of structural steel</td></tr>
<tr><td>Production of precast reinforced concrete elements</td></tr>
<tr><td rowspan="2">Transport and logistics</td><td>Transport of building materials (concrete, steel, etc.)</td></tr>
<tr><td>Transport of tunnel boring machine components</td></tr>
<tr><td rowspan="3">Construction</td><td rowspan="2">Operation of the tunnel boring machine</td><td>Mechanized tunnel excavation</td></tr>
<tr><td>Operation of cooling and ventilation systems</td></tr>
<tr><td>Ground freezing</td><td>Operation of the machines</td></tr>
<tr><td rowspan="2">Post-construction work</td><td rowspan="2">Transport and logistics</td><td>Spoil transport</td></tr>
<tr><td>Removal of the tunnel boring machine components</td></tr>
</table>

Source: Own illustration

This methodological approach enabled the reduction of complexity without compromising the validity of the results. The process of data collection presented a significant challenge, as the manufacturer's information was frequently incomplete and lacked standardization. To address this challenge, a methodology was developed that enables adaptability to diverse projects and ensures transparent documentation. Following the selection and elucidation of the pertinent items, a systematic calculation scheme was formulated (see Table 3).

This establishes a connection between the summarized items and the corresponding calculation approaches, thereby serving as a guideline for a structured approach to determining emissions.

Table 3. *Methodological Calculation approaches for identified CO_2 Accounting Items*

Position	Calculation Approach
Transport	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ \left[{}^{t}/_{km}\right] * Total\ distance\ S\ [km]$ $Total\ distance\ S\ [km] = Distance\ per\ trip\ s\ [km] * Number\ of\ trips\ n$ $Number\ of\ tips\ n = \frac{Mass\ to\ be\ transported\ m\ [t]/Volume\ V\ [m^3]}{Transportable\ Mass/Volume\ per\ trip}$
Production of the tunnel boring machine and materials	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ \left[{}^{t}/_{t}\right]\ or\ \left[{}^{t}/_{m^3}\right] * Mass\ m\ [t]\ or\ Volume\ V\ [m^3]$
Operation of tunnel boring machine, cooling and ventilation systems	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ \left[{}^{t}/_{kWh}\right] * Total\ energy\ requirement\ W\ [kWh]$ $Total\ energy\ requirement\ W\ [kWh] = Operating\ hours\ t\ [h] * Power\ P\ [kW]$
Operation of the machines for ground freezing	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ \left[{}^{t}/_{kWh}\right] * Total\ energy\ requirement\ W\ [kWh]$

Source: Own illustration

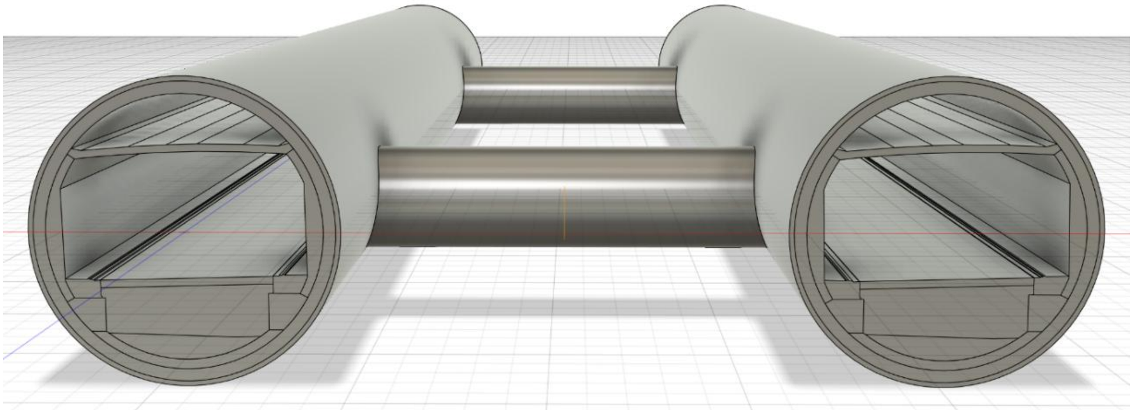
In the next phase, the methodology is systematically implemented through the use of a case study exemplifying tunnel construction.

Validation

The validation process employs a real-world tunnel project situated in Munich, comprising two parallel tunnel tubes, each with an approximate length of 3.034 m, interconnected by cross-passages at 60-meter intervals. This configuration exemplifies a standard layout frequently implemented in urban tunnel infrastructure and functions as a representative case for assessing the applicability of the developed CO_2 accounting methodology. Figure 4 presents a three-dimensional representation of the tunnel structure, developed using Fusion 360 for the purpose of visualization. This depiction facilitates a more nuanced spatial understanding of the structural elements that are considered in emission accounting. The choice of this case study was guided by its practical relevance and the availability of generalized yet realistic design parameters, allowing the methodology to be tested under conditions that reflect actual construction practices while maintaining broad applicability to similar projects.

To transition from the conceptual framework to practical implementation, the methodology was applied to the selected tunnel case. The primary challenge in CO_2 accounting in tunnel construction was the selection of reliable values that met the requirements of both realism and plausibility. Due to the extensive array of data sources and the significant discrepancies observed among public databases, a meticulous selection and validation process was imperative for the emission values.

Figure 4. *Idealized Tunnel Cross-section with Two Tunnel Tubes and Cross-passages*



Source: Own illustration

Consequently, Table 4 provides a consolidated overview of all emission factors utilized in the analysis, including material production, energy consumption, and transportation. These values form the empirical basis for estimating the magnitude of greenhouse gas emissions attributable to each element of the construction process and may serve as a point of reference for other tunnel infrastructure projects of comparable scope.

Table 4. *Overview and Sources of all CO_2 Emission Values*

Building materials and electricity	**Emission factor** e	**Source**
Structural steel	$2{,}875\ [t\ CO_2/t]$	*IOER Research Data Centre* of the Leibniz Institute of Ecological Urban and Regional Development, 2024
Reinforcing steel	$0{,}615\ [t\ CO_2/t]$	
Asphalt	$0{,}102\ [t\ CO_2/t]$	
Normal concrete C12/C15	$0{,}063\ [t\ CO_2/t]$	
Normal concrete C25/C30	$0{,}075\ [t\ CO_2/t]$	
Normal concrete C30/C37	$0{,}082\ [t\ CO_2/t]$	
Normal concrete C35/C45	$0{,}092\ [t\ CO_2/t]$	
Truck > 18t	$0{,}0009454\ [t\ CO_2/km]$	Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, Umweltbundesamt GmbH, based on

		GEMIS Austria, 2024
Segments (concrete C40/50 and steel)	0,716 $[t\ CO_2/kWh]$	Own calculation based on Kou *et al.*, 2024, p. 18
Gravel	0,002739 $[t\ CO_2/m^3]$	*ÖKOBAUDAT* of the Federal Ministry of Housing, Urban Development and Construction, 2024
Annular gap mortar (cement mortar)	0,314 $[t\ CO_2/m^3]$	
Green electricity	0,000032 $[t\ CO_2/kWh]$	Hakenes and Weißbach, 2023, p. 5
Electricity mix	0,000445 $[t\ CO_2/kWh]$	Icha and Lauf, 2024, p. 8

Source: Own illustration

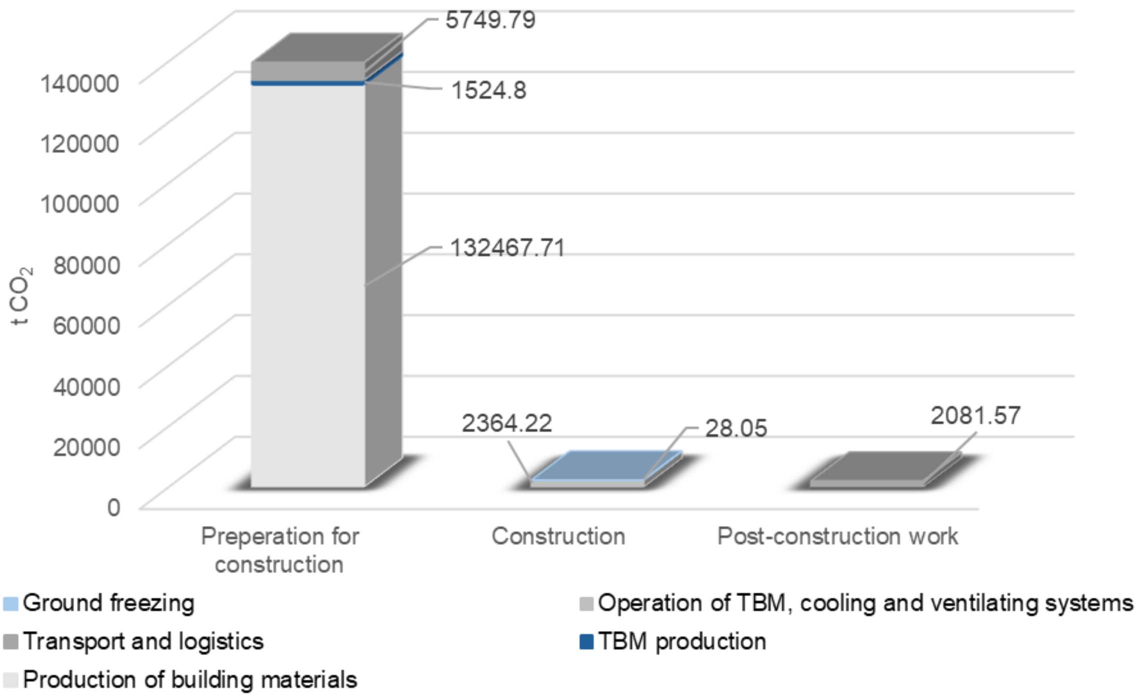
A comparison with values reported in the literature and applied in industry-standard approaches further substantiated the methodological robustness and transparency of the selected parameters. The validation process substantiates the conclusion that the calculation model is both logically consistent and practically applicable across a range of tunnel construction scenarios.

The findings derived from the implementation of the methodology highlight its aptitude for comprehensively capturing a diverse array of emission sources in a cohesive and traceable manner, encompassing the production of construction materials, on-site operations, and transportation logistics. Figure 5 provides a visual representation of the aggregated CO_2 emissions associated with each major accounting item.

A comparison with values in existing literature and common approaches confirmed the comprehensibility and accuracy of the methodology. The validation process has yielded results that demonstrate the versatility of the developed calculation approaches, suggesting their applicability to a range of scenarios.

Preliminary to the calculation, geometric measurements of the tunnel components were conducted, and material volumes were derived accordingly. These volumetric data were utilized as input variables for the carbon accounting model, thereby ensuring consistency and precision in the quantification of emissions per unit process. The calculation results demonstrate that the methodology facilitates a consistent and transparent recording of all relevant emission sources, from material production to operation and logistics. To illustrate the results, the emissions determined for the individual balance sheet positions are shown in Figure 5.

Figure 5. *Total CO_2 Emissions of the Exemplary Tunnel Construction Project*



Source: Own illustration

The total CO_2 emissions resulting from the tunnel construction project amount to 144 216.14 metric tons of CO_2. The most significant contribution originates from construction preparation, encompassing the production of construction materials, which generates 132 467.71 t CO_2. This is followed by transport and logistics emissions, accounting for 5 749.79 t CO_2, and the production of the tunnel boring machines, responsible for 1 524.80 t CO_2. During the construction phase, the energy required to operate the tunnel boring machine, cooling, and ventilation systems generates emissions of 2 364.22 t CO_2, while ground freezing contributes an additional 28.05 t CO_2. A total of 2 081.57 t of CO_2 emissions were documented during the post-processing stage of construction, attributable to transportation-related activities.

Even though transport and logistics, tunnel boring machine operation, cooling and ventilation systems, and the operation of ground freezing machines generate substantial emissions, a direct comparison reveals that they account for a negligible proportion of total emissions, amounting to 8.15%. Consequently, the most significant potential for reducing emissions is identified in the domain of material production (Kou et al. 2024). The increased use of low-CO_2 cement and steel, as well as the incorporation of resource-saving segments, has the potential to significantly contribute to the reduction of emissions. This finding aligns with the results of the carbon footprint assessment of the Brenner Base Tunnel, which identified concrete production, tunnel excavation, material transportation, and construction equipment as the primary sources of emissions (Bergmeister 2022).

The calculated total emissions of 144 216.14 t CO_2 for the construction of the tunnel demonstrate the substantial climatic impact associated with an infrastructure project of this magnitude (Elbers 2022, Emig 2024). The high emissions prompt the critical question of how infrastructure projects can be reconciled with the objectives of sustainability and climate protection in a time of global climate crisis.

Discussion

The following discourse aims to provide a critical examination of the utility, limitations, and transferability of the proposed CO_2 accounting methodology for tunnel construction. It contextualizes the methodological strengths and data-related challenges, while addressing unresolved tensions between the need for standardization and the necessity of project-specific adaptation. The ensuing discourse delves into the foundational contributions of the developed framework, its practical relevance, and its future prospects for refinement and application.

Methodological Development

The proposed framework was developed to address the existing gap in standardized CO_2 accounting practices for tunnel construction projects, with a particular focus on tunnel boring machine-based excavation methods. In order to guarantee scientific robustness and practical applicability, the methodology synthesizes principles from the Greenhouse Gas Protocol and Life Cycle Assessment, integrating their respective strengths.

The approach prioritizes transparency, scalability, and simplicity. The study emphasizes major emission sources, primarily the production of construction materials such as steel-reinforced concrete and the operation of heavy machinery. It deliberately excludes minor sources whose accounting effort would not be proportionate to their emissions share.

A systematic, criteria-based selection process was conducted to evaluate different methodological approaches based on technical feasibility, ecological relevance, regulatory compatibility, and stakeholder acceptance. A utility value analysis revealed that the GHG Protocol (55/70 points) and the LCA approach (54/70) were the most suitable foundations, owing to their structured formats and scientific credibility. Alternative systems, including hybrid LCAs and certifications such as BREEAM and LEED, received lower scores due to their more limited scope and the presence of data inconsistencies.

A significant challenge encountered during the development process pertained to the limited availability of specific emissions data concerning tunnel boring machine components and processes. In several instances, particularly with regard to the manufacturing of tunnel boring machines and their subsystems, data had to be obtained through direct cooperation with manufacturers such as CREG TBM Germany GmbH or supplemented with estimations based on proxy processes. These discrepancies across publicly accessible databases necessitated rigorous validation procedures.

Key Findings and Limitations

The application of the methodology yielded several insights, as well as inherent limitations.

1. Scope Restrictions: At present, the framework's scope is confined to the analysis of CO_2 emissions, with a notable exclusion of more extensive ecological and socio-economic dimensions. These dimensions encompass, but are not limited to, land use changes, biodiversity impacts, and social externalities. This narrow focus fosters clarity and ease of use but limits the comprehensive evaluation of sustainability.
2. Data Uncertainty: However, reliable emission factors with a specific focus on tunnel construction are limited, leading to a persistent reliance on assumptions and approximations. For instance, the calculation of emissions from ground freezing operations for cross-passage construction necessitated sophisticated modeling approaches that employed tools such as MATLAB and GeoGebra to approximate energy demand and associated emissions.
3. Trade-offs in Practical Application: In order to maintain user-friendliness and enable practical implementation, the methodology involves simplifying assumptions. To illustrate, subordinate emission sources, such as auxiliary machinery, are excluded from this analysis. While this compromises completeness to some extent, their marginal contribution to total emissions justifies this exclusion within the current scope.

Case Study

To assess its real-world applicability, the methodology was implemented in a large-scale tunnel construction project in Munich. The case study confirmed the approach's utility in quantifying emissions and identifying mitigation strategies.

1. Material Optimization: The incorporation of recycled concrete and low-carbon cement types played a substantial role in the mitigation of embodied emissions.
2. Process Efficiency: The electrification of construction machinery, in conjunction with enhancements in logistics planning, has resulted in a quantifiable decrease in diesel consumption and operational emissions.
3. Support for Decision-Making: The framework facilitated a systematic evaluation of emission reduction measures in terms of their cost-effectiveness, providing a valuable instrument for planning and investment decisions. However, the high costs associated with certain mitigation options-imposed limitations on the full range of options that could be considered.

Broader Implications

The methodology has implications that extend beyond the individual project level.

1. Standardization Potential: The modular configuration of the framework enables its adaptation to diverse regional contexts, while maintaining a consistent template for TBM-based tunnel projects. This approach fosters transparency, facilitates cross-project comparability, and enables benchmarking.
2. Areas of Research that Require Further Exploration and Development: There is an urgent need to expand emissions databases that are tailored specifically to underground infrastructure. Furthermore, subsequent research endeavors should investigate the incorporation of life cycle costing and the monetization of ecological impacts to facilitate more comprehensive sustainability assessments.
3. The relevance of the policy is as follows: The methodology aligns with broader climate protection goals and can serve as a foundation for regulatory development. It furnishes public authorities and planning institutions with a structured approach to establish emission benchmarks and promote sustainable practices in infrastructure development. This alignment is consistent with the objectives set out in the European Green Deal and forthcoming regulatory frameworks that emphasize sector-specific decarbonization and life-cycle-based assessment methods within the construction industry. The proposed framework therefore directly contributes to these evolving policy targets by providing a transparent, data-driven calculation and reporting structure that can be integrated into future sustainability assessment systems and environmental regulations.

Conclusions

The present study developed and applied a methodology for CO_2 accounting in tunnel construction, specifically tailored to mechanized tunnel construction. The proposed approach tackles the dearth of standardized practices by integrating the Greenhouse Gas Protocol and Life Cycle Assessment, thereby offering a balance between scientific rigor and practical usability. A systematic literature review and empirical data revealed significant methodological gaps, particularly the absence of project-specific data and consistent emission factors.

The developed framework places emphasis on significant emission sources, including material production (concrete, steel), tunneling machinery, and transport processes. It is designed to allow for modular adaptation to the specific conditions of each project. The application of the method to a real-world tunnel project in Munich demonstrated its practical relevance, highlighting that substantial emissions stem from segment production and logistical operations. The findings substantiate the efficacy of the method in the initial planning stages and accentuate the significance of transparent and reliable data.

Notwithstanding certain limitations, including incomplete data on minor emission sources, the methodology establishes a substantial foundation for CO_2 assessment in tunnel construction and demonstrates considerable potential for transferability to other infrastructure projects. Subsequent endeavors should prioritize the establishment of standardized, tunnel-specific emission databases to enhance comparability and support more extensive decarbonization objectives in the construction industry.

The future of tunnel construction must be characterized by a balanced integration of technological innovation and ecological responsibility. Tunnels, as pivotal components of contemporary mobility infrastructure, are required to incorporate environmental criteria into all phases of their life cycle to ensure sustained viability. The CO_2 accounting methodology developed in this study provides a foundation for such integration and could serve as a model for future infrastructure design. With appropriate standardization and collaboration among stakeholders, the construction of tunnels has the potential to become a model for sustainable infrastructure development.

References

Bartels N, Höper J, Theißen S, Wimmer R (2022) *Application of the BIM method in sustainable construction – status quo of potential applications in practice.* Wiesbaden: Springer Fachmedien.

Bascompta M, García H, Rodríguez R (2024) Carbon footprint evaluation in tunnels excavated in rock using tunnel boring machine (TBM). *International Journal of Civil Engineering* 22(6): 995–1009.

Benitz-Wildenburg J, Lass JP, Seehauser C (2023) Bewertung von Bauelementen und Baustoffen für nachhaltiges Bauen. Ökobilanz, Umweltproduktdeklaration und CO_2-Fußabdruck als Instrumente [Assessment of building components and materials for sustainable construction. Life cycle assessment, environmental product declaration, and carbon footprint as tools]. In: Fuad NA (ed.) *Bauphysik-Kalender 2023: Nachhaltigkeit*, 417–446. Berlin: Ernst & Sohn GmbH.

Bergmeister K (2022) Der Brennerkorridor – eine europäische Dimension für Mobilität und Nachhaltigkeit [The Brenner Corridor – a European dimension for mobility and sustainability]. In: Laimer S, Perathoner C (eds.) *Mobilitäts- und Transportrecht in Europa. Bestandsaufnahme und Zukunftsperspektiven*, 179–196. Berlin: Springer.

Bischofberger AD (2024) *Sustainability in tunnelling – application potential of the resource-efficient tubbing in mechanized tunnelling.* MSc Thesis, Technical University Wien, Vienna.

Blöcker A (2022) Grüner Stahl – wie geht das? Eine Studie im Rahmen des Projekts „Sozial-ökologische Transformation der deutschen Industrie" [Green steel – how does it work? A study conducted as part of the project "Social-ecological transformation of German industry"]. Berlin: Rosa-Luxemburg-Stiftung & Alternative Wirtschaftspolitik.

Deutscher Ausschuss für unterirdisches Bauen (2023) *Empfehlungen für die Ermittlung von Lebenszykluskosten für Tunnel* [Recommendations for determining life cycle costs for tunnels]. Available at: https://www.daub-ita.de/fileadmin/documents/daub/gtcrec4/20 23-03-24_DAUB_LZK_Empfehlung_mit_%C3%96PNV_und_DB.pdf

Druffel R, Wittke M, Wittke W, Wittke-Gattermann P, Wittke-Schmitt B (2022) Einsparung von Energie und Rohstoffen und Verringerung des CO_2-Fußabdrucks durch Innovationen im Tunnelbau [Saving energy and raw materials and reducing the carbon footprint through innovations in tunnel construction]. *Tunnel* 40(3): 10–27.

Edenhofer O, Flachsland C, Kalkuhl M, Knopf B, Pahle M (2019) *Optionen für eine CO_2-Preisreform. MCC-PIK-Expertise für den Sachverständigenrat zur Begutachtung der gesamtwirtschaftlichen Entwicklung, Arbeitspapier 04/2019* [Options for CO_2 price reform]. Wiesbaden: Sachverständigenrat zur Begutachtung der Gesamtwirtschaftlichen Entwicklung.

Elbers U (2022) Ressourcenschonendes Bauen – Wege und Strategien der Tragwerksplanung [Resource-efficient construction – approaches and strategies for structural design]. *Bautechnik* 99(1): 57–64.

Emig N (2024) *CO_2-Bilanz für Unternehmen: Pflicht und Chancen [Carbon footprint for companies: obligations and opportunities].* Available at: https://klimahelden.eu/blog /co2-bilanz-unternehmen.

Engelhardt S, Schwarz J, Thewes M (2014) The lifecycle cost concept for implementation of economic sustainability in tunnel construction. *Geomechanics and Tunnelling* 7(5): 593–600.

Federal Ministry of Housing, Urban Development and Construction (Germany) (2024) *ÖKOBAUDAT.* Available at: https://www.oekobaudat.de/.

Friess J, Golser J, Luniaczek T (2022) CO_2 reduction in tunnelling from the point of view of construction design and implementation. *Geomechanics and Tunnelling* 15(6): 792–798.

Galluccio M (2022) *Klimawandel und Extremgefahren. Wissenschaft und Diplomatie. Aushandeln wesentlicher Allianzen* [Climate change and extreme hazards. Science and diplomacy. Negotiating essential alliances]. Basel: Springer Nature Switzerland AG, 95–111.

Geist M, Heinze C, Weiher K, Werner C, Vierhub-Lorenz V (2021) *Automatisierte akustische Prüfung von Tunnelstrukturen mit Hilfe von Lasersystemen und maschinellem Lernen* [Automated acoustic testing of tunnel structures using laser systems and machine learning]. DGZfP-Jahrestagung 2021. Available at: https://jt2021.dgzfp.de/portals/jt2021/bb176/inhalt/10.pdf.

Hakenes J, Weißbach A (2023) *Ökostrom-Vergleich: echte Ökostrom-Anbieter finden* [Green electricity comparison: find genuine green electricity providers]. Available at: https://www.co2online.de/energie-sparen/strom-sparen/strom-sparen-stromspartipps/was-ist-echter-oekostrom.

Handler H (2024) *Krisengeprüftes Europa: Die EU auf dem Weg zu einer neuen Identität* [Crisis-tested Europe: The EU on the path to a new identity]. Wiesbaden: Springer Gabler.

Icha P, Lauf T (2024) Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990–2023 [Development of specific carbon dioxide emissions from the German electricity mix in the years 1990–2023]. *Climate Change* 45: 210–220.

Karlsson L-M (2024) *Sustainability in tunnel projects.* MSc Thesis, Tampere University, Finland.

Kou L, Li W, Liang H, Shi X, Wang Y (2024) Evaluating carbon emissions during slurry shield tunnelling for sustainable management utilizing a hybrid life-cycle assessment approach. *Sustainability* 16(2702): 1–25.

Leibniz Institute of Ecological Urban and Regional Development (2024) *IOER Research Data Centre.* Available at: https://ioer-isbe.de/grundlagen/baumaterialinduzierte-emissionen.

Lorse B (2021) *Carbon footprints als Instrument zur Nachhaltigkeitsbewertung. Eine Untersuchung am Beispiel Hochschulgastronomie* [Carbon footprints as a tool for sustainability assessment. A study based on the example of university catering]. Trier: University of Trier.

Menge M (2023) *Building Bridges Starts in the Mind. Engineering – More than Technical Solutions.* Wiesbaden: Springer Fachmedien.

Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology Austria and Umweltbundesamt GmbH (2024) *Emissionsfaktoren der Verkehrsträger* [Emission factors of transport modes]. Available at: https://www.umweltbundesamt.at/fileadmin/site/themen/mobilitaet/daten/ekz_fzkm_verkehrsmittel.pdf.

Sauer J (2016) *Ökologische Betrachtungen zur Nachhaltigkeit von Tunnelbauwerken der Verkehrsinfrastruktur* [Ecological considerations regarding the sustainability of tunnel structures in transport infrastructure]. Munich: Technical University of Munich.

VDI Center for Resource Efficiency (2019) *Ökobilanz – DIN EN ISO 14040/44. Leitfaden Ressourceneffizienz* [Life cycle assessment – DIN EN ISO 14040/44. Resource efficiency guidelines]. Available at: https://www.ressource-deutschland.de/leitfaden-re/methoden/oekobilanz-din-en-iso-14040/44.

World Resources Institute (2025) *Greenhouse Gas Protocol.* Available at: https://www.wri.org/initiatives/greenhouse-gas-protocol

Wühle M (2022) Ökobilanz und CO_2-Fußabdruck: Entscheidende Instrumente für nachhaltiges Wirtschaften [Life cycle assessment and carbon footprint: crucial tools for sustainable business practices]. Available at: https://www.nachhaltigkeit-management.de/okobila nz-und-co2-fussabdruck.

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Scalability and Cyber Resilience in Gated Array Blockchain Enabled Devices

By John M. Medellin[*]

This research expands on previous works for usage of blockchain in key negotiation between machines. In addition to providing key negotiation, it expands to enabling value transactions in a network of zero-trust nodes. It further describes attacks in an Internet of Things (IoT) on machines that are constrained in resources similar to those of mobile devices or other types of small components. Attacks are formulated and the method of protection is described in light of architecture vulnerabilities. Each set of key exchanges is modeled and the level of protection and vulnerability is described for five cyber-attacks. The core of the research uses a protocol previously published in a time-dimensioned, randomized set of epochs and uses the reversibility property in the exclusive -or-/-nor- gates (XOR/XNOR). The role of a manager and assistant manager are defined within random dimensioned duration slices or epochs and the time requirements to make the change are measured as network nodes are scaled. An optimized model for election of managers, key generation and propagation into the blockchain network during an epoch change is presented. In that model, number of managers are optimized to yield the smallest completion time for each epoch change.

Keywords: *cybersecurity, blockchain, internet of things, consensus, VHDL*

Introduction

This document is a continuation of research on special purpose machines that constitute nodes in a blockchain network operating in zero-trust. The machines are based on the Internet of Things (IoT) formats which are small and prevalent in society today. The dual-mode machines can be either participants or managers in the blockchain network and communicate by storing relevant keys in their blockchain memories. This document explains how those blocks interact and are regenerated in time slices called "epochs" by the "manager" mode of operation of the blockchain node. Randomization of parameters tends to result in greater confusion to potential attackers which decreases the ability to formulate and execute egregious behavior.

As explained in Alharby et al. (2018), these devices are very sensitive to resource consumption (time, power, memory resources) and that makes the design of solutions for them more challenging. However, in Wazid et al. (2020) it is explained they are coming of age with newer technologies such as 5G networks (and potentially 6G) and widespread adoption in the medical, automotive, defense and other significant segments of society. These devices are also more prone to attack because of the more simple communication protocols used between them (Khan and Chowdhury 2021).

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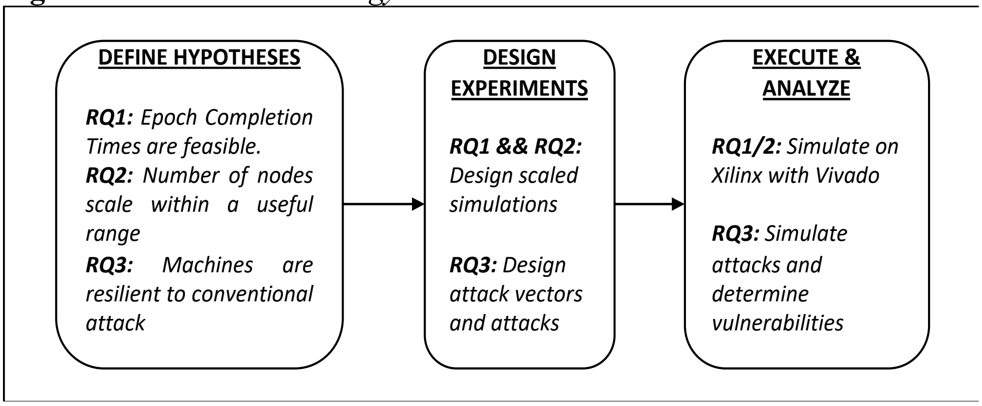
Many protocols and suites exist for managing permissioned networks, notably the IBM Fabric has been successfully implemented in these situations (Muralidharan et al. 2019). The main difference between this approach and those outlined is that these devices do not rely on permissioned networks and establish their own identity and trust by storing keys in their blockchains. In addition, those keys are regenerated again in randomly chosen slices of time to further confuse the attack surface for aggressors.

In this study the following questions are researched under the research methodology in Figure 1.

RQ1: Are the epoch completion times feasible as the networks scale in number of nodes?
RQ2: What if any are the scaling limits for these machines in number of nodes?
RQ3: How can these machines defend themselves against cyber-attacks?

Figure 1. *Research Methodology*



Prior Work

This is continuing research on the application of blockchain principles to gated-array machines. In this area, the focus has been on creation of zero-trust (Knapp and Langill 2015) blockchain (Nakamoto 2019) networks that rely on the XOR and the XNOR gates while randomizing the time-slice to regeneration, the key values and the consensus protocols. Significant results have been achieved in power conservation, time of execution and compaction of results in previous publications (Medellin 2024).

This section provides more insight into previous research in the following topics:

- Zero-Trust Blockchains
- Reliance on Reversible Gate Patterns
- Randomization is critical
- Resource conservation.

This research assumes there are no trust parameters between machines prior to the initialization of communication requests ("zero-trust"). The networked machines have two modes of operation Manager/Assistant Manager and Participant corresponding to their roles in the network at a particular time-slice or "epoch" of operation. An "epoch" is defined as: randomly generated amount of time in the context of the network of blockchain nodes (Medellin 2022). Based on configuration items, these can be regenerated (with associated keys) within limits as can the key lengths and number of keys. Research so far has used 4 keys which are described below.

The participant mode has previously been studied (Medellin 2024) thus the focus of this work is to test the Manager/Assistant Manager modes of operation in light of the research questions. The operating modes and the four keys typically exchanged are further discussed in the following subsections.

The Manager/Assistant Manager Modes

In the election process, a new Manager is elected by the previous Manager's generation of a random binary array that corresponds as closely to a security key length (explained below) used in previous epochs and comparing those values through an XOR operation to all the security keys available (those security keys are stored as blocks in the blockchain). The resulting array with the most "0"s in the outcome will be deemed the next epoch manager (in case of a tie, the first one evaluated will win). The algorithm is repeated for finding the next closest and that is deemed to be the Assistant Manager. At least one assistant manager should be elected for the next epoch so as to provide continuity in case of the Manager being absent when the next epoch should begin.

At the start of the new epoch, the Manager will execute the tasks of communicating with the Assistant Manager(s), election of the next Manager/Assistant Manager(s), generation of new epoch and operation keys (described below), additional keys if required, admission/deprecation of new participants, definition of next epoch duration and validation/encryption of new blocks, and propagation of those new blocks.

During the epoch, the Manager will call on the Assistant Manager(s) to communicate the new keys. The Manager will communicate the specific keys to the newly admitted machines and will validate/encrypt and broadcast new blocks for the blockchain. The Assistant Manager(s) will communicate individually with member machines by being assigned to specific epoch of admission and communicating with those machines the new keys that are public to the existing machines. In the event the Manager has not begun their tasks within a given time lapse of the start of a new epoch, the Assistant Manager will assume the duties of the Manager and execute them.

The Manager and the Assistant Manager(s) secret keys for the epoch will have been communicated in the prior epoch to the participant machines in the propagated payload. Once the epoch is concluded, they will return to participant mode for the next epoch (unless they are re-elected, in which case the process above will repeat itself again with those machines).

The Participant Mode

As mentioned above, the machines have dual modes and one of them is the "participant" mode. The scope of this is to dialogue with other machines through binary key exchanges of secrets that are stored in their individual blockchain memories and shared knowledge. The keys employed in dialogues can either be current epoch keys, prior epoch keys or combinations of keys since they are stored in the blockchain are therefore known to all nodes.

Blockchain Blocks / Keys

The keys (in binary valued arrays) are as follows:

- EK: Epoch key (common to all): the key of the epoch being referenced.
- OP: Operation key (common to all): 0 is use XOR, 1 is use XNOR in that epoch.
- SK: Security key (unique to participants): unique in the blockchain
- PK: Private key (unique to participants & known to them and the epoch Manager)

Communication and Encryption via Reversible Gate Patterns

The 2-way XOR and XNOR truth tables effectively create a three value data set with 2 inputs and one output. By adding another data point to the set (the operation) where a "0" corresponds to usage of the XOR and "1" usage of the XNOR to evaluate the inputs this effectively creates a 4 data point set. If this is further extended by creating arrays of 1's and 0's for each value, we can create a 4 column array with the inputs, operation to perform and the output (all in binary forms). The following sections describe the reversibility property of this approach and its usefulness in deriving arrays of keys that are operated by Boolean algebra (Huang and Cheng 2002).

The XOR/XNOR Gates and Reversibility

The XOR gate (also known as the "equivalence" gate) is a binary logic comparator that outputs a result of "1" if the two inputs are the same or a "0" if they are different. The XNOR gate reverses the process; if the two are different then it produces a "1" for the output and the inverse if they are the same. A common format for illustration of this concept is the "truth table" which outlines the only possible outcomes for all possible inputs when two binary values are input. The truth tables for the XOR and the XNOR[1] are shown in Figure 2.

[1]https://www.elprocus.com/basic-logic-gates-with-truth-tables/.

Figure 2. *XOR XNOR Truth Tables*

XOR

X (in)	*Y (in)*	*Z (out)*
0	0	1
1	0	0
0	1	0
1	1	1

XNOR

X (in)	*Y (in)*	*Z (out)*
0	0	0
1	0	1
0	1	1
1	1	0

As mentioned in this subsection's introduction, the inclusion of a fourth value in the truth table, the operation to use, effectively transforms the three valued array into a four value array as shown in Figure 3.

Figure 3. *Four Value Array Examples (XOR, XNOR)*

XOR

X (in)	*Y (in)*	*OP*	*Z (out)*
0	0	0	1
1	0	0	0
0	1	0	0
1	1	0	1

XNOR

X (in)	*Y (in)*	*OP*	*Z (out)*
0	0	1	0
1	0	1	1
0	1	1	1
1	1	1	0

Furthermore, if we extend the concept to binary arrays they can be used to derive value when 3 of them are known. This was given in Medellin (2024) and elaborated further below:

"For any combination of three binary digits, 1 or 0 when the XOR or the XNOR gate is used to evaluate the logic between two of them, the fourth digit shall be equal to 1 when any combination of the first three has all the values of 0 or more than one digit has the value of 1 else the value of the fourth digit shall be 0."

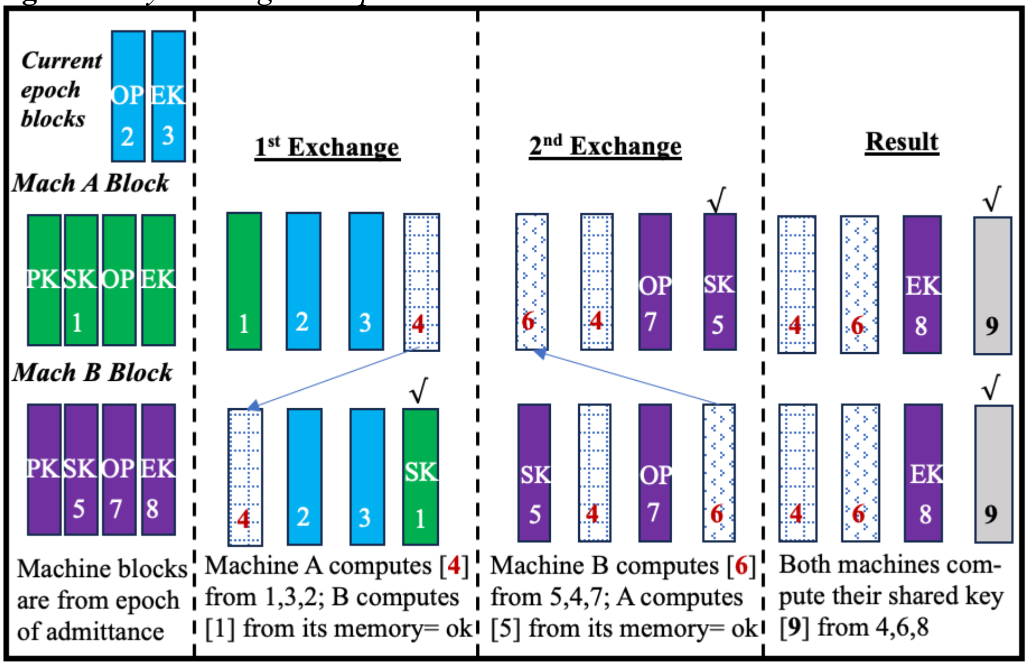
Proof:

$$\{0\ 0\ [0/\oplus]\} = 1 \Rightarrow [0\,0\,0\,1]\ \&\&\ \{0\ 0\ [1/\odot]\} = 0 \Rightarrow [0\,0\,1\,0]$$
$$\{0\ 1\ [0/\oplus]\} = 0 \Rightarrow [0\,1\,0\,0]\ \&\&\ \{0\ 1\ [1/\odot]\} = 1 \Rightarrow [0\,1\,1\,1]$$
$$\{1\ 0\ [0/\oplus]\} = 0 \Rightarrow [1\,0\,0\,0]\ \&\&\ \{1\ 0\ [1/\odot]\} = 1 \Rightarrow [1\,0\,1\,1]$$
$$\{1\ 1\ [0/\oplus]\} = 1 \Rightarrow [1\,1\,0\,1]\ \&\&\ \{1\ 1\ [1/\odot]\} = 0 \Rightarrow [1\,1\,1\,0]$$

Key Exchanges and Reversibility of Results

Figure 4 gives a visual example of how key exchanges would work if we had 4 binary arrays interacting with current and prior epoch knowledge. In the current state, all keys are known to machines A and B. Machine A initiates the dialogue request by computing array 4 and sending to machine B. Machine B validates the A's Secret Key 1 by taking its knowledge from the blockchain and computing 1 from 4,2 and 3. It next computes 6 from 5,4 and 7 and sends it to machine A who validates 5 ensuring it is communicating with the right machine. In the final dialogue, they both compute their shared key by taking 4,6 and 8 to derive 9.

Figure 4. *Key Exchange Example*



Randomization as an Attribute

Use of random numbers provides for creation of alternatives that can enhance protection for attack surfaces. Randomization can provide a continuous infinite distribution that is very challenging to attack since it requires the attacker to reformulate an attack on a moving target. Enhancing solutions with randomization in the following areas can further confuse the attack surface:

- Duration of time between regeneration of keys referenced above
- Length of keys (number of binary digits).
- Number of keys (more can be used in the model).
- Direct election of network managers and assistant managers.
- Voting for managers and assistant managers (not all have to vote).

When randomization is combined with large binary keys it forms a phenomenal protection combination (Medellin 2022). The aspects of binary key size and traversal of blockchain in order to secure additional required keys are discussed below.

Key Size and Probabilities of Attack Success

As mentioned above, the keys in this document are binary arrays with 1 or 0 in each location. For example if the key (array) is 4 bits long then there are 2^4 number of combinations of 1 or 0s contained in that array (i.e.: 0000, 1000, 0100… 1111). The probability of guessing without prior knowledge is 1/16 (in decimal notation). With replacement (knowledge that one or more numbers previously guessed are not correct) becomes (in the single case and through exponentiation):

$$P(x) = \frac{1}{N-z} \quad P(x) = \frac{1}{[(N1^{y1})*(Nn^{yn})]-z}$$ (Johnsonbaugh 2018)

Where:

N : Number available in the Universe or sub-component Universe
z : Number previously drawn
yn : Sub-component Universe size exponent

In the previous example, if a first try did not guess correctly, the next guess would have a $P(x) = \frac{1}{16-1}$ = 1/15 probability of guessing correctly and the number of tries that did not guess correctly would be accumulated until the last guess (if all were incorrect) would have a $P(x) = \frac{1}{16-15} = P(x) = \frac{1}{1}$ probability of guessing correctly (at that point it is a certainty and not a guess).

If the case was expanded to two arrays of the same size, the probability of guessing correctly the first time both combined numbers would be $P(x) = \frac{1}{2^4*2^4}$ or $P(x) = \frac{1}{2^8} =$ expressing the result in decimal is $\frac{1}{256}$; if we had 4 arrays of the same size, the combined probability of success would be $\frac{1}{4096}$. If the first guess was incorrect, the next guess (with replacement) would be $\frac{1}{4096-1}$ and so on, subtracting one more for each failed try. Furthermore, if four keys were used that were 64 bits long, the probability of success would be $P(x) = \frac{1}{2^{256}}$ and $P(x) = \frac{1.158}{10^{77}}$ in decimal notation (1,158 with 74 0's after it). Therefore by implication, adding more keys and increasing key length further lessens the probability of attack success without knowledge.

Previous Resource Usage Results

Previous work [0] has indicated that exchanges between machines use less than 1/1,000 watt of dynamic power in computation for a 256 bit array key-exchange versus 2.408 watts using a SHA-256 key-exchange using FPGAs. The same study concluded that the speed of execution when compared to Diffie-Hellman's algorithm (also 256 digits) executed in 10.70 CPU seconds vs 0.58 CPU seconds in a digital computer representing a significant differential in favor of the gated algorithm.

The above studies were simulated in peer machines participating in a network exchange dialog.

The Role of Dual-Purpose Machines in the Model

Two key aspects dominate this research; the machine modes and the actual dialogues that happen within those modes. The following sections detail the participant mode communication, the general dialogue model and the manager communications and operations.

Communication in the Participant Mode

The participant mode is the more common mode of operation of the machines. In this mode, the machines interact with each other by exchanging arrays of binary digits or keys. The key lengths can be varied and are stored as blocks in previous or current epochs on the blockchain. In order for the dialogues to be successful, both machines need to know previous and current epoch blocks. These keys are used to execute exchanges which lead them ultimately to exchange something of value between them.

<u>Participant Mode Characteristics</u>

In the participant mode of operation, the machines achieve identity, trust, contract and value exchanges through logic operations using the above mentioned XOR or XNOR gates. Identity is achieved by sharing keys that are derived from components in the blockchain that would not be known to an uninformed participant. Trust is achieved by negotiating a mutual key based on products of blockchain keys that are unique to the two of them. Contract (or the ability to exchange value) is also achieved by another key which is only known to each machine a product of which is communicated using operations with the blocks. Finally, value exchange is achieved by operating the mutual contract keys and notifying the manager to encrypt into the blockchain network. The next section provides an example of that process.

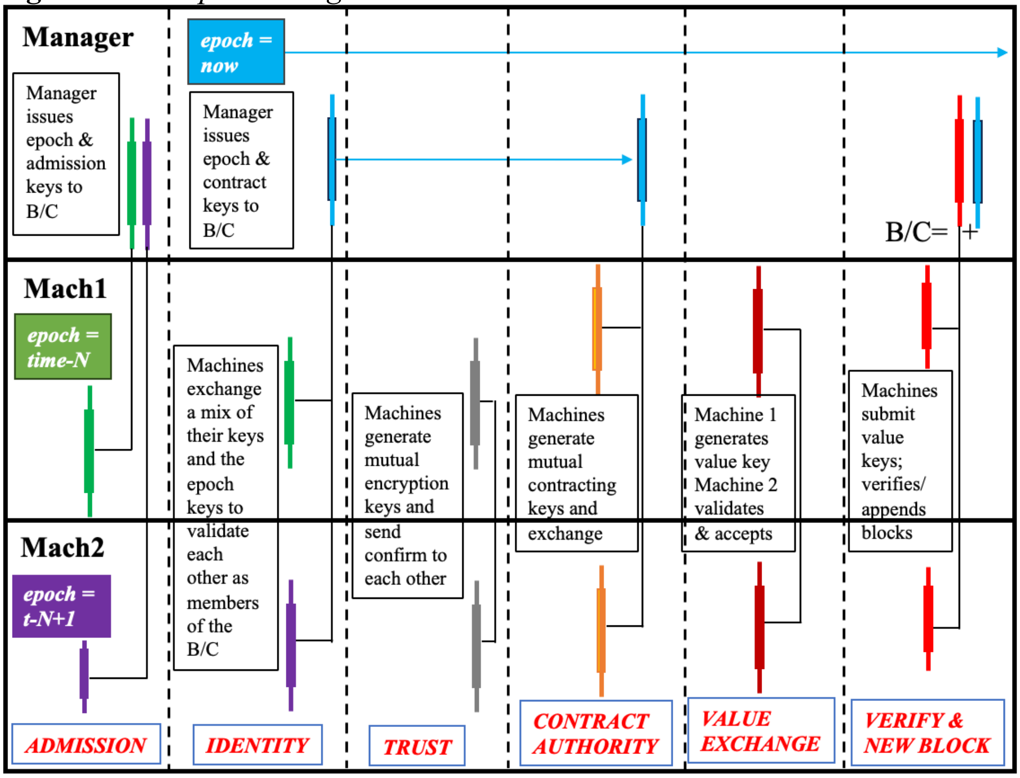
<u>Sample Dialogue Model</u>

In Figure 5, an example of a dialogue model is given and the following events take place:

a. <u>Admission:</u> the two machines have been included in the blockchain by a prior manager in 2 prior epochs. They are given their secure, private and contract keys and also all the current and prior blockchain blocks that are known to their peers in the network.
b. <u>Identity and Trust:</u> one machine initiates the dialogue by sending current epoch keys with their secret key operationalized with the current operation and epoch keys in a fashion described in 2.2.1. Using knowledge of the blockchain, the second machine de-aggregates and confirms the first's secure key and executes a similar operation. Both machines with that knowledge generate a third key that they will use in generation of another contract key in the next phase.
c. <u>Contract Authority and Value Exchange:</u> in this phase, the two machines generate mutual keys with their previous contract keys and use the unique contract keys they have generated to transfer value (one gives value and one receives it).

d. Verify & New Block: in this final phase, the machines independently report their give/receive transactions to the epoch Manager who appends to the blockchain and notifies the network of the new transaction.

Figure 5. *Participant Dialogue Model*



Machine Operations and Communication in the Manager Mode

The manager operation mode is more complex than the participant mode since more operations must be completed for a new epoch to exist and for the appending of blocks. The concept of consensus through manager elections has been explored in the RAFT (Ongaro and Ousterhout 2014), Intel's PoET[2] and others. These type of algorithms resolve the common Byzantine General's Problem (Ferguson et al. 2010) through an election among the machines. The election algorithm presented here will resolve that selection by the previous manager generating and comparing a random key to the machines' secret keys and finding the machine that is the closest to that generated key.

Once the selection of the future manager has occurred, the manager will proceed to generate either the current or next-future epoch's duration through a random process again and will announce that duration to the next manager. Next steps after this election are: admission and deprecation of machines, generation of operation and epoch keys, appending of blocks to the blockchain, referral of new block to audit function. These key steps are detailed in the following sections.

[2]https://archlending.com/glossary/proof-of-elapsed-time.

Manager Tasks

When a new epoch begins, the machine designated as the new epoch manager will switch state from participant to manager mode (this state change will be effected by the passing of time). Next, the manager will elect the following epoch manager and if necessary the number of backup managers that are to be elected (this process of election is discussed later in greater detail). Once the new manager(s) are elected and notified, the manager will execute generation of the following keys:

- Admission keys for each new node:
  - Secret Key (SK) which must be unique in the blockchain
  - Private Key(PK) known to the node and manager
  - Contract Key (CK) known to node and manager

- Deprecation of Secret Keys of machines that are leaving (if any)
- Epoch keys: Epoch Key (EK) and Operation Key (OK)

The manager and assistant managers will propagate the keys by individually notifying each node through the participant dialogue process in Figure 4. The nodes will replicate those keys in their local blocks. Finally, the manager will switch to that mode if required in order to append blocks to the blockchain, change states temporarily to enact its own participant role if necessary or to restart another epoch in the event of a validated attack (see attack sections below). More propagation processes will execute as value exchanges occur.

Election of the Managers and Substitute (Sub) Managers

The election of the managers and any alternate or assistant-managers will be done by random binary number generation. The procedure described below is translated to digital logic hardware definition language (VHDL) below in the experiment section. The procedure is as follows:

:Begin Do
a. Generate Random Number Array
b. Set value to max numbers
c. Traverse Blockchain get next Secret Key (SK)
d. Execute Comparator
e. Execute Accumulator
f.IFF Accumulator < value {value =Accumulator}
g. IFF Next Secret Key {a} else {:End-do}
:End-do

In the above algorithm, items c-g will continue to be executed for the number of alternate or assistant managers required.

Vulnerabilities During Epoch Changes

Times of change in any system increase the risks of operation of that system (Knapp and Langill 2015). The author believes the risk increases during an epoch change due to inherent factors mentioned below:

1. Time to determine new machine elections and notification of those machines.
2. Time required to generate new keys and in the case of Security Keys and guaranteeing uniqueness by traversing the blockchain.
3. Time to propagate new keys throughout the network.
4. Potential for out-of-synchronization between peers (machine thinks it's in a different epoch).

Some of the above are machine dependent, network dependent or both. The most important risk mitigation however, is to shorten the amount when the epoch change is happening. A risk mitigation approach or a large change time might be to have machines communicate in the ending epoch until most or all of the machines have been notified of new epoch changes (overlap of epochs).

Experiments Design

Two forms of experiment were conducted. In the first, the objective is to measure the epoch change when number of nodes are scaled. The second determines the potential attack survivability under five common attack types. The cyber-attacks are defined in more detail (since many variations exist of each), then they are operationalized and finally the vulnerability if any is identified.

Epoch Change Time in Manager Mode of Operation

This section includes an experiment on the model's epoch change time during the Manager's mode of operation. The model is operationalized using gated array and digital logic concepts into hardware language that targets FPGAs (Pedroni 2020). The main objective is to determine the completion time required in order to effect a shift to a new epoch. The VHDL follows patterns defined in Haskell and Hanna (2018). The steps executed and measured in the results section by the toolkit are in Figures 6 and 7.

Figure 6. *Election Process VHDL Pseudo-code*

```
// Begin election
: ARRAY1-GEN-RND // generate random array, 64 bits
: ARRAY2-SET-1 // set second array to all 1's
: ARRAY3-SET-1 // set third array to all 1's
: ADDER1-SET-1 // set value to all 1's
: ADDER2-SET-1 // set value to all 1's
    : DO-WHILE MEM-IDX-MORE == // Begin loop to traverse and compare
      : READ-MEM-IDX // Read block in blockchain
      : IFF {SK} DO // if it is a secure key
        : COMPARATOR SK&&ARRAY1→ARRAY3 // compare SK to array 1 eq array 3
        : ADDER ARRAY3→ADDER1 // add up array 3
          : IFF {ADDER1<ADDER2}{ADDER2=ADDER1&&ARRAY1=SK}
            // If adder 1 lt adder 2: adder2 eq adder1 and array 1 equals SK (closest)
      : ENDIF {SK} DO // close logic loop
    : END-WHILE MEM-IDX-MORE // close read loop
// End election
```

The process in Figure 7 was scaled according to the following assumptions:

1. Number of managers elected: 1 to 1,200 depending on number of nodes in network (Manager plus assistants/backup).
2. Number of nodes in the blockchain: 1,000 to 100,000.
3. Number of blocks in chain before another Security Key is found: 100 includes notification in epoch plus transactional blocks for exchange of value.
4. Key lengths: 256 and 512 bits.

Figure 7. *Machine Admission Key Generation Process VHDL Pseudo-code*

```
// Begin new keys for admission
: ARRAY1-GEN-RND // generate random array1, 64 bits (CK) Contracting Key
: ARRAY2-GEN-RND // generate random array2, 64 bits (PK) Private Key
  : DO-WHILE !IFF {SK} // while SK is not in blockchain
    : ARRAY3-GEN-RND // generate random array3, 64 bits (SK)
      : DO-WHILE MEM-IDX-MORE == // Begin loop to traverse and compare
        : READ-MEM-IDX // Read block in blockchain
        : IFF {SK==ARRAY3} BREAK // if the secure key exists break
      : END-WHILE MEM-IDX-MORE // close read loop
  : END-WHILE !IFF{SK} // close loop if SK is not in blockchain
: WRITE-IO →ARRAY1&&ARRAY2&&ARRAY3 // communicate keys
// End generate new keys for admission
```

The process in Figure 6 was scaled as follows (see Manager election for assumptions above):

1. Number of managers participating in notification: 1 to 1,200.
2. Number of nodes in the blockchain: 1,000 100,000.
3. Number of blocks in chain before another Security Key is found: 100 (corresponding to the number of blocks per node).
4. Key lengths: 256 and 512 bits.

The scaled results for the above 2 experiments are reported in the results section of this document.

Test Infrastructure

The test infrastructure consists of the following:

- CAD: Vivado VHDL Design, Synthesis and Simulation v. 2023.2
- Target FPGA: Xilinx Baysys3 part number XC7A35T-1CPG236C[3]
- OS Environment: MS Windows Tablet, 8MB RAM

Survivability During Attacks

No one really knows how many attacks there are in total in the world today, it is almost impossible to determine, no one agency will accumulate, typify and report them. There are however some that are well known with many variations and five of them will be described in this section. As with most attack patterns, they begin with a small probe volume and are successively scaled in order to progress to a next level (a foothold from which to formulate a new one and proceed with escalation of malfeasance).

The five attacks are described below. The objectives of the attacker are either to exhaust resources (DoS) or to penetrate and begin next stage of attack. The gated array dialogue is presented to indicate the attack progression and repelling if possible.

Brute Force Attack (BF)

The objective of a Brute Force Attack is to gain an entry point into a target. The method of attack is to generate data and forward that data to the target and try to obtain some feedback as to the method of communication that is typically required to begin a dialogue. As detailed above, the brute force attack due to the nature of the keys has a very low probability of success and is directly proportional to the size of the key. In a first stage, the size of the key is not known to the attacker so it will attack with a variety of sizes and contents. If one of those tries is successful in matching the size, the next stage must start to find a correct key based on the dialogue model.

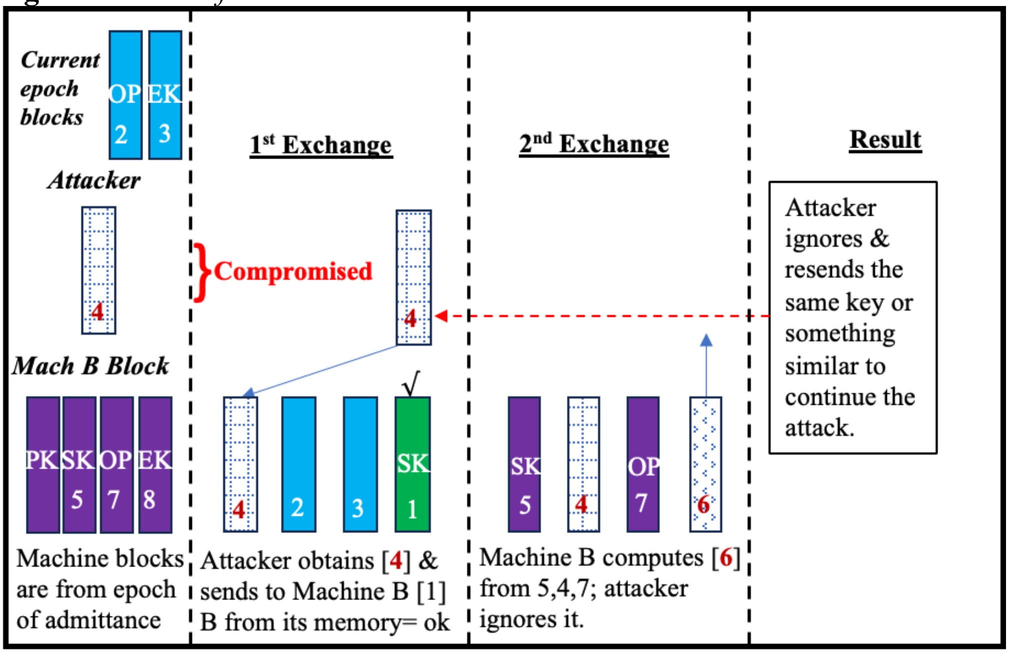
That second stage is also quite difficult since the correct combination of keys to frame the first valid key must be derived. The probability of that has been shared in 2.4 and until that key has been derived, an attack will not receive feedback as to anything.

Denial of Service (DoS)

The objective of a DoS is to exhaust the resources of the victim by overwhelming it with requests in such a frequency that it will deploy its resources to the fullest in attention of those requests. This outcome denies the resources to legitimate users and effectively makes the node unusable to service its required objectives.

[3]https://digilent.com/shop/basys-3-artix-7-fpga-trainer-board-recommended-for-introductory-users/?srsltid=AfmBOor_jHsGMqKH-

Figure 8. *Denial of Service*



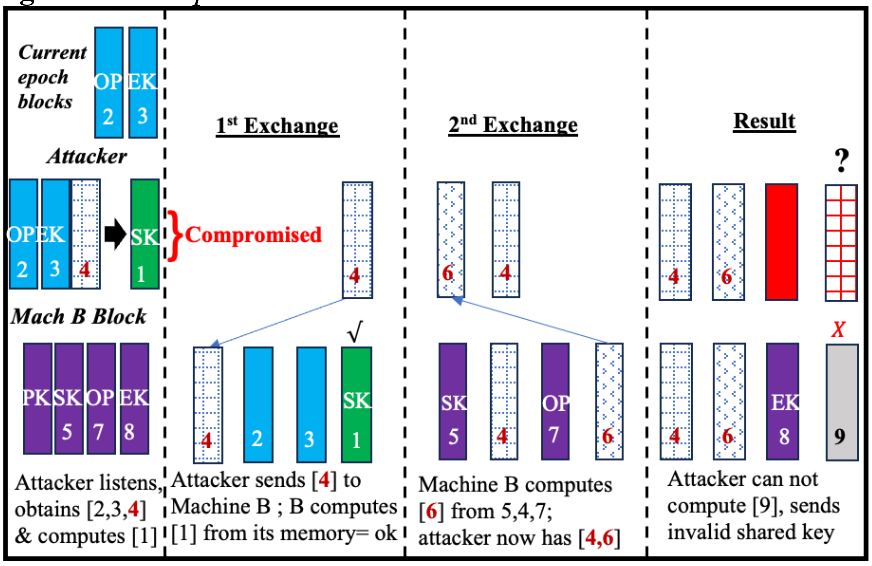
In Figure 8, an attacker has obtained limited knowledge of a message that has been sent before through listening, spoofing or some other means. It sends this key to the target machine and the target machine responds after it validates. The response is ignored (since the attacker has no other knowledge) but the attack continues by sending either the same value or other values that are similar.

As the attack is detected (by number of failed tries), the node under attack would request from the manager that another epoch be started as soon as possible.

Credential Simulation ("impersonator")

The objective of an impersonator attack is to obtain a session into another machine by means of sending valid messages until a "foothold" is achieved in the machine and the next steps of the attack can be progressed.

Figure 9. *The Impersonator*



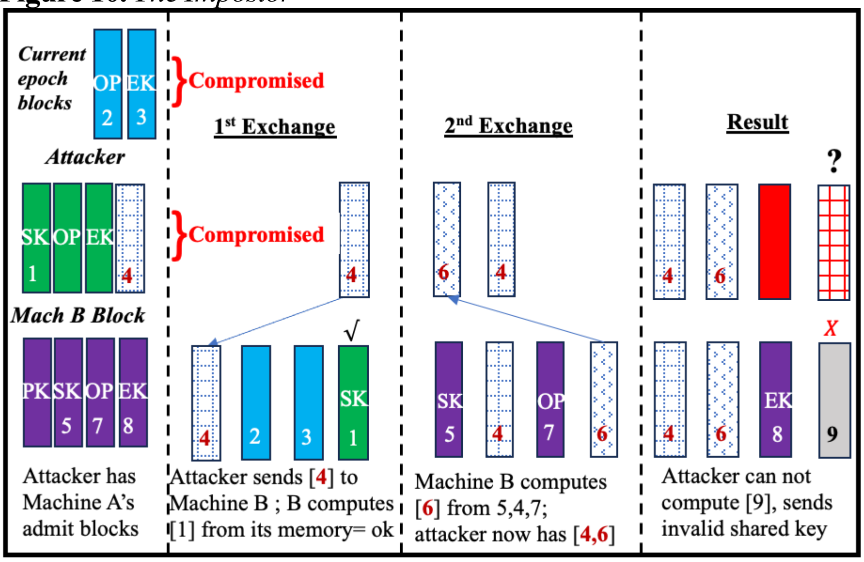
In Figure 9, an attacker has obtained knowledge of the key exchange methodology, the current operation and epoch keys and another key that has been used to communicate. It begins the attack with the communication key and does receive a response. This response cannot be progressed since the attacker does not have knowledge of the machine's blockchain and the attack fails when the two machines have different negotiated keys (at step 9 in Figure 8).

In a same manner as the DoS above, repeated failed attempts would elicit the node under attack to request a new epoch be started.

Impostor

The objective of an impostor is to coexist with a valid node and confuse the system by posing as that machine.

Figure 10. *The Impostor*



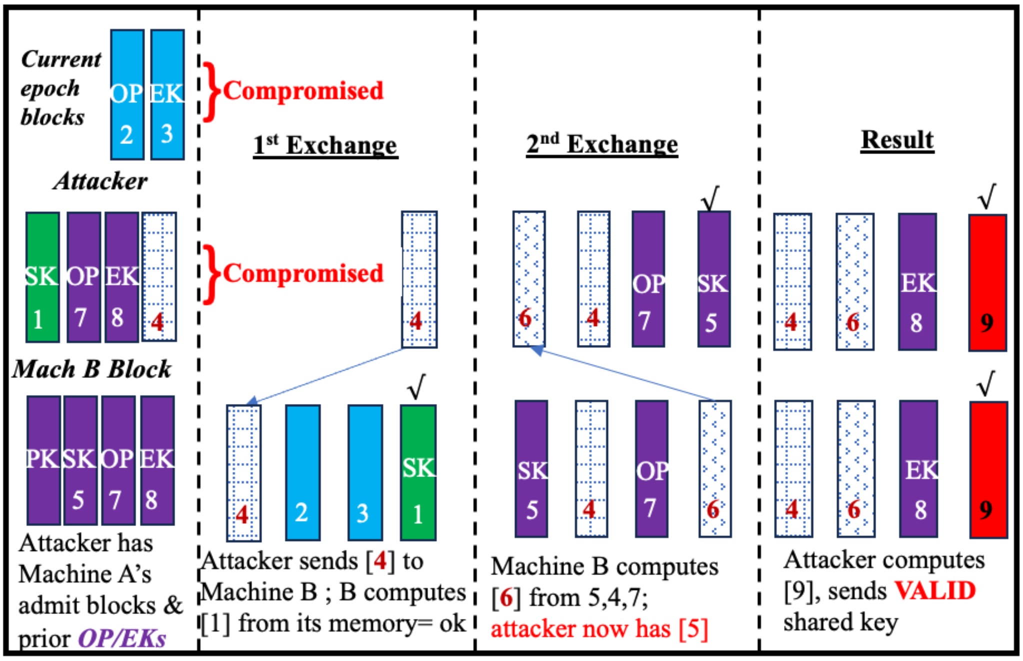
In Figure 10, an attacker has obtained knowledge of the key exchange methodology, the current operation and epoch keys, another key that has been used to communicate and a machine's epoch of admission keys. It begins the attack with the communication key and does receive a response. This response also cannot be progressed since the attacker does not have knowledge of the relevant blockchain epoch keys. The attack fails when the two machines have different negotiated keys (in step 9 of Figure 9).

Again, repeated failed attempts would elicit the node under attack to request a new epoch be started.

Machine Control ("hijacker")

The objective of a hijacker is also to execute transactions and exchange of value in the blockchain network to the exclusion of a legitimate machine (hijacking the dialogue to exclude the other). The ultimate goal is to extract value from the network or other nefarious outcome (getting a node to send value to them).

Figure 11. *The Hijacker*



In Figure 11, an attacker has obtained knowledge of the key exchange methodology and the necessary components of the blockchain data in order to simulate another machine and extract value. It begins the attack with the communication key and proceeds to negotiate a key (step 9 in Figure 10). The attack potentially will fail in the next stages since the contracting keys are not publicly known in the blockchain rather communicated directly from the managers to the participants upon admission. They are stored at the local level in a contract with the admitting machine's memory. Nevertheless, this level of intrusion is extremely dangerous and might be overcome by trial and error with some knowledge of prior value blockchain transactions. This illustrates that most successful attacks will include insider knowledge (Stallings 2018).

Execution and Results

The Vivado suite in simulation mode for the FPGA mentioned above was used in the election and key generation sub-processes. Two key sizes were selected: 256bits and 512bits and an average occurrence of a security key every 100th block (meaning, every node will produce an average of 100 transactional value blocks). The selection of block frequency is difficult since the Transactionality requirements are defined when the purpose of the blockchain is given (however, one must be chosen for the model). That size represents a range of exchange of 20 times per year or 100 in one year.

The number of new admissions was simulated to equal the size of the network over 5 years with one epoch occurring every month (plus one key for epoch and one key for operation code). Each security key (SK) was assumed to be unique. The manager node must compute the difference between the generated key and the keys in the blockchain which becomes a factor as the network nodes increase.

VHDL scripts were constructed to simulate the code concepts referenced above and several test scenarios were constructed; one for a "unitary" scope (two manager election, generation of one set of keys for admission of one node and new epoch keys) and more for a multiple-manager/assistant manager election and admission of large amounts of new nodes. Within that scaling environment, the second (multi-participant or "gang" scenario) was further defined into two types of networks; the small with 1,2 and 3 thousand nodes and the large with 10,30,50 and 100 thousand nodes.

Once initial results were received for election and key generation sub-processes, they were combined with previously published results for key dialogue. Please note that the process for the actual computation involved in the exchanges between nodes is minimal compared to the latency in any network (the network is almost always the slowest component). For purposes of notification of keys, it was assumed there would be an initial exchange between machines of 4 keys to establish identity and trust as per the model discussed above and one exchange for the payload of the new epoch and the admitted machines.

It is also important to note that the FPGA used has a limitation of 1,800,000 bits of RAM. This clearly would need to be augmented in a field trial for networks of nodes greater than 3,000 in the attached experiments. FPGAs and IoT devices that can house storage greater than those dimensions do exist and they could be sourced with the same processor configuration as the one used here with reasonably similar results.

Individual Task Component Results

As mentioned above, the results were run on "unitary" and "gang" basis. The unitary results are shown in Table 1. The "gang" results were obtained by first using empirical estimation of a range of high and low participation rates for managers and executed in the vivado suite for each range and network size, those results are shown in Table 2.

Table 1. *Unitary Results*

	Total	**Election**		**Generation**		**Notification**	**Epoch**
OBS	Nodes	Mgrs.	Time	# Keys	Time	Time	Time
	Key Size: 256 bits						
1	1,000	2	00:09	1	00:09	33:20	33:38
2	2,000	2	00:09	1	00:09	66:40	66:58
3	3,000	2	00:09	1	00:09	4 hours	4 hours
4	10,000	2	00:13	1	00:09	12.5 hrs	12.5 hrs
5	30,000	2	00:17	1	00:09	37.5 hrs	37.5 hrs
6	50,000	2	00:18	1	00:09	125 hrs	125 hrs
7	100,000	2	00:20	1	00:10	250 hrs	251 hrs
	Key Size: 512 bits						
8	1,000	2	00:09	1	00:09	33:20	33:38
9	2,000	2	00:09	1	00:09	66:40	66:58
10	3,000	2	00:09	1	00:09	4 hours	4 hours
11	10,000	2	00:10	1	00:09	12.5 hrs	12.5 hrs
12	30,000	2	00:11	1	00:09	37.5 hrs	37.5 hrs
13	50,000	2	00:13	1	00:09	125 hrs	125 hrs
14	100,000	2	00:17	1	00:17	250 hrs	251 hrs

Table 1 depicts the time observations received when two managers were elected and one machine was admitted. Notification time is calculated as 5 seconds per machine divided by the number of nodes in the network. The process of notification is the same as establishing dialogue up to the trust and identity level plus the communication of the payload (5 seconds per machine as previously noted).

Table 2. *Multiple Managers – Election & Key Generation*

ELECTION		MM's	**Key: 256 b**		**Key: 512 b**		**KEY GENERATION**			**Key: 256 b**		**Key: 512 b**	
Mgrs.	Nodes	Blocks	CPU s	Time	CPU s	Time	Mgrs.	# Keys	Nodes	CPU s	Time	CPU s	Time
10	1,000	0.1	5	00:09	5	00:09	10	19	1,000	3	00:09	4	00:10
20	2,000	0.2	5	00:09	5	00:10	20	35	2,000	4	00:11	4	00:13
30	3,000	0.3	5	00:13	4	00:12	30	52	3,000	4	00:13	6	00:15
100	10,000	1.0	9	00:43	7	00:46	100	169	10,000	5	00:29	6	00:49
200	30,000	3.0	13	02:42	18	04:11	200	502	30,000	17	04:13	34	08:03
420	50,000	5.0	40	10:04	50	13:38	420	835	50,000	20	05:11	42	10:42
1000	100,000	10.0	162	45:22	254	67:03	1000	1,669	100,000	133	28:31	136	38:26
20	1,000	0.1	5	00:09	5	00:09	20	19	1,000	3	00:09	3	00:09
30	2,000	0.2	5	00:11	5	00:12	30	35	2,000	4	00:09	3	00:10
50	3,000	0.3	5	00:13	5	00:16	50	52	3,000	5	00:13	5	00:14
150	10,000	1.0	7	00:51	8	01:05	150	169	10,000	5	00:27	7	00:48
300	30,000	3.0	17	04:02	25	05:49	300	502	30,000	11	02:19	34	04:20
500	50,000	5.0	41	11:19	59	15:47	500	835	50,000	20	05:04	44	10:20
1200	100,000	10.0	303	77:22	271	77:45	1200	1,669	100,000	68	20:51	138	39:21

Table 2 depicts the time observations obtained during the election and key generation process. The top part of that table shows the lower elected manager number range of the executions while the lower part shows the higher elected manager number (notice the number of managers are higher in the lower part of the table). This was used to derive the average time per machine in the optimized results.

Optimized Results

Once the VHDL results were obtained, individual performance statistics using average time and average number of managers for each network size were used to build the models for shortest overall epoch completion time with least managers elected, those results are shown in Table 3.

Table 3. *Optimized Multiple Manager Model*

	Total	MM's	**Election**		**Generation**		**Notificati**	**Epoch**
OBS	Nodes	Blocks	Mgrs.	Time	#Keys	Time	Time	Time
	Key Size: 256 bits							
1	1,000	0.1	59	00:35	19	00:35	01:08	02:18
2	2,000	0.2	91	00:36	35	00:36	01:28	02:40
3	3,000	0.3	108	00:35	52	00:35	01:51	03:01
4	10,000	1.0	234	01:28	169	00:52	02:51	05:11
5	30,000	3.0	213	02:52	502	02:55	09:23	15:10
6	50,000	5.0	261	06:04	835	02:55	12:46	21:45
7	100,000	10.0	273	15:14	1,669	06:15	24:25	45:54
	Key Size: 512 bits							
8	1,000	0.1	59	00:35	19	00:39	01:08	02:22
9	2,000	0.2	82	00:36	35	00:39	01:38	02:53
10	3,000	0.3	109	00:38	52	00:41	01:50	03:09
11	10,000	1.0	220	01:39	169	01:26	03:02	06:07
12	30,000	3.0	203	04:28	502	05:02	09:51	19:21
13	50,000	5.0	240	07:41	835	05:29	13:53	27:03
14	100,000	10.0	257	16:55	1,669	08:56	25:56	51:47

Table 3 depicts the optimized number of managers admitted in relation to the total epoch time based on average times and average machines from the raw results obtained from the vivado suite. Note the million blocks (MM's Blocks) per blockchain assuming the 100 block transactional-per-node metric in the introduction to this section. The case for 100,000 blocks is shown only for a top level benchmark and will not be in the large network case Figures below (such large results inhibit visual comparison to the other large format networks).

Results Analysis and Discussion

This section describes the factors that are inherent in the model results and provides a comparative analysis between the individual observations. The formulaic approach to the epoch completion time optimization simulation is presented as follows.

Figure 12. *Optimization Formulae*

$$\boldsymbol{min}\ Ct\ \boldsymbol{s.t.}\ Nn, Kn\ \boldsymbol{where}: Ct = \sum Et, Gt, Pt$$
$$\boldsymbol{Et} = Mn * St;\ \boldsymbol{Gt} = [Kn * St] / Mn;\ \boldsymbol{Pt} = [Dt * Nn] / Mn$$
$$\boldsymbol{Ct}: Completion\ Time, \boldsymbol{Nn}: Nodes\ in\ Network, \boldsymbol{Kn}: Keys\ to\ Generate,$$
$$\boldsymbol{Et}: Election\ Time, \boldsymbol{Gt}: Generation\ Time, \boldsymbol{Pt}: Propagation\ Time,$$
$$\boldsymbol{Mn}: Number\ of\ Managers, \boldsymbol{St}: Blockchain\ Key\ Search\ Time$$

Overall Factors

The results above give some very good insight into the behavior of the manager model during epoch changes. Depending on epoch change time, there would need to be an overlap between one epoch finishing and another one beginning. The overlap creates a constraint as to the elapsed time of the epoch regeneration. As a result, epochs may not be regenerated as frequently as desired or elected by the randomized duration algorithm and that would need to be adjusted into the constraints of the model being implemented.

Another important factor is the number of managers elected. In the "unitary" case, the number of managers elected are 2 and may only be feasible in networks that are less than 1,000 nodes due to the time to effect the epoch change. In networks of greater size (above 1,000 nodes) the "gang" approach is almost required, this brings its own challenges. A first challenge is to determine the number of managers to admit (the current algorithm is based on assumptions of number of blocks and no duplicates which increases blockchain search time). Furthermore, when multiple nodes generate admission keys that necessitates a partitioning algorithm so they do not potentially generate the same key. In that case, how should the key generation be partitioned among the machines, given partitioning itself would mean constraining the randomization of keys along some boundaries and reduce the true random aspect. Finally and due to the distributed nature of the network, what happens if managers are unavailable and what is the impact on the completion time (given machines used and their availability characteristics within IoT parameters). The above all are adjustments to the constraints of the model as well.

A significant component of the epoch change also is the notification of nodes due to network communication latency (1 second per message assumed in the experiment). This is sequential and no concurrency has been assumed for the machines' handling of multiple sessions (based on prior work, the machines are able to execute a key exchange in 0.05 seconds), in theory the machines could manage multiple sessions (one for each partial key exchange/payload, refer to Figure 4 for partial exchange key dynamics). If concurrency of machine states were added, it would result in additional memory and complexity that would increase resource usage and potentially impact a primary service objective of transactionality between the blockchain nodes.

Finally, the results are derived from the simulator in vivado which is dependent on several operating memory factors (other items that could be working in the MS machine environment for example). Some of this is reflected in results being slightly different in one run versus another. These results are directional and do not substitute for field trials with actual machines populated in a network. This was infeasible given resources available and is a constraint of this research.

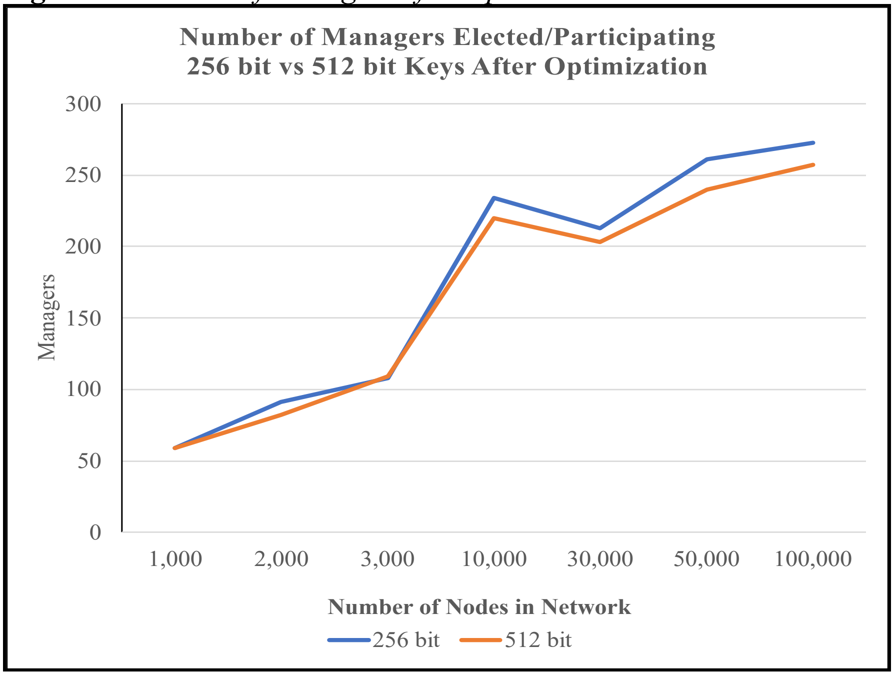
Individual Observation Analysis

As mentioned above, the vivado simulator results are good from a directional perspective and they are useful in gauging the feasibility of the model to operate in certain IoT conditions. The unitary case is feasible mostly for networks under 1,000 nodes and may very well work if something like a network of cameras around a manufacturing plant is being implemented. On the other hand, it may be infeasible for a transactional network of individuals in large volumes of crypto currency.

In the small network sizes (1,000-3,000 nodes) the number of managers increase consistently between the three alternatives and key sizes. The number of managers elected is smaller in the case of the 512bit key size due to the additional computation that is required in order to determine the closeness of the Security Key (SK) to the random election number (since each key must be compared for and determined if it lies in the target number of managers to be elected). A similar pattern is also replicated and magnified in the large network cases. In the 100,000 node network, the election of managers tapers off significantly when compared to the 50,000 node network. This is because of computation of differences (interwoven in the search time through the blockchain) in a much larger number of memory blocks.

In the case of generation of keys the number of keys to be generated between the two key sizes is the same in both cases and the variations in completion are due to a combination of the number of keys, the number of managers generating keys and the number of blocks to traverse. In this case, each Security Key (SK) must be compared for uniqueness with previously generated SKs in the blockchain with the computation being higher for the larger 512bit key (twice as many bits to evaluate).

Figure 13. *Number of Managers After Optimization*



On a more detailed basis, comparing observations 12 and 13 in 512 bit key, where the completion times for key generation are close we can see that one alternative has more machines and more keys to generate but it is not that different than the one that has less managers and less keys to generate on a smaller network footprint (less managers are needed to search through a smaller blockchain).

As mentioned above, the optimization model finds the smallest number of machines that will yield the lowest completion time given the raw inputs. When the optimization is on the total outcome on a multiple component model it may penalize some of the components in order to minimize the overall time. It is for this reason that we see these differences between the observations at different network sizes in Figure 13 (the number of managers elected actually decreases). In that graphic, we see how the number of managers increases on a positive slope until it dips at the 30,000 level and then turns positive again after that. We can also witness how the number of managers elected stays within the range of 213 to 273 for much larger networks after that.

Figure 14. *Optimized Completion Times by Key Size and Network Scale for Small Networks*

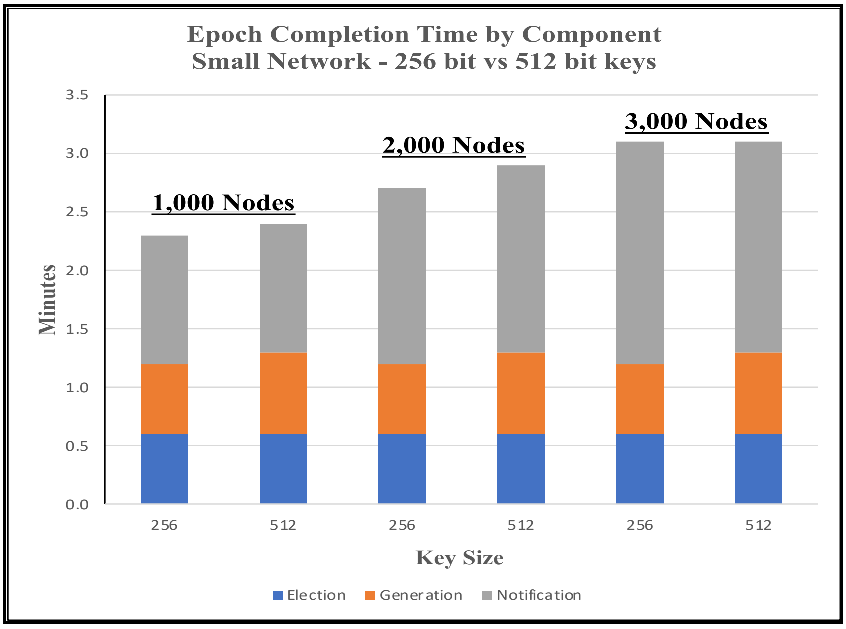
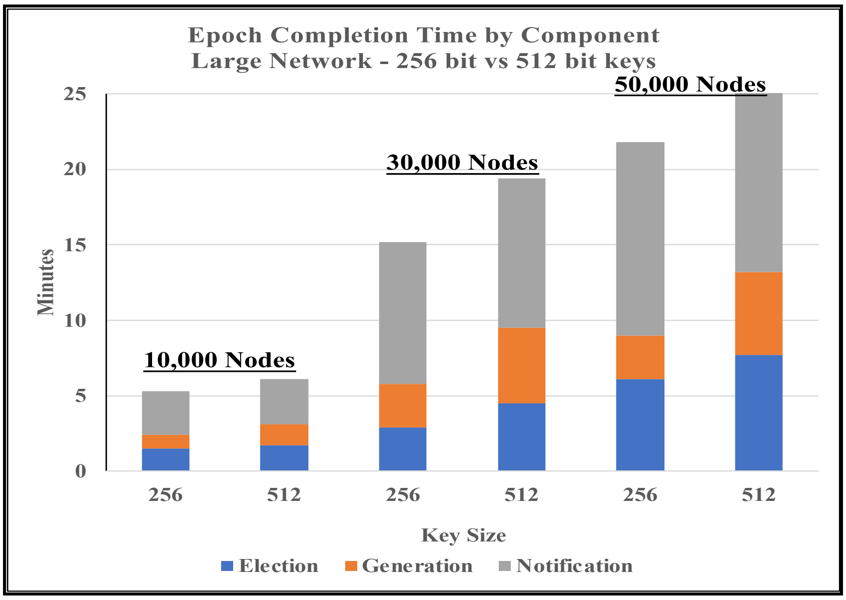


Figure 15. *Optimized Completion Times by Key Size and Network Scale for Large Networks*



When we direct our attention to the overall results we can observe how the epoch completion times increase on a fairly linear basis for each network size with some impact from key size in Figures 14 and 15 above, the most dramatic increases are in the notification or propagation (P_t from the formulaic model above) phase as the nodes scale. This relationship is what would be expected from a scaling model and may yield predictive aspects as to how the machines would behave if the blockchain networks would be built as described.

Conclusions

The simulation portion of this study focuses on the feasibility of epoch change in small factor IoT devices configured as managers, the potential limitations on number of nodes and key lengths in a zero-trust network (presumably the internet or large extranets). It appears that the feasibility of machine operation could be potentially scaled to 50,000 nodes with value exchanges of 100 blocks per node if the overlap between one epoch beginning and the previous one ending was under 30 minutes. This requirement would need to be validated with the objectives of the protection and Transactionality required by the assets or processes using such a configuration. In reality however, most IoT networks that operate on an independent basis seem to be much smaller in size. However, given the resource requirements and potential speed of epoch change a network with 100,000 nodes could also be feasible if the machines were able to concurrently process without impacting their primary service objectives (the reduction in epoch change time would be dramatic). It might seem that the "safe-zone" for operation could be in the 10,000 and under node range with a much smaller SLA for epoch change. If a smaller network size was selected, and cyber-attacks noted required an epoch change, it could be more efficiently managed than in the case of the larger format networks.

However, one of the significant adjustments to be explored in this area is the proposition of "stacked keys". Sending more than one key in the dialogue to reduce the time of propagation. For example and referring to Figure 4 again, if the initial approach dialogue from Machine 1 included keys 4 and 9 and machine 2 replied with a challenge for key 6 then the dialogue would be concluded in 2 key exchanges (2 seconds) rather than the 5 seconds included in the model. This would reduce the time of propagation, the number of managers and the election times needed as well.

The second focus of this research is in attack resilience. As shown, most of the common attacks presented can be overcome by the key dialogues mentioned and eventual epoch change. The only attack that could prevail and enter the network would be the hijacker. This is not uncommon since a high percentage of successful hacks come from an attacker with inside knowledge. In order to remediate that vulnerability, there would need to be an additional protocol for the Private Key (PK) which is under research for future studies.

References

Alharby Sultan, et al. (2018) The security trade-offs in resource constrained nodes for IoT applications. *International Journal of Electronics and Communication Engineering* 12(1).

Ferguson N, Schneier B, Kohno T (2010) *Cryptography Engineering, Design Principles and Practical Applications*. Indianapolis, Indiana: Wiley Publishing, Inc.

Haskell R, Hanna D (2018) *Digital Design Using Diligent FPGA Boards*. VHDL Edition. Auburn Hills, Michigan: LBE Books.

Huang SY, Cheng KT (2002) *Formal Equivalence Checking and Design Debugging* Norwell, Massachusetts: Kluwer Academic Publishers.

Johnsonbaugh R (2018) *Discrete Mathematics*. 8th Edition. New York: Pearson Education, Inc.

Khan JA, Chowdhury MM (2021) Security analysis of 5g network. Presented at *2021 IEEE International Conference on Electro Information Technology (EIT)*. IEEE.

Knapp E, Langill J (2015) *Industrial Network Security, Securing Critical Infrastructure Networks for Smart Grid, SCADA and other Industrial Control Systems*. 2nd Edition. Waltham, Massachusetts: Syngress Elsevier.

Medellin J (2024) Exploiting Efficiencies in IoT Key Exchanges Through Reversible Logic Blockchains. Presented at *7th EAI International Conference, iCETiC 2024*, Essex, UK, August 15–16, 2024.

Medellin J (2022) Generation, Regeneration and Validation of Binary Secret Keys through Blockchain in IoT Devices. *Athens Journal of Sciences* 9(1): 25–46.

Muralidharan S, et al. (2019) *Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains*. Available at: https://arxiv.org/pdf/1801.10228.pdf.

Nakamoto S (2019) *Bitcoin: A Peer-to-Peer Electronic Cash System*. www.bitcoin.org.

Ongaro D, Ousterhout J (2014) In Search of an Understandable Consensus Algorithm. Proceedings *ATC'14 USENIX Annual Technical Conference*. USENIX.

Pedroni V (2020) *Circuit Design with VHDL*. 3rd Edition, Cambridge, Massachusetts: Massachusetts Institute of Technology Press.

Stallings W (2018) *Cryptography and Network Security, Principles and Practice*. 7th Edition. London, United Kingdom: Pearson Education Limited.

Wazid M, et al. (2020) Security in 5G-enabled internet of things communication- issues, challenges, and future research roadmap. *IEEE Access* 9.

Appendix

A1. VHDL Code for Election
A2. VHDL Code for Key Generation
[Are both available from the author upon request]

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Global Research Trend on Web 2.0 Usage among Higher Learning Institution Educators: A Bibliometric Analysis of the Recent Decade

By Hapini Awang, Zahurin Mat Aji± & Nor Iadah Yusop°*

This study, which focuses on the utilization of Web 2.0 in higher education, provides a comprehensive analysis of all document types found in the Scopus database between 2006 and 2022, with a cut-off date of February 15, 2023. A total of eight hundred five relevant documents from the Scopus database between 2006 and 2022 were analyzed, with a specific focus on the use of Web 2.0 tools in higher education. The findings, which showed a sharp increase in publications in 2011 and 2014 and a higher proportion of conference papers than other document types, are limited to the scope of the Scopus database and may only represent part of the landscape of Web 2.0 tool usage in higher education. However, they provide valuable insights and suggest several future research directions, including investigating the reasons for the decline in interest in Web 2.0 tools, studying the factors of its success, exploring the effectiveness of Web 2.0 tools in different subject areas, and examining their role in promoting active and collaborative learning, intercultural competence, and social justice. This bibliometric study can be helpful for policymakers and researchers interested in understanding the present Web 2.0 tool usage in higher education and improving educational practices and policies.

Keywords: *web 2.0, tertiary education, bibliometric, ICT in education, 21st century education*

Introduction

The practical applications of Web 2.0 in tertiary education are vast. These technologies enhance the effectiveness of educational materials and resources, offering more dynamic and robust online teaching and learning virtual environments. Some tools, such as blogs, Wikinews, survey builders, discussion boards, audio/video chat, RSS readers, file sharing, social media platforms, WebOffice, and interactive whiteboards, can be used by students to collaborate and communicate with their peers and teachers. Through these tools, knowledge and ideas can be shared, and various activities can be participated in, enriching the learning experience (Awang et al. 2018).

Web 2.0 provides opportunities for students and teachers to use supporting tools to enhance their teaching and learning experience. The growing popularity of Web 2.0 platforms in education has caught the attention of scholars in educational

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and information systems (Donmuş Kaya 2022). In Malaysia, the Tenth Malaysia Plan (2011-2015) was implemented to integrate information and communication technology (ICT) in teaching and learning activities, specifically blended learning approaches. As a result, higher learning institutions (HLIs) in Malaysia have started using Web 2.0 tools after the Malaysian government made a substantial investment in ICT. Web 2.0 tools usage is considered essential among educators in HLIs for teaching and learning activities.

In many developing countries, Web 2.0 tools have not been widely used by academics, although they provide advantages such as enhanced availability of educational resources and opportunities for collaborative content creation (Padayachee & Moodley 2022). However, as the Internet became prevalent, the situation gradually changed. Initially hesitant, teachers eventually incorporated Web 2.0 into higher education as its pedagogical value became apparent (Isaias et al. 2021). Students can collaborate and communicate using Web 2.0 tools, which can be influenced by their attitude and self-efficacy (Anusha & Rani 2021). While e-learning platforms and Web 2.0 technologies are prevalent in universities, not all faculty members utilize them (Esguerra 2019). This inequality in the excellent practice of Web 2.0 tools usage to meet instructional requirements explicitly highlights a loophole in its practice that requires further research.

Therefore, it is necessary to understand the current status and trends of Web 2.0 utilization in tertiary education. This paper presents a bibliometric analysis of scholarly publications on using Web 2.0 learning tools by educators in HLIs. Bibliometric analysis is a quantitative technique that examines related publications to analyze research fields' knowledge structure and progress. In this paper, the first section elucidates the significance of bibliometric analysis, whereas the subsequent section outlines the approach utilized. The third section presents the bibliometric indicators' outcomes pertinent to the research. Finally, the last section summarizes the findings, highlights potential research directions, and acknowledges certain limitations related to the topic.

Literature Review

Web 2.0 is a significant advancement in Internet technology that emphasizes interactivity, collaboration, and user-generated content. It enables users to participate in creating and sharing content without complex installations. This shift has revolutionized communication and content creation, enabling virtual communities and collaborative projects. Among the positively impacted is the educational sector that embraced Web 2.0 tools to enhance collaborative learning experiences and facilitate more active employee participation in content creation and decision-making processes (Isaias et al. 2021). Web 2.0 technologies have been found to foster interactive and collaborative learning environments, resulting in a significant improvement in the quality of education over the past decade (Aced & Toledano 2013, Alcocer-Vázquez & Zapata-González 2021, Anusha & Rani 2021, Awang et al. 2018b). In the context of the COVID-19 epidemic, where they have proven crucial in delivering interactive learning environments without time and space limits, instructors have warmly commended the usability and educational affordance of Web 2.0 technologies (Yildirim & Gurleroglu 2022). Integrating Web 2.0 resources into educational settings is seen as a valuable pedagogical approach to enhance teaching practices and student engagement.

Similarly, Web 2.0 technologies have had a significant impact on postsecondary education (Holik et al. 2023). These technologies provide new avenues for student participation, personalized educational paths, and interactive learning. Students are now at the center of the learning process, thanks to the use of Web 2.0 tools in the classroom, which encourages cooperation and resource sharing. Indeed, several studies have shown that integrating Web 2.0 technologies in higher education enhances student engagement and performance and promotes a technologically advanced learning environment. This leads to increased usage among both instructors and students in HLIs (Isaias et al. 2021, Zakir et al. 2022). For educators, the resources provide creative methods to produce dynamic and interesting educational content for students. As evidenced by Roy (2023), teachers perceive that integrating Web 2.0 technology into their lesson plans speeds up language learning and enhances students' language skills. Furthermore, instructors' viewpoints on the usability of Web 2.0 tools have been investigated, demonstrating that educators swiftly acclimate to these technologies and perceive them as advantageous for the educational process (Aced & Toledano 2013, Awang et al. 2024, Roy 2023, Zakir et al. 2022).

Web 2.0 tools have significantly changed how students and teachers collaborate in educational settings. Wikis, blogs, and ePortfolios are examples of platforms that educators have used to improve communication and knowledge exchange (Aced & Toledano 2013, Alcocer-Vázquez & Zapata-González 2021, Anusha & Rani 2021, Awang et al. 2018a). Particularly important during situations like the COVID-19 epidemic, these platforms provide chances for content creation, distribution, and the promotion of interactive learning settings without time or space constraints (Donmuş Kaya 2022). Creative materials backed by Web 2.0 tools have been designed and developed to address science and technology teachers' issues, enhancing learning settings and encouraging significant experiences. In general, educators have embraced the incorporation of Web 2.0 tools, perceiving them as valuable resources for augmenting the educational experience and fostering cooperative learning.

With the advent of online software that engages users in various activities, Web 2.0 has wholly changed education. Accessibility, participation, cooperation, and customization are some of its most essential features. Web 2.0 enables personalization through tailored learning experiences that meet the needs of each individual. Free digital tools improve engagement by facilitating the production and exchange of student-generated products (Holik et al. 2023, Sakai et al. 2024). Teachers, students, and the community are encouraged to work together, which opens up new lines of connection. Online tools also simplify accessibility, benefiting teachers and students by streamlining education and cooperation. Teachers incorporate these tools to create dynamic, interactive learning environments that enhance the educational process.

The use of Web 2.0 technology in education has been thoroughly studied in the past. The use of Web 2.0 services to personalize students' educational trajectories and enhance individual learning (Kolyvanova et al. 2015), the general trends in using Web 2.0 tools in educational technology (Genç & Kırmızıbayrak 2024), instructors' perceptions and challenges in incorporating Web 2.0 tools into literacy instruction (Luo et al. 2022), the usability and educational affordance of Web 2.0 tools from teachers' perspectives (Krouska et al. 2020), and the analysis of Web 2.0 in special education to identify trends and pave the way for further research (Kanbul et al. 2020) are just a few of the topics covered in these studies. When taken as a whole, these studies demonstrate how Web 2.0 tools improve student engagement, interaction, and individualized learning in classroom environments.

Methodology

Bibliometric studies are a quantitative method used to analyze scientific and scholarly literature. Citation analysis is one of the methods used to evaluate the impact of research and identify trends in a particular field. In this study, the focus is on the literature about Web 2.0 and higher education. The paragraph discusses the methodology and results of the bibliometric study. The study retrieved 805 documents from a search query, all of which were deemed eligible and included in the study after screening. The search strategy used for this bibliometric study is shown in Figure 1. It encompasses all document types found in the Scopus database between 2006 and 2022, with a cut-off date of February 15, 2023. The search only considered the article title, suggesting that all the retrieved documents are relevant to the study's primary topic of "Web 2.0" or "higher education" literature. The document search was conducted based on keywords in the title (“Web 2.0” AND “higher education”).

Results

This study provides an in-depth analysis of the research trend in higher education, focusing on the development and distribution of the usage of Web 2.0 tools among HLI around the world. The research investigates the publications based on their publication year, source, document type, and source title to provide insights into the emerging trends and patterns in the field.

Documents Profiles

Table 1 summarizes the types of documents deemed suitable and relevant for further analysis. Out of 805 documents, approximately 43% are articles, just over 35% are conference papers, and the remaining publications are distributed, as illustrated in Table 1. These documents were obtained from various sources, such as journals, conference proceedings, books, book series, and trade journals, all considered seminal publications.

Figure 1. *Flowchart of the Search Strategy*

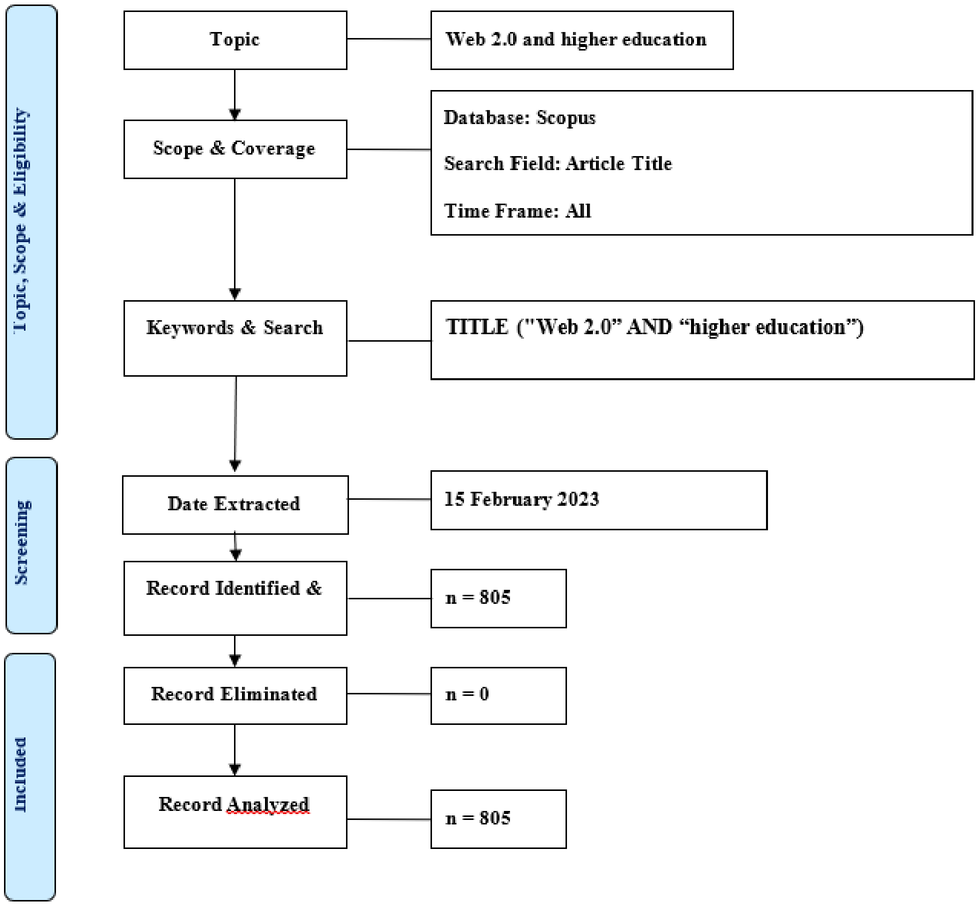

Table 1. *Document Types*

Document Type	Total Publications (TP)	Percentage (%)
Article	344	42.73%
Book	11	1.37%
Book Chapter	121	15.03%
Conference Paper	285	35.40%
Conference Review	18	2.24%
Editorial	3	0.37%
Note	1	0.12%
Review	21	2.61%
Short Survey	1	0.12%
Total	*805*	*100.00*

Table 2 shows that the documents were primarily written in English, with around 94.22% of publications using this language. Spanish and Portuguese came in second and third, representing 4.18% and 0.86% of the publications, respectively. The remaining languages, German, Arabic, Chinese, Croatian, and Turkish, each comprised 0.25% or less of the publications.

Table 2. *Languages of Publications*

Language	Total Publications (TP)*	Percentage (%)
Arabic	1	0.12%
Chinese	1	0.12%
Croatian English	1 766	0.12% 94.22%
German	2	0.25%
Portuguese	7	0.86%
Spanish	34	4.18%
Turkish	1	0.12%
Total	*805*	*100.00*

Pertaining to the publications' subject areas, Table 3 shows that Social Sciences has the highest number of publications, comprising 66.46% of the total. Computer Science follows closely behind with 54.16% of the publications. Other subject areas with a significant number of publications include Business, Management, and Accounting (8.07%), Engineering (10.43%), Mathematics (5.47%), and Arts and Humanities (4.60%). The remaining subject areas have a much smaller percentage of publications, with some having only one or two.

Table 3. *Publication Subject Areas*

Subject Area	Total Publications (TP)	Percentage (%)
Social Sciences	535	66.46%
Psychology	22	2.73%
Physics and Astronomy	3	0.37%
Pharmacology, Toxicology and Pharmaceutics	3	0.37%
Nursing	5	0.62%
Neuroscience	2	0.25%
Medicine	9	1.12%
Mathematics	44	5.47%
Materials Science	1	0.12%
Immunology and Microbiology	1	0.12%
Health Professions	5	0.62%
Environmental Science	7	0.87%
Engineering	84	10.43%
Energy	4	0.50%
Economics, Econometrics and Finance	18	2.24%
Earth and Planetary Sciences	2	0.25%
Dentistry	1	0.12%
Decision Sciences	28	3.48%
Computer Science	436	54.16%
Chemistry	1	0.12%
Business, Management and Accounting	65	8.07%
Biochemistry, Genetics and Molecular Biology	1	0.12%
Arts and Humanities	37	4.60%
Agricultural and Biological Sciences	2	0.25%

Research Trend

The distribution of published articles over the years is presented in Table 4, which shows that the highest publications on Web 2.0 in higher education were in 2012, accounting for 12.17% of the total publications since 2006. The data reveals a rising trend in the number of publications starting from 2006, with a decline observed in 2013 and continuing until recent years (2022). This trend may indicate a decreased interest among researchers in Web 2.0 tools in higher education. However, it is noteworthy that the concept has regained momentum since the outbreak of the COVID-19 pandemic.

Table 4. *Year of Publication*

Year	**TP**	**NCP**	**TC**	**C/P**	**C/CP**	**h**	**g**
2022	10	1	1	0.10	1.00	1	1
2021	13	11	26	2.00	2.36	3	3
2020	24	20	252	10.50	12.60	9	15
2019	41	25	184	4.49	7.36	6	12
2018	39	31	213	5.46	6.87	9	13
2017	40	31	289	7.23	9.32	10	15
2016	47	37	505	10.74	13.65	13	21
2015	57	45	420	7.37	9.33	11	18
2014	67	52	706	10.54	13.58	13	25
2013	77	62	1753	22.77	28.27	17	41
2012	98	82	2404	24.53	29.32	17	48
2011	84	65	1101	13.11	16.94	15	32
2010	85	66	1536	18.07	23.27	18	38
2009	72	55	1084	15.06	19.71	15	32
2008	36	32	887	24.64	27.72	14	29
2007	11	8	312	28.36	39.00	4	11
2006	4	1	3	0.75	3.00	1	1
Total	*805*						

The following metrics are commonly used to evaluate academic publications: total number of publications (TP), number of cited publications (NCP), total citations (TC), average citations per publication (C/P), average citations per cited publication (C/CP), h-index, and g-index.

As revealed by Table 5, Malaysia has the highest number of publications, with nine institutions producing 24 publications. Australia comes in second with 22 publications produced by six institutions. The USA has 18 publications from 3 institutions, while Taiwan and China each have 20 and 17 publications from four and three institutions, respectively. The institutions with the highest publications are Universidad de Salamanca (Taiwan), with 13 publications; Monash University (USA), with 11 publications; and the University of Melbourne (China), with ten publications. The total number of publications for each country is included in a separate section, where Malaysia has the highest total with 24 publications, followed by Australia with 22 publications.

Table 5. *Most Dominant Institutions with More Than Seven Publications*

Affiliation	**Country**	**TP**
Australian Catholic University	Malaysia	9
Deakin University	Malaysia	7
Universiti Teknologi Malaysia	Malaysia	7
Universidade Aberta	Malaysia	8
Universidad de Sevilla	Australia	8
University of Plymouth	Australia	7
Monash University	USA	11
Universidad de Murcia	USA	7
Universidad de Salamanca	Taiwan	13
University of the West of Scotland	Taiwan	8
UNITEC Institute of Technology	Taiwan	7
University of Melbourne	China	10
The Open University	China	7
Universidade de Aveiro	Hong Kong	8
Universitat Rovira i Virgili	Hong Kong	7

Next, Table 6 lists authors, their affiliations, countries, and the number of publications they have contributed. Cochrane, T. has the highest number of publications with nine, followed by Waycott, J., Ebner, M., García-Peñalvo, F.J., Gillet, D., Gray, K., Grosch, M., Kennedy, G., Lee, M.J.W., and Miranda, P., each with five publications. These authors come from different countries and institutions, including universities and educational computing associations.

Table 6. *Most Productive Authors*

Author's Name	**Affiliation**	**Country**	**TP**
Cochrane, T.	Centre for Teaching and Learning Innovation, Unitec	New Zealand	9
Waycott, J.	Cardiff University	UK	7
Ebner, M.	Universidad Nacional Mayor San Marcos	Peru	6
García-Peñalvo, F.J.	Computer Science Department/Science Education Research Institute/GRIAL Research Group, University of Salamanca	Spain	5
Gillet, D.	Ecole Polytechnique Fe´de´rale de Lausanne (EPFL)	Switzerland	5
Gray, K.	School of Medicine and Department of Information Systems, The University of Melbourne	Australia	5
Grosch, M.	Association for the Advancement of Computing in Education	Germany	5
Kennedy, G.	University of Melbourne	Australia	5
Lee, M.J.W.	Charles Sturt University	Australia	5
Miranda, P.	Escola Superior de Tecnologia de Setúbal, IPS, Campus do IPS, Estefanilha	Portugal	5

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Table 7 provides an overview of the most active source titles, categorized based on the total number of publications. Social Sciences is the leading category with 535 publications, followed by Computer Science with 436 publications, Engineering with 84 publications, Business, Management, and Accounting with 65 publications, and Mathematics with 44 publications. Conversely, other categories such as Decision Sciences, Arts and Humanities, Econometrics, Psychology and Economics, and Finance each contribute fewer than 30 publications. This comprehensive breakdown highlights the prominence of specific disciplines in the scholarly landscape, offering valuable insights into the distribution of publications across various academic domains.

Table 7. *Most Active Publication Titles*

Source Title	*TP*
Social Sciences	535
Psychology	22
Mathematics	44
Engineering	84
Economics, Econometrics and Finance	18
Decision Sciences	28
Computer Science	436
Business, Management and Accounting	65
Arts and Humanities	37

Citation Analysis

Table 8 provides a citation analysis that includes 805 papers with a total of 11,676 citations over 17 years, resulting in an average of 686.82 citations per year. The average number of citations per paper is 14.50. The h-index, which measures an author's productivity and impact, is 52, while the g-index, which considers the distribution of citations among papers, is 90. The table shows the top nine papers in education and technology, classified by the total citations received. The papers cover various topics such as digital reading practices, e-learning, web 2.0 tools in higher education, and the impacts of the COVID-19 pandemic on distance education. The paper with the highest number of citations is by (Tawafak et al., 2021), with four citations, followed by six papers, three and two, with one citation each. The table also includes the number of citations per year, which indicates the papers' impact over time.

Table 8. *Highly Cited Articles*

Authors	Title	Cites	Cites per Year
(Alcocer-Vázquez & Zapata-González 2021)	Digital reading practices among social science and exact science university students	3	1.5
(García-Martínez 2021)	Tools linked to informal learning: Opportunities to strengthen personal learning environments of university students during the times of pandemic	3	1.5
(Hernández Suárez et al. 2021)	Strategic technological management: Use of the Social Web 2.0 ecosystem in higher education	2	1
(Isaías et al. 2021)	Framework for Web 2.0 implementation in higher education: Experts' validation	3	1.5
(Küçük-Avci et al. 2022)	The Effects of the Covid-19 Pandemic on Distance Education in Higher Education: A Bibliometric Analysis Study	1	1
(Li & Wong 2021)	The Opportunities and Challenges of Social Media in Higher Education: A Literature Review	1	0.5
(Shire & McKinney 2021)	Web 2.0 tools and information literacy instruction in UK university libraries: Hype or reality?	2	1
(Sivankalai 2021)	Academic Libraries support E-Learning and Lifelong Learning: A case study	1	0.5
(Tawafak et al. 2021)	Integration of TAM and MOOC for e-learning purposes	4	2
(Tomasena 2021)	Who are the booktubers? Characteristics of Spanish-language Literary Video Bloggers	3	1.5

Table 9 shows the number of authors per document in a particular dataset. The total number of publications analyzed in the dataset was 101. Most publications were authored by either one (26.09%) or two (34.04%) authors. Only a small percentage of publications had more than five authors, with the highest being 12 (0.12%). There were also 20 publications (2.48%) with no authors listed.

Table 9. *Number of Authors (S) Per Document*

Total Publications (TP)	Author Count	Percentage (%)
210	1	26.09%
274	2	34.04%
168	3	20.87%
68	4	8.45%
42	5	5.22%
12	6	1.49%
6	7	0.75%
2	8	0.25%
1	9	0.12%
1	11	0.12%
1	12	0.12%
20	0	2.48%
Total	-	*100.00%*

*Conference review document. No author is listed.

Keywords

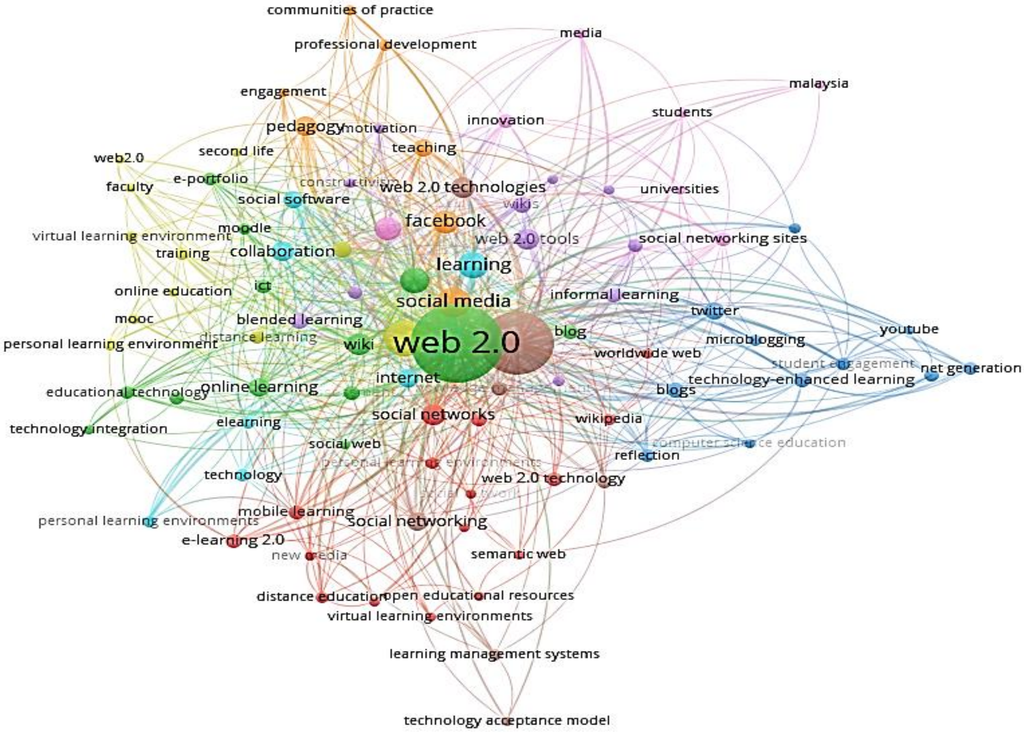
Table 10 lists author keywords, their total publications (TP), and their percentage in descending order based on TP. The keyword "Web 2.0" has the highest TP with 369 publications, followed by "Higher Education" with 299 publications. The top 15 keywords have TPs ranging from 369 to 40, while the remaining have TPs of 19 or less. The list includes many keywords related to education, technology, and social media, reflecting the growing interest in these areas.

Table 10. *Top Keywords*

Author Keywords	Total Publications (TP)	Percentage (%)
Web 2.0	369	45.84%
Higher Education	299	37.14%
Students	187	23.23%
E-learning	171	21.24%
Teaching	143	17.76%
World Wide Web	129	16.02%
Education	119	14.78%
Social Networking (online)	102	12.67%
Engineering Education	86	10.68%
Computer Aided Instruction	65	8.07%
Web 2.0 Technologies	53	6.58%
Social Media	51	6.34%
Collaborative Learning	48	5.96%
Learning	44	5.47%
Higher Education Institutions	40	4.97%

The author's keywords were also counted as essential to reflect the associated issues in Web 2.0 utilization in tertiary education studies. The web visualization of author keywords was shown using VOSviewer. It is important to note that features like color, font size, circle size, and connecting line thickness are indicators used to show the relationships between keywords. The analysis identified three clusters associated with Web 2.0 utilization in higher education: the green cluster for Web 2.0, the red cluster for higher education, and the yellow cluster for students, as shown in Figure 2.

Figure 2. *Network Visualization Map of the Author Keywords*



Discussion and Conclusions

The term "web 2.0" was first scientifically used and popularized by Tim O'Reilly in 2003 (Aced & Toledano 2013). This term has kept growing and used across various fields, including tertiary education. Over the past two decades, the number of scientific publications associated with Web 2.0 in higher education has significantly increased. This is probably due to the popularity of the Internet in supporting higher education activities, including online learning, massive open online courses (MOOCs), micro-credentials, and more. The objective of this study was to explore the utilization of Web 2.0 in higher education research by identifying the patterns of scientific productivity, publication, and citation trends—additionally, the research aimed to determine the most productive authors and research patterns across various sources. Eight hundred five documents retrieved from the Scopus database between 2006 and 2022 were analyzed, with a cut-off date of February 15, 2023, all of which were deemed relevant to the study's main topic of "Web 2.0" or "higher education" literature. The findings focused on developing and distributing Web 2.0 tool usage in higher education. They analyzed publications by year, source and document type, source title, language, and subject area. The data revealed a sharp increase in publications during specific years, particularly in 2011 and 2014, and a higher proportion of conference papers than other types of documents. Additionally, the study found that computer science had the highest number of publications, comprising 54.16% of the total.

This study comprehensively overviews the development and distribution of Web 2.0 tool usage in tertiary education. It contributes to existing literature by identifying popular subject areas and document types and providing insights into publication trends. The study also identifies the dominant language used in the field, which may affect international collaboration and communication. Based on the findings, several future research directions have been identified. First, investigating the reasons behind the decline in interest in Web 2.0 tools in higher education in recent years is essential. It may be worth investigating whether this decline is due to a saturation of the field, a shift in focus to other technologies, or a lack of perceived value in Web 2.0 tools.

Additionally, exploring the effectiveness of Web 2.0 tools in different subject areas and the factors influencing their adoption and success is another critical area for future research, given the shift towards open distance learning in tertiary education. This, in turn, is expected to support the agenda of Education Revolution 4.0. The role of Web 2.0 tools in promoting active and collaborative learning in higher education is also an exciting area for future research. Furthermore, research could explore how Web 2.0 tools can foster intercultural competence and global learning. Finally, examining the ethical and social implications of Web 2.0 tool usage in higher education is essential.

Future research in Web 2.0 and artificial intelligence can explore integrating these technologies to enhance the teaching and learning experience. With the increasing use of AI in education, researchers can study the effectiveness of AI-powered tools in providing personalized learning experiences to students. Additionally, research can investigate the use of AI in creating intelligent tutoring systems that can provide students with feedback and guidance based on their individual needs.

Another area of future research could be examining the ethical implications of using AI-powered Web 2.0 tools in education. As AI-powered tools become more prevalent, it is essential to understand their impact on student privacy, data protection, and bias. Researchers can explore how to ensure that these tools are used ethically and in a way that benefits all students, regardless of their background. In conclusion, future research in Web 2.0 and artificial intelligence can significantly benefit the education sector by providing insights into how to use these technologies to enhance teaching and learning while also addressing ethical concerns.

However, it is essential to note the limitations of this study, including the fact that it only covers documents published in the Scopus database and did not differentiate between the quality of the publications. Future research could improve the findings by exploring more databases, such as Google Scholar and Web of Science. In conclusion, this bibliometric study provides valuable insights into developing and distributing Web 2.0 tool usage in higher education. The study highlights the high interest in the topic across various document types, the dominance of the English language in the field, and the popularity of Computer Science and Social Sciences as the most prominent subject areas. These findings can be helpful for policymakers and higher education researchers interested in understanding the current state of Web 2.0 tool usage in this domain. The study also reveals interesting trends and areas for future research, including the decline in interest in Web 2.0 tools in recent years and the potential for exploring their role in promoting active and collaborative learning, intercultural competence, and social justice. Pursuing these research areas can contribute to the ongoing evolution and improvement of higher education practices and policies.

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References

Aced C, Toledano CA (2013) Web 2.0: The Origin of The Word That Has Changed The Way We Understand Public Relations. *Representing PR: Images, Identities and Innovations*, 1–12.

Alcocer-Vázquez E, Zapata-González A (2021) Digital reading practices among social science and exact science university students. *OCNOS* 20(3).

Anusha R, Rani TS (2021) Assessing Web 2.0 tools adoption by students in higher education-A structural equation modeling approach. *Annals of the Romanian Society for Cell Biology* 25(5): 769–777.

Awang H, Mansor NS, Harun NH, Bakar JA, Al-Mashhadani AFS, Hassan MG (2024) A New Interactive Gaming Approach for Enhancing Math Learning Among Marginalized Communities. *2023 1st IEEE International Conference on Smart Technology: Advances in Smart Technology for Sustainable Well-Being, ICE-SMARTec 2023*, *March*, 155–160.

Awang H, Zahurin MA, Wan Rozaini SO (2018a) Measuring Virtual Learning Environment Success from the Teacher's Perspective: Scale Development and Validation. *Proceedings of the 3rd International Conference on Applied Science and Technology (ICAST'18)*.

Awang H, Zahurin MA, Wan Rozaini SO (2018b) Modeling the Virtual Learning Environment Success among Malaysian Teachers: The Initial Investigation. *Journal of Information System and Technology Management* 3(7): 67–87.

Awang H, Zahurin MA, Wan Rozaini SO, Ishak MS (2018) Examining Virtual Learning Environment Success using DeLone and McLean IS Success Model. *Pacific Asia Conference on Information Systems*.

Donmuş Kaya V (2022) A Bibliometric Analysis of Using Web 2.0s in Educational Research Area. *International Online Journal of Education and Teaching (IOJET)* 9(1): 194–216.

Esguerra MA (2019) Educational applications of Web 2.0: Strategies to enrich the teaching and learning in the graduate school. *ACM International Conference Proceeding Series*, 217–222.

Genç G, Kırmızıbayrak Ö (2024) The use of Web 2 . 0 tools in English language learning: A systematic review. *Multidisciplinary Reviews* 2022: 0–12.

Holik I, Dániel Sanda I, Molnár G (2023) The Necessity of Developing Soft Skills in

STEM Areas in Higher Education, with Special Focus on Engineering Training. *Athens Journal of Technology & Engineering* 10(4): 199–214.

Isaias P, Miranda P, Pífano S (2021) Practice from implementing Web 2.0 tools in higher education. In *Practice From Implementing Web 2.0 Tools in Higher Education* (pp. 71–91). IGI Global.

Kanbul S, Soykan E, Erçağ E (2020) Examination on implications of Web 2.0 Tools in the field of Special Education. *Revista de La Universidad Del Zulia*.

Kolyvanova LA, Dudina EV, Iakovinich NP (2015) The use of Web 2.0 services in organizing the individual educational trajectory of students. *Geography, Computer Science, Education*.

Krouska A, Troussas C, Sgouropoulou C (2020) Usability and educational affordance of Web 2.0 tools from teachers' perspectives. *ACM International Conference Proceeding Series*.

Luo T, Lee GL, Muljana PS, Shah S (2022) An investigation of teachers' perceptions and integration of Web 2.0 tools into literacy instruction. *International Journal of Social Media and Interactive Learning Environments*.

Padayachee I, Moodley K (2022) Factors influencing Web 2.0 technology usage among academics: A case study of two South African tertiary institutions. *International Journal of Technology and Human Interaction* 18(1).

Roy P (2023) The use of Web 2.0 tools and technologies in English language teaching-learning process. *Gyan Management Journal* 17(2): 23–30.

Sakai BM, Miki H, Nakamura S (2024) Early STEAM Education Practice: Application of Graph Theory through Teaching Assistants. *Athens Journal of Technology and Engineering* 11(2): 145–166.

Tawafak RM, Romli A, Malik SI, Alfarsi G (2021) Integration of TAM and MOOC for e-learning purpose. *AIP Conference Proceedings*, 2339.

Yildirim M, Gurleroglu L (2022) A teaching suggestion in the COVID-19 disease pandemic period: The educational website enriched by Web 2.0 tools. *International Journal of Web-Based Learning and Teaching Technologies* 17(2).

Zakir S, Maiyana E, Jehwae P (2022) Improving student academic performance through web base learning. *Jurnal Educative: Journal of Educational Studies* 7(2): 173.