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The development of a blockchain-based business model simulator with an application to civic medical data management

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ABSTRACT

Blockchain technology is reshaping business models by altering how transactions and data integrity are managed. This shift necessitates evaluating long-term profitability and operational efficiency across various blockchain frameworks. Our research describes the development and application of a business model simulator, beginning with use case analysis, followed by the simulator's design and application to the Civic Data Identity Partnership project. We developed a transaction model, ran simulations, and analyzed outcomes to identify key cost drivers and assess the viability of different blockchain architectures. The results highlight the influence of execution costs, legal frameworks, and blockchain selection on financial outcomes, providing insights into the scalability and sustainability of blockchain applications in real-world scenarios.

1. Introduction

Blockchain, the technology underlying Bitcoin and other cryptocurrencies (Nofer et al., 2017), is now used as the technological basis of a wide range of use cases and operating models (Zheng et al., 2018). The technology allows for a distributed consensus mechanism to underpin data storage and exchange, removing the need for trusted third parties to become involved in the verification and storage of data. This has benefits for business models that would be negatively impacted in terms of the perception of their potential users or in terms of the costs associated with reliance on third party entities (Hughes et al., 2019). However using blockchain technology as the underlying data layer for a business or organization comes with running costs and additional complexities in terms of implementation and maintenance (Jabbar & Dani, 2020).

A significant factor in the implementation and running of a blockchain-based business model lies in the choice of the type of blockchain architecture being used (Xu et al., 2017). The original design philosophy and therefore implementation of the Bitcoin cryptocurrency called for a fully open and decentralized data model to be used (Nakamoto, 2008). As such the default for blockchain models is for them

to be open and public, with data exchanged via peer-to-peer protocols across the internet. However, with the development of the technology and advances in the type and number of use cases to which the technology was being applied, the need for alternative models of blockchain deployment have emerged (Morkunas et al., 2019). Blockchain architectures can exist as private networks, where participation in the network and access to the network itself is limited to whitelisted participants, and so-called hybrid models, with permissioned access to third party run networks, exist. These three models, public, hybrid and private come with different associated costs and potential revenue sources associated with them.

In designing a blockchain based information architecture designed to support a sustainable business model, the choice of underlying model for the blockchain and the parameters used to determine the exact operating model of the architecture, will have a significant impact on the potential profitability of the business over a medium or long-term time horizon (Davidson et al., 2016). The choice of model in the short term though will effect the operational model of the business, and a choice for this often needs to be made in the initial formulation of the business plan. An accurate means of estimating the costs of these various models

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for is important for determining the viability of a business designed around a blockchain based operating model. However determining the costs and revenues associated with these models has two main complexities. One is that public blockchains have market based costs associated with them which vary, often in a very volatile manner, based on usage and the market for the underlying cryptocurrency associated with a particular blockchain, and the other is that the given costs for an operating model will often depend on the particular computational models that are used to host and exchange data within a given blockchain architecture.

This paper describes the development of a business model outcome simulator tool, designed to model the costs and benefits over time stemming from the underlying use of a smart-contract based core architecture. The tool is derived from the development and analysis of a series of use cases pertaining to such modeling. From these we developed a python-based simulator that utilises historical blockchain volatility data in order to model the potential costs and benefits of running smart-contract based systems. This tool was then applied to a specific business case modeling exercise pertaining to the Civic Data Identity Partnership (CDIP) project. This project aimed to develop a system for the management and coordination of the use of personal healthcare data for participating groups of patients. The tool was used to model a series of business case scenarios varied around potential scenarios relating to the type of underlying blockchain model, pricing for participants in the system and charges relating to blockchain gas and hosting costs.

2. Background

2.1. Distributed ledger technology

Blockchain and Distributed Ledger Technology (DLT) have emerged as transformative innovations that have shown the potential to revolutionize various industries and business models in recent years (Gupta et al., 2020). The inception of blockchain technology, best known as the underlying infrastructure for cryptocurrencies such as Bitcoin, marked a significant milestone in digital finance and distributed systems (Nakamoto, 2008). Blockchains are decentralized and tamper-proof digital ledgers that enable secure, transparent, and immutable record-keeping. The core concept behind these technologies lies in creating a distributed and consensus-driven network of nodes, or participants, who collectively validate and record transactions without the need for a centralized authority. This potential shift from centralized to decentralized systems has far-reaching implications for business operations, trust-building, and value exchange in the digital age (Upadhyay et al., 2021).

Blockchain has had significant impact on the financial sector but beyond this has found utilization across various other domains, including supply chain management, healthcare, real estate and beyond (Knezevic, 2018). These technologies offer solutions to long-standing challenges, such as data security, authenticity verification, and trust establishment in digital interactions (Karafiloski & Mishev, 2017). Blockchain's architecture ensures data immutability through cryptographic hashing and consensus mechanisms, rendering data alterations virtually impossible once recorded. The transparent nature of blockchain facilitates real-time auditing and accountability, instilling trust among stakeholders and reducing the risk of fraud. As these technologies continue to develop, businesses are increasingly exploring their potential to create novel revenue streams and operational efficiencies (Morkunas et al., 2019).

While DLT has garnered significant attention and enthusiasm for its potential to revolutionize business operations, challenges exist. Of note is the scalability issue that many DLT-based platforms face (Zhou et al., 2020). As more participants join a network and the volume of transactions increases, the performance of some DLT systems can degrade, leading to slower transaction times and higher costs. Additionally, DLT's energy consumption, particularly in the case of proof-of-work

blockchains like Bitcoin and, previously, the Ethereum network, has raised environmental concerns due to the substantial computational power required for mining. The legal and regulatory frameworks surrounding DLT are still evolving, leading to uncertainty and potential legal issues for businesses operating within these ecosystems (Malhotra et al., 2022). Furthermore, the lack of interoperability among different DLT platforms can create silos, limiting the seamless exchange of data and assets across networks. In light of these challenges, businesses must carefully assess the suitability of DLT for specific use cases and consider potential drawbacks alongside the advantages.

A significant innovation in the space has been the development of the concept of smart contracts (Balcerzak et al., 2022). Smart contracts are self-executing agreements directly written into code. These programmable contracts are stored on the blockchain, enabling automated execution of actions when predefined conditions are met. Unlike traditional contracts, which rely on intermediaries and manual enforcement, smart contracts operate in a trustless environment, where transactions occur automatically and securely. They have been used as the core of a wide range of applications across industries, from finance and supply chain management to healthcare and beyond (Sharma et al., 2023).

The introduction of smart contract technology within the Ethereum ecosystem represented a significant advancement in blockchain-based technologies. Ethereum allowed for the creation of programmable smart contracts, which are scripted in Solidity, the platform's native programming language, and stored on its blockchain (Dannen, 2017). This capability empowered developers to design decentralized applications (DApps) capable of autonomously executing predefined actions upon meeting specific conditions (Metcalf et al., 2020). Ethereum's integration of smart contracts facilitated a wide array of use cases spanning decentralized finance (DeFi), non-fungible tokens (NFTs), supply chain management, and voting systems, among others (Nzuva, 2019).

The Ethereum blockchain employs a so-called 'gas' model of transaction payment. Ethereum's blockchain operates as a decentralized and trustless system, where block proposers validate and process transactions. To prevent the overloading of the network with computationally expensive operations or infinite loops, Ethereum introduced the concept of "gas." In this model, each operation or computation within a smart contract is assigned a specific gas cost, reflecting the computational resources required for its execution. When a user initiates a transaction or interacts with a smart contract, they must specify a gas limit and a gas price. The gas limit represents the maximum amount of gas they are willing to consume for the transaction, while the gas price indicates the price they are willing to pay per unit of gas (Li, 2021). The Ethereum gas model secures the network by preventing system overload, incentivizes miners with transaction fees, and offers users cost transparency and predictability for executing smart contracts, despite adding complexity (Carl & Ewerhart, 2020).

Cryptocurrency markets have long been characterized by a striking degree of volatility, setting them apart from traditional financial markets. The term "volatility" in this context refers to the rapid and often unpredictable price fluctuations exhibited by digital currencies like Bitcoin, Ethereum, and others (Liu & Serletis, 2019). Factors influencing markets, include market sentiment, news events, regulatory changes, and speculative trading. Unlike traditional fiat currencies, cryptocurrencies lack a centralized authority or intrinsic value, which can make them particularly susceptible to sharp price swings. This inherent volatility has implications for businesses that incorporate cryptocurrencies into their operations, as it can impact the financial stability and profitability of such ventures. It is therefore important account for volatility in the context of blockchain and Distributed Ledger Technology (DLT) business models (Almeida & Gonçalves, 2022).

In addition to the inherent price volatility of the underlying currency unit, another layer of complexity arises from the price fluctuations of gas, particularly notable in Ethereum's blockchain (Faqir-Rhazoui et al., 2021). These prices are influenced by network congestion, which occurs

when there is a high demand for Ethereum's computational resources, often during periods of increased user activity or the launch of popular decentralized applications (DApps). During network congestion, gas prices can skyrocket, creating a dynamic and unpredictable cost structure for businesses relying on Ethereum-based smart contracts. This congestion-induced gas price volatility can significantly impact the cost-effectiveness of executing transactions and smart contracts, necessitating careful planning and risk management strategies for businesses operating within this ecosystem.

As such the use of decision-making tools in structuring business operations based around these technologies are essential given the uncertainties inherent in the technologies (Almeshal & Alhogail, 2021). The complexities of fluctuating cryptocurrency and gas prices necessitate simulation tools for modeling potential outcomes. These tools enable businesses to explore financial impacts and strategic options within virtual environments that reflect real-world scenarios, helping to optimize strategies and mitigate risks before full-scale implementation, bridging theory and practical application in blockchain-based business models (Smetanin et al., 2020).

2.2. Types of blockchain architecture

Blockchain architectures are primarily categorized into three types: public, private, and hybrid, each offering distinct features and implications for business use.

Public blockchains are decentralized and operate without any central authority, allowing anyone to participate in transaction verification and mining. The transparency and immutability of these blockchains make them suitable for scenarios requiring high levels of trust among unknown participants (Zheng et al., 2017).

Private blockchains are controlled by a single organization or a consortium. Access to these networks is restricted, which allows for greater privacy and faster transaction speeds compared to public blockchains. They are commonly used for internal business processes where trust is established and data confidentiality is critical. (Pahlajani et al., 2019).

Hybrid blockchains combine elements of both public and private blockchains. They allow organizations to set up a private, permissioned system that can also interact with public blockchains. This architecture provides a flexible solution for businesses that need to maintain privacy for internal processes while still interacting with external data or verifications on a public blockchain.

Each type of blockchain architecture offers different benefits and trade-offs in terms of speed, cost, security, and transparency, impacting the choice of the most appropriate technology for specific business applications:

2.2.1. Public blockchains

Offer high transparency and security, making them ideal for applications that require immutable data and trust among participants. However, they tend to have slower transaction speeds and higher operational costs due to the energy-intensive mining process and the need to maintain a large network of nodes.

2.2.2. Private blockchains

Provide faster transaction speeds and lower costs relative to public blockchains because they operate within a controlled group with fewer nodes. While they offer greater privacy and are efficient, the centralization can be a drawback as it reduces transparency and potentially increases the risk of data manipulation.

2.2.3. Hybrid blockchains

Aim to balance the benefits and drawbacks of public and private systems. They can be customized to allow selective transparency and more controlled access to transactions. However, the complexity of maintaining both private and public components can lead to increased

design and maintenance challenges. (Alkhateeb et al., 2022).

These trade-offs must be carefully considered when selecting a blockchain architecture to ensure alignment with specific business objectives and operational requirements.

2.3. Current applications in business models

Blockchain technology has expanded beyond its origins in finance, now impacting various sectors by enhancing data integrity, increasing transparency, and reducing the need for intermediaries. This highlights blockchain's capability to streamline operations, secure transactions, and build trust in diverse business environments. The technology's decentralized nature ensures that data remains tamper-proof, transforming traditional business models through improved efficiency and accountability. Examples of its use include:

2.3.1. Financial services

Blockchain is extensively used in financial services for improving the efficiency and security of transactions. It enables faster payment processing, reduces fraud, and enhances transparency in banking operations (Chang et al., 2020; Javaid et al., 2022).

2.3.2. Supply chain management

In supply chains, blockchain provides traceability and transparency by securely recording each step of a product's journey. This capability can help with verifying the authenticity of goods and ensuring compliance with regulations (Blossey et al., 2019; Cole et al., 2019; Gurtu & Johny, 2019).

2.3.3. Healthcare

Blockchain applications in healthcare include managing patient records securely and enabling the sharing of medical data across providers while ensuring patient privacy and consent. (Attaran, 2022; Hölbl et al., 2018; Leeming et al., 2019).

2.3.4. Real estate

In real estate, blockchain facilitates property transactions by streamlining processes, reducing paperwork, and ensuring that records are immutable and transparent. (Garcia-Teruel, 2020; Saari et al., 2022).

2.3.5. Legal services

Blockchain supports the legal industry by enabling smart contracts that automatically execute agreements when certain conditions are met, thus reducing the need for intermediaries. (Corrales et al., 2019; Donovan, 2019).

2.4. Economic impacts of blockchain technology

Blockchain technology significantly alters the economic landscape of industries by enabling more efficient transaction processes and reducing costs (Sakız & Gencer, 2019). It eliminates the need for intermediaries in many financial and contractual interactions, thereby lowering transaction fees and administrative costs (Tian et al., 2022). Blockchain facilitates microtransactions and fractional ownership, opening up markets to a broader audience (Quiniou, 2019). Additionally, the immutable and transparent nature of blockchain can lead to increased trust and reduced instances of fraud, further economizing operations for businesses across sectors (Mahtani, 2022). Innovations like smart contracts automate and enforce agreements without human intervention, speeding up operations and reducing potential legal costs.

2.5. Challenges and limitations of blockchain adoption

Despite its potential, blockchain adoption faces technical and operational challenges. Scalability remains a primary concern as most blockchain solutions struggle to handle large volumes of transactions

quickly, a critical requirement for global business operations (Khan et al., 2021). The energy consumption of blockchain, particularly Proof of Work (PoW) systems, also raises sustainability concerns. Interoperability between different blockchain systems is another significant hurdle, complicating the integration with existing digital infrastructure (Schinckus, 2021). Additionally, the nascent nature of the technology means that best practices and robust security measures are still under development, which may deter some organizations from adopting blockchain solutions (Islam et al., 2021).

2.6. Regulatory landscape

The regulatory landscape for blockchain technology is complex and varies widely between jurisdictions, adding a layer of uncertainty for businesses (Karisma, 2022). In the financial sector, blockchain faces stringent scrutiny under various compliance regimes that govern data security and privacy. The absence of standardized regulations can hinder cross-border blockchain applications, such as international payments and supply chain management (Yano et al., 2020). Additionally, the dynamic nature of blockchain development often outpaces the formulation of new regulations, creating a gap that can either lead to restrictive initial regulations or a complete absence of guidelines, both of which can stifle innovation and adoption (Prewett et al., 2020).

2.7. Simulation and business modeling

2.7.1. Approaches to simulation

Simulation is a methodological approach used to model and analyze complex systems that are difficult to study analytically (Sokolowski & Banks, 2011). It involves creating computational models that replicate the behavior of real-world processes over time. Simulations enable researchers and practitioners to experiment with different scenarios, parameters, and variables in a controlled environment without the risks and costs associated with real-world experimentation (Bossel, 2018).

There are several approaches to simulation, suited to different types of systems and research questions:

2.7.2. Discrete event simulation (DES)

DES models systems where changes occur at discrete points in time, typically as a result of specific events. It is widely used in operations research and engineering to simulate processes such as manufacturing systems, network communications, and service operations. In DES, the state of the system changes only at the occurrence of events, and time progresses by jumping from one event to the next (Babulak & Wang, 2010).

2.7.3. Agent-based modeling (ABM)

ABM focuses on modeling the behaviors and interactions of autonomous agents within a system. Agents represent individual entities such as people, organizations, or components that make decisions based on a set of rules. ABM is particularly useful for studying complex adaptive systems where macro-level phenomena emerge from micro-level interactions (Helbing, 2012). It has applications in economics, social sciences, ecology, and more (Bruch & Atwell, 2015; Heckbert et al., 2010).

2.7.4. System dynamics (SD)

SD employs differential equations to model and analyze continuous feedback loops within complex systems. It is used to understand the behavior of systems over long periods and is effective in capturing accumulations, delays, and non-linear relationships. SD is commonly applied in fields like economics, environmental studies, and public policy to study long-term strategic issues (Bala et al., 2017).

2.7.5. Monte carlo simulation

This approach uses random sampling and statistical methods to model uncertainty and assess risk in systems. Monte Carlo simulations

are valuable for financial modeling, risk assessment, and decision analysis, where they help estimate the probability distributions of outcomes based on probabilistic inputs (Harrison, 2010).

2.7.6. Hybrid simulation

Hybrid simulation combines elements of DES, ABM, and SD to model systems that have both discrete events and continuous processes or require modeling at both micro and macro levels. Hybrid models can provide a more comprehensive understanding of complex systems by integrating different modeling paradigms (Lättilä et al., 2010).

The choice of simulation approach depends on the specific characteristics of the system under study, the research objectives, and the level of detail required. Factors influencing this choice include the nature of the interactions within the system, the importance of individual entities versus aggregate behavior, and the temporal dynamics of the processes involved.

2.7.7. Business model formalization

Business model formalization involves the use of structured frameworks and methodologies to represent, analyze, and communicate the components and dynamics of a business model. Several established approaches exist in the literature to formalize business models, each offering unique perspectives and tools for understanding and designing business strategies.

One prominent framework is the **Business Model Canvas**, which provides a visual chart comprising nine essential building blocks: customer segments, value propositions, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure (Murray & Scuotto, 2015). This tool helps organizations map out their business models in a clear and concise manner, facilitating strategic discussions and innovation.

Another approach is the **e3Value** methodology, which focuses on modeling and analyzing value exchanges between actors in a business network (Curry & Fill, 2023). It enables the representation of how economic value is created, distributed, and consumed among stakeholders, emphasizing the value propositions and revenue mechanisms within complex business ecosystems.

The **Resource-Event-Agent (REA)** model is an accounting model used to describe business processes by capturing the resources involved, events that occur, and agents participating in those events (Nikitkov, 2020). REA provides a semantic framework for modeling economic phenomena within enterprises, supporting detailed analysis of transactions and resource flows.

ArchiMate is an open and independent modeling language for enterprise architecture, offering instruments to describe, analyze, and visualize relationships among business domains in an unambiguous way (Josey et al., 2016). It supports modeling across different layers, including business processes, application structures, and technological infrastructure, enabling comprehensive enterprise architecture modeling.

These formalization methods offer structured ways to capture the complexities of business models, facilitating better understanding, communication, and analysis. They provide tools that can be used to simulate business scenarios, assess the impact of strategic decisions, and support the design of robust and innovative business models.

2.7.8. Business model simulation

Business model simulation involves using computational techniques to model, analyze, and predict the performance of business models under various scenarios. It allows organizations to explore the potential outcomes of strategic decisions, assess risks, and identify opportunities for optimization (Bock et al., 2021).

Key aspects of business model simulation include:

Scenario Planning and Analysis: Simulation enables businesses to test how changes in external factors—such as market conditions, regulatory environments, or technological advancements—impact their

business model. By modeling different scenarios, organizations can prepare for potential challenges and adapt their strategies accordingly (Täuscher & Chafac, 2016).

Financial Modeling: Simulating financial performance helps in projecting revenues, costs, cash flows, and profitability over time. It allows businesses to evaluate the financial viability of different strategies, investment decisions, and operational changes by incorporating uncertainties and variabilities in key financial drivers (Aleksandr, 2018).

Operational Efficiency: Simulation can model internal business processes to identify bottlenecks, inefficiencies, and areas for improvement. By optimizing processes through simulation, businesses can enhance productivity, reduce costs, and improve service delivery (Worobel et al., 2018).

Strategic Decision Support: Business model simulation provides insights into the potential impacts of strategic choices, such as entering new markets, launching new products, or adopting new technologies. It supports evidence-based decision-making by highlighting the risks and benefits associated with different options (Yan, 2018).

2.7.9. Blockchain focused simulation

2.7.9.1. Blockchain simulation methods. Simulation methods can play a role in understanding blockchain technologies due to their decentralized nature combined with the cost and complexity of analyzing real-world usage of the technologies. Various approaches have been developed to model the behavior of blockchain networks, evaluate their performance, and assess their scalability and security features (Paulavičius et al., 2021).

Approaches include DES for simulating the operational aspects of blockchain networks, such as transaction processing, block propagation, and consensus mechanisms, giving insight into the impact of network parameters on performance metrics (Li et al., 2021); the use of agent-based modeling for looking at the behavior of network participants such as miners, users and attackers (Lohmer et al., 2020); and hybrid models for exploring how changes in protocol parameters or incentive structures influence the overall performance and robustness of the network (Smetanin et al., 2020).

2.7.9.2. Blockchain based business simulation. Simulation of blockchain-based business models enables organizations to evaluate the feasibility and impact of integrating blockchain technology into their operations. Although research in this area is still developing, several studies have proposed methodologies for simulating blockchain-enabled business processes.

Argento et al. present a simulation-based and data-driven framework for analyzing and designing business processes that utilize blockchain and smart contracts (Argento et al., 2020). Their approach combines virtual environments with simulation techniques to create, validate, and stress-test blockchain-reliant business processes, assisting organizations in mitigating adoption risks.

Purusottama et al. employ a soft system dynamics modeling approach to experimentally design blockchain business models (Purusottama, Simatupang, & Sunitiyoso, 2024). By simulating dynamic complexities and policy-based scenarios, they identify key parameters affecting system performance and demonstrate the value distribution within blockchain-based systems.

Dehbasteh et al. use a hybrid method combining content analysis and system dynamics to identify determinants of blockchain-based business models (Dehbasteh et al., 2019). Their research highlights critical factors influencing blockchain adoption and success, providing insights into how simulation can support effective business model design.

These studies illustrate the potential of simulation in understanding and optimizing blockchain business models. Through modeling technical and economic aspects, organizations can assess performance and

sustainability of proposed approaches before implementation, aiding strategic planning related to blockchain adoption.

2.8. The civic data identity partnership project (CDIP)

The potential of health data to drive economic development in areas such as machine learning, digital healthcare, genomics, and wellbeing is well recognised (Abernethy et al., 2022). As the global healthcare market faces diminishing returns on late, expensive, imprecise, and unfairly distributed care, the use of health data in research becomes increasingly significant. The application of blockchain and Distributed Ledger Technology (DLT) provides a unique opportunity for digital government to facilitate civic access to medical data while ensuring privacy, identity, and trust. The Civic Data Identity Partnership (CDIP), has leveraged DLT to create a platform for patients and clinicians to manage their data and interactions with digital health solutions (Neumann et al., 2023).

CDIP aimed to create a social contract and currencies for experimenting with algorithms in supply chains across different healthcare providers. By building the platform on DLT, CDIP ensured secure and decentralized properties of the technology to guarantee privacy, identity, and trust. The platform's goal was to provide patients and clinicians with a way to manage their data and interactions with digital health solutions, such as predictive algorithms. The use of DLT in health data management has been considered but not yet resolved, with approaches often being led by technology enthusiasts rather than driven by user needs, including the views of citizens, the NHS, research organizations, and industry. Nonetheless, CDIP successfully utilized DLT to promote civic access to medical data while ensuring privacy, identity, and trust, and provide a foundation for further innovation in healthcare research (Cunningham et al., 2024).

This paper describes the development of a simulator designed to assess the costs and profits associated with business models built around blockchain and DLT, shedding light on the financial implications of adopting these innovative technologies.

3. Aims & objectives

The objective of this research was to develop a business model simulator tool that evaluates the financial viability of blockchain-based business models, specifically applied to the Civic Data Identity Partnership (CDIP) project. This project focused on scenarios involving third-party access to medical data.

The primary goal was to employ the simulator to determine long-term profitability under various blockchain architectures, including public, private, and permissioned blockchains. This assessment aimed to understand the financial implications these technologies have on business models managing healthcare data. We aimed to define the viability of these business models over a ten-year horizon, with viability measured by net profitability. This involved analyzing direct and indirect costs associated with each type of blockchain architecture.

The broader implications of this research for the blockchain industry and businesses considering blockchain technology were also examined. This study aimed to provide insights that could influence future research and development in blockchain applications. The expected outcomes of the study were to provide detailed insights into the cost-benefit analysis of different blockchain implementations. This would include identifying the key cost drivers and revenue streams, and evaluating their impact on the sustainability of business models.

4. Methods

4.1. Approach

We adopted a Design Science Research (DSR) methodology to develop the business model simulator. This began with a specification of

the scope and requirements of the tool, focusing on the functionalities necessary to support blockchain-based business models. We identified the core functionalities needed for simulating business model viability: transaction flow simulation; financial assessments; and scenario analysis across different blockchain architectures—public, hybrid, and private.

Initial steps included selecting relevant use cases that the simulator could address, covering potential business applications. We specified the simulator's capabilities to model the economic and operational dynamics of blockchain deployment in various settings. The design phase involved specifying the API's usage guidelines and an outline of its functionality to accommodate both technical and non-technical stakeholders.

The primary objective was to use the simulator to determine long-term profitability under different blockchain architectures. We aimed to assess the financial implications of public, hybrid, and private blockchain technologies on business models managing healthcare data. Viability over a ten-year horizon was measured by net profitability, analyzing direct and indirect costs associated with each blockchain approach.

We also examined the broader implications of this research for the blockchain industry and businesses considering blockchain technology. The study aimed to provide insights that could inform future research and development in blockchain applications. Expected outcomes included a cost-based analyses of different blockchain implementations, identification of key cost drivers and revenue streams, and evaluation of their impact on the sustainability of business models.

4.2. Application of design science research methodology

We applied a Design Science Research (DSR) methodology, following the stages and approach outlined by Peffers et al. (Peffers et al., 2007), to guide the development of the business model simulator. DSR is a research paradigm that emphasizes the creation and assessment of artifacts intended to address identified problems (Venable et al., 2017). It defines an iterative approach — problem identification, objectives definition, artifact design and development, demonstration, evaluation, and communication — to information systems research. This systematic approach was appropriate here as our objective was to develop and evaluate novel solutions to a complex domain space.

An outline of how our research mapped to this approach is given below.

4.2.1. Problem identification and motivation

The initial step was the identification of the need for a tool capable of simulating business models that incorporate blockchain technology in healthcare data management. This was motivated by the absence of existing tools that evaluated the financial viability of public, hybrid, and private blockchain architectures in such models. Understanding the economic implications of these architectures could aid organizations interested in blockchain adoption.

4.2.2. Objectives definition

The simulator was designed to:

- Model transaction flows and operational dynamics of blockchain-based business models.
- Perform financial assessments over a ten-year horizon.
- Enable scenario analysis across public, hybrid, and private blockchain architectures.
- Provide flexibility in defining simulations.

These capabilities were intended to support the evaluation of the viability and sustainability of different blockchain-based business models.

4.2.3. Design and development

The simulator was developed through an iterative process that involved selecting relevant use cases, designing a transaction model, and implementing a simulation tool.

4.2.3.1. Selection and analysis of use cases. Literature and industry applications were reviewed to identify relevant use cases for the simulator. The focus was on blockchain technologies with clear market needs and sufficient technological readiness to ensure that the selected scenarios were both applicable to real-world business models and feasible for simulation.

The selected use cases informed the simulator's functionalities by defining key features required to model blockchain-based business models. This included determining appropriate data inputs, structuring outputs, and specifying the operational conditions under which the simulator should function. This approach ensured that the tool could represent a range of business scenarios and support meaningful analysis of different blockchain architectures.

4.2.3.2. Development of the transaction model. A transaction model was designed to represent key transaction types relevant to blockchain-based business models, including registrations, data transactions, and governance activities. This structure reflected the operational flows observed in typical blockchain applications.

Adjustable parameters were incorporated to allow adaptation to different blockchain architectures—public, hybrid, and private. These parameters included transaction costs, administrative costs, and fees, enabling scenario analysis under varying business conditions. The model allowed for modifications to cost structures, revenue mechanisms, and execution complexities to facilitate financial assessments.

The framework was designed to handle transactions dynamically, allowing users to define specific parameters and obtain tailored outcomes and the evaluation of different blockchain architectures in terms of their impact on cost and operational efficiency.

4.2.3.3. Simulator tool development. The simulator was implemented as a modular tool that structured business models as a set of transactions executed over a defined time horizon. The transaction model was integrated into the simulator, linking transaction types and parameters with the simulation process, enabling dynamic interaction between user-defined inputs and the model's logic.

A simulation controller was developed to manage business models, execute transactions, and collect results. Parameter sweeping functionality was incorporated to systematically vary input parameters and explore multiple business scenarios, allowing users to assess the impact of different blockchain configurations and business model parameters on financial and operational outcomes.

Testing was conducted to ensure accuracy and reliability in simulation outputs. This included unit testing, integration testing, and system testing to identify and address issues while verifying that the simulator met the specified requirements. Outputs were structured for further analysis, supporting detailed evaluation of modeled scenarios.

4.2.4. Demonstration and data collection

The simulator was applied to a business scenario based on the Civic Data Identity Partnership (CDIP), where third parties pay for access to medical data. The scenario was evaluated under different blockchain architectures to assess financial viability and operational characteristics. This application demonstrated the simulator's ability to model transaction flows, apply parameter variations, and analyze the economic implications of blockchain-based business models.

To support the simulation, data on costs, user growth rates, and transaction fees were collected from secondary sources, including industry reports and academic publications. This data was used to define the economic environment in which the simulated business models

operated. Assumptions were introduced to simplify the modeling process, such as fixed growth rates, stable transaction fees, and a constant regulatory environment unless explicitly varied in scenario analyses. Market behavior and technology adoption trends were incorporated to align simulations with realistic business conditions.

4.2.5. Evaluation and scenario modeling

The simulator was evaluated by applying it to a business scenario in which third parties pay for access to medical data, with the potential for payments to be distributed to data owners. The scenario included parameters such as payment structures, transaction frequency, and membership fees for participants. Administrative costs related to transaction management, data security, and regulatory compliance were also incorporated.

Simulation runs were conducted using parameter sweeps to explore variations in key business model inputs. Data on costs, user growth rates, and transaction fees were obtained from secondary sources, and assumptions were introduced where necessary to create simulation environments representative of real-world conditions. The output data was analyzed to identify factors influencing profitability and sustainability, assessing both the simulator's functionality and the financial implications of the modeled business models.

4.2.5.1. CDIP use case. The business model scenario was based on the Civic Data Identity Partnership (CDIP). In this framework, individuals who own medical data can access a platform to specify their preferences regarding third-party access to their data. Third-party data consumers, such as research or commercial organizations, can access this data according to the participants' preferences. Users in the system can also participate in governance activities, particularly concerning access permissions for third-party consumers.

Third parties that consume data pay for access, with payments going either to the data owners or to the platform as an organizational entity. The infrastructure for hosting preference data, coordinating third-party access, and performing governance actions is enabled by an underlying blockchain model. This allows for enhanced trust in the system's operations and provides an open auditing system for participants and regulatory bodies to review actions coordinated by the system.

We modeled different blockchain architectures—public, hybrid, and private—to assess their impacts on business operations. Each architecture was defined with parameters reflecting their operational characteristics. Public blockchains were modeled emphasizing accessibility and transparency, with higher transaction visibility but potentially increased costs due to competition for transaction space. Private blockchains simulated controlled access environments, focusing on lower costs and increased transaction privacy. Hybrid blockchains combined elements of both, allowing for selective transparency and control over network participation.

4.2.6. Communication

Results were presented to stakeholders to gather feedback for refining the simulator. Workshops were conducted with project analysts and technical experts from the CDIP project, where simulation outputs were reviewed and discussed. Feedback from these sessions informed adjustments to the models, ensuring alignment with practical business requirements.

4.2.6.1. Workshops for model refinement. We conducted modeling workshops to refine the business models. These workshops involved members of the CDIP project, including project analysts, technical experts, and strategic planners, who provided insights based on their analysis of desired business outputs and use cases.

Participants reviewed simulation outputs and provided feedback focused on practical implementation in real-world settings. Feedback was analyzed and used to adjust the models, ensuring alignment with

practical business needs and refining parameters for more accurate simulations.

Potential challenges and operational risks associated with each model were explored, including scalability, cost-effectiveness, and technological feasibility. Input from these discussions was integrated into the final models, enhancing their relevance and applicability to the CDIP project goals.

4.2.7. Iteration and refinement

Throughout the process, we iterated between design, demonstration, and evaluation. Adjustments were made based on findings and stakeholder feedback, enhancing the simulator's accuracy and relevance.

4.2.7.1. Model assessment. To assess the financial viability of this model, we incorporated variables that could influence revenue streams and cost factors, such as the scale of user adoption, the pricing model for data access, and the percentage of revenue shared with data owners. We also considered different blockchain architectures to determine how each could support or hinder transaction efficiency and payment distribution. This analysis helped us understand the conditions under which this business model could be profitable and sustainable, providing insights into strategic planning for CDIP deployment.

We conducted simulations over a ten-year timeframe to compare the effects of blockchain architecture on the viability of these models. Parameter sweeping techniques were employed to systematically vary key inputs such as membership fees, transaction rates, and revenue-sharing percentages. This allowed us to explore a range of scenarios and their outcomes, providing an understanding of how different blockchain architectures could affect the sustainability and profitability of the business model.

4.2.7.2. Simulation runs and output analysis. We conducted simulation runs using parameter sweeps to model the mean profitability over a ten-year horizon for the three core business models based on different blockchain architectures: public, hybrid, and private. By systematically varying key inputs such as transaction costs, membership fees, and revenue-sharing percentages, we explored various scenarios.

The simulation outputs provided data on the profitability of each model. We analyzed this data to identify which elements had the most significant impact on profitability, helping us understand the strengths and weaknesses of each blockchain architecture in terms of financial performance. From these results, we identified the model elements that had the most substantial influence on profitability, providing insights into how different blockchain architectures affect the economic viability of business models.

5. Results

5.1. Use cases

We developed the following series of use cases relating to the use of a business model simulator tool in order to derive a generic set of aims and objectives relating to the functionality of such a tool.

1. Startup viability assessment

The simulator should provide functionality for assessing the viability of startups within the blockchain and smart contract space. Entrepreneurs and investors can utilize the tool to model and evaluate the financial aspects of their ventures. This includes projecting revenue, costs, and profitability over time, allowing them to make data-informed decisions. Startups can explore different scenarios, adjusting variables such as user growth, value per user, and cost per user to optimize their business models.

2. Blockchain integration in financial institutions

Financial institutions looking to integrate blockchain and smart contracts can leverage the simulator to assess the financial implications

of utilising such technology. By inputting data specific to their operations, they can model potential cost savings, transaction efficiencies, and regulatory compliance. The tool allows institutions to experiment with various integration strategies and evaluate their impact on overall financial performance.

3. Smart contract complexity analysis

Businesses engaged in smart contract development can use the simulator to analyze the financial impact of contract complexity. It provides a platform to model cost structures, estimate gas costs, and optimize contract design. This use case assists in making informed decisions about the level of complexity that aligns with operational efficiency and budget constraints.

4. Cryptocurrency investment portfolios

Investors can benefit from the simulator when managing cryptocurrency portfolios. They can input their portfolio composition, investment strategies, and risk tolerance. The simulator then projects portfolio performance under different market conditions, considering cryptocurrency price volatility, transaction fees, and asset allocation strategies. This use case empowers investors to fine-tune their portfolios for optimal returns and risk management.

5. Tokenization projects

Businesses exploring tokenization projects can use the simulator to assess the financial feasibility of tokenizing assets or securities. By inputting data related to tokenization costs, regulatory compliance, and revenue projections, they can model the financial impact of tokenization initiatives. The simulator helps in making informed decisions about the viability and profitability of tokenization projects.

5.2. Generic simulator model

5.2.1. Overview

We developed a generic simulator model to evaluate the viability of blockchain-based business models over time. The simulator was designed to provide a flexible framework for modeling and analyzing different business scenarios by defining transaction models and simulating operational processes. It allowed for the specification of various business models, each characterized by distinct transaction models and operations, enabling simulations to assess their financial performance.

The simulator facilitated the systematic exploration of how different configurations of business models and transaction parameters impact overall profitability and sustainability. By defining the core operations of a business as transactions within the model, we simulated the execution of these operations under varying conditions and analyzed the resulting outcomes.

Simulations were conducted by specifying business models that encapsulated the strategic and operational characteristics of different blockchain architectures, such as public, hybrid, and private blockchains. Each business model was associated with a transaction model detailing the specific operations carried out within the business, including parameters such as costs, revenues, and smart contract complexities.

The transaction models comprised a set of operations representing the key activities within the business, including registration, preference setting, data exploration, data purchase, profit distribution, audit, and governance. By simulating these operations over a defined period, we assessed the financial viability of each business model under various scenarios.

5.2.2. Conceptual design

We designed the simulator based on a modular conceptual framework that allowed for flexible modeling and analysis of different blockchain-based business models. The key components of the simulator included core classes representing business models, transaction models, and operations. These components interacted through defined class interfaces, enabling the simulation of complex business processes by combining various operations and parameters.

The underlying principles guiding the simulation involved representing business activities as a series of transactions, each with associated costs, revenues, and execution complexities. By modeling these transactions and their interactions, we simulated the financial performance of different business models over time. The simulator was structured to allow parameterization of key variables, facilitating the exploration of how changes in operational costs, transaction volumes, and other factors affected overall profitability.

5.2.3. Key concepts

The simulator is designed around the following fundamental concepts:

Transaction Modeling: We represented each business operation as a transaction within the simulator. This approach allowed us to capture the financial and operational characteristics of each activity, including direct costs, revenues, and the complexity of associated smart contracts. Transactions formed the basic units of the simulation, enabling detailed analysis of individual operations and their contributions to the overall business model.

Parameterization: We parameterized key variables within the transaction models, allowing adjustments to values such as costs, transaction frequencies, and growth rates. This enables the simulation of a wide range of scenarios by systematically varying parameters. Parameterization was essential for performing sensitivity analyses and understanding the impact of different factors on business viability.

Simulation Strategies: We employed simulation strategies that included parameter sweeping and scenario analysis. Parameter sweeping involved systematically varying one or more parameters across specified ranges to observe their impact on simulation outcomes. Scenario analysis allowed us to evaluate the performance of business models under different hypothetical conditions, such as changes in market dynamics or technological developments.

5.2.4. Simulator class model

The simulator is structured around a modular class model designed to represent and simulate blockchain-based business models. The core classes—`Simulator`, `BusinessModel`, `TransactionModel`, and `Operation`—define business models, specify transaction models, and execute simulations without hardcoding implementation-specific details. Each class plays a distinct role in structuring, parameterizing, and executing the simulation.

5.2.4.1. Simulator class. The `Simulator` class acts as the central controller for executing simulations. It manages multiple business models, applies simulation parameters, and orchestrates the iterative execution of transactions over a defined time period. The simulator also facilitates parameter sweeps, enabling systematic variation of input parameters to explore different scenarios.

5.2.4.2. Business model class. The `BusinessModel` class represents an abstract business scenario within the simulation. It provides a structured way to define operational and financial parameters while managing interactions with a `TransactionModel`. This allows different business configurations to be tested under the same simulation framework. Each business model defines high-level strategic variables, such as revenue sources, fixed costs, and operational scaling factors, which influence how transactions are executed.

5.2.4.3. Transaction model class. The `TransactionModel` class serves as the intermediary layer between business models and individual transactions. It defines and manages a set of `Operation` instances that represent specific business activities. This class allows transactions to be dynamically adjusted based on overarching business rules, including modifying execution costs, revenue structures, and contract complexities. It also provides methods to compute the aggregate financial impact

of transactions.

5.2.4.4. Operation class. The *Operation* class represents the fundamental unit of activity within the simulation. Each operation corresponds to a discrete business action, such as a registration, data exchange, or governance vote. These operations include financial characteristics (e.g., direct costs, variable costs, revenue potential) and execution parameters (e.g., complexity of smart contracts). The class structure allows the creation of specialized operation subclasses for domain-specific behaviors.

5.2.4.5. UML diagram. Fig. 1 illustrates the class structure of the simulator, showing the relationships and associations between the classes in the generic model. (See Tables 1–4.)

5.2.5. Class interactions

During the simulation process, the classes interact in the following manner:

5.2.5.1. Simulator and businessmodel. The *Simulator* instantiates and manages multiple *BusinessModel* objects, each representing a different business scenario to be simulated. The *Simulator* invokes the `run_simulation()` method, which iterates over each *BusinessModel* instance. For each business model, it passes global parameters and manages the simulation timeline.

5.2.5.2. Businessmodel and transaction model. Each *BusinessModel* holds a reference to a *TransactionModel* that defines the set of operations for that business scenario. The *BusinessModel* uses the `adjust_parameters()` method to modify the transaction model’s parameters based on the business model’s specific parameters. This allows for customization of the transaction model to reflect different operational conditions, such as varying execution costs due to different blockchain architectures or adjustments based on growth projections.

5.2.5.3. TransactionModel and operation. The *TransactionModel* manages a list of *Operation* instances, representing the individual business activities. When the `calculate_costs()` and `calculate_revenues()` methods are called, the transaction model iterates over each operation and invokes their respective `compute_cost()` and

Table 1

Simulator Class.

Responsibility	Manages and controls the execution of business model simulations.
Key Attributes	<code>business_models</code> : List of <i>BusinessModel</i> instances. <code>simulation_period</code> : Integer defining the total simulation duration. <code>global_parameters</code> : Dictionary of global parameters. <code>results</code> : Data structure storing simulation outcomes.
Key Methods	<code>run_simulation()</code> : Executes the simulation for all business models. <code>collect_results()</code> : Gathers and stores simulation outcomes.

Table 2

BusinessModel Class.

Responsibility	Represents a specific business model scenario.
Key Attributes	<code>name</code> : Identifier for the business model. <code>transaction_model</code> : Instance of <i>TransactionModel</i> . <code>parameters</code> : Dictionary containing business model parameters.
Key Methods	<code>adjust_parameters()</code> : Modifies transaction model parameters based on business model settings.

Table 3

TransactionModel Class.

Responsibility	Defines business operations and calculates financial metrics.
Key Attributes	<code>operations</code> : List of <i>Operation</i> instances. <code>parameters</code> : Dictionary of global parameters affecting the transaction model.
Key Methods	<code>calculate_costs()</code> : Computes total costs for all operations. <code>calculate_revenues()</code> : Computes total revenues generated by operations.

`compute_revenue()` methods. The transaction model incorporates relevant parameters from both the *BusinessModel* and its own parameters into these computations.

5.2.5.4. Operation class calculations. Each *Operation* computes its costs and revenues based on its own parameters and those passed from the *TransactionModel* and *BusinessModel*. This flexible parameterization allows for the inclusion of any specific cost or revenue factors

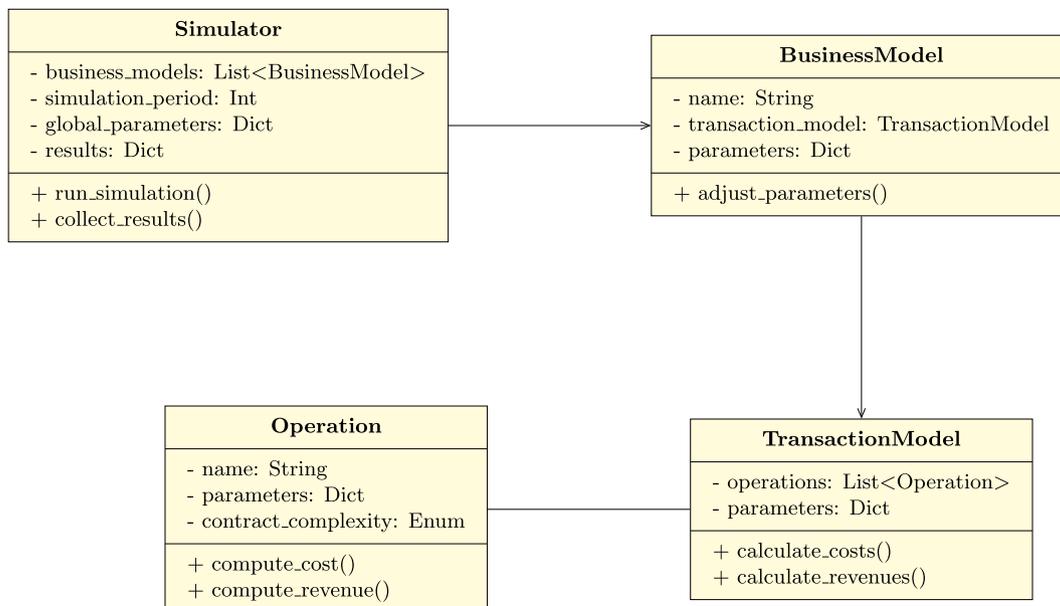


Fig. 1. UML Class Diagram of the Simulator’s Class Model.

Table 4

Operation Class.

Responsibility	Defines individual business activities within the transaction model.
Key Attributes	name: Identifier for the operation. parameters: Dictionary of operation-specific parameters. contract_complexity: Enum for smart contract complexity (High, Medium, Low).
Key Methods	compute_cost(): Calculates the total cost of the operation. compute_revenue(): Computes revenue generated by the operation.

relevant to the operation. For example:

- `compute_cost()` calculates the total cost of the operation by utilizing parameters such as direct costs, execution costs (influenced by `contract_complexity` and other factors), and any additional costs specified.
- `compute_revenue()` calculates the revenue generated by the operation based on parameters like transaction fees, access fees, or other revenue streams.

5.2.5.5. *Data flow and parameter passing.* The data flow during the simulation involves the propagation of parameter values through the class hierarchy:

- The `Simulator` sets global simulation parameters and manages the overall simulation process.
- Each `BusinessModel` provides specific parameters to its `TransactionModel`, influencing how operations are executed.
- The `TransactionModel` adjusts operation parameters based on both its own parameters and those from the `BusinessModel`.
- Each `Operation` computes its costs and revenues using parameters that can be customized to include any relevant factors.
 - o Key methods facilitating class interactions include:
- `Simulator.run_simulation()`: Orchestrates the simulation, invoking methods on `BusinessModel` instances and managing the simulation timeline.
- `BusinessModel.adjust_parameters()`: Modifies transaction model parameters to reflect the business model's specifics.
- `TransactionModel.calculate_costs()` and `calculate_revenues()`: Aggregate costs and revenues from operations, incorporating relevant parameters.
- `Operation.compute_cost()` and `compute_revenue()`: Calculate individual operation costs and revenues based on provided parameters.

This class interaction framework allows for a hierarchical and organized simulation process, where high-level business strategies and parameters influence lower-level operational details. By using flexible parameter dictionaries in the `BusinessModel`, `TransactionModel`, and `Operation` classes, the simulator can accommodate specific features and parameters of any particular implementation, such as administrative costs or recruitment costs in the CDIP model, without hardcoding them into the generic model. This design ensures that the simulator remains generic and adaptable to various use cases.

5.2.6. *Simulator operational model*

The simulator operates by modeling the economic and operational dynamics of blockchain-based business models over a specified time horizon. It incorporates various parameters representing costs, revenues, transaction volumes, and other factors influencing profitability. The simulator allows users to perform parameter sweeps to analyze how changes in these parameters affect the overall performance of different blockchain architectures.

Simulation Workflow. The simulation workflow consists of several sequential steps:

1. **Initialization:** The business models to be simulated are defined (e.g. public, hybrid, private) along with the initial parameters for the simulation. This includes setting fixed costs, variable costs, revenue streams, growth projections, and other relevant variables.
2. **Parameter Definition:** Parameters to be varied during the simulation are specified. The range and increments for each parameter are defined, establishing the scope of the parameter sweep.
3. **Simulation Execution:** For each combination of parameters in the sweep, the simulator executes the simulation over the defined time horizon (e.g., ten years). The simulation progresses in discrete time steps (e.g., months or quarters), updating the state of the system at each step based on the operational model.
4. **Transaction Modeling:** At each time step, the simulator models the occurrence of transactions according to the transaction model. This includes processing registrations, preference settings, data explorations, data purchases, audits, profit distributions, and governance events.
5. **Cost and Revenue Calculation:** The simulator computes costs and revenues for each transaction based on the parameters and the blockchain architecture's characteristics. Execution costs, data access costs, reward payments, and other expenses are calculated, as well as revenues from access fees and data purchases.
6. **Data Recording:** The simulator records outputs at each time step, such as total costs, total revenues, net profit, user base size, and transaction volumes.
7. **Iteration:** Steps 3 to 6 are repeated for each set of parameters in the parameter sweep.
8. **Result Aggregation:** After all simulations are completed, the results are aggregated for analysis. This includes compiling the outputs from each simulation run into a structured format suitable for further examination.

Parameter Sweeping Methodology. The parameter sweeping methodology involves systematically varying one or more parameters to assess their impact on the simulation outcomes. The approach includes the following steps:

- **Selection of Parameters:** Key parameters that are likely to influence the performance of the business model are selected for variation. Examples include execution costs, user adoption rates, transaction volumes, reward payments, and access fees.
- **Definition of Ranges and Increments:** For each selected parameter, a range of values is defined based on realistic operational limits or theoretical considerations. Increments are specified to determine the granularity of the sweep. For instance, execution costs per transaction might range from \$0.10 to \$10.00, with increments of \$0.10.
- **Creation of Parameter Combinations:** The simulator generates all possible combinations of parameter values within the specified ranges. This involved varying one parameter at a time over varying multiple parameters simultaneously e.g. a full factorial design approach.
- **Simulation Runs:** For each parameter combination, a separate simulation run is executed, following the workflow described in the previous paragraph.
- **Control of External Variables:** Parameters not being varied are held constant to isolate the effects of the variables under investigation.

Data Collection and Analysis. Data from the simulation runs are collected and organized for analysis:

- **Data Storage:** Outputs from each simulation run are stored in CSV files. Each dataset includes the parameter values used and the corresponding simulation outputs at each time step.
- **Data Processing:** The collected data are processed to compute aggregated metrics such as mean profitability, cumulative costs and revenues, return on investment, and other key performance indicators over the simulation horizon.
- **Visualization:** Graphs and charts are generated to visualize trends and compare results across different parameter settings and blockchain architectures. This may include line graphs of net profit over time, bar charts comparing total profitability across scenarios, and sensitivity plots showing the impact of individual parameters.

• **Interpretation of Results:** The analyzed data are interpreted to derive insights into the performance of different business models under varying conditions. Conclusions are drawn regarding the viability and sustainability of each blockchain architecture, and recommendations are made based on the findings.

5.3. CDIP simulation

5.3.1. CDIP business models

We applied the simulator to three blockchain-based business models in the Civic Data Identity Partnership (CDIP) project: a Public Blockchain approach, a Hybrid Blockchain approach, and a Private Blockchain approach. Each model presented distinct characteristics that influenced the simulator’s configuration. Table 5 summarizes the key features of each approach, while Table 6 outlines the specific parameter settings used in the simulator.

By configuring execution costs, transaction volumes, contract complexity, and access control as indicated in Table 6, we were able to capture the operational realities of each approach in the simulator. The Public Blockchain approach involved higher transaction fees and open participation, the Hybrid approach balanced transparency with privacy by distributing transactions between public and private channels, and the Private approach used a permissioned environment with lower fees but reduced decentralization.

Each parameter set was tested in the simulator over a ten-year horizon to assess the financial viability, scalability, and sustainability of the blockchain models under varying conditions. The simulator’s parameter sweep functionality facilitated sensitivity analysis, helping to identify the factors that most significantly influenced profitability.

5.3.2. CDIP transaction model

We developed a comprehensive transaction model for the CDIP project to simulate the key operations within the platform. This model includes essential activities, their associated parameters, variables for simulation, and the relationships between the elements. By incorporating these components, we analyzed how each transaction contributes to the financial viability of the CDIP platform under different business models.

5.3.2.1. Diagrammatic representation. Fig. 2 presents a UML sequence diagram of the CDIP transaction model. The diagram illustrates the interactions between the main entities involved in the platform, showing the sequence of transactions and how they relate to each other.

Table 5
Summary of Business Models (Public, Hybrid, Private).

Approach	Key Characteristics
Public Blockchain	Transparency: Transactions are publicly visible, enhancing accountability and trust. Decentralization: No single entity controls the network. Security: Large number of validators increases resistance to attacks. Higher transaction fees and potential scalability limitations due to congestion.
Hybrid Blockchain	Selective Transparency: Public transactions ensure accountability, while private transactions protect sensitive information. Moderate Fees: Some transactions are handled on private infrastructure to reduce costs. Balanced Approach: Combines openness with control over sensitive operations.
Private Blockchain	Controlled Environment: Network access is restricted to authorized participants. Enhanced Privacy: Transactions and data visibility are limited to permissioned users. Lower Transaction Costs: Operating in a closed network reduces per-transaction costs. Less decentralized than public blockchain models.

Table 6
Simulator Parameter Configurations for Each Business Model.

Configuration Aspect	Public Blockchain	Hybrid Blockchain	Private Blockchain
Execution Costs	High transaction fees	Mixed fees (public + private)	Lower fees in controlled environment
Transaction Volume	Unrestricted; open participation	Split between public and private transactions	Restricted access, lower volume
Smart Contract Complexity	High due to security and transparency needs	Some operations run on public, others on private	Lower complexity due to trusted environment
Access Control	Open participation	Partly permissioned, partly open	Fully permissioned, restricted network
Costs/Fees (Fixed and Variable)	High gas fees, congestion-driven	Moderate costs depending on public/private usage	Primarily administrative expenses, lower per-transaction costs

Table 7
Transaction Elements and Assigned Parameters in the CDIP Model.

Transaction	Role	Assigned Parameters
Registration	Onboarding new users	Administrative costs, execution costs, contract complexity (low)
Preference Setting	User control over data privacy and consent	Execution costs, contract complexity (low)
Data Exploration	Enables data consumers to search available data	Data access costs, execution costs, contract complexity (medium)
Data Purchase	Execution of data transactions	Licensing fees, execution costs, contract complexity (medium)
Profit Distribution	Compensation for data owners	Reward payments, execution costs, contract complexity (medium)
Audit	Ensures compliance and trustworthiness	Legal costs, execution costs, contract complexity (high)
Governance	Platform management and policy updates	Governance costs, execution costs, contract complexity (high)

Table 8
Impact of Transactions on the CDIP Model.

Transaction	Impact
Registration	Expands the user base, increasing the potential number of participants for other transactions.
Preference Setting	Determines data availability, influencing the volume of data exploration and purchases.
Data Exploration	Drives engagement by allowing data consumers to identify relevant datasets, influencing transaction volume.
Data Purchase	Generates revenue, directly affecting the profitability of the business model and the incentive for data owners.
Profit Distribution	Incentivizes data sharing by providing financial returns to data owners, potentially increasing user retention.
Audit	Ensures compliance with regulatory and operational policies, affecting trust and credibility of the platform.
Governance	Shapes long-term policy decisions and operational strategies, impacting cost structures and participant engagement.

5.3.2.2. Description of the diagram. In the UML sequence diagram, the lifelines represent the primary entities involved in the CDIP platform:

- **User:** An individual who registers on the platform and sets data sharing preferences.
- **CDIP Platform:** The system that manages user registrations, preferences, data transactions, and coordination with other entities.
- **Data Owner:** The owner of the data whose preferences determine data availability.
- **Data Consumer:** An entity that explores and purchases data from the platform.

Table 9
CDIP-Specific Transaction Classes.

Transaction Class	Description
RegistrationOperation	Handles user onboarding and initialization within the CDIP platform.
PreferenceSettingOperation	Allows users to configure data-sharing preferences and permissions.
DataExplorationOperation	Enables consumers to search and explore available datasets.
DataPurchaseOperation	Manages transactions where consumers purchase access to datasets.
ProfitDistributionOperation	Executes scheduled profit distribution to data owners.
AuditOperation	Conducts compliance checks to maintain platform integrity.
GovernanceOperation	Facilitates governance processes such as policy decisions.

Table 10
CDIP Simulation Parameters.

Parameter	Description	Initial Value	Range	Increment
Administrative Costs	Fixed costs for platform administration	\$500,000	Fixed	-
Legal Costs	Regulatory compliance and legal activities	\$200,000	Fixed	-
Recruitment Costs	Attracting and onboarding users	\$400,000	Fixed	-
Operational Costs	Running platform infrastructure	\$100,000	Fixed	-
Technological Overheads	Technology maintenance costs	\$150,000	Fixed	-
Third-Party Costs	Payments to external providers	\$100,000	Fixed	-
Licensing Fees	Blockchain technology fees	\$10,000	Fixed	-
Execution Costs (per transaction)	Cost per transaction execution	\$1.00	\$0.10–\$10.00	\$0.10
Data Access Costs (per transaction)	Accessing and processing data	\$100.00	\$10.00–\$1000.00	\$10.00
Reward Payments (per transaction)	Payments to data owners	\$1.00	\$0.10–\$10.00	\$0.10
Governance Costs (per event)	Governance activities costs	\$5000	Fixed	-
Access Fees (per user)	User platform access fees	\$1.00	\$0.10–\$10.00	\$0.10
User Adoption Rate	Rate of new user growth	5 % per year	1 %–10 %	1 %
Transaction Volume Growth	Annual transaction volume growth	10 %	5 %–20 %	1 %

Table 11
Mean Outcomes for Blockchain Models Over 10 Years.

Year	Public Blockchain Model	Self-Hosted Blockchain Model	Third-Party Blockchain Model
0	-1,290,580	-1,298,120	-1,299,300
1	-1,238,000	-1,246,000	-1,252,500
2	-1,166,860	-1,165,720	-1,183,300
3	-1,077,160	-1,057,280	-1,091,700
4	-968,900	-857,500	-977,700
5	-842,080	-527,500	-841,300
6	-696,700	-117,500	-682,500
7	-532,760	372,500	-501,300
8	-350,260	942,500	-297,700
9	-149,200	1,592,500	-71,700
10	70,420	2,322,500	176,700

Table 12
Most Significant Variables of each Model.

Model	Most Significant Variable	Optimal Assumption
Public Blockchain	Execution Costs	Base Transaction Cost set to 0
Self-hosted Blockchain	License Costs	Maximize Data Consumers
Third-Party Blockchain	Distribution Costs	Minimize distribution execution costs

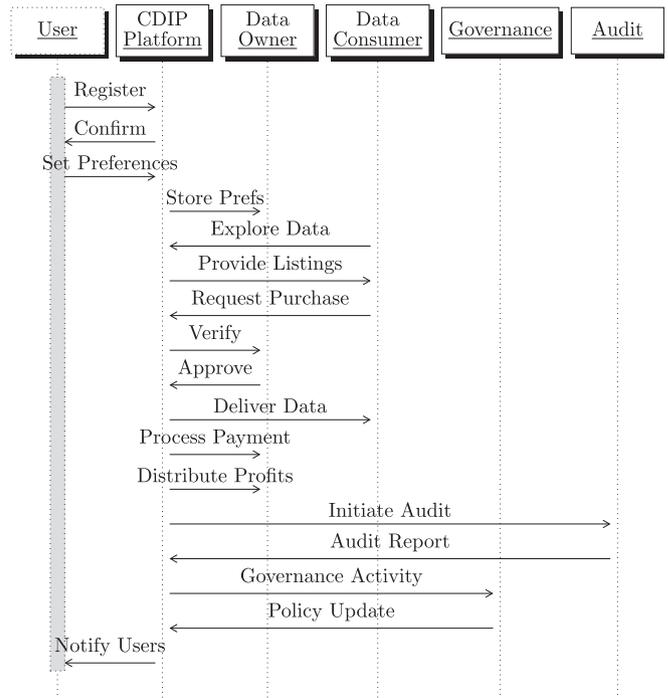


Fig. 2. UML Sequence Diagram of the CDIP Transaction Model.

- **Governance:** The body responsible for decision-making processes and policy updates within the platform.
- **Audit:** The entity that conducts compliance checks and provides audit reports.
- The interactions are as follows:
 1. **Registration:** The User sends a registration request to the CDIP Platform, which confirms the registration back to the User. This initiates the user’s participation in the platform.
 2. **Preference Setting:** The User sets data sharing preferences, which the CDIP Platform stores and communicates to the Data Owner. This defines what data can be shared and under what conditions.
 3. **Data Exploration:** The Data Consumer requests to explore available data from the CDIP Platform, which provides data listings based on the users’ preferences and available datasets.
 4. **Data Purchase:** The Data Consumer sends a data purchase request to the CDIP Platform. The platform verifies access with the Data Owner, who approves the access. The platform then delivers the data to the Data Consumer and processes the payment to the Data Owner.
 5. **Profit Distribution:** The CDIP Platform distributes profits to the Data Owner based on data purchases. This compensates data owners for sharing their data.
 6. **Audit:** The CDIP Platform initiates an audit by interacting with the Audit entity, which returns an audit report. This ensures compliance with policies and regulations.
 7. **Governance Activities:** The CDIP Platform engages with

Governance for policy updates and decision-making processes. Governance communicates any policy changes back to the platform, which then notifies the Users.

This sequence diagram emphasizes the interactions and message exchanges between entities, highlighting the flow of transactions and the dependencies between them.

5.3.2.3. Transaction elements and parameters. Each transaction in the CDIP model represents a distinct operational process within the platform, contributing to different aspects of the business model. These transactions have associated execution costs, complexities, and variables that are parameterized within the simulation. Table 7 provides an overview of each transaction, its role, and its assigned parameters.

Each transaction influences different aspects of the business model, such as platform sustainability, revenue generation, and user participation. Table 8 summarizes the broader impact of these transactions on the CDIP ecosystem.

5.3.2.4. Transaction model setup and configuration. To implement these transactions in the simulator, a dedicated `TransactionModel` instance is created for the CDIP use case. The model defines all relevant operations (e.g., `RegistrationOperation`, `DataPurchaseOperation`) and integrates CDIP-specific parameters such as user adoption rates, cost structures, and contract complexities. This process is generally code-based, meaning that parameters are stored and passed as Python dictionaries throughout the simulator classes (`Simulator`, `BusinessModel`, `TransactionModel`, and `Operation`).

However, the simulator is flexible enough to load these parameters from external configuration files (e.g., JSON or YAML) if desired. In such a setup, the file would be parsed at runtime, and its values would populate the parameter dictionaries. This approach facilitates customization and reproducibility, allowing different scenarios to be tested by modifying a single configuration file. In both cases—code-based or file-based—the simulator reads the same data structure to instantiate and run each transaction.

Transactions are implemented in the same vein as generic operations: each transaction subclass may override methods such as `compute_cost()` or `compute_revenue()` to incorporate CDIP logic. The `Simulator` orchestrates these transactions over the simulation period, applying parameter sweeps where relevant. As a result, users can modify the `TransactionModel` or provide a new configuration file to explore alternate blockchain architectures, cost assumptions, or user growth scenarios without making fundamental changes to the simulator's codebase.

5.3.2.5. Technical implementation in the simulator. The CDIP transaction model is implemented using the generic simulator model as a foundation. The framework was extended to accommodate CDIP-specific logic, transaction structures, and financial mechanisms. This was achieved by subclassing the core `Operation` class, introducing additional parameters, and modifying execution logic.

Extending the Operation Class Each transaction in the CDIP model is implemented as a subclass of the `Operation` class. These subclasses override or extend methods such as `compute_cost()` and `compute_revenue()` to reflect CDIP-specific characteristics, including execution costs, transaction fees, and contract complexities. Table 9 lists the transaction classes defined in the model.

5.3.2.6. CDIP-specific parameters. The CDIP simulation introduces additional parameters to represent administrative costs, transaction fees, execution complexities, and participation rates. These parameters are structured at different levels:

- **BusinessModel parameters:** Define administrative costs, legal costs, and user adoption rates.
- **TransactionModel parameters:** Include global settings such as transaction fees and growth projections.
- **Operation parameters:** Specify execution costs and contract complexity for individual transactions.

Scheduling Regular Events Certain transactions occur at regular intervals rather than being triggered by user interactions. These include:

- `ProfitDistributionOperation`, which is executed at predefined time intervals.
- `GovernanceOperation`, which is scheduled based on governance cycle parameters.

Event scheduling is handled dynamically within the `Simulator` class, ensuring that scheduled operations are executed at the correct time steps.

Adjusting Transaction Volumes Transaction volumes vary dynamically based on simulation parameters. Key influencing factors include:

- **User adoption rate:** Affects the number of `RegistrationOperation` executions and determines long-term platform growth.
- **Participation rate:** Impacts the frequency of governance and preference-setting activities.
- **Transaction volume:** Governs the frequency of `DataExplorationOperation` and `DataPurchaseOperation` based on behavioral models.

Incorporating Smart Contract Complexities Execution costs in the simulation are adjusted based on contract complexity. Each transaction is categorized as:

- **Low complexity:** Applies to simple operations such as user registration.
- **Medium complexity:** Covers transactions like data purchases involving financial flows.
- **High complexity:** Includes operations with significant computational requirements, such as audits and governance events.

The `compute_cost()` method dynamically adjusts execution costs based on these classifications.

5.3.2.7. Data flow and parameter passing. The simulator follows a structured approach to parameter passing:

1. **Global parameters** are initialized by the `Simulator`, setting key values such as simulation duration and baseline costs.
2. **Business model parameters** are passed to the `TransactionModel`, allowing customization based on the selected blockchain architecture.
3. **Transaction parameters** are distributed to the respective `Operation` instances, ensuring that each transaction has access to its relevant cost structures and execution constraints.
4. **Operations compute costs and revenues** using their assigned parameters, updating the simulation outputs accordingly.

Simulation Execution The simulation progresses through a structured execution cycle:

1. **Initialization** – The CDIP-specific business model is instantiated within the simulator.
2. **Transaction processing** – Operations are executed based on dependencies and schedules.
3. **Result collection** – Aggregated outputs, such as costs and revenues, are recorded at each simulation step.
4. **Parameter sweeps** – Input parameters are adjusted

systematically to perform sensitivity analysis.

5.3.2.8. *Relationship to the generic simulator model.* The generic simulator model provides a flexible framework that we leveraged for the CDIP simulation:

- **Modular Design:** Allowed us to extend classes and add CDIP-specific logic without altering the core structure.
- **Parameterization:** Enabled the incorporation of CDIP-specific parameters through dictionaries, facilitating customization.
- **Extensibility:** Supported the addition of new transaction types and scheduling mechanisms for regular events.

By extending the generic classes and implementing CDIP-specific subclasses, we maintained the integrity of the generic model while tailoring it to the needs of the CDIP project. This approach ensures that future changes or additions can be accommodated with minimal disruption, highlighting the versatility of the simulator framework.

5.3.3. CDIP parameter specifications

In the CDIP simulations, we utilized a set of specific parameters to model the financial and operational aspects of the platform accurately. These parameters included initial values, ranges for parameter sweeping, and were carefully selected based on their significance to the platform's performance under different blockchain architectures.

5.3.3.1. *Parameter tables.* Table 10 summarizes the parameters used in the CDIP simulations, providing their descriptions, initial values, ranges, and increments used during parameter sweeping.

5.3.3.2. *Parameter justifications.* Each parameter was carefully selected for its significance in the CDIP simulation:

- **Administrative Costs:** Represent fixed overhead expenses necessary for business operation, set as a fixed value to focus on variable cost impacts.
- **Legal Costs:** Include expenses related to compliance with data protection regulations.
- **Recruitment Costs:** Reflect the investment needed to attract and onboard new users, impacting the user base growth.
- **Operational Costs:** Cover the day-to-day expenses of maintaining the platform's infrastructure, essential for uninterrupted service delivery.
- **Technological Overheads:** Include costs for technological upgrades and maintenance, affecting long-term sustainability and scalability.
- **Third-Party Costs:** Account for services provided by external entities, such as data storage or analytics providers, influencing operational expenses.
- **Licensing Fees:** Represent costs for using specific blockchain technologies, varying based on the chosen architecture (public, hybrid, or private).
- **Execution Costs (per transaction):** Critical in simulating the impact of transaction fees on overall costs, especially significant in public blockchain scenarios with higher fees.
- **Data Access Costs (per transaction):** Reflect the costs associated with retrieving and processing data for transactions, affecting the cost structure of data-related operations.
- **Reward Payments (per transaction):** Incorporated to simulate incentives for data owners to share their data, influencing data availability and user engagement.
- **Governance Costs (per event):** Represent the expenses of conducting governance activities, important for platform evolution and participant involvement.
- **Access Fees (per user):** Model potential revenue from charging users for platform access, impacting profitability and user adoption.

- **User Adoption Rate:** A key variable influencing the number of platform users over time, affecting transaction volumes and revenue potential.
- **Transaction Volume Growth:** Simulate the growth in transaction activity, reflecting increased platform usage and scalability considerations.

The ranges and increments for parameters subject to sweeping were chosen to encompass realistic operational scenarios and to analyze sensitivity across a broad spectrum. For example, execution costs per transaction were varied from \$0.10 to \$10.00 to represent different blockchain fee structures between private and public blockchains. Similarly, user adoption rates were tested from 1 % to 10 % to assess how different growth scenarios impact the platform's performance.

5.3.3.3. *Impact on simulation.* Varying these parameters allowed us to observe their effects on the CDIP platform's financial performance:

- **Execution Costs:** Higher execution costs reduced profitability, particularly in models relying on public blockchains with higher fees, highlighting the importance of cost-efficient transaction processing.
- **Data Access Costs:** Increases in data access costs impacted operational expenses, affecting net revenue from data transactions and the attractiveness of the platform to data consumers.
- **Reward Payments:** Adjusting reward payments influenced user incentives for data sharing, affecting data availability and, consequently, transaction volumes and revenue.
- **User Adoption Rate:** Higher adoption rates led to increased transaction volumes and revenue but also increased operational costs due to higher activity levels, emphasizing the need for scalable infrastructure.
- **Access Fees:** Modifying access fees impacted revenue streams; higher fees could deter user adoption, while lower fees might not sufficiently cover operational costs, affecting profitability.
- **Transaction Volume Growth:** A higher growth rate in transaction volume indicated scalability potential but required the platform to manage increased operational demands, influencing long-term sustainability.

Analyzing these impacts provided insights into the conditions under which each blockchain model performed optimally. It aided in identifying strategies for enhancing profitability, such as optimizing execution costs or adjusting reward payments to balance user incentives with financial sustainability.

5.4. Parameter sweeping methodology

5.4.1. Definition of parameter range

The simulation tool was designed to allow for extensive parameter range definitions. Users can specify the range and increment values for each key parameter, such as transaction fees and block sizes. This setup ensures that the parameter space is comprehensively explored.

5.4.2. Setup of Simulation Runs

The tool automates the setup of multiple simulation runs, each configured to test different combinations of parameters. This includes both single-parameter sweeps and multi-parameter sweeps to capture interaction effects.

5.4.3. Execution of sweeps

Parameter sweeping is executed automatically by the simulator, iterating over the entire defined range of parameter values. This process is managed through a batch execution mode that systematically processes all possible parameter combinations, collecting data on each run.

5.4.4. Data collection and analysis

The simulator captures detailed output from each simulation run, which is then analyzed to assess the impact of different parameter values on the simulation outcomes. Analysis tools integrated within the simulator help in identifying trends, optimal settings, and parameter sensitivity.

5.5. Outcomes

We ran simulations across the three models, varying the parameter inputs in order to find the best-case business outcomes in terms of overall profit and loss for each model. The simulation parameters were selected to cover a broad spectrum of operational and financial variables relevant to blockchain-based business models. These included key factors such as transaction volume, user adoption rates, operational costs, and technological overheads.

Our analysis focused on identifying the optimal conditions under which each blockchain architecture (public, private, and permissioned) could achieve maximum profitability over a ten-year period. By systematically varying these parameters, we aimed to uncover the best-case scenarios for financial performance, providing insights into the scalability and sustainability of different blockchain applications in healthcare data management.

To assess the long-term financial viability of each blockchain model, we averaged the simulation results over a 10-year period. This analysis provided a view of how each model performs under varying conditions. The parameters varied during the simulations allowed us to capture a range of potential outcomes, allowing an evaluation of each model's financial performance.

The Public Blockchain Model showed a consistent trend of improving profitability over the decade, starting from significant initial losses and gradually moving towards positive net income. This model's average outcome was reflective of a steady increase in user adoption and transaction volume, important factors in achieving long-term financial stability.

The Self-Hosted Blockchain Model demonstrated the most significant improvement in financial performance over the 10 years. This model benefits from controlled operating costs and higher flexibility in managing blockchain infrastructure. As user adoption and transaction volumes increase, the model quickly shifts from initial losses to substantial profits.

The Third-Party Blockchain Model presented moderate financial performance, with steady improvements over the years but at a slower pace compared to the Self-Hosted model. While this model reduces the burden of managing blockchain infrastructure, it incurs higher third-

party costs, which impact overall profitability.

As shown in Fig. 3, the financial trajectories of each model reveal distinct patterns of profitability and loss over time. The Public Blockchain Model starts with significant initial losses, gradually improving towards positive net income. The Self-Hosted Blockchain Model exhibits the most significant improvement in financial performance, transitioning from initial losses to substantial profits within a few years. In contrast, the Third-Party Blockchain Model shows moderate financial performance, with steady but slower improvements compared to the Self-Hosted model.

This graph provides a visual representation of the data presented in Table 11, highlighting the dynamic changes in financial outcomes as the models evolve over the decade. The visualization aids in understanding the long-term viability and potential financial benefits of each blockchain model under varying conditions.

We further analyzed the simulation results to variable with the most effect on the output values. These results are summarised in Table 12. The results from the simulation across different blockchain models illustrate specific cost impacts on each model's financial performance. In the public blockchain model, execution costs were identified as the most significant variable, indicating that minimal transaction costs can enhance viability. Setting the base transaction cost to zero was found to be the most favorable condition.

For the self-hosted blockchain, license costs emerged as a significant factor. This emphasizes the potential financial benefit of increasing the number of data consumers, which could help distribute the licensing costs more effectively and improve the economic feasibility.

In the third-party blockchain model, distribution costs were the key variable affecting financial outcomes. Reducing these costs is essential for maintaining cost-effectiveness. The optimal strategy involves minimizing distribution execution costs, which could be achieved through more efficient service arrangements or improved platform technology.

6. Discussion

This work was centered on the development and evaluation of a parameterized transaction model and associated simulation tool used to assess the financial viability of different blockchain-based business models. Key components of this transaction model included registration and preference setting, data exploration, data purchase, audit, profit distribution to members, and governance through voting mechanisms. These components were integrated into a simulation tool that allowed for extensive parameter sweeps to analyze various scenarios.

To construct the transaction model, we identified and categorized a set of input parameters affecting costs and revenues. Fixed costs, such as administrative, legal, and recruitment expenses, were considered alongside variable costs, including third-party service payments and transaction-specific expenses. Revenue streams were modeled based on data consumer payments and licensing fees. The simulation model also incorporated the complexity of smart contracts and projected growth rates for members and data consumers to reflect potential scalability and its impact on financial outcomes.

The simulation tool was used to run across three scenarios, systematically varying input parameters to explore a wide range of possible outcomes. This approach enabled an examination of the operational and financial impacts of different business models over a ten-year horizon. The resulting data provided insights into the relationships between various parameters and the overall profitability and sustainability of each model. By analyzing these results, we aimed to identify conditions under which each business model could achieve long-term viability.

6.1. Choice of modeling strategy

In developing this simulation model, we adopted a discrete event simulation (DES) approach. This modeling strategy was reflected in describing the system as a sequence of distinct events occurring at

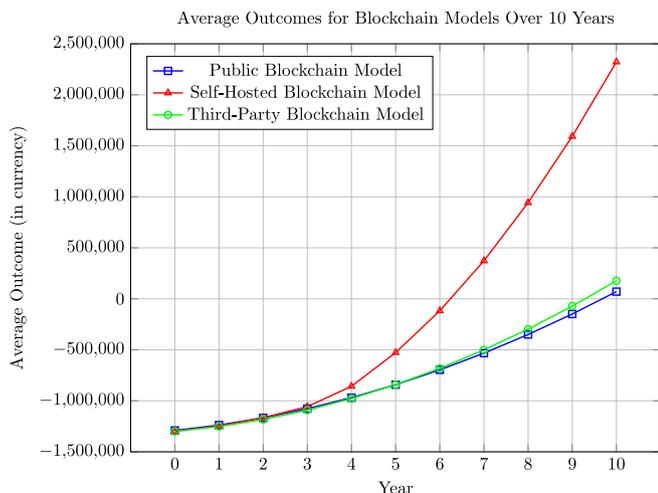


Fig. 3. Average Outcomes for Blockchain Models Over 10 Years.

specific points in time, where each event marks a change in the system's state. The choice of DES was informed by the transactional nature of the business models we wished to simulate and the need to account for the timing and sequence of operations.

The business models operate through a series of discrete transactions, such as user registrations, data explorations, data purchases, audits, profit distributions, and governance activities. These transactions are inherently event-driven, making DES an appropriate modeling choice. For example, a new user registering on the platform changes the size of the user base but also affects the potential for subsequent events like data sharing preferences being set, in turn affecting data availability for exploration and purchase.

This approach allowed us to capture the temporal dynamics of the system, which worked well for financial modeling over the ten-year simulation period. For instance, the timing of revenue-generating events like data purchases and the scheduling of cost-incurring events like profit distributions and audits could be precisely represented. This temporal precision facilitated cash flow analysis, enabling us to assess the platform's profitability under different business models and parameter settings.

As an alternative we could have adopted an agent-based modeling (ABM) approach, focusing on simulating the behaviors and interactions of individual agents within the system. While ABM is powerful for capturing emergent phenomena resulting from complex agent interactions, it was less suited to our objectives. The primary interest of our study was on the aggregate effects of transactions and operational flows rather than the individual behaviors of users. Implementing an ABM would have introduced unnecessary complexity by requiring detailed modeling of user decision-making processes, which may not have significantly enhanced the insights for our analysis.

6.2. Positioning of our approach to Blockchain-oriented simulation

Our approach presents a generic simulation model designed to evaluate business models that incorporate blockchain technology, while remaining flexible enough to be applicable to non-blockchain scenarios. By focusing on high-level aspects of blockchain integration, such as the costs associated with smart contract execution and transaction fees, our model allows for the assessment of financial viability without requiring detailed technical knowledge of blockchain operations.

A key benefit lies in its ability to simulate the economic implications of adopting blockchain technology within a business model. By abstracting the complex technical mechanisms of blockchain systems, we focus on results relating to strategic decision-making such as cost structures, revenue streams, and overall business sustainability. This high-level representation may be valuable for organizations evaluating whether the integration of blockchain technology aligns with their financial and operational objectives.

In our simulation, blockchain-specific factors such as execution costs and smart contract complexities are incorporated through adjustable parameters. These parameters abstract blockchain's impact on the business model without a need to model the intricacies of the underlying technology. For instance, we model execution costs associated with smart contracts as variable expenses that can be adjusted to reflect different blockchain architectures—public, hybrid, or private—allowing for comparative analyses.

6.3. Consideration of established business model formalization approaches

While established business model formalization approaches such as the Business Model Canvas, e3Value, REA, and ArchiMate provide valuable frameworks for representing and analyzing business models, they were not directly applied in this study. Our primary focus was on developing a simulation model specifically tailored to assess the financial viability of blockchain-based business models over a long-term

horizon.

Not incorporating these approaches was offset against the need for a flexible and adaptable simulation tool that could accommodate the unique characteristics of blockchain technologies. Our model emphasizes high-level financial and operational parameters, such as transaction costs and revenue streams, which are critical for evaluating the economic implications of different blockchain architectures.

Integrating detailed formalizations such as e3Value might have added complexity without significantly enhancing the financial simulation objectives. These frameworks often require comprehensive modeling of business processes, value networks, and enterprise architectures, which could constrain the adaptability of our simulator to various blockchain scenarios.

Future research could explore the integration of these formal frameworks into our simulation model to enrich the analysis. Incorporating elements from the Business Model Canvas or e3Value could provide additional insights into the strategic positioning and value creation mechanisms of blockchain-based business models. However, for the scope of this study, we determined that a high-level simulation approach was most appropriate to meet our objectives.

6.4. Applications beyond CDIP

While the application of our generic business model simulator tool in the CDIP project demonstrates its adaptability and utility in the context of patient data cooperatives in healthcare, its use can be extended beyond this specific use case. Here we highlight a number of other potential use cases.

1. Supply Chain Optimization: Across industries such as manufacturing, logistics, and retail, the tool could provide utility in optimizing supply chain operations. Users can model the financial implications of integrating blockchain for smart contract-driven traceability, transparent supply chain management, and automated contract execution. This includes assessing the cost-effectiveness of blockchain in reducing fraud, improving transparency, and enhancing supply chain resilience.

2. Tokenization and Asset Management: In the area of finance and investment, the simulator can assist businesses in evaluating the financial viability of tokenization projects. This encompasses tokenizing assets like real estate, securities, or art collections. Users can model the costs and potential revenue streams associated with smart contracts, including transaction fees, compliance costs, and revenue sharing mechanisms.

3. Legal and Regulatory Compliance: Legal and regulatory compliance is paramount in various industries. The tool can be used to model the costs of implementing smart contract-based compliance solutions. This includes evaluating the financial implications of using blockchain to automate and verify compliance processes, reducing legal overhead and minimizing risks.

4. Intellectual Property and Content Distribution: In the entertainment and creative industries, the tool can assist in modeling the financial aspects of smart contract-based content distribution and intellectual property management. Users can assess the costs of deploying blockchain solutions for royalty tracking, content licensing, and digital rights management.

5. Procurement and Vendor Management: For businesses engaged in procurement and vendor management, the simulator can help model the financial impact of smart contract automation. Users can evaluate the cost savings associated with streamlined procurement processes, automated vendor payments, and contract enforcement through blockchain technology.

6. Energy and Utilities: Within the energy and utilities sector, the tool can aid organizations in assessing the financial feasibility of smart contract-driven energy trading and grid management. Users can model the costs and potential revenue from peer-to-peer energy trading, demand response programs, and grid optimization.

These potential use cases illustrate the tool's potential flexibility across different sectors given a relevance of modeling smart contract-based costs in business processes. In various industries, assessing the financial implications of blockchain and smart contract adoption will increasingly become an important factor in making informed and cost-effective business decisions.

6.5. Drawbacks

While the tool we have described can potentially offer valuable insights and analytical capabilities, its positioning as a generic simulation tool within the broad area of blockchain oriented business models means it is necessarily limited in a number of areas. These limitations encompass both technical constraints and inherent challenges in modeling dynamic blockchain ecosystems.

1. **Price-User Growth Association:** In some cases, there may exist an association between the price of blockchain assets and user growth. Higher asset prices can generate significant media attention and hype, attracting more users and investors. The tool assumes a user growth function that operates independently of asset prices. Therefore, it may not fully reflect the potential interplay between user growth and price dynamics.

2. **Blockchain-Specific Focus:** The simulator is designed to model business models specific to Ethereum-type blockchains. It may not be directly applicable to other blockchain platforms with distinct technological features and dynamics. As the blockchain landscape rapidly evolves, the tool's applicability may be constrained by its specificity to certain blockchain architectures.

3. **Lack of Black Swan Event Modeling:** Black swan events, characterized by their rarity and extreme impact, are challenging to predict and model accurately. The simulator does not explicitly account for such events, which can have a profound impact on blockchain-based business models. Users should be aware that the tool's projections may not fully incorporate the potential effects of unforeseen disruptive events.

4. **Market Dynamics and Technological Evolution:** The blockchain and cryptocurrency markets are highly dynamic and subject to rapid technological advancements. The tool's static modeling approach may not adequately capture the evolving landscape, including changes in blockchain consensus mechanisms, regulatory developments, and emerging technologies. Particularly the emergence of cheaper 'layer 2' networks, which operate on top of existing chains such as Ethereum, and offer significantly reduced gas prices, facilitated through the use of technologies such as zero-knowledge proof based transaction systems, need to be accounted for. Consequently, it may not fully anticipate market shifts and their implications for blockchain-based businesses.

5. **General Assumptions:** The tool is built on a set of general assumptions and simplifications about user behavior, contract complexity, and other factors. These assumptions may not align perfectly with the intricacies of specific business models or real-world scenarios, necessitating careful consideration of individual use cases.

While our business model simulator tool can offer insights into blockchain-based business scenarios, it is, by necessity built around simplifications. The drawbacks highlighted indicate the use of the tool as a complementary resource rather than a definitive predictor of outcomes, especially in the context of rapidly evolving and highly dynamic blockchain ecosystems.

6.6. CDIP

In the context of the Civic Data Identity Partnership (CDIP), we utilized the business model simulator tool to as a versatile means of evaluating three distinct approaches to blockchain hosting: public blockchain, hybrid permissioned blockchain, and private blockchain. The analysis provided valuable insights that have implications for the future utilization of the CDIP platform.

6.6.1. Leveraging the simulator tool for informed decision-making

The use of the business model simulator tool enabled us to gain insights into the financial implications and feasibility of each blockchain hosting approach. These insights are vital for making informed decisions regarding the CDIP platform's future direction and potential applications within civic data and identity management.

6.6.2. Private Blockchain hosting: Balancing privacy and necessity

One notable insight emerged from the private blockchain hosting model. While offering a high level of data security and privacy, questions arose regarding the necessity of such privacy measures for all CDIP use cases. Whilst this emerged as potentially the most viable business case, its use might not align with the cooperative's data-sharing objectives. This insight prompts consideration of a more nuanced approach to data privacy within the CDIP ecosystem.

6.6.3. Hybrid permissioned model: flexibility and governance

The hybrid permissioned blockchain model proved flexible, accommodating various levels of access control. Insights from this model highlight the potential for CDIP to offer a range of access control mechanisms, allowing participants to choose between public and permissioned components based on their specific needs. This flexibility can promote broader adoption of the CDIP platform across diverse use cases. Costs associated with this approach derive mainly from the publically facing aspects of the blockchain infrastructure.

6.6.4. Public Blockchain: wider adoption and network effects

The public blockchain hosting approach demonstrated the benefits of openness and transparency. Insights from this model suggest that public blockchain networks can facilitate network effects and wider participation within the CDIP ecosystem. Leveraging public blockchains can potentially enhance CDIP's reach, particularly for use cases where trust and transparency are essential. This scenario however emerged as the least viable in terms of costing over a ten year horizon.

6.6.5. Future applications of CDIP

The results from the business model simulations provide insights into potential future applications of CDIP. The findings support the evaluation of different hosting approaches, allowing CDIP to align its infrastructure with the specific requirements of various data-sharing initiatives. Depending on the context, CDIP can be configured for private patient data exchanges or open civic data collaborations, ensuring adaptability to stakeholder needs.

Additionally, the ability to model and simulate different hosting scenarios establishes a structured framework for decision-making. As the platform develops and new use cases arise, these insights can inform the design of data-sharing strategies that balance cost, security, and operational efficiency.

7. Conclusion

Through a series of modeling workshops, we constructed a set of three fundamental business models that could be used to host and run the technical architecture as a viable ongoing concern. We ran a series of simulations in order to compute the yearly profit and loss of these models given ranges of potential values for their parameters. Having done this we analyzed the results in order to look at which of these models would be viable from a business perspective. Our broad conclusions are as follows:

- The most viable business strategy under our assumptions was option of hosting a permissioned blockchain and charging for access to this from data consumers
- Smart contract execution cost impact most highly on profit/loss in the context of utilising a public blockchain

- Assumptions regarding redeemed costs from hosting and other paid third-party services impacted most in the context of a self-hosted permission blockchain, though this was potentially offset through charging other parties for the use of the provided services
- The third-party permissioned blockchain model was impacted most by the impact of payments to third parties offset by a lack of income stream from charging of data consumers

Having run detailed simulations of the three models over what we determined was a realistic assumption as to the viable ranges of the various parameters of the models, the only currently viable model that could be operated as an ongoing concern and would become self-funding within a ten-year time horizon was the option of hosting and charging for access to this system. There is however room for further analysis, particularly around the analysis of the public blockchain option, where there exist other options for the underlying blockchain technology that is used and potential variation in our assumptions as to the costs associated with deploying and running the smart contracts that underpin the technical solution.

The purpose of the simulator we wrote was to perform a basic ‘parameter sweep’ over the input variables that we had specified for each of the business models that we were simulating. The results of this were values over time that allowed us to extract ranges of parameters that produced a positive outcome in terms of the relative profitability of the associated model. The simulator model could be further expanded to analyze the most significant parameters affecting the results of the model. This would be useful from the perspective of analyzing what factors most impacted a given business model and in practical determination of how best to fine tune the workings of that model to produce a profitable outcome.

Over the course of the workshops, we considered a range of possible business models and analyzed the various complexities and interrelations of the factors affecting their profitability. Our conclusion was that the main factor affecting the business models, and the core distinguisher between them, was the type of blockchain model that was used to implement the underlying technological solution. This led us to produce three core models which we ran the simulator over. This was beneficial in terms of the relative simplicity of the models we had to create and, given time constraints within the project, gave us a manageable quantity of output to analyze. With capacity to carry out further analysis we would consider a wider range of models, possibly with other core differentiators outside of the type of underlying blockchain. It would also be possible to introduce additional complexities into the models regarding the interrelation of variables within the models, and to model the variation of input parameters over time in more complex ways than the simplified model that we have included in the simulator.

7.1. Future research opportunities

We have developed a business model simulator to evaluate blockchain-based data-sharing platforms, with a specific focus on the CDIP use case. The simulator provides a framework for assessing financial viability, governance structures, and operational dynamics under different blockchain architectures. While the current implementation offers insights into key cost drivers and scalability considerations, further research could extend the platform to support additional analytical capabilities and broader applications.

7.1.1. Refinement of cost and revenue models

Future research could refine the financial modeling within the simulator by incorporating dynamic pricing mechanisms, variable transaction costs, and context-specific revenue models. This would allow for a more granular assessment of profitability under varying economic and operational conditions.

7.1.2. Integration of empirical data

There is potential to explore the integration of real-world empirical data into the simulation framework. This would enable validation against observed trends in blockchain-based data exchanges, improving the accuracy of modeled scenarios and informing practical deployment strategies.

7.1.3. Exploration of alternative governance structures

The simulator currently models governance as a predefined structure with periodic decision-making processes. Future work could investigate alternative governance mechanisms, such as decentralized autonomous organizations, dynamic governance policies, or stakeholder-driven voting systems, to evaluate their long-term sustainability and operational efficiency.

7.1.4. Scalability and performance analysis

Future work could extend the simulator to model scalability constraints and computational performance trade-offs across different blockchain architectures. This would allow a more detailed exploration of how blockchain networks handle increased transaction volumes and data storage demands over time.

7.1.5. Broader application to other domains

Although the simulator was developed for the CDIP use case, the underlying framework could be extended to model blockchain applications in other sectors. Further research could investigate adaptations for supply chain management, healthcare data interoperability, or digital identity verification, assessing the generalizability of the simulation framework.

7.1.6. Interoperability between blockchain networks

The current model evaluates business models within the context of a single blockchain architecture. Future research could explore interoperability between multiple blockchain networks, assessing how cross-chain interactions influence economic feasibility, security considerations, and transaction complexity.

7.1.7. User behavior modeling and adoption patterns

Incorporating behavioral modeling into the simulator could improve the understanding of user adoption dynamics. Future work could explore how factors such as trust, incentives, and regulatory frameworks influence participation rates in blockchain-based data-sharing platforms.

7.1.8. Regulatory and compliance considerations

As blockchain adoption continues to evolve, regulatory landscapes will influence its viability. Future research could incorporate compliance costs, jurisdictional constraints, and evolving data privacy laws into the simulation model to assess their impact on business model sustainability.

By addressing these areas, future work in this area could enhance the applicability of such a simulator to provide deeper insights into the viability and scalability of blockchain-enabled data-sharing businesses and ecosystems.

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Davies: Investigation, Funding acquisition, Conceptualization. **Sarah Devaney:** Investigation, Funding acquisition, Conceptualization. **Mike Harding:** Investigation, Conceptualization. **Søren Holm:** Investigation, Funding acquisition, Conceptualization. **Victoria Neumann:** Investigation, Funding acquisition, Conceptualization. **John Ainsworth:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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