A paradigm shift to Railway Asset Tokenization for optimized CAPEX and OPEX funding strategies

by

Alaa eldin HELOU

MANUSCRIPT-BASED THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE IN PARTIAL FULFILLMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY Ph.D.

MONTREAL, 04 MARCH 2026

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

BOARD OF EXAMINERS

THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS

Dr. Gabriel J. Assaf, Thesis Supervisor
Department of Construction Engineering, École de technologie supérieure

Dr. Maarouf Saad, President of the Board of Examiners
Department of Electrical Engineering, École de technologie supérieure

Dr. Constantine J. Katsanis, Member of the jury
Department of Construction Engineering, École de technologie supérieure

Dr. Mohamad Kassab, External Evaluator
Boston University

THIS THESIS WAS PRENSENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND PUBLIC

13 FEBRUARY 2026

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

FOREWORD

“Innovation is the ability to see change as an opportunity - not a threat..” - Steve Jobs

The origins of this thesis trace back to two defining experiences that reshaped how I understood infrastructure, value, and the systems that bind them.

The first emerged from years of observing how public infrastructure projects particularly rail systems struggle not because of a lack of vision, but because of the persistent constraints of funding. I witnessed how capital-intensive assets, essential to the functioning of cities and regions, were often delayed, downsized, or abandoned altogether due to rigid financing structures. The paradox was striking: societies depend on infrastructure to grow, yet the mechanisms to fund that infrastructure remain slow, opaque, and exclusionary. This disconnect led me to question why, in an era of unprecedented technological innovation, our financial models for public assets remained largely unchanged.

The second experience unfolded as I began exploring blockchain technology beyond the hype. What initially seemed like a speculative digital frontier revealed itself to be a profound rethinking of ownership, governance, and trust. The idea that real-world assets such as bridges, railways, energy systems could be represented digitally, fractionally owned, and transparently governed challenged my assumptions about how infrastructure could be financed. At the same time, I saw how misconceptions, regulatory uncertainty, and the absence of real-world use cases prevented meaningful progress. This tension between potential and hesitation became a central motivation for my research.

As I navigated these two worlds of the entrenched realities of infrastructure finance and the emerging possibilities of distributed ledger technologies, I realized that the gap between them was not merely technical. It was conceptual. It required reimagining how value is created, shared, and sustained across the lifespan of an asset. It required acknowledging that infrastructure is not just concrete and steel, but also trust, governance, and long-term stewardship.

This thesis is an attempt to bridge that gap. It explores how asset tokenization can complement, rather than replace, conventional financing models as well as how it can democratize participation without compromising regulatory integrity and how it can introduce transparency and liquidity into a domain historically defined by opacity and rigidity. Through empirical analysis, methodological development, and a case study of the Réseau express métropolitain (REM), this work aims to offer a grounded, practical contribution to an emerging field still searching for its first large-scale success story.

Ultimately, the intent of this thesis is not to claim that tokenization is a universal solution, but to provide a structured, evidence-based foundation for understanding when, where, and how it can meaningfully enhance the funding of public infrastructure. My hope is that it serves as a starting point for policymakers, engineers, financiers, and technologists who are ready to rethink the future of infrastructure investment.

Alaa eldin Helou, ing.
Montréal, 2026

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude to my supervisor, Dr. Gabriel J. Assaf, for his unwavering support, guidance, and patience throughout the development of this thesis. Your ability to challenge my thinking while giving me the freedom to explore my own ideas has been invaluable. Thank you for believing in the importance of this research and for providing the intellectual space necessary for it to take shape. I am truly fortunate to have learned from you and to have shared this journey under your mentorship.

I would also like to thank Dr. Maarouf Saad, Dr. Constantine J. Katsanis, and Dr. Mohamad Kassab for serving on my examination committee. Your thoughtful feedback, probing questions, and constructive insights have significantly strengthened the quality and direction of this dissertation. I am grateful for the time and expertise you dedicated to this work.

My sincere thanks go to all the industry professionals, engineers, financial experts, and blockchain practitioners who generously shared their time and perspectives with me. Your openness in discussing the realities of infrastructure financing, digital transformation, and the challenges of implementing tokenization provided the foundation for much of this research. Without your contributions, this thesis would not have been possible.

I would like to acknowledge the organizations and networks that helped circulate my survey and interview requests, enabling me to reach a diverse group of experts across the infrastructure and blockchain sectors. Your support played a crucial role in gathering the empirical data needed for this study.

To my colleagues and peers who engaged with me in countless discussions about infrastructure finance, blockchain, and public–private partnerships thank you for your encouragement and for entertaining my enthusiasm for a topic that often-required long explanations and even longer debates. Your curiosity and support helped sustain my motivation.

I would also like to extend my heartfelt gratitude to my family especially my wife for their unwavering support, patience, and encouragement throughout this journey. Your belief in me has been a source of strength during the most challenging moments. I am equally grateful to the companies that supported me along the way, including WSP and AECOM, whose professional environments and opportunities contributed meaningfully to my growth and to the completion of this work.

Many people have contributed to the thinking, writing, and completion of this thesis. I am profoundly grateful for all of your help. Any errors or omissions that remain are entirely my own.

Un changement de paradigme : la tokenisation des actifs ferroviaires pour optimiser les stratégies de financement CAPEX et OPEX

Alaa eldin HELOU

RÉSUMÉ

Cette thèse explore le potentiel de la tokenisation des actifs comme solution innovante pour optimiser le financement des projets d'infrastructure publique, en particulier dans le secteur ferroviaire. Face à la difficulté persistante de mobiliser des fonds suffisants et stables pour les grands projets d'infrastructure, la tokenisation, rendue possible par la technologie blockchain, permet de fractionner la propriété d'actifs physiques en jetons numériques. Cette approche vise à démocratiser l'accès à l'investissement, à accroître la liquidité et à attirer une base d'investisseurs plus diversifiée, y compris les investisseurs institutionnels et particuliers.

L'étude s'appuie sur une méthodologie mixte, combinant une revue systématique de la littérature, des analyses quantitatives (modélisation DCF) et qualitatives (entretiens avec des experts du secteur). Elle propose un cadre méthodologique pour intégrer la tokenisation dans les modèles de financement conventionnels, en tenant compte des défis réglementaires, des risques de gouvernance et des attentes des parties prenantes. Un accent particulier est mis sur l'utilisation d'accords de type SAFT (Simple Agreement for Future Tokens) et d'un compte séquestre (escrow) pour garantir la transparence et la sécurité des investissements, tout en protégeant les intérêts des investisseurs secondaires.

La thèse valide ce cadre à travers une étude de cas appliquée au projet du Réseau express métropolitain (REM) à Montréal. Les résultats montrent que la tokenisation, qu'elle soit basée sur l'équité ou sur le partage des revenus, peut améliorer la viabilité financière des projets d'infrastructure, réduire le coût du capital et élargir la base d'investisseurs. Le modèle basé sur le partage des revenus s'avère particulièrement attractif, offrant une meilleure performance ajustée au risque.

Cependant, la mise en œuvre de la tokenisation dans les infrastructures publiques reste confrontée à des défis majeurs : incertitude réglementaire, complexité opérationnelle, gestion de la gouvernance et cybersécurité. La thèse recommande une collaboration accrue entre les régulateurs, les développeurs de projets et les investisseurs pour adapter les cadres réglementaires et favoriser l'expérimentation à travers des projets pilotes.

En conclusion, la tokenisation des actifs ferroviaires représente une opportunité prometteuse pour compléter les modèles de financement traditionnels, sans les remplacer. Elle offre un levier pour améliorer l'efficacité, la transparence et l'accessibilité du financement des infrastructures publiques, à condition de surmonter les obstacles réglementaires et technologiques et de garantir la protection des investisseurs.

Mots-clés : tokenisation d'actifs, blockchain, financement d'infrastructures, partenariat public-privé, ferroviaire, gouvernance, innovation financière

A Paradigm Shift To Railway Asset Tokenization For Optimized CAPEX And OPEX Funding Strategies

Alaa eldin HELOU

ABSTRACT

Large-scale infrastructure projects are central to economic development. However, a key difficulty in these projects is not simply obtaining funds but ensuring a consistent supply of liquidity to repay investors throughout the asset's lifespan. Traditional financing options, while widely available, can sometimes struggle to effectively distribute long-term credit and liquidity risks among those involved. This can encourage investors to favor shorter-term, more easily sold assets, which can limit the involvement of private companies.

This thesis investigates the potential of asset tokenization to improve funding for public infrastructure projects. The research addresses a need for innovative approaches to capital investment in large-scale infrastructure developments. First, the feasibility of asset tokenization within existing financing models was assessed, examining stakeholder views, the role of different funding mechanisms, and potential barriers to adoption. Second, a methodology was developed to improve conventional capital investment strategies using asset tokenization. Finally, the methodology was validated by evaluating the financial viability of tokenization in a specific infrastructure project, namely Réseau express métropolitain (REM), comparing different tokenization models and gathering expert perspectives. The findings aim to provide practical guidance for policymakers and infrastructure developers considering asset tokenization as a means of securing funding and enhancing project outcomes.

Keywords: asset tokenization, blockchain, infrastructure project, public-private partnership

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS AND ACRONYMS

AML	Anti-Money Laundering
ARTM	Autorité Régionale de Transport Métropolitain
BIM	Building Information Modelling
CDBC	Central Bank Digital Currency
CDPQ	Infra Canadian Infrastructure Investment Corporation
CEO	Chief Executive Officer
CIB	Canadian Investment Bank
DCF	Discounted Cash Flow
DeFi	Decentralized Finance
DLT	Distributed Ledger Technology
EMDE	Emerging Markets and Developing Economies
ERBD	European Bank for Reconstruction and Development
ESG	Environmental, Social, Governance
FCA	UK's Financial Conduct Authority
FinTech	Financial Technology
GDP	Gross Domestic Product
ICO	Initial Coin Offering
IDO	Initial DeFi Offering
IEO	Initial Exchange Offering
IoT	Internet of Things
IRR	Internal Rate of Return

KYC	Know Your Customer
NFTs	Non-Fungible Tokens
NPV	Net Present Value
O&M	Operation and Maintenance
OECD	Organisation for Economic Co-operation and Development
P2P	Peer-to-Peer
PoS	Proof of Stake
PoW	Proof of work
PPP	Public Private Partnerships
RAB	Regulatory Asset Base
REM	Réseau Express Métropolitain
RWA	Real-World Asset
SAFT	Simple Agreement for Future Tokens
SDGs	Sustainable Development Goals
SEC US	Securities and Exchange Commission
SIC	Short Interval Controls
SPE	Special Purpose Entity
SPT	Speed per Transaction
SPV	Special Purpose Vehicle
STOs	Security Token Offerings
SWIFT	Society for Worldwide Interbank Financial Telecommunication
TGE	Token Generation Event
TPS	Transactions per Second

UT	Ultrasonic Testing
WACC	Weighted Average Cost of Capital
XR	Extended Reality
ZKP	Zero-Knowledge Proof

INTRODUCTION

0.1 Context

Trillions of dollars' worth of public infrastructure is currently owned by government and private stakeholders. Capital investments in public infrastructure do not meet the rise in demand hence widening the funding gap and resulting in poor asset condition. The main issues faced today is the lack of liquidity and funding mechanisms that are cost effective and generating additional revenue for both the owner and the funder. An innovative way of funding has been developed as of late. The emergence of Bitcoin and other cryptocurrencies introduced an array of use cases adopting distributed ledger technology leading to Asset Tokenization. Infrastructure assets are illiquid or physical assets that are funded and maintained by local stakeholders. The limited key players funding or maintaining the assets allows for a limited capital investment or maintenance fund. The lack of liquidity will therefore either prompt "least cost/least risk" instead of "most efficient/desirable" capital or O&M choices or halt the pursuit of tendering infrastructure projects. Asset tokenization democratizes ownership or revenue sharing of infrastructure, thereby attracting various financing stakeholders including retail investors, and generating liquidity in a fair, transparent, and secure manner. Several research papers have addressed the concept of asset tokenization of infrastructure projects however, as of this writing, no use case currently exists besides visions and conceptualizations. This research will address the main issues and limitations of conventional financing and funding strategies of public infrastructure. Nevertheless, the focus of this research is to develop a methodology to fund public infrastructure capital projects through asset tokenization.

0.2 Background and Rationale

Recent developments in financial technology have brought blockchain and asset tokenization to the forefront. These technologies are seen as ways to improve openness, make investment more accessible, and increase the ease of buying and selling of infrastructure assets, which are often difficult to trade. Asset tokenization allows for the division of ownership or debt related to a project into smaller parts. This can potentially allow a wider range of investors to participate and make trading easier, without changing how the project is initially funded. Blockchain technology can also be used to create smart contracts. These contracts can automatically and securely manage payments of interest, which can reduce administrative costs and speed up the process. Furthermore, systems that can be programmed to manage contracts and investor rights offer the possibility of automating some aspects of legal agreements.

Studies have suggested that asset tokenization could lead to a future of more open investing. It may lower the obstacles for new investors, improve liquidity through secondary markets, and allow for the use of programmable governance frameworks. Initial research supports the idea that tokenized infrastructure finance can make it easier for projects to gain funding. However, these developments also present challenges, such as ensuring compliance with regulations and educating investors. These changes suggest a move towards more inclusive and open systems for investing in infrastructure.

The potential benefits of using tokenization are recognised, but its application within existing project finance frameworks remains relatively unstudied. There is a lack of clarity concerning how tokenised claims on infrastructure assets relate to conventional debt and equity structures. This uncertainty extends to the effects on governance procedures and how risk is managed and assets are handled. Asset tokenization allows for the possibility of shared ownership, but infrastructure projects require strong governance to manage complicated risks. Furthermore, infrastructure projects progress through different stages, each with its own level of risk and potential return. Initially, investors seeking higher returns and willing to accept greater risk are often involved. Later, more conservative investors, focused on long-term stability, take over. Tokenization strategies need to be adaptable to accommodate these shifts in investor types and strategies for refinancing.

The considerations above show that it is important to contextualize tokenization within project finance and the realities of infrastructure funding. This is why the present work aims to clarify both the benefits and the drawbacks of using blockchain technology to meet infrastructure investment needs. This is addressed in Chapter 2, which investigates the views of industry stakeholders regarding the integration of tokenization and blockchain-based smart contracts with project finance structures.

At the same time, analysis of asset tokenization projects frequently reveals a staged approach to investor participation. Initially, primary investors are given preference, with secondary investors only able to access the asset after liquidity is available on decentralized or centralized exchanges. This sequence can create imbalances, potentially putting secondary investors at a disadvantage and restricting broader market involvement. Fairer methods of distribution could help build trust and improve the long-term success of these projects. A common concern among secondary investors is the size of holdings already possessed by primary investors. This raises questions about the stated aim of asset tokenization, namely, to provide smaller investors with opportunities for fractional ownership. Some perceive this as a way for primary investors to guarantee a profitable exit, potentially at the expense of those investing later. Consequently, a key challenge in the tokenization of real-world assets is ensuring that the rights of both primary and secondary investors are equal.

A potential solution to this issue involves the use of a Simple Agreement for Future Tokens (SAFT). Initial Coin Offerings (ICOs) have often been criticized for potentially exploiting investors. SAFTs offer a different approach, avoiding the immediate distribution of tokens. Instead, early investors contribute funds to a Special Purpose Vehicle (SPV) and receive SAFTs. These agreements guarantee the investors will receive tokens at a later point, once the project is underway. This solution is further elaborated upon in Chapter 3 of the present thesis.

While interest in tokenised infrastructure finance is increasing, there has been limited systematic investigation into its economic effects on large infrastructure projects such as Réseau Express Métropolitain (REM). Previous research has largely concentrated on the regulatory and technical elements of tokenisation rather than its financial consequences. This study attempts to address this gap by using a discounted cash flow method to examine various tokenisation approaches for the REM project, which is done in Chapter 4.

0.3 Research Objectives

The objectives of the thesis are as follows:

Objective 1: Assessing the opportunity of Asset Tokenization to fund public infrastructure capital projects using conventional financing and funding models.

Within Objective 1 are three sub-objectives:

- *Sub-objective 1.1*: To validate the Layered Model Framework by assessing stakeholder receptivity and empirical support for the proposed layered model of asset tokenization in public infrastructure projects;
- *Sub-objective 1.2*: To explore the role of financing mechanisms by examining the comparative roles of traditional (e.g., bank loans, bonds) and blockchain-enabled financing approaches in integrating a layered model to enhance infrastructure project viability;
- *Sub-objective 1.3*: To examine implementation barriers and facilitators by identifying practical, institutional, and regulatory constraints and enablers influencing adoption of tokenized financing structures for large-scale infrastructure investments.

The first publication assesses the opportunity of the application of asset tokenization to fund public infrastructure capital projects using conventional financing and funding models. It addresses ESG concerns and the legal, regulatory, and organisational challenges. Infrastructure projects evolve through distinct phases with varying risk-return profiles. High-risk, high-return equity investors predominate during early stages, while long-term, risk-averse investors replace them during stable operational phases. Tokenization models must be flexible to accommodate these changing investor profiles and refinance strategies over the project lifecycle. By grounding tokenization explicitly in the context of project finance and the realities of infrastructure funding, this work seeks to clarify the potential and the limitations of blockchain-enabled innovations in addressing infrastructure investment needs. Furthermore, by focusing on issues of risk distribution, investor governance, transparency, and implementation, the study contributes both to infrastructure finance scholarship and to the developing literature on digital asset markets and decentralized finance.

Objective 2: Developing a methodology to optimize conventional capital investment strategies of public infrastructure projects with Asset Tokenization.

Within Objective 2 are three sub-objectives:

- *Sub-objective 2.1*: To infer a general model of asset tokenization;
- *Sub-objective 2.2*: To identify potentially overlooked directions of research that may be relevant to the problem;
- *Sub-objective 2.3*: To develop a framework of asset tokenization within public infrastructure projects.

The second publication develops a framework of asset tokenisation in public infrastructure that may appeal to secondary investors. The framework is designed to include features to resolve common issues that have previously restricted their involvement in infrastructure tokenization. In particular, the use of an escrow account ensures that the funds contributed by the initial investors may remain in this account until the project achieves specific, agreed-upon goals. A blockchain oracle then reports the account balance to smart contracts on the blockchain. This allows secondary investors to independently check that the number of tokens available is fully supported by the funds held in the escrow account. This level of transparency helps to build trust, as it reduces the possibility of tokens being issued without sufficient financial backing, a problem that has previously damaged confidence in token sales.

Objective 3: Validating the methodology to optimize conventional capital investment strategies of public infrastructure projects with asset tokenization by assessing whether tokenisation can offer a more efficient and attractive funding model for large-scale infrastructure developments.

Within Objective 3 are three sub-objectives:

- *Sub-objective 3.1*: To assess the financial viability of asset tokenisation in the REM project;
- *Sub-objective 3.2*: To compare equity-based tokenisation and revenue-based tokenisation models for the REM;
- *Sub-objective 3.3*: To evaluate perceptions of industry experts with regards to tokenisation in large infrastructure projects.

The third publication explores whether asset tokenisation can enhance financing possibilities for this large-scale infrastructure development. The research investigates whether tokenisation could provide a more effective and appealing funding model for similar projects. A discounted cash flow analysis is used to compare conventional financing methods with two different tokenisation scenarios. To complement this quantitative approach, the study also includes data from interviews with experts in the field. This qualitative data offers valuable perspectives on the practical considerations and potential difficulties involved in using asset tokenisation within the rail sector.

0.4 Thesis Overview

This thesis is organized into five chapters.

Chapter 1 is a literature review summarizing and identifying gaps in relevant literature on three research streams, namely (a) asset tokenisation, (b) financing instruments of public infrastructure, and (c) and railway asset management. The review provides a background to the problem, allowing for assessing problems with existing solutions and contextualizing proposed frameworks and analyses.

Chapter 2 aims to advance the literature by empirically validating a stakeholder-centric framework that situates asset tokenization within the layered financial and legal structures of large-scale infrastructure project delivery. The study draws on a survey of industry participants including institutional investors, regulators, sponsors, and blockchain service providers to evaluate the feasibility and practical challenges of this approach. Overall, the results suggest that experts in the field consider tokenized financing to have considerable benefits while also being possible to be implemented in practice. Chapter 2 addresses Objective 1, including Sub-Objective 1.1, Sub-Objective 1.2, and Sub-Objective 1.3.

Chapter 3 proposes a framework for solving the problem of linking token and RWA values. A framework is examined where an escrow account is introduced to hold the pool of invested funds, while a blockchain oracle is used to assess the information on the amount of funds in the escrow account. It is argued that the potential for primary investors to immediately sell their tokens after issuance may undermine the confidence of secondary investors, and the proposed framework may help alleviate this. Chapter 3 addresses Objective 2, including Sub-Objective 2.1, Sub-Objective 2.2, and Sub-Objective 2.3.

Chapter 4 investigates the potential of asset tokenisation to improve financing options within the rail industry. Specifically, it examines the Réseau express métropolitain (REM) project in Montreal, Canada, as a case study. The results suggest that using tokenisation could be a useful option for funding large infrastructure projects over traditional methods. While tokenisation does mean existing shareholders will have a smaller share, the reduced cost of raising funds can compensate for this. Chapter 4 addresses Objective 3, including Sub-Objective 3.1, Sub-Objective 3.2, and Sub-Objective 3.3.

Chapter 5 concludes this thesis with an overview of the work and a summary of recommendations based on the findings. These recommendations may help incorporate new financing methods based on the use of digital assets and deliver successful infrastructure projects.

CHAPTER 1

LITERATURE REVIEW

The need for significant investment in public infrastructure is a global challenge. Traditional financing models, while established, often struggle to meet these demands, encountering limitations in access to capital and perceived risk profiles. This review focuses on three distinct but interconnected research streams. First, the literature on asset tokenisation is examined. This explores the process of representing ownership rights to assets as digital tokens on a blockchain. Second, the existing literature on financing instruments for public infrastructure is considered. This includes a review of conventional approaches and emerging models. Finally, the body of work relating to railway asset management is reviewed, which is chosen as a representative example of complex, long-lived infrastructure requiring ongoing investment.

The structure of this review is designed to build a logical argument. The review begins by outlining the core concepts within asset tokenisation, establishing a foundation for understanding its potential application. Following this, the chapter surveys the established methods for financing public infrastructure projects. The final section then brings these two areas together, considering the opportunities and challenges of integrating asset tokenisation into existing infrastructure funding strategies. This approach allows for identifying gaps in current understanding and justifying the development of a methodology, as outlined in the study's objectives, to optimise conventional capital investment strategies through the application of asset tokenisation.

1.1 Asset Tokenization

1.1.1 An Introduction to Distributed Ledger Technology DLT

To shed light on the implementation of distributed ledger technology DLT, it is important to highlight the history of money and banking. Money has always been a financial instrument to act as a medium of exchange, a unit of account and a store of value. There have been numerous representations of money throughout history where Gold is a prime example. This element was chosen as a financial technology for millenniums and has been established as an international monetary system as in the Bretton Woods system in 1944 which ended in 1971 by President Nixon. This mineral was chosen for its profound characteristics as it was scarce, portable, divisible, verifiable, and durable. Its durability has been portrayed in its resilience to other substances, temperatures and time, its portability proved its efficient transportation, its divisibility has no effect on its value, its verifiability has proven that Gold cannot be imitated and lastly its scarcity is a hedge against inflation. Since the end of the Bretton Woods system, Currency has not been pegged to Gold or other tangible assets but by the supply and demand and the confidence of its holders in their state's ability to defend its economical interests.

Throughout history, civilisations exchanged value through debts and credits (Demirors, 2020). Since the introduction of Double entry accounting in the 15^{th} century, a system of bookkeeping to maintain financial information, Banks have emerged. Citizens have since entrusted Banks, centralized institutions, to manage the financial system. Nowadays, money has been represented as information in a centralized database where central banks have full control on the supply of money to the economy.

The last century has witnessed the information revolution where it enabled the advent of big data that shaped the way how information was stored and shared at the speed of light thanks to the advances of the internet and hardware. The latter paved the way to new business models where information has economic value that could be traded with other assets. While the information revolution impacted society and the economy, we still lack an efficient system to exchange value. The current financial system is centralized with each bank its own centralized database often referred to in accounting as a ledger. The main challenge that financial technology faces today in creating money as information is the risk of double spending. Double spending is a problem that arises when transacting digital currency that involves the same tender is being spent multiple times (CFI, n.d.). For this reason, if a bank does not have a direct relationship with the receiving bank, then a third central trusted party such as correspondent bank will act as a clear house between both financial institutions. The latter creates friction in the financial corridors with transactions fees and long settlement times. Moreover, the transactions are not actually transferring money, but the exchange of information occurs through a messaging system called SWIFT where payments are credited to recipients. The figure below portrays a payout journey in international Bank wires.

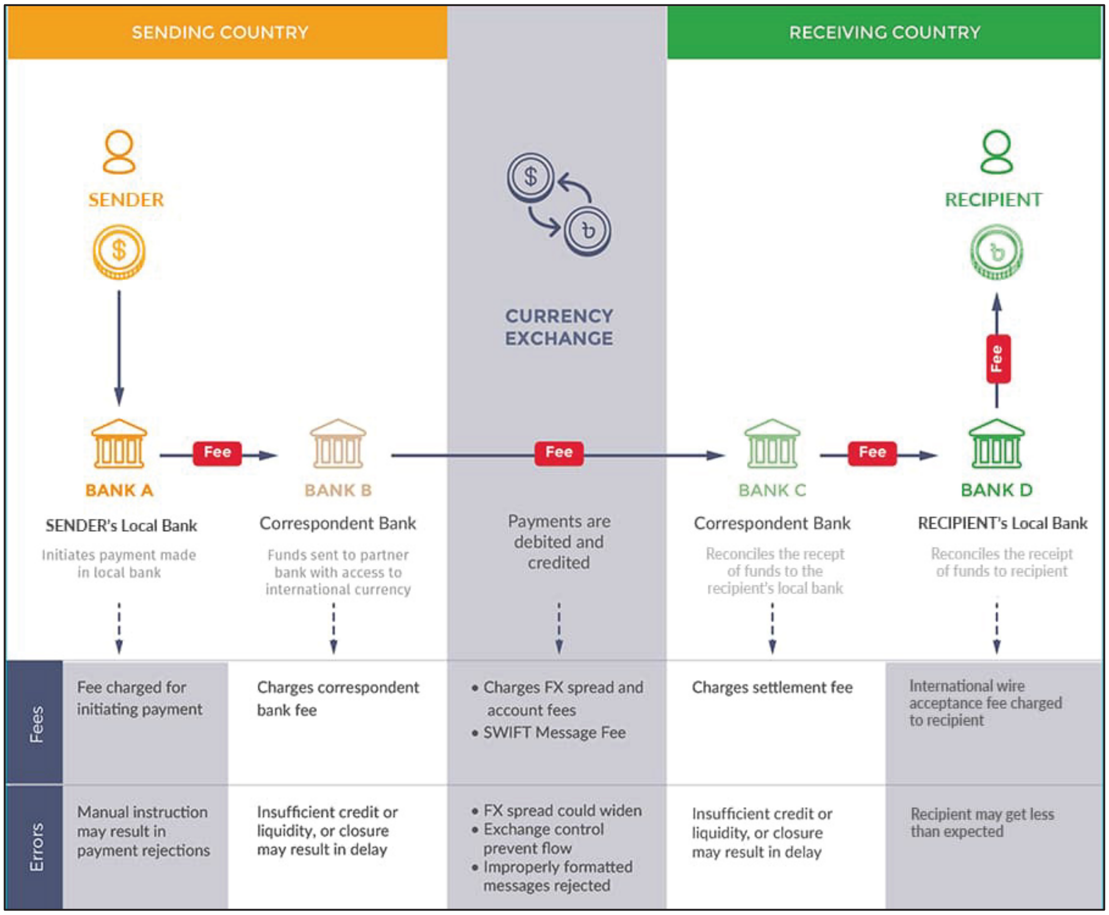

Figure 1.1 Payout Journey of international bank wires.
Taken from Panos (2020)

With the rise of the digital economy, Central banks have been piloting and researching the issuance of Central Bank Digital Currencies CDBCs. The implementation of CBDCs and DLT will revolutionise monetary and fiscal policies enabling automated and efficient payment corridors, taxation, welfare distribution amongst others. With the implementation of CBDCs and DLTs, all is traceable and is deemed to diminish criminal activity such as tax evasion, money laundering, terrorist activity and trafficking of illegal matters (Allen et al., 2020). At this time of writing, there are 65 central banks exploring CDBCs including 2 already launched and 18 currently piloting (CBDC Tracker, 2021).

When building a technological solution, there are three primary networks: centralized, distributed and decentralized. In a centralized system, data is owned, and resources are managed all by a single entity which makes it easy to maintain. The latter results in a single point of failure. In a distributed system, data is owned by a single entity, but the resources are distributed at multiple locations where the solution provider does not own the system such as a cloud computing service. In a decentralized system, ownership of data and resources are shared amongst all participants. Decentralized systems such as Blockchain provide a Peer-to-Peer P2P network architecture.

The advent of distributed ledger technology, also known as blockchain technology, made what was not potentially feasible a possibility. DLT uses cryptography which promotes data confidentiality and preserves it permanently from being manipulated. Data on a blockchain can only be added and cannot be deleted or edited. The sender encrypts the transaction with a public key and remains not readable in transit until it is decrypted by its recipient by his private key.

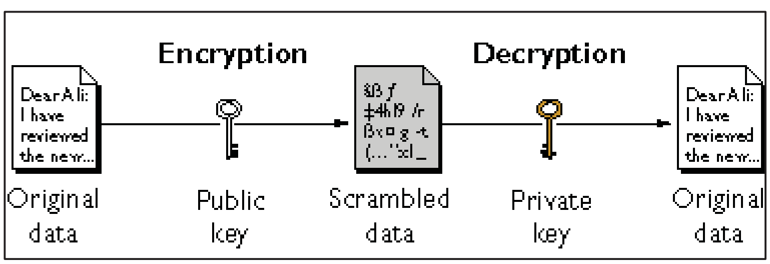

Figure 1.2 Public-Key Cryptography

Taken from IBM (n.d.)

DLTs are comprised of nodes that are linked together to form a network. Each node is a hardware such as a computer that is used to validate the transactions in the network and contains a global copy of the network's ledger which is immutable. All DLTs are designed to be decentralized as no central authority governs the network. For a transaction to be validated and stored in the ledger, it needs to be validated by all the nodes using a consensus mechanism to prevent fraudulent acts such as double spending.

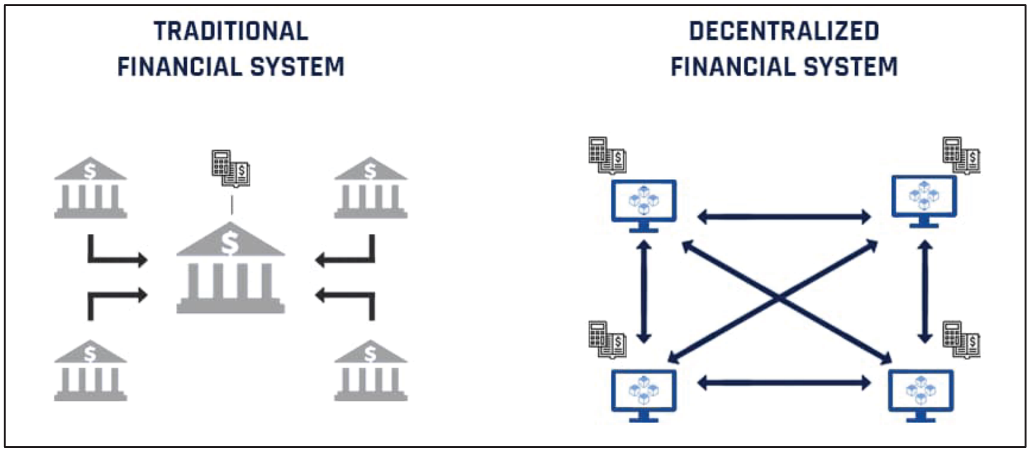

Figure 1.3 Comparison of Traditional and Decentralized Financial Systems
Taken from Stably (n.d.)

The consensus mechanism dictates the protocol implementation to validate transactions and store them in the ledger. There are different consensus mechanisms employed in a DLT network each with its distinct feature favoring at most two of the following characteristics: security, scalability, and decentralisation. To this time of writing, there has not been any consensus mechanism that satisfies all three characteristics (Buterin, 2021). Some examples of Blockchain consensus mechanisms are Proof of work (PoW) and Proof of Stake (PoS). However, there are other technologies that are blockless solutions where transactions are validated by peer nodes instead of being grouped together in blocks that are indexed using a *Merkle Tree* and validated by the entire network. The latter offers great performance and scalability but diminished level of security. It is important to understand the notions of consensus mechanisms when implementing a DLT in order to select/create the most appropriate ecosystem. For example, a proof of work consensus mechanism such as the one used in the Bitcoin network favours security and decentralisation over scalability. The proof of work consensus mechanism requires massive computing power which consumes as much energy per year as a medium-sized country such as Denmark resulting with high carbon emissions (Küfeoğlu, 2019). Scalability in a proof of work protocol such as the Bitcoin network is low with a 7 TPS (Transactions per second), a 60+ minutes SPT (Speed per transaction) and an average transaction fee of 15+$ (Stedas,2021). Bitcoin was the trend setter and created the attraction required for this space. However, it's consensus mechanism is antiquated and does not meet the ESG standards. There has been many projects that have been developed that are much more efficient and meet the ESG requirements. The figure below displays a comparison between Bitcoin and XRP, two cryptocurrencies.

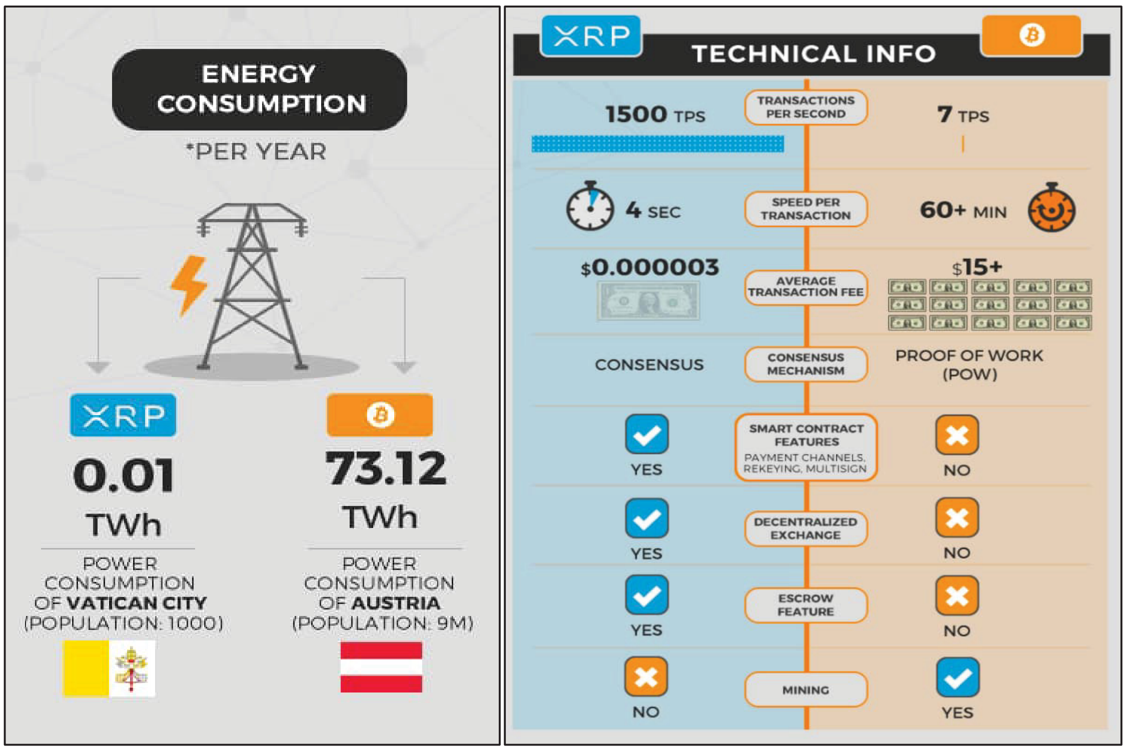

Figure 1.4 Comparison between the two cryptocurrencies Bitcoin and XRP
Taken from Stedas (2021)

In a DLT ecosystem, the monetary unit is defined by a token native to that network. The token is a decentralized, self governing and a programmable asset. Nevertheless, the token also shares the same characteristics of modern-day money as it is a medium of exchange, a store of value and a unit of account. In some protocols, participants are rewarded with the ecosystem's native currency for participating in the consensus. It is important to note that there are many types of tokens such as utility tokens, security tokens and Stablecoins etc. Stablecoins are tokens pegged to a legal tender such as the U.S. dollar. Non-Fungible Tokens NFTs are distinguishable where each token is one of a kind with its unique identifier. NFTs allow the transfer of ownership of digital and physical assets in the digital world such as artwork, collectibles, tickets, properties etc.

A DLT protocol will define the number of tokens to be issued and whether the total supply is fixed or such as in the case of protocols with mining activities a fixed issuance of tokens will be supplied in the network. The latter makes tokens or digital assets to be perceived as scarce and valuable just as physical assets such as Gold. There are many tokens today that are accepted for payments of goods and services such as Bitcoin, Ether etc. Although the total market capitalization of digital assets at the time of this writing is roughly $1.67T whilst the total market capitalization of global stocks is roughly $100T, the digital assets market is still immature hence volatile. However, digital assets would serve as a store of value once wide adoption occurs. The figure below shows the evolution of the Web where the Web 1.0 is the readable version with static data, the Web 2.0 is the read-write version with interactive data and the Web 3.0 is the next internet revolution that is the read-write-trust version of the web that runs on DLT and enables the advent of the metaverse. The World Economic Forum reports that 10% of global GDP will flow through blockchain by 2025 (Herweijer et al. 2018). Goldman Sachs states that the Metaverse is a $8 trillion opportunity (Helms, 2022). Blockchain will do for transactions what the internet did for information (Ginni Rometty, CEO, IBM)

Figure 1.5 Evolution of the Web
Taken from CoinGecko (2022)

One of the concepts driven by this technology is Smart Contracts which allowed the advent of decentralized applications. A Smart contract is a self executed program with predetermined sets of rules that runs on a DLT. Similar to the ledger, the Smart Contract is immutable. Although smart contracts are coded, they act as a firmware and not a software where the smart contract cannot be updated or deleted. To update an executed smart contract, a new smart contract needs to be created. To put an end of the old smart contract that cannot be deleted, a killed functionality is executed where the smart contract would no longer accept any new transaction. When all parties of a smart contract meet the contract's predefined terms, the contract executes the predefined rules where tokens can be transferred to investors without any intervention of third parties once conditions are met. Smart contracts could set restrictions to comply with domestic regulatory frameworks. The latter would eliminate the need for a third party and has introduced many services and business models such as custodial services, exchanges, lending or staking of assets, revenue generation from asset appreciation, supply chain etc. The figure below illustrates the potential new revenue generation by implementing an enterprise blockchain.

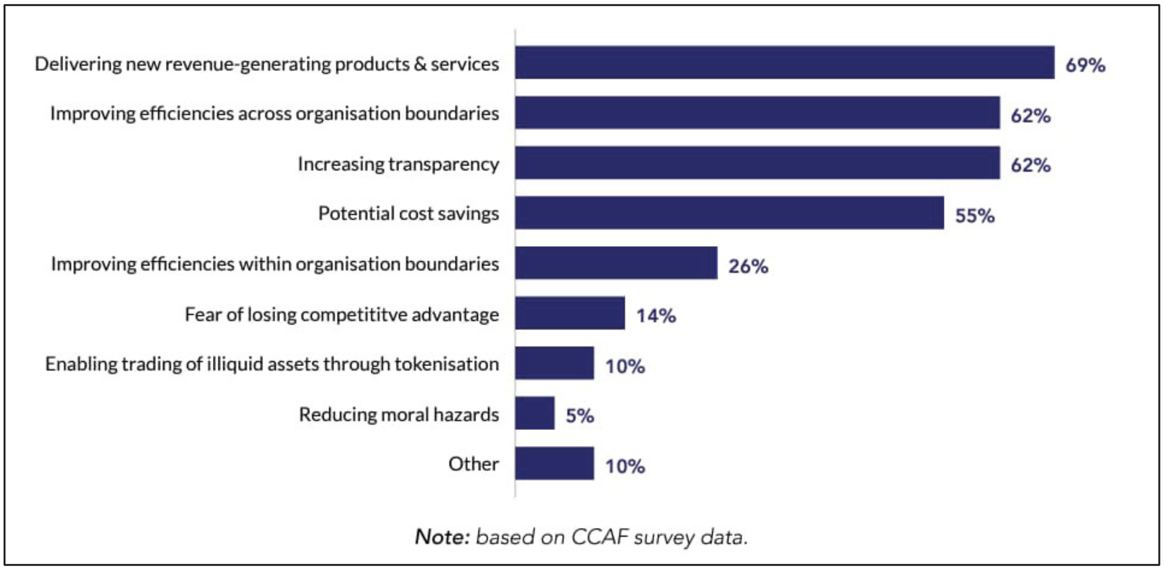

Figure 1.6 Key drivers of enterprise blockchain strategy
Taken from Rauchs et al. (2019)

While investment banks create liquidity in the market by trading securities and providing brokerage services for enterprises, many industries are striving for financial disintermediation also known as “cutting out the middleman” to reduce costs (Walter, 2012). Decentralized finance DeFi provides disintermediation through peer-to-peer networks allowing access to the masses including the unbanked to financial services all while sharing the characteristics of a DLT such as privacy, ownership of data etc. For example, an NFT can be used as a collateral on a DeFi loan. In that case, the NFT would be locked in an escrow and the terms and conditions of the loan are coded in the smart contract for self execution. If the borrower defaults on the payment, the NFT would be transferred to the lender.

1.1.2 Asset Tokenization of Public Infrastructure

DLT has introduced the concept of Asset Tokenization, which is the focus of this paper. Asset tokenization is the process of creating fractional interests of digital or real physical assets through tokens. Real assets such as buildings, warehouses, residential homes and financial assets such as stocks and bonds can all be converted into tokens to access larger investor pools of liquidity and satisfying the risk spectrum. The latter process allows the conversion of economic value and proprietary rights from real assets to digital tokens (OECD, 2020). Security tokens offering STOs are tokenized assets that are regulated securities equivalent to an IPO in traditional finance. They are fungible tokens that serve as financial instruments linked to an underlying asset such as equity and debt where their value is *wrapped* to a real asset such as a property or a company. STOs can also be an NFT, however it is important to clarify if the NFT represents a commodity or an investment contract. The STO token contains the ownership information that is recorded on a DLT and can be dynamically updated. Once issued on a DLT platform, all regulatory compliance checks, *AML/KYC* verifications and trading notions are handled by the platform. Propy, a dApp running on the Etherium Blockchain, is revolutionizing the real estate industry by tokenizing residential real estate and automating all the steps required in acquiring a property using smart contracts. The latter has made history by auctioning for the first time a home in Florida in the form of NFT. The auction attracted 7000 bidders and the house was sold for 210 Ether (Cryptocurrency that runs on the Etherium Blockchain) which is equivalent to $650,000 (Quiroz-Guitierrez, 2022). The latter illustrates with the implementation of DLT and tokenization, the transfer of ownership and value of any real or digital asset instantaneously.

Moreover, Tian et al. (2020) defines asset tokenization of infrastructure assets as the process of tokenizing public listing, private equity or debt issued by a company owning the infrastructure. However, in my research I explore the tokenization and issuance of tokens representing the ownership interest in the form of securities of the infrastructure itself and not the company enabling the direct ownership and revenue generation of an asset. Nevertheless, investors include institutional and retail investors or a mixture of both (Herweijer et al. 2018). The figures below illustrate the principle of asset tokenization and the token trading process.

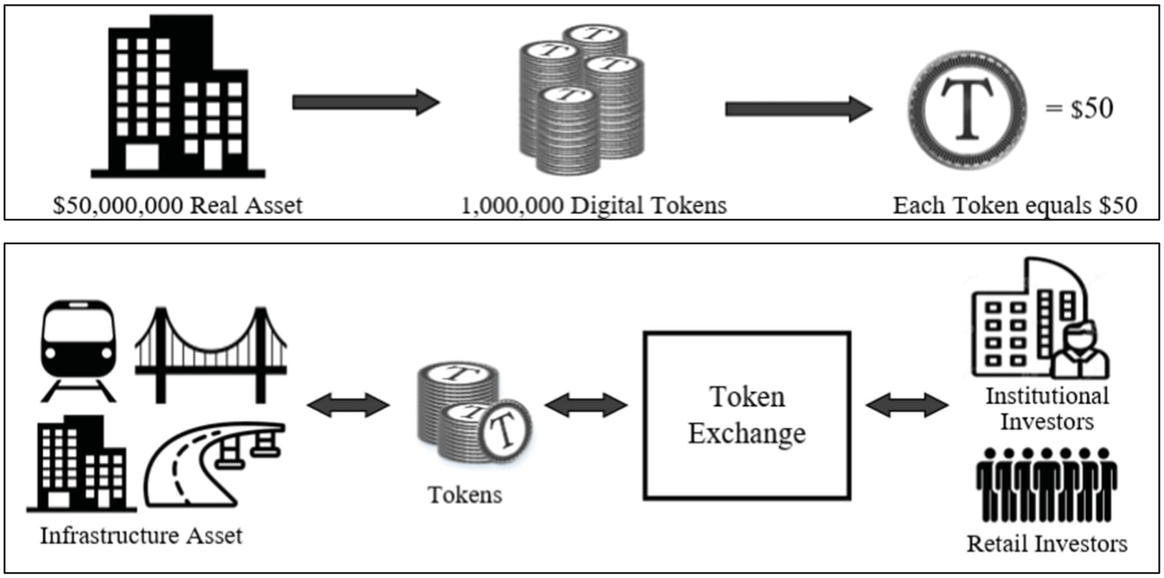

Figure 1.7 Principle of asset tokenization and the Token Trading Process
Taken from Tian et al. (2020)

However, it is important to ensure the link between the issued tokens and their underlying asset. The OECD states that a trusted central authority guarantees and monitors the connection. In my research, I will explore how to establish and monitor the link between issued tokens and their underlying real assets without the need of a central authority.

While NFTs are non fungible. It is possible to fractionalize the ownership of an NFT where each owner would own a percentage of that NFT. Although NFTs are unique and cannot be exchangeable, the fraction of an NFT is fungible and can be exchanged with the other fractions of that NFT. The latter gives the opportunity to investors to diversify their NFT holdings and invest partially in an NFT they might not afford. Nevertheless, fractionalized NFTs would allow asset owners to reach a larger pool of investors to increase liquidity which may lead to price increases (Maynoylov, 2021).

While there are many DLTs with different objectives and use cases, value and information can be transferred across siloed DLTs with interoperability functionalities such as the use of "Cross-Chain". Another functionality that enables efficient interoperability between ledgers is

Quant's Overledger DLT. On the other hand, Oracles create a bridge to the *off-chain* data which is data that is found outside of a DLT.

One of the breakthroughs of DLT is shared governance. Unlike traditional centralized systems in today's corporate world that follows a hierarchical structure, decentralized system has no central authority. In a fully decentralized ecosystem, members can all have equal voting power and participate in all decision making for a particular matter. However, governance can vary whether the DLT is private, public or hybrid. In a private Blockchain, the ledger is only accessed in a private network composed of selected entities just like a VPN where only certain participants can write data. In a public DLT, the ledger is accessed by everyone just like the internet of today where everyone can add a record. Lastly, a hybrid blockchain, often referred to as permissioned Blockchain, is a combination of public and private blockchains where all have access to the ledger but only a selected few participate in the decision making. It is important to note that regardless of the blockchain technology implemented, private or public, there are two options to select in determining who can read data such as the open and closed blockchains. An open blockchain allows everyone to read data whilst a closed blockchain only allows certain selected participants. For example, a public-closed blockchain allows everyone to write data but only selected participants to read the data. The figure below is an overview of the Blockchain Decision Path to define which type of Blockchain is suitable.

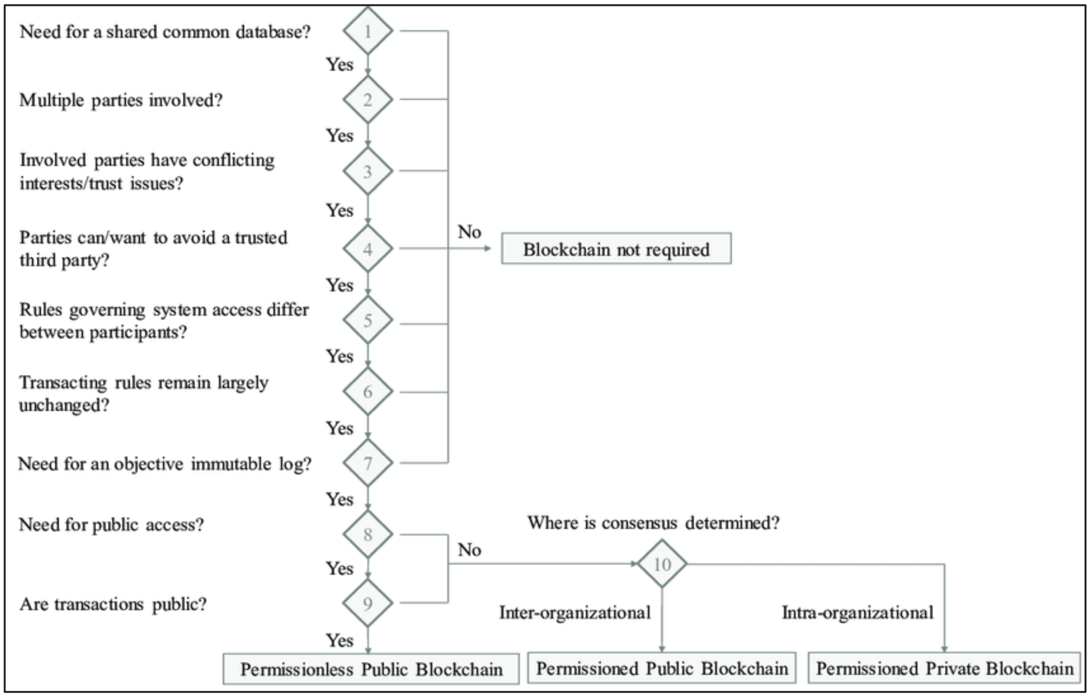

Figure 1.8 Overview of the Blockchain Decision Path

Taken from Pedersen et al. (2019)

The DLT technological advances are happening at a rapid pace, the two figures below illustrate the Gartner Blockchain spectrum which consists of four archetypes composed of five elements provided in the left figure that projects a timeline for the near future of the technology.

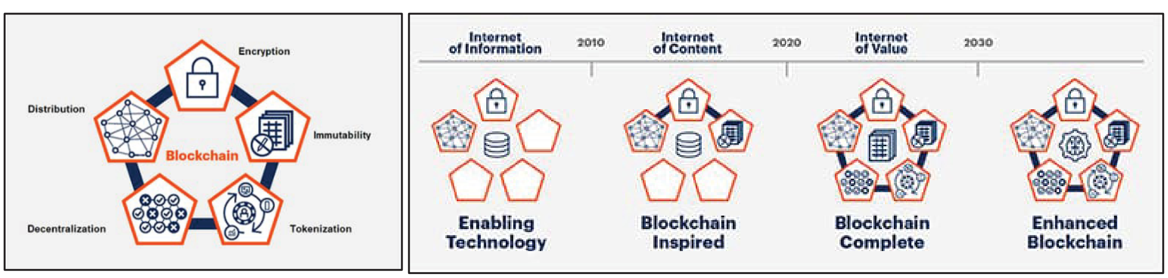

Figure 1.9 Gartner Blockchain Spectrum

Taken from Wood (2019)

According to Gartner, Blockchain complete solutions will emerge around the year 2023 comprising of all five elements: Encryption, Distribution, Immutability, Decentralization and

Tokenization. At this stage, deployment of smart contracts to tokenise digital and physical assets will take place (Wood, 2019).

Based on second Global Enterprise Blockchain Benchmarking Study, 67 enterprise blockchain networks were analysed to determine the timeline considerations for implementing DLT. It has been concluded that there are four stages for a project to reach the status of production whilst the stage of proof of concept consumed the majority of the timeline, as shown in the figure below.

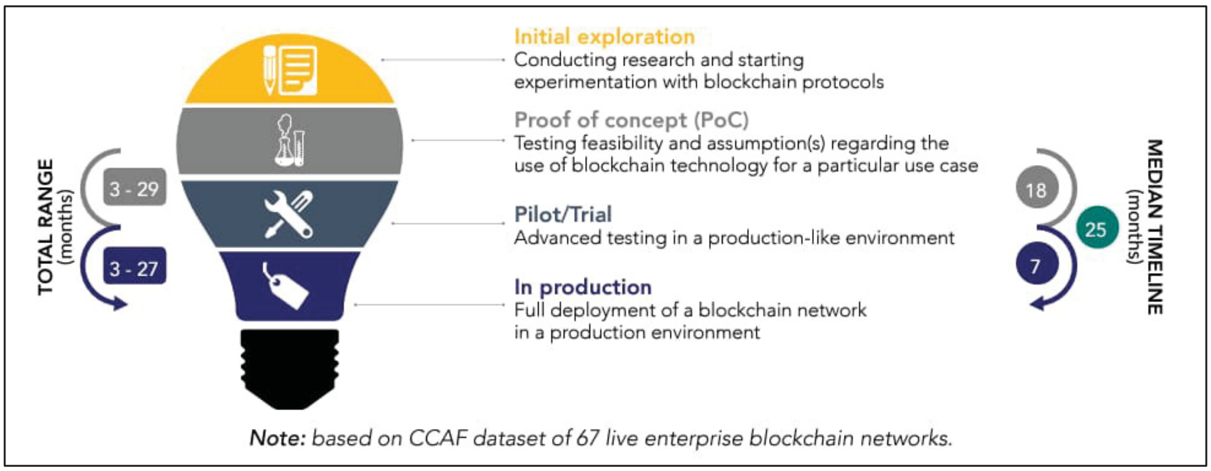

Figure 1.10 Four main stages of Enterprise blockchain projects
Taken from Rauchs et al. (2019)

While we have explored the different types of DLT's such as public, private and hybrid, there are two market approaches in implementing DLT solutions. The first market approach is to join an existing network whilst the second approach is to launch a new network. Each approach has its advantages and its drawbacks as shown in the figure below (Rauchs et al., 2019). It is important to analyze which market approach is most suitable before a business use case is developed.

MARKET APPROACH	POTENTIAL ADVANTAGES	POTENTIAL DRAWBACKS
A) JOIN EXISTING NETWORK	• **Speed:** faster go-to-market • **Cost-effective:** limited to no coordination costs and development costs • **Reduced complexity:** technological infrastructure has already been set up and workflows have been tested • **Business case validation:** use case fit has already been tested and validated, and potential network effects may already in place • **Accelerated learning:** lessons learnt by other network members	• **Fees:** on-boarding and/or licensing fees • **Existing terms and conditions:** limited influence over decision-making process, technical standards, and commercial mode • **Limited flexibility:** subject to potential technical and operational debt originating from existing architecture • **Reduced commercial opportunity:** depending on the project stage, the commercial benefit for revenue-generating use cases may potentially be less obvious
B) CREATE NEW NETWORK	• **Influence:** retain influence over use case fit, technical architecture and standards, as well as governance and commercial model • **Flexibility:** create new system from scratch free from technical debt • **Relevance:** potential to create a new industry-leading utility • **Commercial up-side:** taking a founders' premium for revenue-generating use cases	• **Costs:** coordination, development, governance, and operations • **Time:** gathering support as well as internal and external buy-in is time-consuming • **Lack of critical mass:** potentially no network effects - project becomes just another isolated network • **Regulatory uncertainty:** taking the initiative (and costs) for regulatory and legal approvals

Figure 1.11 Pros and cons of different blockchain market approaches

Taken from Rauchs et al. (2019)

With regards to privacy and intellectual property IP concerns, the application of the Zero-knowledge proof ZKP protocol enables data protection on DLTs. The ZKP can confirm the validity of transactions or run verification checks without the need to reveal sensitive details about the transaction or the investor (Lesavre et al.,2021) which enables investors to take control of their data.

There are many funding strategies enterprises can implement with DLTs. A simple agreement for future tokens SAFT is an investment contract that enables fundraising in exchange for tokens that would be issued at a defined time (Peters, 2021). Moreover, there are several Crowdfunding models such as the Initial coin offering ICO, Initial exchange offering IEO, Initial DeFi offering IDO and Security token offering STO. ICOs is an innovative approach for raising funds through digital assets. ICOs are not equivalent to IPOs as they do not provide equity in a corporation and may be issued for several purposes depending on the project such as being issued as a utility token to be used within a dApp. Similar to ICOs, IEOs are issued on an exchange where the exchange acts as an intermediary between the project to be financed and the retail investors. IDOs are similar to IEOs but they are issued on a decentralized exchange or by creating a *liquidity pool* on a dApp network. The latter tokens are not regulated hence posing a risk of violation of securities laws and fraudulent acts (SEC, 2020).

1.1.3 The Metaverse

With the advent of the DLT, the metaverse has been introduced and started gaining attraction especially after the announcement of Facebook to changing its name to Meta. The Metaverse is a 3D virtual space blending the physical and virtual worlds that runs on the Web 3.0 involving technologies such as DLT and Extended reality XR that has enabled an array of business use cases such as Digital art galleries, business offices, gaming platforms and advertisements. The latter also enabled the digitization of physical environments in the form of digital twins. The metaverse will transform many aspects of our lives to occur in a digital world such as learning and training, E-commerce and entertainment. Users will have real life experiences all while being fully immersed in a digital environment saving time and cost and promoting sustainability. Experiences such as attending a class or a meeting in the virtual word, real life shopping experiences where products can be tried and purchased, and gaming experiences never experienced before.

Extended Reality XR is a combination of Augmented, Virtual and Mixed realities. XR contains both real and virtual environments generated by software and wearable devices that bridges virtual entities with physical environments. Augmented reality AR is the concept of merging the virtual and real-world giving users alternated experiences which enhances our physical world by interacting with 3D objects which has the ability to enhance our learning practices. In Virtual reality VR, users are immersed in fully virtual environments using wearable devices such as headsets interacting with a 3D world. In Mixed Reality MR, physical and digital objects interact in real time such as in holographic projections (Hourcade et al., 2024).

With the implementation of Internet of Things IoT sensors, Building Information Models BIM are becoming smart. IBM defines digital twin as being “A digital twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making" (IBM, n.d.). The BIM model linked to real time data creates the digital twin that could be used for various purposes and facilitate asset management.

Transitioning to digital solutions will enable planning and scheduling in real-time with short interval controls SIC, the integration of digital asset management and digital twin operations and will increase capacity and organizational readiness for SIC and business expansion. Digital twins act as a bridge between physical and digital worlds by using sensors to collect real-time data about a physical object. The latter will enable 3D visualization, monitoring and simulation of a physical asset. The digital twin in the metaverse would then reflect the physical asset in the real world in real-time. The figure below illustrates the key technologies and Ecosystems that enable the interoperability between the physical word and the metaverse.

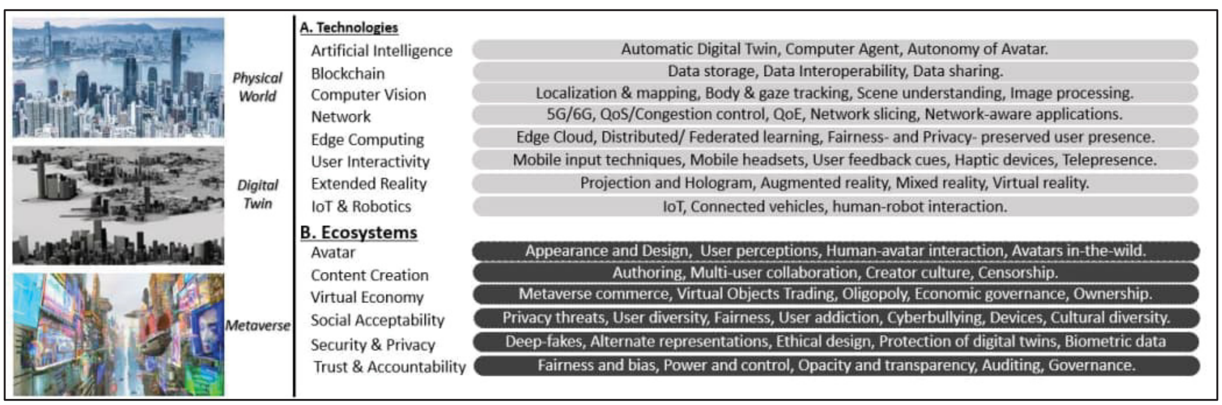

Figure 1.12 Connecting the physical world with its Digital Twins, and further shifting towards the Metaverse

Taken from Hourcade et al. (2024)

Today although BIM is gaining its rapid implementation in the construction industry, all the systems remain centralized. Elghaish et al. (2022) have developed a financial management system on Hyperledger fabric for construction projects. The figure below shows the implementation of smart contracts within several BIM dimensions on the blockchain network where the financial obligations and rights are calculated. The schedule data is obtained from the 4D BIM models, and the cost data is obtained from the 5D BIM models. When pending invoices are not paid, the project closeout is suspended until all financial duties are delivered. The latter process is differing between the several payment methods such lump-sum, cost-plus or target cost.

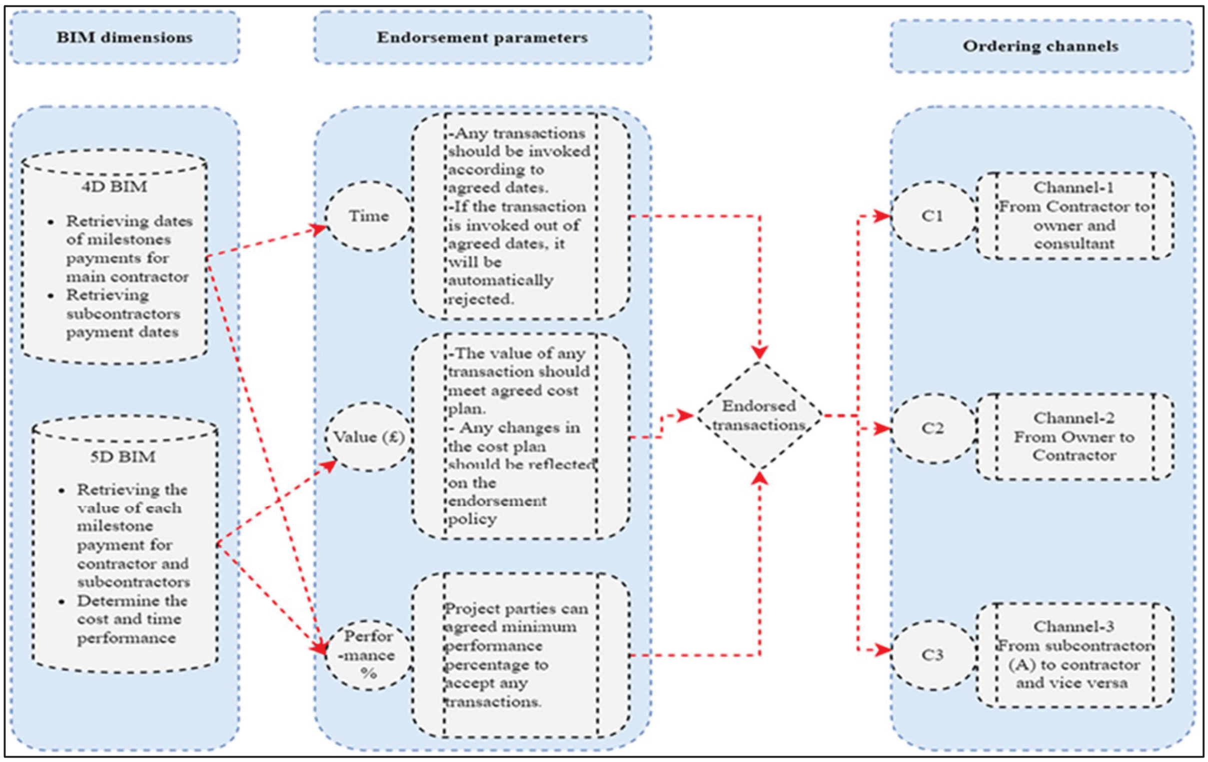

Figure 1.13 The interrelationships between BIM and Hyperledger-fabric consensus mechanism

Taken from Elghais et al. (2022)

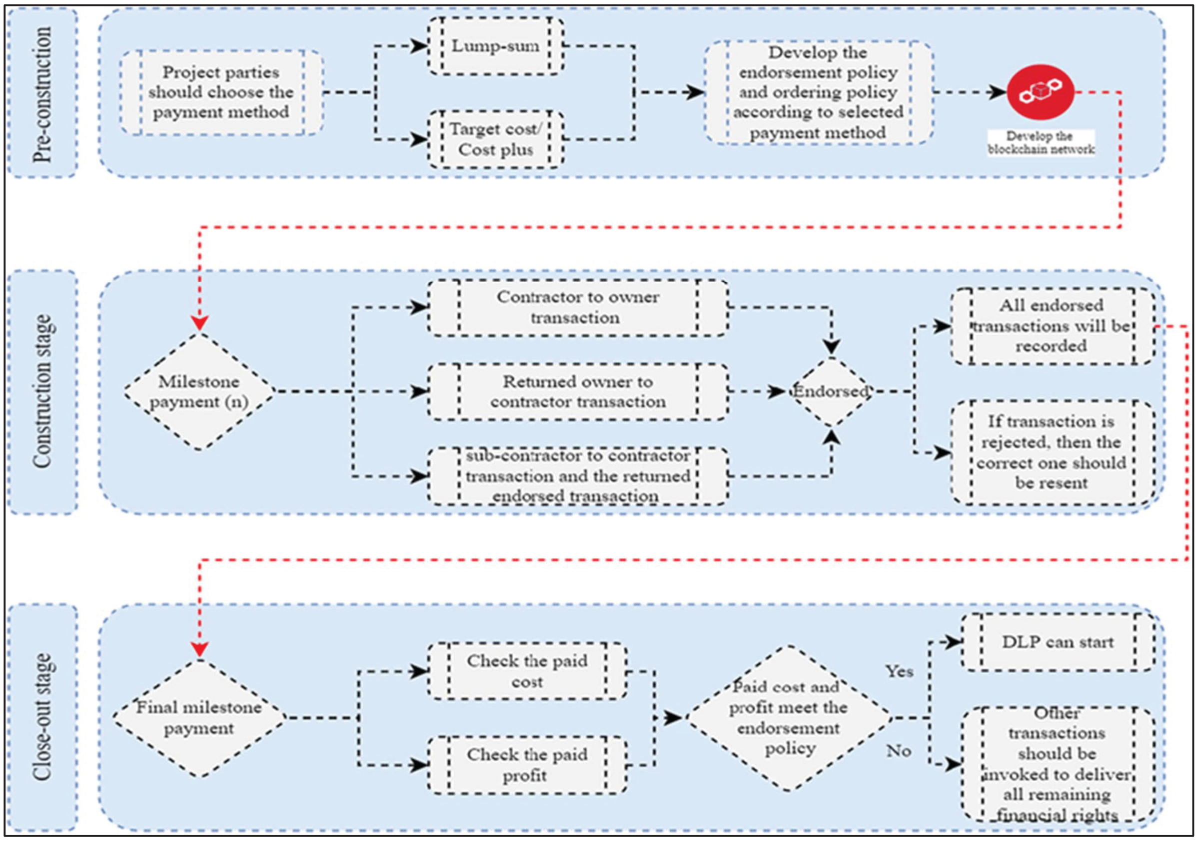

Figure 1.14 The alignment of the decentralised financial system with construction delivery stages

Taken from Elghais et al. (2022)

Overall, existing research provides a useful foundation for understanding asset tokenisation and its potential applications. Several studies have explored the technological aspects of tokenisation and its impact on financial markets more broadly. These works highlight the benefits of increased liquidity and accessibility that tokenisation can offer. However, the application of asset tokenisation to public infrastructure financing remains relatively underdeveloped. Current literature tends to focus on the theoretical possibilities rather than practical implementation within established public sector funding models. A significant gap exists in the literature concerning the practical integration of asset tokenisation into conventional public infrastructure financing. This presents an opportunity to explore the potential for tokenisation to unlock new sources of capital and improve the attractiveness of public infrastructure projects to investors.

1.2 Financing Instruments of Public Infrastructure

1.2.1 An Introduction to Conventional Financing Instruments of Public Infrastructure

Infrastructure is an asset class that gained wide attraction from institutional investors acting as a revenue generating asset and a store of value with low volatility. According to the European Bank for Reconstruction and Development ERBD, a 60% return of investment is projected for every dollar invested in infrastructure (ERBD 2019). Public fund has been the main traditional financing instrument for infrastructure projects (OECD, 2015; Sclar, 2015). Globally, the public sector holds 83% of infrastructure investments where 34% are managed by public entities and 66% are managed by state-owned enterprises. For emerging markets and developing economies EMDE, there is a lack of confidence and trust in governments due to the lack of transparency and their commitments to co-finance has led to an increase to up to six percent in borrowing costs (Inderst and Stewart 2014 & Olken and Pande 2012). Currency risks are also considered a major risk that prevent private investments in EMDE (Verdouw et al., 2015). Throughout history, retail investors have been excluded from infrastructure investments (Regan 2017). The figure below illustrated by RARE Investment Infrastructure depicts the global hierarchical distribution of infrastructure asset ownership.

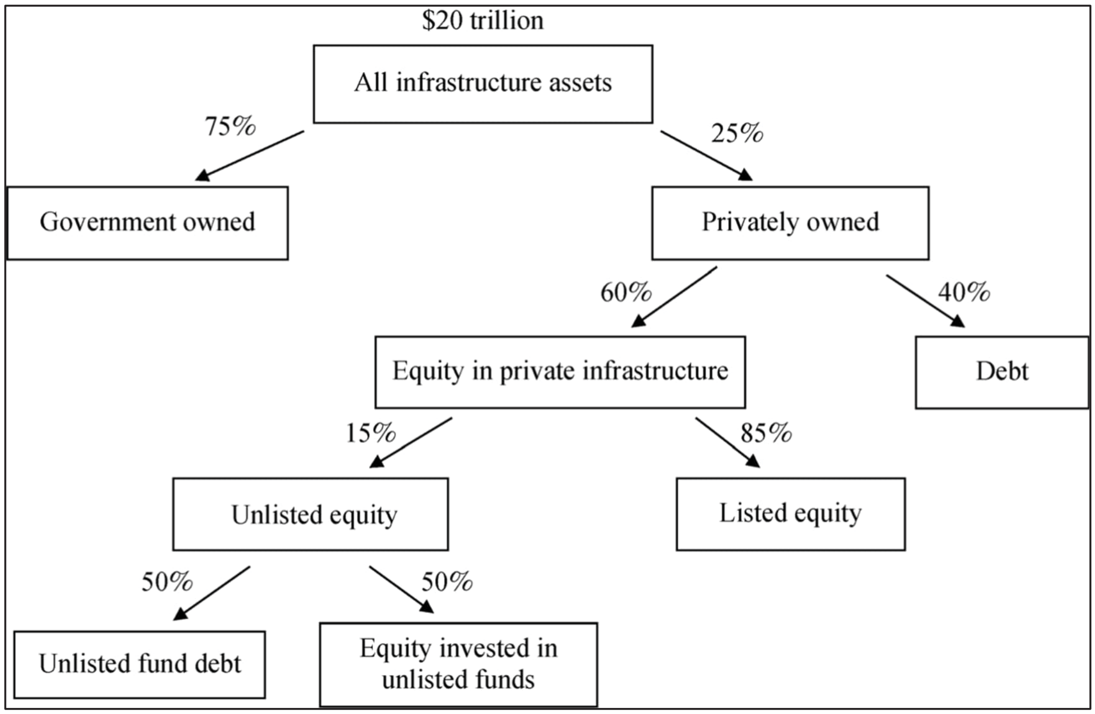

Figure 1.15 Global hierarchical distribution of infrastructure asset ownership
Taken from Walter (2016)

The traditional model is based on government ownership and operation of the infrastructure. The private sector role in infrastructure investments is limited (World Bank, 2017). The main limitations found in the traditional model are the limited public funds and poor O&M. The planning, construction and operation is performed by different stand-alone entities. The latter has limited incentives to reconsider decision consequences which leaves no room for life-cycle cost optimization. The sponsor of the infrastructure is also influenced by political agendas whereby opting for low quality and low-cost infrastructure instead of optimizing the life cycle cost (OECD, 2016). The latter would lead to a low initial investment but would result in high maintenance costs and poor asset condition.

Public infrastructure has gained attraction by the private sector as an asset investment class. It has been empirically determined that the performance of private ownership is superior to public ownership (Megginson and Netter 2001). However, it is important to note that private involvement is only economical for large scale projects due to the involvement of third parties

(Adigwe, 2012). There are two infrastructure financing models by the private sector: the Regulatory Asset Base RAB and the Public Private Partnerships PPP.

In the RAB financing model, private or state-owned companies act as the infrastructure manager who owns and operates the assets and generates its revenue from it (Makovˇsek & Veryard, 2016). The generated revenue is used to cover investment and operation costs. In order to prevent the infrastructure manager to monopolise the market and manipulate prices, an economic regulator designated by the government to cap prices in order to promote social welfare. Nevertheless, the RAB model provides an incentive to efficiency where design, construction and operations are bundled (OECD, 2016).

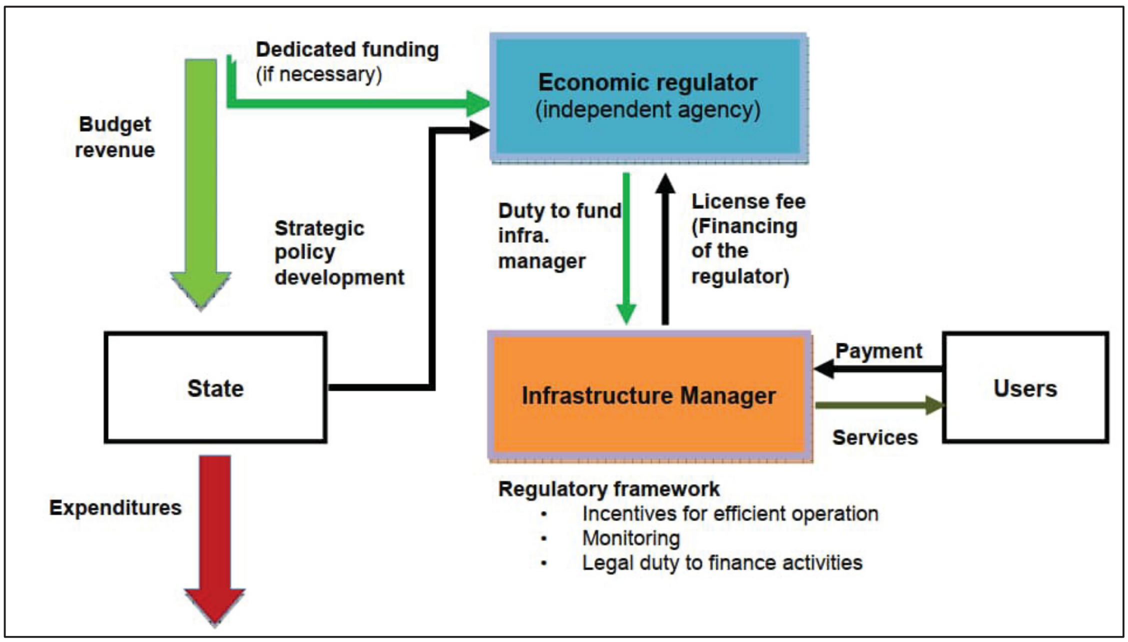

Figure 1.16 Regulatory Asset Base structure example
Taken from OECD (2016)

In the PPP financing model, a private consortium bids for the infrastructure project and is responsible for the financing and all the phases of the project for periods spanning for decades. Debt and equity are the main financing instruments which are paid back by the project's revenue. The contract that is signed between the government and the project company often referred to as the special purpose entity SPE defines how the consortium will generate its revenue (Liu et al., 2017; Makovˇsek & Veryard, 2016). The revenue could be derived by *availability payments* paid by the governments, or it could be directly derived by the users. The latter revenue model is similar to that of the RAB regulated incentive model, however, in the PPP there are no efficiency savings during the operational phase (OECD, 2016). Due to the long contractual agreements in PPP, renegotiations are common and less structured than the RAB due to the absence of a regulator which is perceived as a risk to the investor (Makovšek et al., 2015).

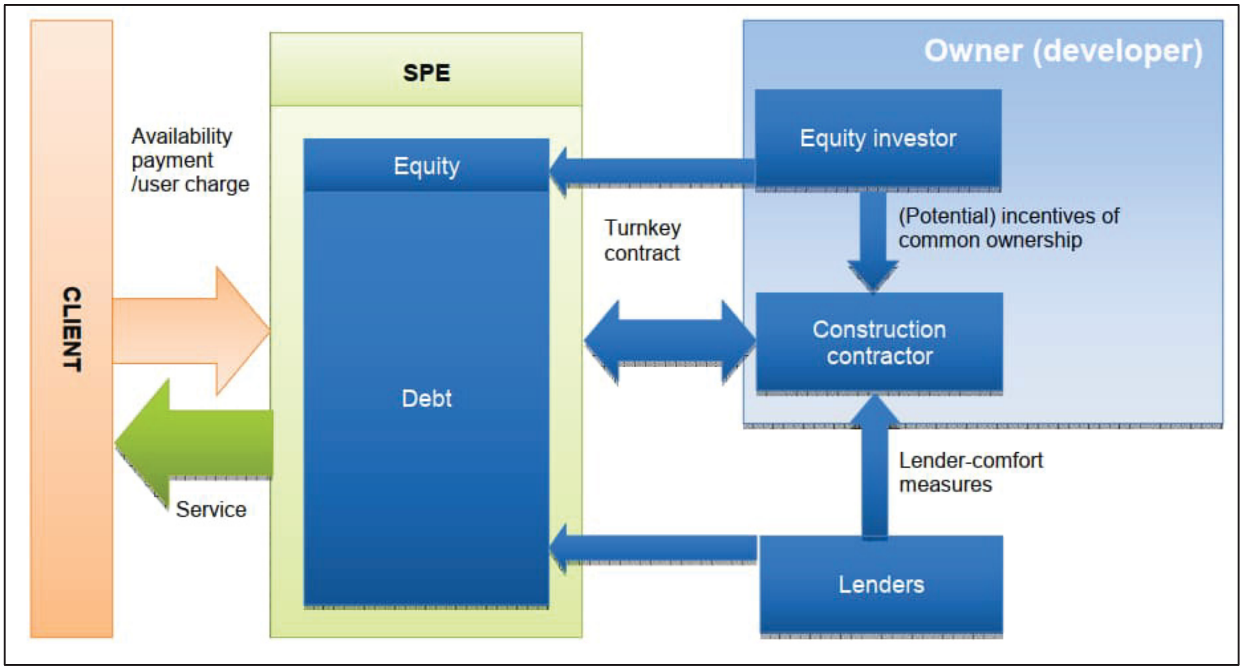

Figure 1.17 PPP model example for infrastructure delivery and operation
Taken from OECD (2016)

As seen in the figure above, debt represents most of the infrastructure financing in PPP. The financing cost in PPP is higher than government debt and in the RAB model where it borrows at a higher interest rate where lenders would require a robust insurance against the risks imposed on the contractor. On the Standard & Poor’s rating scale shown below, an RAB achieves an A rating where PPPs fall between the BB+ and BBB- range (EIB, 2012). The table below provides an overview of the main characteristics and differences between the RAB and PPP models.

Analysis element	Financing/management models compared	
	RAB (Incentive based regulation)	PPP
	Project delivery	
Quality and delivery approach	Challenged regulated company has strong incentive to consider future cost of operation risk of capex bias	Adequate SPE has a strong incentive to consider the future cost of operation
Delivery efficiency	Challenged rough target to be achieved in terms of on budget/time delivery some part of cost overruns passed on to the user	Adequate incentive present – if risk in project delivery is not efficiently managed, serious cost overrun /delay reduces SPE profit (may become unviable)
	Project operation	
Operational efficiency	Adequate regulator exerts an efficiency incentive on the regulated company through detailed monitoring and periodic price cap reviews	Challenged no economic regulator means that social welfare outcomes are determined at time of bid, which implies some inefficiency over the long run
Operational flexibility (renegotiations)	Adequate periodic price reviews are a series of contract renegotiations within a clearly defined framework	Challenged contract renegotiations do not occur within a clearly defined framework renegotiations typically involve costs to government
	Other value for money considerations	
Cost of debt finance	Low	High
Compensation to equity holders	Challenged limited risk transfer for construction allows for a strong competition; performance contracts and full risk transfer also possible; over-estimated WACC may give equity bias	Challenged returns possibly too high (uncertainty, low competition); full construction risk transfer in conjunction with reduced competition between risk averse contractors leads to higher base cost

Figure 1.18 Characteristics of alternative infrastructure delivery and operation models
Taken from OECD (2016)

Moreover, a unique model has emerged in the province of Quebec in Canada by CDPQ Infra is the Investor & Builder model as shown in the figure below. CDPQ Infra, an entity that manages public and parapublic funds acts as the financial investor and provides the technical expertise to fund infrastructure projects such as the Réseau express métropolitain R.E.M in the city of Montreal.

	TRADITIONAL MODEL	PPP MODEL	CDPQ INFRA MODEL
PLANNING AND FINANCING			
Responsibility for planning	Government	Government	**CDPQ Infra** + government
Sources of financing	New public debt	Private consortium Federal and provincial subsidies covering a portion of the costs (variable)	**CDPQ Infra** + partners Participation of public entities
EXECUTION			
Responsibility of construction	Government	Private consortium	**CDPQ Infra** + partners
OPERATION			
Operation of projects	Government	Private consortium	**CDPQ Infra** + partners
Controlling shareholder	Government	Private consortium	**CDPQ Infra**
Assets on government balance sheet	Yes	Yes	No
Ownership of assets	Governement	Private consortium (35 years) and then the government	**CDPQ Infra** + partners

Figure 1.19 Comparison of Traditional model and PPP model with CDPQ Infra model
Taken from CDPQ Infra (n.d.)

One of the risks to consider in investing in infrastructure is the liquidity risk. Since infrastructure is a physical asset, it might not be possible to liquidate the asset at a certain point in time. For this reason, it is important to have long term exit strategies put in place (Mercer, 2021). The information asymmetry in infrastructure investments created other risks such as inadequate governance, corruption, unfair competition and other matters that diminish the interest of investors in infrastructure assets (Burguet et al., 2004).

There are several ways to invest in infrastructure. In the primary market, a high initial capital investment to fund the infrastructure project is followed by substantial payments in the future. In the secondary market, investors buy shares of the project special purpose vehicle SPV in the operation phase and receive dividends. Financing instruments of infrastructure assets are composed of loans and bonds, hybrid instruments and equities. Loans and bonds form the largest portion in infrastructure finance where investors can generate fixed income with an attributed coupon rate or trade the bonds in the derivatives market. Equity provides ownership of the infrastructure asset where investors can maximize their profits through dividend yields and asset price appreciation. Hybrid financial instruments are comprised of both debt and equity (OECD, 2015; Sclar, 2015). Nevertheless, another financing instrument used to fund investments in infrastructure are pension and insurance funds which account 0.8% of their assets under management (The Economist, 2014). There are many limitations in conventional infrastructure financing such as cross-border transactions, data inefficiencies and the financing of small and medium sized projects (Walter 2016).

Modes		Infrastructure finance instruments		Market vehicles
Asset category	Instrument	Infrastructure project	Corporate balance sheet /Other entities	Capital pool
Fixed income	Bonds	Project bonds, Municipal sub-sovereign bonds, Green bonds, Sukuk	Corporate bonds, Green bonds, Subordinated bonds	Bond indices, Bond funds, Exchange traded funds (ETFs)
	Loans	Direct/Co-investment lending to infrastructure project, Syndicated project loans	Direct/Co-investment lending to infrastructure corporate, Syndicated loans, Securitized loans, Collateralized loan obligations	Debt funds, Loan indices, Loan funds
Mixed	Hybrid	Subordinated loans/bonds, Mezzanine finance	Subordinated bonds, Convertible bonds, Preferred stock	Mezzanine debt funds, Hybrid debt funds
Equity	Listed	YieldCos	Listed infrastructure & utilities stocks, Closed-end funds, Real estate investment trusts, Infrastructure investment trusts, Master limited partnerships	Listed infrastructure equity funds, Indices, Trusts, ETFs
	Unlisted	Direct/Co-investment in infrastructure project equity, PPP	Direct/Co-investment in infrastructure corporate equity	Unlisted infrastructure funds

Figure 1.20 Taxonomy of infrastructure financing instruments and vehicles
Taken from Croce et al. (2015)

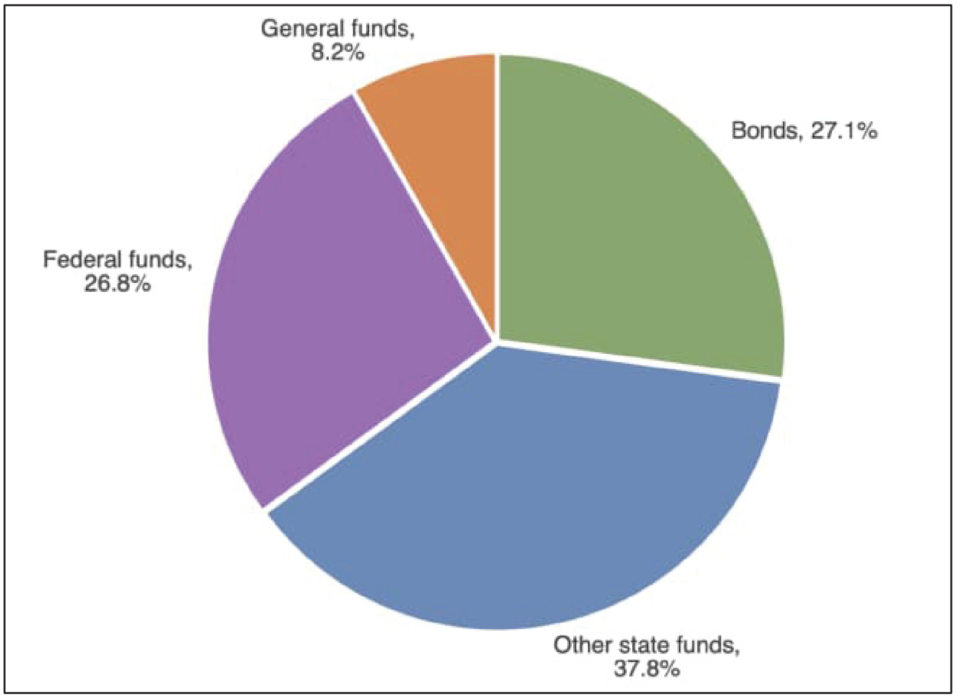

Figure 1.21 Fiscal resources for U.S. infrastructure spending in 2019

Taken from NASBO (2019)

The figure below shows that the infrastructure index EDHEC infra300 has a higher return on investments compared to other indices.

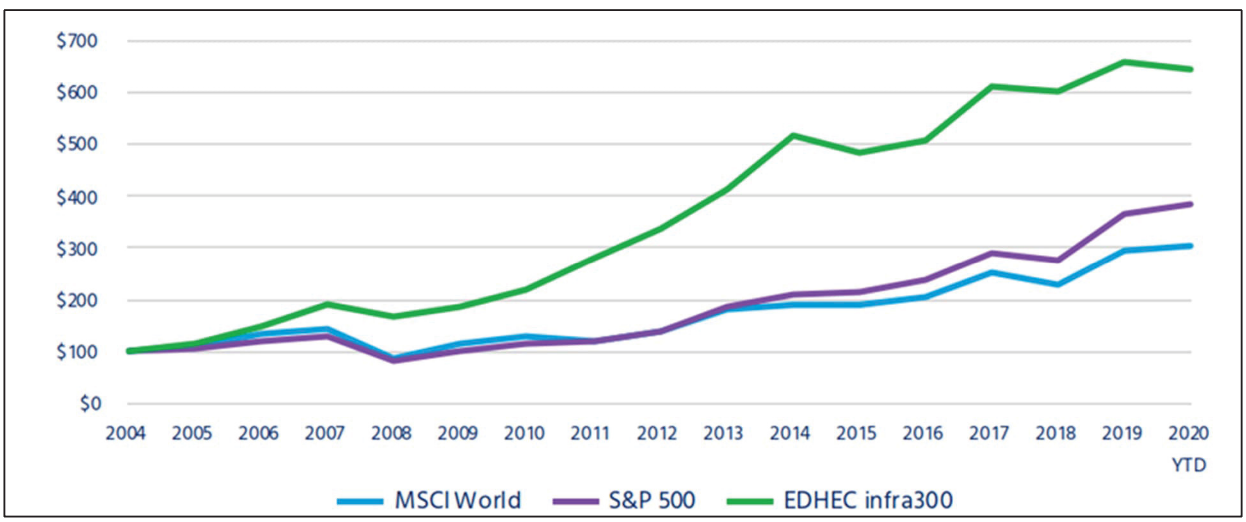

Figure 1.22 Comparison of cumulative historical return on investment of a 100$ between EDHEC infra 300 index with other indices

Taken from Mercer (2021)

While the terms funding and financing has been used interchangeably, they are two distinct terms. Funding is defined by who pays for the infrastructure whilst financing is defined by how the infrastructure is paid overtime (Beecher, 2021).

1.2.2 Current State of the Assets

Due to a lack of capital investments and maintenance, the U.S. infrastructure is described as "crumbling" (Deloitte, 2021; DeGood et al., 2019). By the year 2040, a global investment valuation of $94 trillion dollars is required for public infrastructure (Global Infrastructure Hub, 2020). The estimated "infrastructure gap" is estimated at USD 57 trillion over the next 30 years (Dobbs et al., 2013). The tables below provide insights on the types, states, and funding gaps of public infrastructure.

United States	Infrastructure
D	Aviation
C+	Bridges
D	Dams
D	Drinking water
D+	Energy
B	Rail
D	Roads
C+	Solid waste
D-	Transit
D+	Wastewater

Figure 1.23 U.S. Infrastructure assets condition 2017 report card

Taken from ASCE (2017)

Infrastructure systems	Total needs	Estimated funding	Funding gap
Roads, bridges, and transit	$2,042	$941	$1,101
Electricity	$934	$757	$177
Dams, levees, waterways, and ports	$162	$38	$124
Water and wastewater	$150	$45	$105
Airports	$157	$115	$42
Rail	$154	$125	$29
Hazardous and solid waste	$7	$4	$3

Figure 1.24 Funding gap (in billions) of infrastructure systems in the U.S. through 2025 Taken from ASCE (2017)

1.2.3 Financing through Asset Tokenization

Tokenization vs PPP Securitization: Where It Adds Value. Traditional PPP securitization packages project cash flows into notes placed via intermediate primary issuance with constrained secondary liquidity. Asset tokenization preserves the SPV, non-recourse cash-flow waterfall and creditor protections but differs on three dimensions: distribution, compliance, and operations. First, distribution: tokenization enables fractional primary participation and 24/7 secondary market access, expanding beyond a narrow syndicate to a long tail of qualified investors and, in some jurisdictions, eligible retail potentially compressing placement premia and bid–ask spreads. Second, compliance: programmable transfer-restriction and whitelisting logic allow a security to embed jurisdiction-specific rules ex-ante, aligning with technology-neutral regulatory stances. Third, operations: on-chain settlement and smart-contracted coupons/dividends can reduce reconciliation frictions and shorten settlement cycles while preserving the SPV legal perimeter. These channels map directly to lower issuance/servicing frictions and improved liquidity versus PPP securitization, contingent on regulatory and market-infrastructure readiness.

The figure below provides a comparison between conventional financing instruments with Asset Tokenization.

Host's View/Features	Direct government spending	Government, municipal, and sub-sovereign bonds	Commercial loan (senior or subordinated)	Listed equity funds	Unlisted direct equity investment and co-investment platforms	Asset Tokens
Pros	No payback obligation	Low borrowing costs High credit quality Tax-free	Reliable funding source Most applied	Direct access to the capital market	Direct ownership and management Higher return	Expanded investor pool Improved efficiency Reduced counterparty risks
Cons	Subject to political uncertainty Public deficits	Unattractive for investors due to low return rate Default risks Country risks	Highly Fragmented Multiple intermediaries High costs	High upfront and fixed fees High risks and volatilities	Limited liquidity Expertise required High upfront investment	Regulation uncertainty Technical Difficulties
Liquidity	*	***	*	***	*	***
Transaction Efficiency	**	*	**	*	*	***
Transparency	*	***	***	**	*	***
Private participation	*	***	***	***	**	***

Note: ***indicates high applicability; ** indicates medium applicability; * indicates low applicability.

Figure 1.25 Comparison of Conventional infrastructure Financing Instruments with Asset Tokenization

Taken from Tian et al. (2020)

When implementing Asset Tokenization of infrastructure, it is important to determine the price and auditing of the assets as well as the risk and return on the investment. Asset tokenization needs to comply with regulatory and legal frameworks before token issuance (Lootsma 2017). The figures below represent the Infrastructure Asset Tokenization process and the transactional flowchart of Infrastructure Asset Tokenization and Trading.

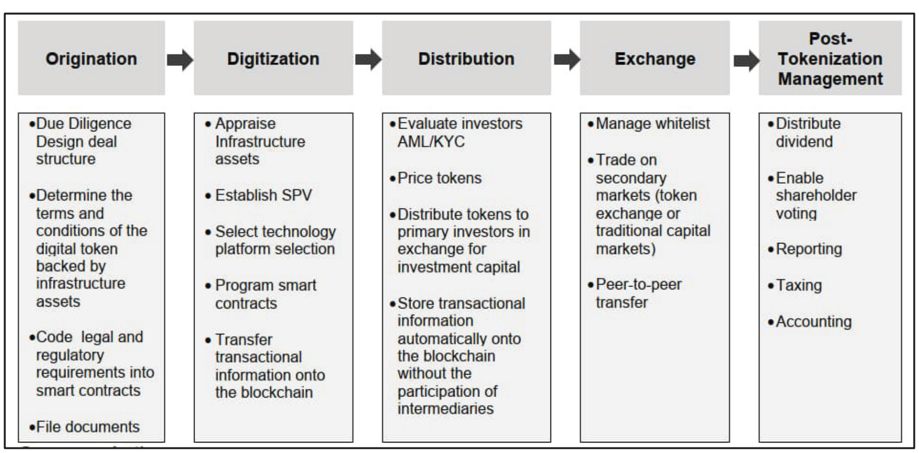

Figure 1.26 Infrastructure Asset Tokenization Process

Taken from Tian et al. (2020)

There are key participants in infrastructure tokenization such as the issuer, the investor, the issuance services provider, escrow services provider, legal firm, regulator, and trading platform. The issuer develops the infrastructure and attracts investors to invest into the assets. The issuance services provider implements the technology infrastructure, smart contracts, and the issuance of tokens. The escrow services provider implements KYC/AML, manages accredited investors whitelist, and provides token transfer verifications. The legal firm ensures compliance with regulations issued by the regulator. The trading platform is the tokenized securities exchange that is registered and regulated. The real-time trading perk in global markets of tokenized assets allows the narrowing of bid-ask spreads and the generation of additional liquidity (Tian et al., 2020).

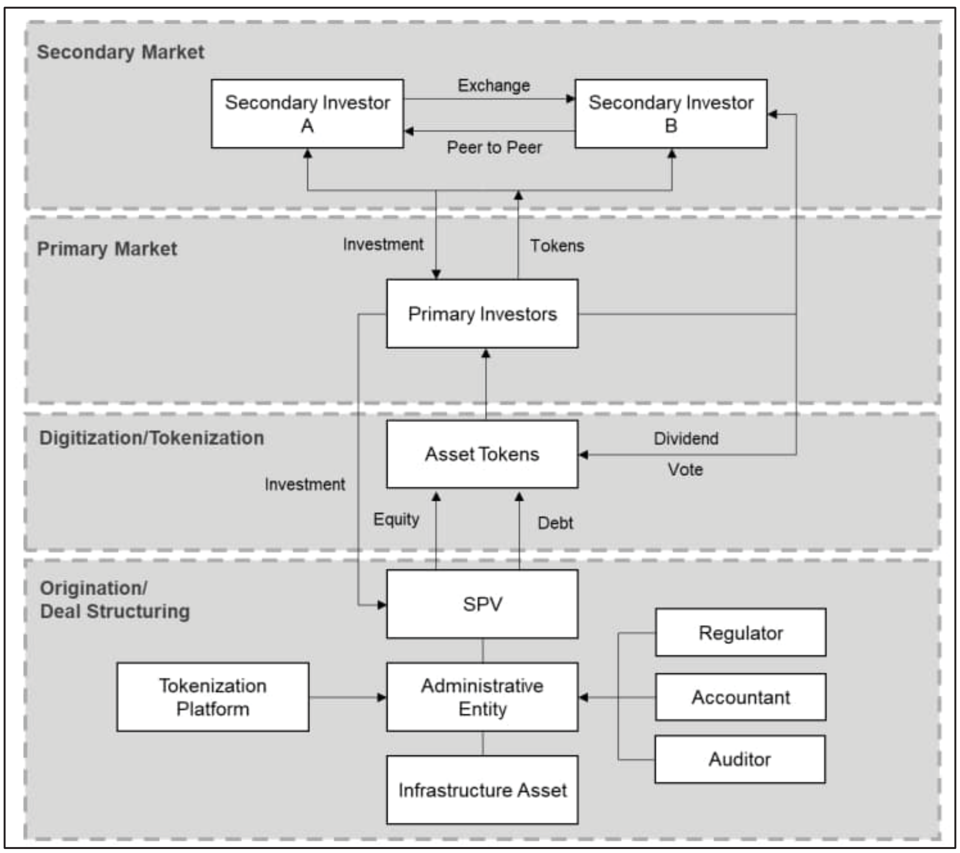

Figure 1.27 Transactional Flowchart of Infrastructure Asset Tokenization and Trading

Taken from Tian et al. (2020)

With the implementation of Asset Tokenization, investors are able to access the infrastructure market regardless of the project's scale (OECD 2020). The role of investment banking in managing investor relations and the marketing of securities will become obsolete. The transaction costs in a peer-to-peer token transaction is as low as 0.0 to 0.1% compared to 10 to 15% in conventional transactions (Uzsoki, 2019). Whilst transactions through tokenization are instantaneous, conventional infrastructure requires days and in the case of loans and bonds months to settle (Tokenist, 2018). According to the International Association for Contract and Commercial Management IACCM, the average cost of processing and reviewing a contract is 6900$ which is a 38% increase in the last 6 years. Stein (2018) states that it takes several months to sell a position in traditional private deals and can cost about USD 10,000-20,000 to re-paper the transaction. Uzsoki (2019) provides interviews in "Tokenization of Infrastructure. A blockchain-based solution to financing sustainable infrastructure" that states that the cost of issuance of tokenized securities is 5% compared to conventional issuance fees of 15-22%. Asset Tokenization will enable the involvement of surrounding communities in the development of infrastructure which galvanizes social acceptance and generates a new source of revenue where previously the lack of support caused risks of disruptions and construction and operation delays (Pereira et al. 2019; Lising, 2026). Nevertheless, blockchain technology is capable of tokenizing debt securities where the issuance cost of tokenizing a green bond accounts for 10% of the conventional process (HSBC and SDFA 2019). The World Bank issued the world's first tokenized bond called Bond-I (Commbank 2019).

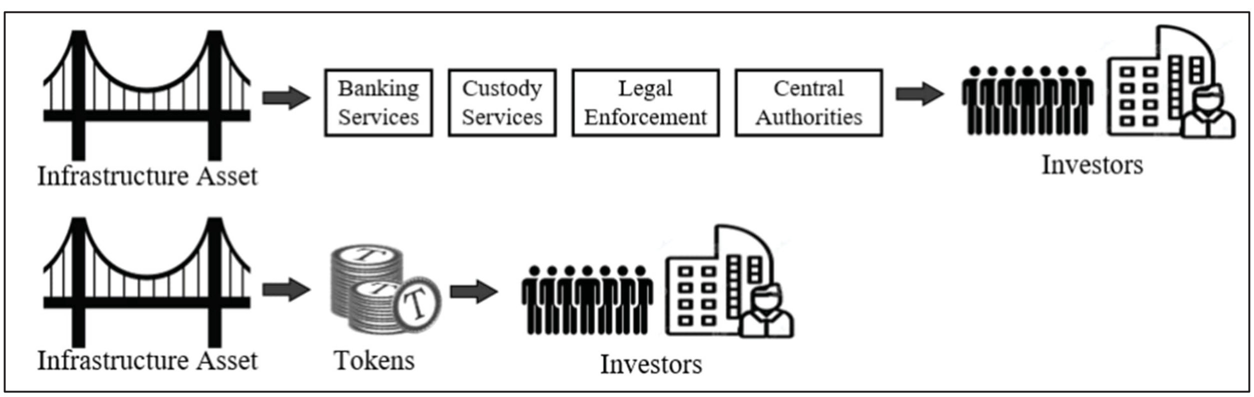

Figure 1.28 Comparison of Token and Traditional Transactions
Taken from Tian et al. (2020)

When launching a project on a blockchain, it is important to determine the token supply. Token supply can be calculated in the same fashion central banks calculate the supply of fiat currency using the quantity theory of money (Liang 2018):

Token supply = Token Supply*Velocity = Price of products*Quantity of products being sold

Token Supply = （Price of products * Quantity of products being sold)/ Velocity

Where the velocity is the speed at which a token could be transferred between two ledgers.

To determine the number of investors required to be onboarded in a project, Khan et al. (2022) has used the following formula: #Investors = Amount/Minimum settlement amount

Although innovations such as blockchain are being introduced, the regulations still lack behind. While there is some legal precedent for native cryptocurrency use cases, very little case law addresses real-world blockchain applications. Aside from case law, blockchain also touches data laws, security laws, privacy laws, antitrust laws, and tax laws. With the fast-growing cryptocurrency industry, crimes have also increased at a fast pace. The hackers and fraudsters are adept at contriving new methods of theft and work hard to stay ahead of being caught in the act. Throughout the world, many different regulatory bodies set rules for cryptocurrencies and blockchain technologies. Regulations are established only when there is enough traction and history with particular blockchain innovations which can be a good position to encourage innovation. Conversely, it can hamper activity by stifling innovation. Money laundering and terrorist financing are two of the most common cryptocurrency crimes that utilise regulatory arbitrage. The challenges that intrapreneurs face range from factors like lack of technical feasibility to a poor fit with company culture or resistance to change and a lack of coordination across departments. Resistance to new technology is an obstacle that faces entrepreneurs and intrapreneurs. Other concerns include concerns on the speed at which blockchain can produce tangible benefits and questions around privacy and IP. Blockchain technology is too early in its adoption cycle to replace standard accounting, legal, or operational practices or the employees and executives in these roles.

Another aspect of the regulatory dilemma is that until this day of writing, the debate whether cryptocurrencies represent a commodity, or a security is still on-going. The SEC U.S. Securities and Exchange Commission uses the Howey test to determine what constitutes a security. In the Howey test qualifies an instrument to be an investment contract and a security if it meets the following criteria: "(1) "individuals were led to invest money, (2) in a common enterprise," (3) "with the expectation that they would earn a profit," (4) "solely through the efforts of the promoter or of someone other than themselves." SEC v. WJ Howey Co. (1946).

The law firm Cooley LLP coauthored a white paper with Protocol Labs introducing the simple agreement for future tokens SAFT. With the SAFT, investors invest in the tokens and do not receive them until a later date once these tokens are functional. The SAFT needs to be compliant with SEC regulations however, all tokens sold after the SAFT do not. (Batiz-Benet et al.)

A digital asset that was once considered a security could transform and no longer represent a security. William Hinman, the former director of the SEC's Division of Corporation Finance, stated during a speech the following:

"Can a digital asset that was originally offered in a securities offering ever be later sold in a manner that does not constitute an offering of a security?"

In cases where the digital asset represents a set of rights that gives the holder a financial interest in an enterprise, the answer is likely "no." In these cases, calling the transaction an initial coin offering, or "ICO," or a sale of a "token," will not take it out of the purview of the U.S. securities laws.

But what about cases where there is no longer any central enterprise being invested in or where the digital asset is sold only to be used to purchase a good or service available through the network on which it was created? I believe in these cases the answer is a qualified "yes." I would like to share my thinking with you today about the circumstances under which that could occur." (William Hinman, 2018)

In Canada, there are no federal regulations on securities. The regulations are only enforced at a provincial level. The regulatory body in Quebec is the Financials Market Authority AMF. While each province has their own regulations, they coordinate the different set of regulations through the Canadian Securities Administration CSA. In 2017, the CSA issued a notice of security laws applicable to initial token offerings ITO and the sale of investment funds comprised of cryptocurrencies (OSC, 2017).

To sum up, existing literature provides an understanding of conventional financing instruments used for public infrastructure, including public-private partnerships, bonds, and direct government funding. These approaches have proven effective in delivering many large-scale projects. However, they often face challenges related to access to capital, investor appetite, and the complexity of project structuring. The emergence of asset tokenization presents a potentially transformative development. Several studies have explored the theoretical benefits of tokenization, such as increased liquidity, reduced transaction costs, and broadened investor participation. These initial explorations highlight the potential for tokenization to address some of the limitations of traditional funding models. Despite this growing interest, the application of asset tokenization within the context of public infrastructure financing remains largely unexplored. There is a noticeable lack of empirical investigation into how tokenization can be practically integrated with established financing models. Furthermore, the literature does not offer clear guidance on how to adapt conventional investment strategies to effectively incorporate tokenized assets. The potential for asset tokenization to genuinely improve project financing outcomes, particularly within the constraints of public sector governance and accountability, requires further study.

1.3 Railway Asset Management

1.3.1 An Introduction to Conventional Railway Asset Management

Transport policies in many countries are promoting the transition from roadway to railway. It has been predicted in the year 2025 a worldwide increase of 14.75% in freight tonne-kilometres and 37.2% in passenger kilometres respectively from 2015 (SCI, 2017). The Institute for Asset Management defines the concept of Asset Management as “systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan” (IAM, 2022).

Whilst transit systems have served our communities and optimized their means of transportation and freight systems served the supply and demand of our economy, railway systems require robust maintenance to keep the tracks in good conditions to maximise passenger comfort and minimize rail breaks, rail defects and derailment risks. As the rail ages and is exposed to accumulated train traffic, the risk of failure increases and is often resulted in internal rail defects. Most transit agencies nowadays use ultrasonic testing UT as a method for rail inspection that is supplemented by eddy currents, track circuits and visual inspections where rail sections are replaced once an internal defect is detected (TCRP 151, 2020). UT testing is the main method for rail inspection as it conducts an internal rail assessment where it detects interior cracks that cannot be detected by the naked eye. Eddy currents detect surface cracking and does not detect internal cracks. Track circuits is not an inspection method, it is installed for signalling purposes to monitor train presence in a *block*. However, when a rail break occurs it falsely signals a presence of a train in that particular *block* which can be an effective measure for identifying broken rails. With the elimination of track circuits by the advent of positive train technology which monitors and controls the movements of trains, the broken rail detection may be compromised. There is no uniform schedule for track inspections in transit agencies. However, the Federal Railroad Administration FRA introduced a risk-based UT scheduling. The risk-based UT scheduling determines the frequency of UT testing required per segment or subdivision (FRA, 2019). The figures below illustrate the distribution of testing equipment ownership and frequency of UT testing that resulted from a survey questionnaire sent to 28 transit agencies where most agencies are located in the U.S. The latter depicts that most transit agencies do not own their testing equipment and conduct UT testing once a year. The TCRP 151 states that it is often challenging finding a contractor in a timely and cost-effective manner. It also states that the larger the system, the more inspection is required.

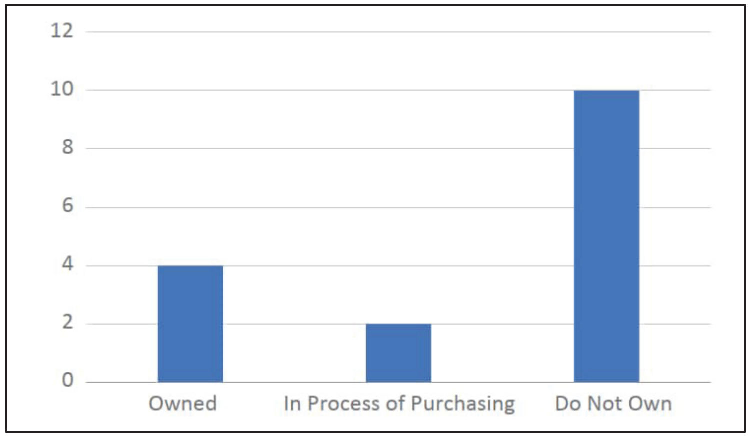

Figure 1.29 Distribution of testing equipment ownership
Taken from TCRP 151

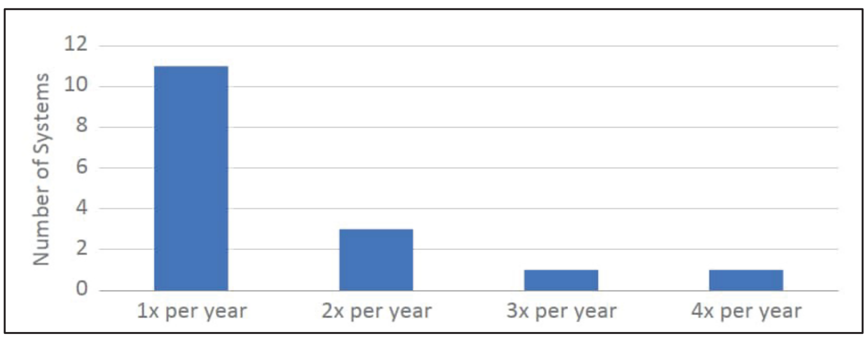

Figure 1.30 Frequency of UT
Taken from TCRP 151

TCRP 151 states that most transit systems do not have a maintenance data system that manages and stores maintenance data records. The latter is important to support risk-based UT scheduling for rail inspection. Moreover, the TCRP 151 suggests exploring alternative innovative methods for detecting broken rails such as fiber optics, drones etc.

Jovanovic (2017) outlines in his paper "Modern Railway Infrastructure Asset Management" the main phases for the Condition-Based Maintenance chain. The main phases are monitoring, analysis, warning, planning, optimization, scheduling and management. The monitoring phase is conducted by measuring vehicles that inspect the track and generates collected data that is analyzed and processed to determine defect locations and classifications whereby generating alerts for maintenance purposes. The planning phase consists of maintenance and replacement plans that are optimized for works execution. The management phase tracks maintenance performances. The figure below illustrates the Condition-Based Maintenance Chain.

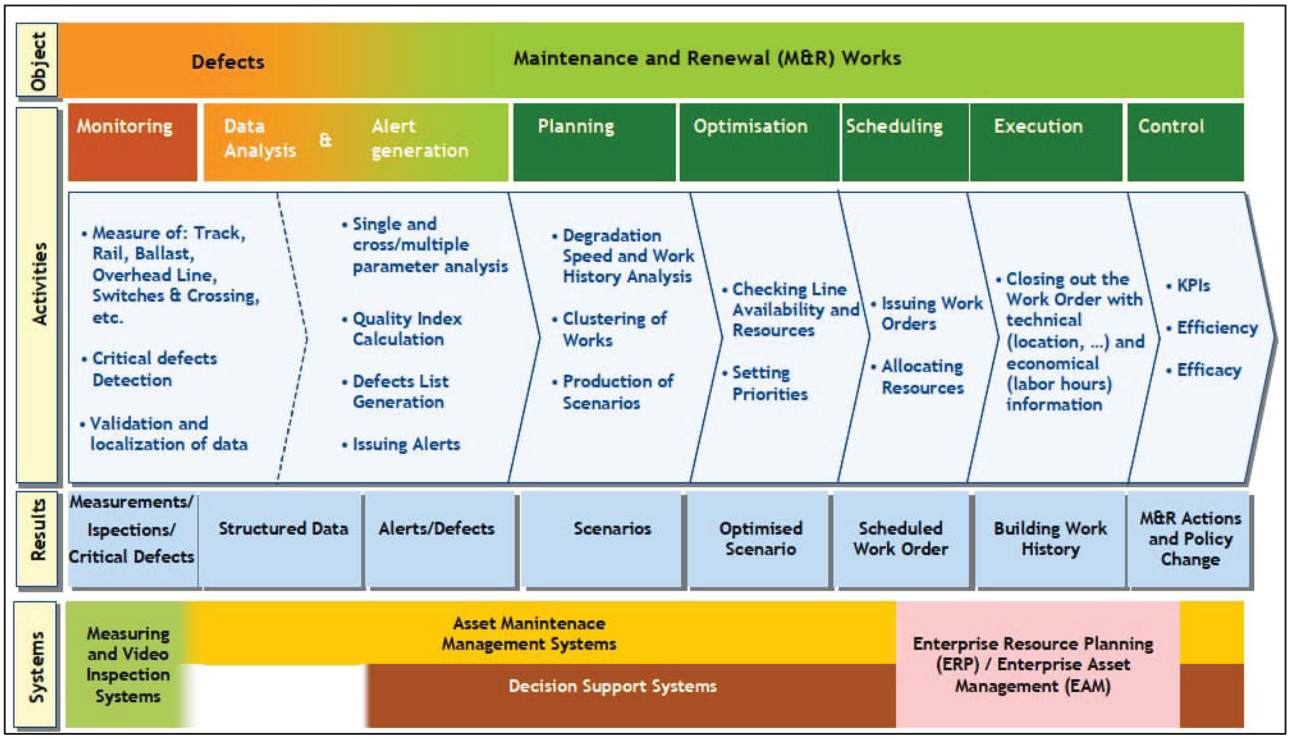

Figure 1.31 Condition-Based maintenance Chain
Taken from Jovanovic (2017)

There are many diagnostic systems implemented in the railway right-of-way available in the market measuring the infrastructure and the surrounding environment. The diagnostic systems such as video and vision systems can either be integrated on dedicated measuring vehicles or on the railway operator's rolling stock. Moreover, several systems can be integrated simultaneously which enables to relate defects to other factors such as environmental conditions. The "ROGER" system developed by MERMEC as shown in the figure below, measures track geometry and profile while the running speed is up to 300 km/h without hindering accuracy.

Figure 1.32 ROGER 800 Track inspection vehicle
Taken from MERMEC (n.d.)

Jovanovic (2017) introduces the track surface inspection systems with automatic detection with MERMEC's approach by implementing "vision technologies" which his classified by three subsystems: Track Surface Inspection Subsystem, Joint Gap and Head Checks Inspection Subsystem, and Track Surface Measurement Subsystem. The Track Surface Inspection System monitors track condition and identifies defects such as cracks and breaks, ballast irregularities, condition of signalling systems such as axle counters and other matters with automatic recognition using real-time video monitoring. The joint Gap and Head Checks Inspection Subsystem accurately measures rail joints, weld gaps and rail head-checks. The Track Surface Defect Detection System uses "line-scan" cameras that identifies and classifies defects based on their properties and positioning in real-time as shown in the figure below.

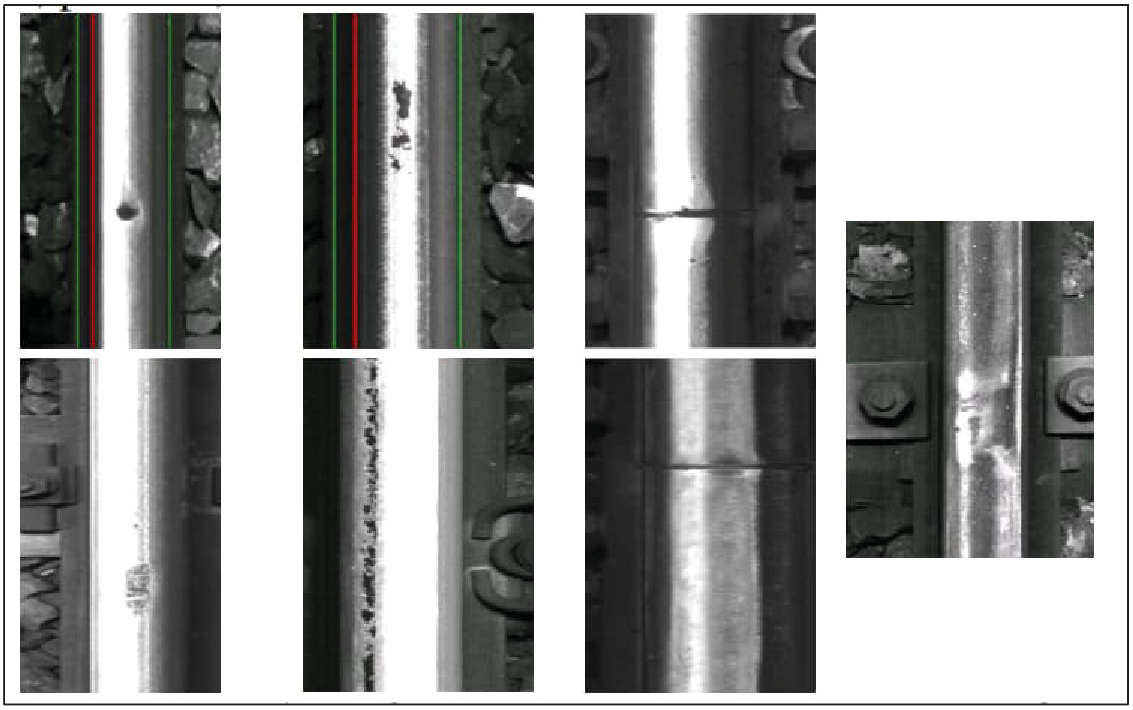

Figure 1.33 Track Surface Inspection System
Taken from Jovanovic (2017)

The Track Surface Measurement Subsystem uses “area scan” cameras that measures the position of track objects such as ballast, vegetation, fasteners and systems such as axle counters. All the diagnostic systems mentioned can be utilized simultaneously to generate deterioration models of each asset and integrate the collected data in a planning software such as the Railway Asset Management System RAMSYS developed by MERMEC to generate optimized maintenance and replacement schedules.

In most cases, railway companies do not have the resources to maintain the railway infrastructure at an optimal performance level. Often, railway companies use prioritization programs to maintain the railway infrastructure under limited resources. Selig and Kasper (1996) introduced the Prioritized Rail Corridor Asset Management which maintains performance and improve asset condition with limited resources and a positive return on investments. The paper outlines a framework with the implementation of Otram’s Railway Infrastructure Management information system which creates a linear model based on collected and correlated multiple datasets along the right-of-way to generate a prioritization program in the near- and long-term periods that are linked to the strategic asset management systems that manages the logistics of labor, materials, and equipment. Successful applications of prioritized rail corridor asset management are the examples of Amtrak and Conrail that resulted in a 10% annual savings in maintenance expenses without the need of any additional capital investment (Anderson et al., 2000). Low track quality restricts speed to avoid derailments which results in delays. In a case study conducted in Scotland for a 47 miles double track passenger line, it has been observed that delay penalties accumulate rapidly where a single delay penalty of a single train costs 2670£. The study implemented prioritized rail corridor asset management and resulted in 10M£ in savings per year with improved asset performance (Scotland Alliance ORIM Pilot Project Report, 2003). It has also been reported on a UK main line, the average cost of a derailment is estimated to be £661 073 (RSSB, 2016). Sasidharan et al. (2022) stated that an increase of 2.5% in maintenance investments resulted in £3000 per meter in annual savings. The current industry fails to acknowledge the whole life cycle costs an its impact on operation and maintenance of each asset. Since railways are linear assets, an interruption of one part of the asset would affect the whole asset.

1.3.2 O&M and Smart Contracts

All the processes of O&M such as inspection, planning, replacement programs, issuance of Work Orders, and payments to third parties could be automated and optimized with the application of smart contracts. As of this writing, no use case currently exists in the implementation of smart contracts in the construction industry besides visions, conceptualizations, and prototypes. Kifokeris and Koch (2020) have developed a digital business model for construction logistics with the implementation of smart contracts. The figure below illustrates the conventional process where independent logistics consultants are hired to optimize.

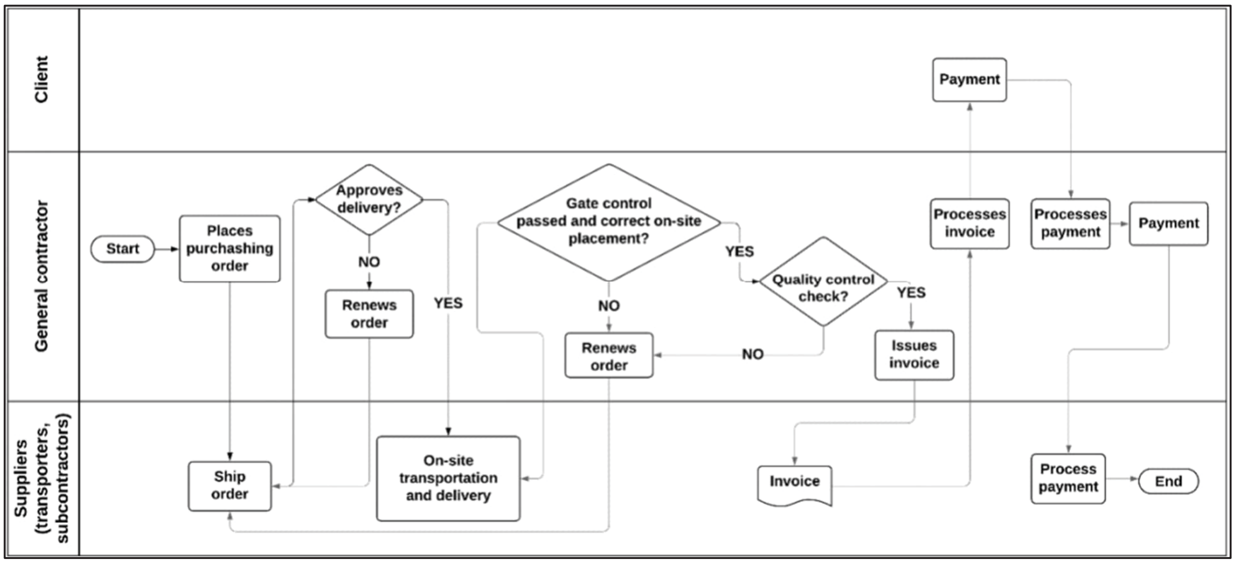

Figure 1.34 Conventional process for construction logistics
Taken from Kifokeris and Koch (2020)

As we can observe in the figure above, there are many recurrent and conflicting steps that precede one another where the logistics consultant attempts to optimize. In this flow, the general contractor has the authority over most of the supply-chain putting the client and the supplier in a passive state. Nonetheless, the material and information flows are not well coordinated.

In the figure below, the process has been optimized with the implementation of a smart contract to accelerate processes and mitigate non accurate data, withheld payments, delivery failures, erroneous data transfers and siloed databases. The latter has promoted a transparent, decentralized, and traceable system between all parties where the supplier and client have a more active role. The implementation of a blockchain solution not only had a positive impact on the construction logistics but as well as on the financial component reflected upon the reduced interaction and rework costs due to the distributed ledger technology.

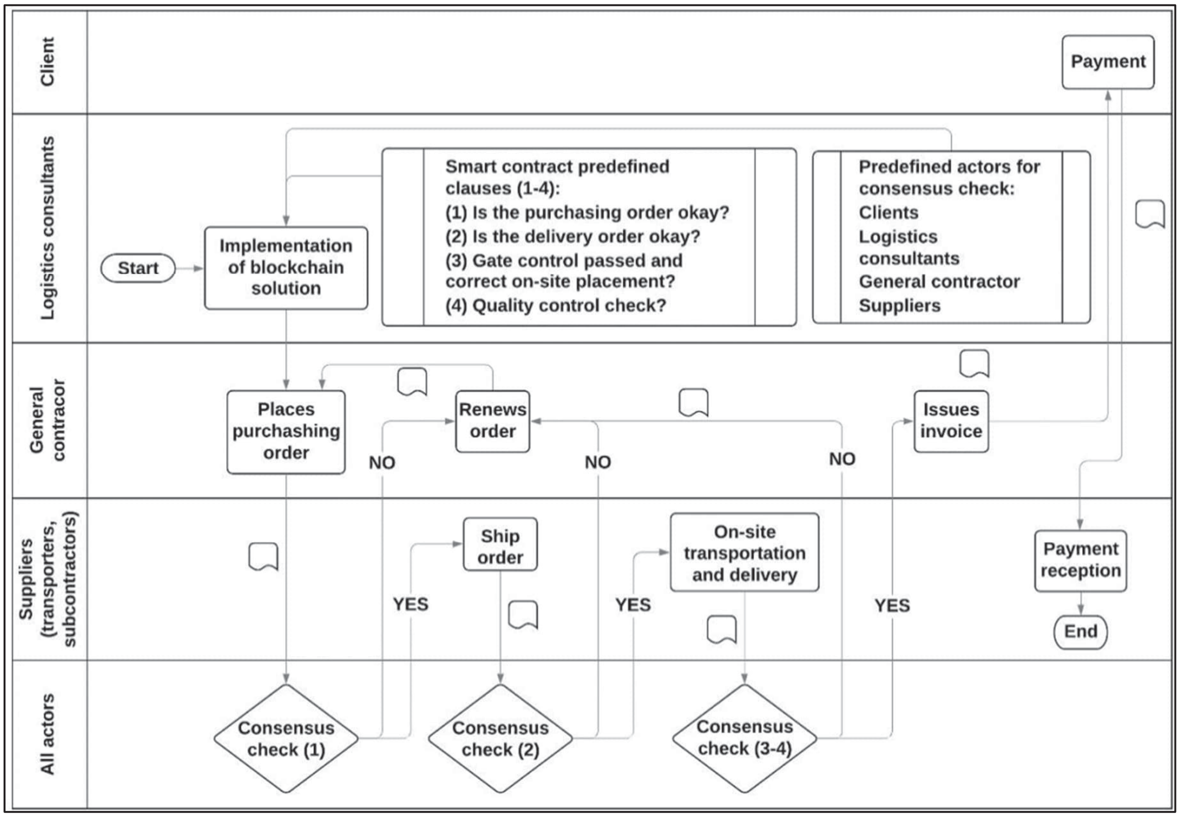

Figure 1.35 Optimized process through Smart Contracts
Taken from Kifokeris and Koch (2020)

In a small-scale demo paper on Asset Tracking with Smart Contracts, Arumugam et al. (2018) developed a workflow with the implementation of Smart Contracts for asset tracking for package deliveries. The workflow starts by setting the shipment's terms and conditions. Once the contract is established and the asset is prepared for shipment, the asset is tracked using positioning technologies and sensors. When the shipment is delivered successfully meeting the conditions set in the contract, the carrier is rewarded. However, if the shipment violates the contract clauses, deductions or penalties are applied.

Overall, existing literature provides a foundation for understanding railway asset management and conventional infrastructure financing. Research consistently highlights the challenges of securing adequate funding for large-scale railway projects, often citing long payback periods and perceived risk as deterrents to private investment. The application of digital technologies, including blockchain and tokenization, has been explored in various contexts, demonstrating potential for increased transparency and efficiency in financial processes. However, the deliberate integration of asset tokenization into established public infrastructure capital investment strategies remains largely unexplored. Current studies tend to focus on the technological aspects of tokenization or its application to specific asset classes, such as real estate or art. There is a relative absence of research examining how tokenization can be strategically employed to enhance the attractiveness and effectiveness of conventional funding models for public railway infrastructure. This lack of focused investigation creates a significant gap in the literature. A clear methodology is needed to guide public sector bodies in assessing and implementing asset tokenization to improve capital investment.

CHAPTER 2

INNOVATIVE FINANCING STRUCTURES FOR LARGE-SCALE INFRASTRUCTURE PROJECTS: A LAYERED MODEL APPROACH

A. E. Helou [a], G. J. Assaf [a]

[a] Department of Construction Engineering, École de technologie supérieure,
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

Article submitted for publication in *Ledger Journal*, November 2025

2.1 Introduction

Infrastructure development is a well-established driver of economic growth, supporting increased productivity, urbanization, and climate adaptation through resilient and sustainable assets. Despite the recognized economic and social value of large-scale (or "megaproject") infrastructure, nations across the globe face persistent challenges in initiating and delivering these projects. According to the World Economic Forum (2023), the projected global gap between needed infrastructure investment and realized activity is estimated at $15 trillion by 2040. Critically, this shortfall does not reflect an absence of available capital for infrastructure financing; rather, it is primarily attributable to insufficient and unreliable sources of project funding, that is, cash flows (from user fees, dedicated taxes, or grants) that ultimately repay investors over the project's life.

It is essential to distinguish between funding, meaning the reliable sources of revenues or transfers (such as user fees, government grants, or dedicated taxes) that ultimately repay investors, and financing, which refers to the financial instruments and markets that convert those future funding streams into the upfront capital required for project delivery. While vast pools of investor capital exist globally, many infrastructure projects suffer from unreliable or politically constrained funding sources rather than shortages of financing mechanisms. Therefore, the primary challenge lies in structuring bankable projects with dependable funding streams to underpin financing.

Unlike traditional corporate finance, project finance is structured around a legally distinct Special Purpose Vehicle (SPV) whose debt and equity are repaid solely from the cash flows generated by the project. The SPV centralizes risk allocation, shields parent companies, and is the contracting party in PPP arrangements. Any innovative financing, including asset tokenization, must therefore integrate into the SPV's capital structure and risk framework to be viable in infrastructure project delivery.

Within this context, many governments face growing fiscal constraints, heightened political sensitivity regarding user fees or new taxes, and the need to achieve greater efficiency in the structuring and delivery of infrastructure projects. In response, there has been a shift toward exploring not only innovative project delivery models such as public-private partnerships (PPPs), which make use of special purpose vehicles (SPVs) and non-recourse project finance structures but also toward more sophisticated financing strategies that could improve risk allocation, transparency, and market access. However, successful project finance depends fundamentally on the existence of adequately structured, bankable projects with reliable funding streams.

Among recent financial innovations, blockchain technology and asset tokenization are increasingly highlighted as mechanisms for enhancing transparency, investor access, and liquidity in the financing of traditionally illiquid infrastructure assets. Asset tokenization enables the fractionalization of project equity or debt claims, potentially broadening the eligible investor pool and enabling greater secondary market trading without altering the core funding structure underpinning repayments. Blockchain-enabled smart contracts can facilitate traceable and secure interest transfers, reducing settlement and administrative costs, while programmable governance frameworks promise to automate elements of contractual compliance and investor rights.

Recent research has demonstrated that asset tokenization facilitates a future of transparent investing by lowering barriers to entry, enhancing liquidity through secondary markets, and enabling programmable governance frameworks (Kreppmeier et al., 2023; Baum, 2021).

Empirical studies have begun to validate the potential of tokenized infrastructure finance to democratize capital access (Louis et al., 2023), while highlighting challenges including regulatory compliance and investor education. These developments signal a paradigm shift towards more inclusive and transparent infrastructure investment ecosystems.

Risk allocation within PPPs is governed by detailed contractual agreements negotiated between public sponsors and private partners, independent of the financing instruments employed. Tax-exempt municipal bonds, a dominant U.S. infrastructure financing tool, offer low transaction costs and efficient access to capital. Our framework respects existing legal and contractual structures, aiming to integrate innovative financing without disrupting effective risk-sharing mechanisms.

Despite this potential, the integration of tokenization within the established project finance model where SPVs serve as the central risk-allocating entities and where both debt and equity are structured according to project-specific revenue, risk, and contractual terms remains underexplored in scholarly and applied literature. Ambiguities persist regarding how tokenized claims on infrastructure assets interact with traditional debt and equity tranches, impact governance, and influence risk-bearing and asset management.

While asset tokenization creates opportunities for fractional ownership, infrastructure projects demand effective governance to allocate complex risks. Research shows that ownership concentration enhances governance effectiveness (Demsetz and Lehn, 1985). Our layered tokenization model incorporates differentiated token classes with governance rights, enabling structured investor participation while mitigating risks inherent in dispersed ownership.

This paper aims to advance the literature by empirically validating a stakeholder-centric framework that situates asset tokenization within the layered financial and legal structures of large-scale infrastructure project delivery. The study draws on a survey of industry participants including institutional investors, regulators, sponsors, and blockchain service providers to evaluate the feasibility and practical challenges of this approach. The research pursues two principal objectives:

1. To empirically assess industry stakeholder perspectives on integrating tokenization and blockchain-enabled smart contracts with SPV-based project finance; and

2. To map a Layered Flow Model that demonstrates the movement of funds and risk allocations across tokenized infrastructure projects at each stage of the asset lifecycle.

Infrastructure projects evolve through distinct phases with varying risk-return profiles. High-risk, high-return equity investors predominate during early stages, while long-term, risk-averse investors replace them during stable operational phases. Tokenization models must be flexible to accommodate these changing investor profiles and refinance strategies over the project lifecycle.

By grounding tokenization explicitly in the context of project finance and the realities of infrastructure funding, this work seeks to clarify the potential and the limitations of blockchain-enabled innovations in addressing infrastructure investment needs. Furthermore, by focusing on issues of risk distribution, investor governance, transparency, and implementation, the study contributes both to infrastructure finance scholarship and to the developing literature on digital asset markets and decentralized finance.

2.2 Literature Review

2.2.1 Overview of infrastructure financing models

The financing of large-scale infrastructure projects constitutes a central challenge in both developed and emerging economies, with critical distinctions to be drawn between funding (the reliable stream of revenues or government transfers used to repay capital costs) and financing (the mechanisms such as debt, equity, or hybrid structures that convert future revenues into upfront capital for project delivery). Traditionally, many countries relied heavily on direct public funding, with state budgets and sovereign borrowing as the primary mechanisms supporting infrastructure roll-out. However, these approaches have come under increasing strain due to fiscal deficits, rising demands for government resources, and the complex, capital-intensive nature of modern infrastructure investments.

As per Grimsey et al. (2017), the past four decades have seen a notable shift: whereas the pre-1980s period was dominated by government-funded megaprojects and sovereign debt, the evolution of financial markets has introduced municipal bonds, concessional lending, and, more recently, public-private partnerships (PPPs) as key vehicles for infrastructure delivery.

The advantage of these models lies in their ability to leverage private sector capital, expertise, and innovation, while seeking to distribute construction, operational, and demand risks more efficiently between public and private actors. Yet, traditional PPPs and municipal bonds are not without their shortcomings: they frequently encounter regulatory complexity, prolonged negotiations, high transaction costs, and, in many cases, fail to adequately address long-term maintenance or whole-life-cycle risks which is an issue exacerbated in politically sensitive or economically volatile contexts.

Crucially, while new sources of capital have emerged, the investment gap persists with the Global Infrastructure Hub (2019) estimating that only about 60% of global infrastructure needs will be met by 2040 at current investment rates. Researchers increasingly recognize that the core barrier is not simply a lack of investor liquidity or sophisticated financing mechanisms, but a shortage of bankable, well-funded projects coupled with structural constraints in existing financing channels. Addressing the shortfall requires innovative approaches that redefine risk allocation, governance, and the mobilization of both public and private resources, as highlighted by Schooling et al. (2023). This has inspired exploration of modern technology-enabled solutions, as well as calls for funding models that are transparent, flexible, and structurally robust.

2.2.2 Digital transformation in infrastructure finance

The ongoing digital transformation of financial markets has begun to exert a profound impact on infrastructure financing. Emerging technologies, especially distributed ledger technologies (DLTs) and, more specifically, blockchain, are recognized for their potential to enhance transparency, lower transaction and intermediation costs, and increase the efficiency of capital mobilization. Blockchain operates via a decentralized ledger system, allowing for direct peer-to-peer transaction records that are immutable, auditable, and tamper-resistant which are qualities that are especially attractive in high-stakes infrastructure investment environments.

Amidst this transformation, asset tokenization has emerged as a promising application within infrastructure finance. Asset tokenization involves the digital representation of ownership rights whether in the form of equity, debt, or hybrid claims on a blockchain, enabling fractional ownership and creating opportunities for both institutional and retail investors to participate in traditionally illiquid, high-value projects. Proponents argue that tokenization expands the investor base, enhances liquidity via secondary market trading, and improves governance via programmable smart contracts. These attributes are particularly valuable in infrastructure finance, where the high minimum investment thresholds and long-term illiquidity have historically acted as barriers to broader capital participation.

Nonetheless, empirical research demonstrates that tokenized models must contend with substantial regulatory complexity, interoperability challenges with existing financial infrastructure, and a lack of standardization around risk management and investor rights. Further, a critical review by Kreppmeier et al. (2023) and Baum (2021) indicates that while tokenization increases transaction efficiency and lowers entry barriers, it must be underpinned by sound project economics, effective legal frameworks, and credible governance structures.

2.2.3 Application of blockchain and crypto asset tokenization

Recent literature has begun to systematically assess the practicalities and limitations of integrating blockchain-based tokenization and decentralized finance (DeFi) concepts into infrastructure project finance. While initial optimism centered on the democratization of project ownership and the automation of contractual obligations with smart contracts, studies such as Tian et al. (2022) and Tolstolesova et al. (2021) underline persistent hurdles: regulatory uncertainty, operational complexity, limited investor awareness, and the intricate mapping of digital tokens to real-world asset cash flows.

Projects like Singapore's Project Ubin exemplify the government-backed experiments with blockchain for financial and settlement systems, with some early successes in cross-border payments and real-time, decentralized transaction finality. However, even these flagship cases highlight the need for robust identity, compliance, and anti-money-laundering protocols which are factors that remain challenging in large-scale, cross-jurisdiction applications. Literature further suggests that most infrastructure tokenization initiatives to date have used fungible tokens, neglecting the diverse risk and governance needs of different investors, and thus limiting widespread adoption.

2.2.4 Role of stakeholders and the Evolution of Layered Models

Modern infrastructure finance increasingly acknowledges that successful innovation hinges not only on the structuring of capital, but also on the effective engagement and alignment of diverse stakeholders such as developers, operators, investors, regulators, and affected communities. Stakeholder misalignment often precipitates governance deadlocks, conflicts over risk-sharing, and suboptimal outcomes in social and environmental performance. Thus, frameworks for digital finance and tokenization must be embedded within layered governance and risk allocation models that integrate technical, financial, and regulatory perspectives.
The concept of layered finance, as articulated by Betz (2014), and its modern iterations in blended finance and financial automation stratifications, provides a theoretical foundation for these new frameworks. By organizing financial flows across distinct legal and functional layers such as core banking, data analytics, process automation. These models facilitate modularity, risk compartmentalization, and enhanced auditability.

2.2.5 The Layered Flow Model

To overcome the challenges faced in integrating blockchain and asset tokenization models in infrastructure financing, this study uses a layered flow model. Layered capital structures have been commonly used in project finance to allocate risks and returns among different types of investors. Betz (2014) described the concept of layering in a financial structure based on how financial firms borrow money from banks. This creates a layering of institutional finance where the financial unit making an investment may have liabilities of its own. However, its ability to fulfil its obligations depends upon the cash flow it receives from its assets. The middle layer represents the leveraging layer that occurs when the investment income from a debt cannot fully service the loan, and the loan must be refunded. Next, the bottom institutional layer of any financial system comprises commercial banks which derive their capital from depositors and make loans to borrowers. Here borrowers can either be consumers, productive businesses, or financial businesses. Additionally, above the bank layer exists a higher layering of financial institutions, which greatly depends upon the banks for financing.

Recent innovations in layered financing include blended finance approaches that combine public and private capital. Convergence (2019) defined blended finance as the strategic use of development finance and philanthropic funds to mobilize private capital flows to emerging and frontier markets, whereas DFI (2018) defined blended finance as a combination of concessional finance from donors or third parties alongside its normal own-account finance or commercial finance from other investors to develop private sector markets, address the Sustainable Development Goals (SDGs), and mobilize private resources. This approach has gained recognition in infrastructure financing, particularly for large-scale projects with significant social or environmental impacts.

Similar to a layered approach in financing, Subramanyam (2024) noted that financial automation systems can also be organized into three architectural layers. The bottom layer, or the core banking layer, can be used to manage transactions, ledgers, customer accounts, and legacy systems. Despite being the slowest layer to evolve, this is one of the most critical layers of financial automation. The next layer includes the Artificial Intelligence (AI) Analytics Layer, which uses machine learning and predictive models to analyse patterns in spending, detect anomalies, and make credit or risk recommendations in financial transactions. This layer is essential for the consumption of real-time data from both structured and unstructured sources. Finally, the top layer consists of the Robotic Process Automation (RPA) Engine, which governs rule-based execution of routine tasks such as account setup, claims verification, or compliance reporting. This layer can interact with both the AI analytics layer to collect insights and the core systems for accessing financial data. These layers are further connected to each other through secure APIs and managed via instrumentation tools that ensure automated decisions are informed, auditable, and dynamically adaptable. The study claimed that this layered structure can be beneficial in ensuring maintainability, modularity, and high performance while mitigating the risks associated with monolithic system design.

2.2.6 Literature Gap and Future of Transparent Investing

Despite the growing volume of studies on digital innovation in infrastructure finance, systematic empirical validation of tokenized, layered models in practice remains limited. Most existing research focuses on the technical and regulatory feasibility of digital tokens, with far less attention paid to the real-world performance of these structures in risk allocation, investor protection, governance, and secondary market liquidity. In particular, the efficacy of creating token classes mirroring debt and equity tranches, and the integration of these digital instruments into the core SPV and project finance frameworks, remains largely theoretical.

This study seeks to address this critical gap by providing evidence-based insights into the practical application and stakeholder reception of a layered tokenization model tailored to large-scale infrastructure finance. The goal is to move beyond conceptual frameworks and generate actionable knowledge for practitioners and policymakers considering the adoption of blockchain-based instruments in real asset funding and financing contexts.

2.3 Methodology

2.3.1 Research Objectives

This research aims to address three primary objectives:

1. Validation of the Layered Model Framework: Assess stakeholder receptivity and empirical support for the proposed layered model of asset tokenization in public infrastructure projects.
2. Role of Financing Mechanisms: Examine the comparative roles of traditional (e.g., bank loans, bonds) and blockchain-enabled financing approaches in integrating a layered model to enhance infrastructure project viability.
3. Implementation Barriers and Facilitators: Identify practical, institutional, and regulatory constraints and enablers influencing adoption of tokenized financing structures for large-scale infrastructure investments.

The clear separation of these objectives ensures that each aspect of the study provides actionable insights for theory and practice.

2.3.2 Research design

This investigation applies a mixed-methods research design, incorporating quantitative and qualitative components to provide a comprehensive understanding of the feasibility and practical utility of layered tokenization models in infrastructure finance. The study adopts a sequential explanatory design as outlined by Creswell and Creswell (2017), initiating with quantitative data collection and analysis to identify general trends and patterns. This quantitative phase is followed by qualitative interpretation aimed at contextualizing and explaining the statistical findings. Such a design is especially suited for interdisciplinary, emerging topics like blockchain-enabled infrastructure financing, where establishing empirical grounding is crucial before further theoretical refinement.

2.3.3 Survey development and Sampling

Rationale for purposive sampling. The target population comprises a specialized, hard-to-enumerate community (infrastructure financiers, PPP sponsors, project lawyers, blockchain service providers). No reliable sampling frame exists to support proportional stratification by role, sector, or jurisdiction. Consequently, purposive sampling through professional associations, targeted outreach, and snowballing was adopted to maximize subject-matter relevance and feasibility within the study window (Nov 2024–Jan 2025). Bias was mitigated by (i) coverage across roles (see Tables 2.1–2.3), (ii) transparent reporting of response distributions, and (iii) non-parametric statistics suited to ordinal data. Future multi-country replications can employ stratified designs once robust sampling frames exist.

To generate quantitative data reflecting industry perspectives, a structured survey instrument was developed based on the theoretical framework established in prior research. The survey captured demographic information and solicited opinions from key stakeholders regarding various infrastructure financing options and the potential for integrating blockchain and tokenization within these frameworks. Survey questions employed a range of response types, including Likert scales, ranking exercises, and multiple-choice formats, to elicit nuanced and comprehensive feedback.

To ensure content validity, the survey instrument underwent rigorous review by a panel of six experts composed of professionals with demonstrated expertise in infrastructure finance, blockchain technology, and project management. Feedback from this panel led to refinements improving the clarity and relevance of survey questions.

Survey administration was conducted electronically via the Qualtrics platform between November 2024 and January 2025. Participants were recruited through purposive sampling, targeting professionals active in infrastructure finance, blockchain applications, and public-private partnerships. Recruitment channels included professional associations, LinkedIn groups, and direct engagement with relevant companies. Out of 193 invitations, 121 responses were obtained, yielding a response rate of approximately 62.7%. While purposive sampling was necessary to engage a specialized population, the approach may limit the generalizability of findings and introduce potential selection biases, particularly an overrepresentation of early adopters or optimists towards technology. Respondents occupied a variety of roles, including executive, managerial, analyst, advisor, researcher, engineer, and technical specialist positions. Responses with more than 20% missing data were excluded to maintain data integrity, which was further checked via automated Qualtrics functions.

It should be noted that the survey achieved a 62.7% response rate, primarily from professionals with a demonstrated interest in blockchain and asset tokenization. This introduces a sampling bias, as the sample may overrepresent early adopters and technology enthusiasts, potentially limiting the generalizability of the findings to the broader infrastructure finance community.

2.3.4 Data analysis methods

Collected survey data were analysed using both descriptive and inferential statistical methods. To explore differences in perspectives across stakeholder groups, the Wilcoxon signed-rank test was employed, chosen for its suitability with ordinal Likert scale data and for not assuming normal distribution. This test served to identify consensus or divergence on key components of the proposed financing framework.

To assess the construct validity of the survey instrument and by extension, the conceptual layered model survey items were directly mapped to the framework's core components such as token structure, regulatory challenges, investor safeguards, and escrow mechanisms. Internal consistency of scale-based items was evaluated through Cronbach's alpha coefficients, with values exceeding 0.70 considered acceptable, ensuring reliability of responses related to each construct.

This quantitative analysis was complemented by qualitative interpretation aimed at refining the model based on real-world constraints and stakeholder expectations, culminating in the validated conceptual framework (see Figure 2.1).

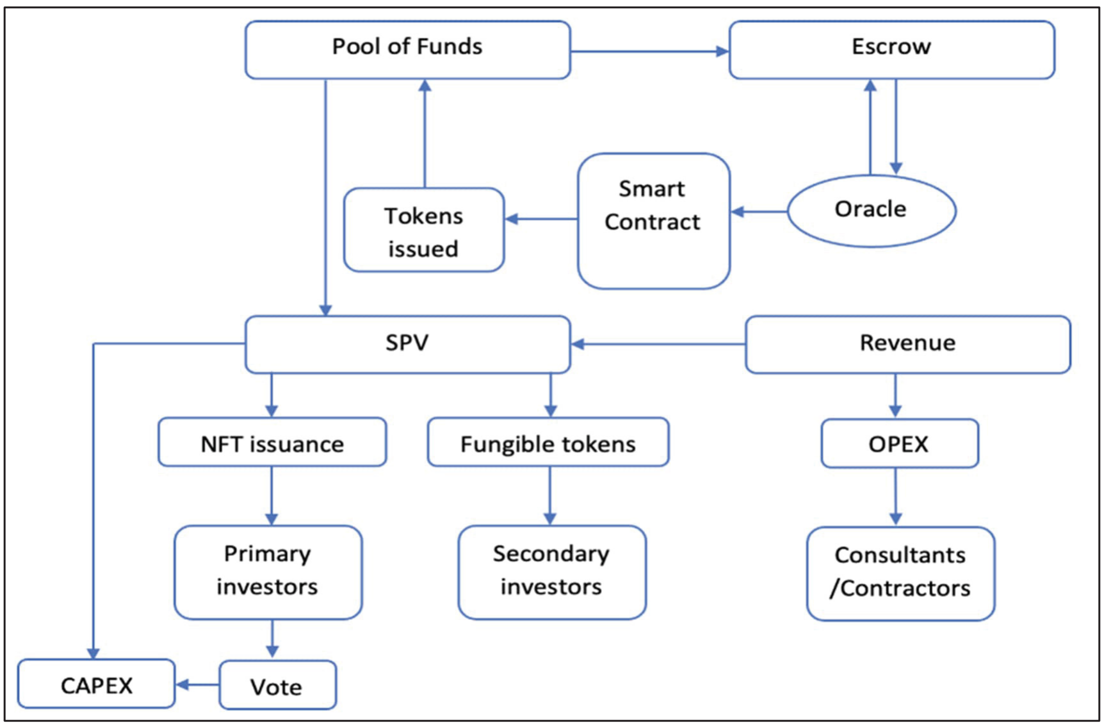

Figure 2.1 Conceptual framework

2.3.5 Limitations

The study acknowledges several inherent limitations. Cryptocurrency and asset tokenization in infrastructure financing constitute relatively nascent fields with evolving regulation and practice, which constrains the breadth of empirical data available. Although efforts were made to include a diverse range of stakeholders, the sample largely represents experts from a single geographic market (North America), limiting the applicability of findings to emerging markets or other regulatory contexts. The purposive sampling and self-selection of participants may result in overrepresentation of technologically enthusiastic or early adopter views. Given the rapid development of blockchain technology and regulatory environments, some findings may lose validity over time or require longitudinal validation.

Despite these limitations, the research presents important empirical validation of theoretical concepts, providing a robust foundation to inform future studies and infrastructure financing innovations.

Future research should aim for more representative sampling, including stakeholders with neutral or skeptical views on digital asset innovations.

2.4 Analysis

The present section contains results from the analysis of survey data. Relevant questions are examined to help inform the design of the infrastructure financing framework. For questions on the importance of a particular framework component, a one-sample one-sided sign-rank Wilcoxon test is used to determine whether respondents tend to find that component fairly important or very important. Specifically, the null hypothesis of the test is that the median response value is 3, corresponding to the “Important” response, while the alternative is that the median response is greater than 3, corresponding to “Fairly Important” and “Extremely Important” responses. Rosenthal’s (1991) correlation coefficient is used as an estimate of the effect size, with Cohen’s (1988) guidelines used to distinguish between small, moderate, and large effects. The R code used to conduct the analysis is provided in Appendix A.

2.4.1 Overview of the sample

Firstly, an overview of the sample is provided to assess the relevance of the participants’ characteristics to the study’s research problem. Overall, around two thirds of the sample work in management (Table 2.1).

Table 2.1 What is your role/position?

Single select option	Count	Response Percent
Executive/Management	81	67%
Analyst/Advisor	23	19%
Researcher/Academic	4	3%
Engineer/Technical Specialist	5	4%
Other (key in)	8	7%

The sample distribution with respect to position suggests that the data can be useful to addressing the study's objectives. This is further supported by the data on the participants' years of experience in infrastructure financing (Table 2.2).

Table 2.2 How many years of experience do you have in infrastructure financing?

Single select option	Count	Response Percent
<1 year	8	7%
1–3 years	24	20%
4–10 years	52	43%
11–20 years	31	26%
20+ years	6	5%

The majority of the sample (73 percent) has at least four years of experience in infrastructure financing, while 31 percent has at least 11 years of experience. As such, the respondents' knowledge should be sufficient for informing the design of the framework.

All participants work in the North America region, making their experience particularly relevant for the case of Canada, such as possible regulatory challenges posed by the Canadian Securities Administrators (CSA) and Quebec's Autorité des marchés financiers (AMF). Table 2.3 further illustrates the respondents' experience with blockchain.

Table 2.3 Have you worked with tokenisation or blockchain-based financing in infrastructure projects?

Single select option	Count	Response Percent
Yes	78	64%
No	43	36%

Almost two thirds (64 percent) of the sample have worked with tokenization or blockchain-based financing in infrastructure projects. As such, sample characteristics appear to be appropriate for the context of the present study.

2.4.2 Sources of financing

Next, the experts' views on traditional sources of financing are explored. This can be valuable for establishing a baseline for the importance of certain approaches to financing, as well as understanding the perceived challenges and incentives for adopting a more traditional approach to financing infrastructure projects.
Table 2.4 summarises the participants' views on the role of government subsidies.

Table 2.4 How important do you consider government subsidies in initiating large-scale infrastructure projects?

Single select option	Count	Response Percent
Not important	2	2%
Somewhat important	20	17%
Very important	48	40%
Essential	46	38%
Depends if required to make the project rewarding	5	4%

Overall, the vast majority (78 percent) of the sample consider government subsidies to be very important or essential in initiating large-scale infrastructure projects. This indicates that simply shifting toward private investors is not sufficient, which may possibly reflect the need to consider a shift in structures and financing platforms instead, in line with the proposed framework.

This view is further supported by the participants' beliefs about challenges associated with government subsidies (Table 2.5).

Table 2.5 In your experience, what are the most significant challenges in securing government subsidies for infrastructure projects?

Multi-select option	Count	Response Percent
Insufficient financing availability	44	36%
Complex application processes	45	37%
Lack of government support for specific sectors	47	39%
Political or bureaucratic delays	52	43%
All of the above	34	28%

In general, there is a relatively uniform distribution across the examined challenges, with 43 percent of the sample viewing political or bureaucratic delays as the most significant challenge, followed by lack of government support for specific sectors (39 percent), complex application processes (37 percent), and insufficient financing availability (36 percent). These results indirectly indicate that securing government subsidies may be an issue of the choice of investment vehicle and underlying relationships between different stakeholders.

Bank loans are also considered important in financing infrastructure projects (Table 2.6).

Table 2.6 How effective are secured bank loans in covering infrastructure project financing gaps?

Single select option	Count	Response Percent
Not effective	2	2%
Somewhat effective	31	26%
Effective	37	31%
Very effective	29	24%
Extremely effective	22	18%

The majority (72 percent) of the sample considers secured bank loans to be effective in covering infrastructure project financing gaps. A major role in large infrastructure projects is also played by private equity and institutional investors (Table 2.7).

Table 2.7 What role do you see private equity or institutional investors playing in large infrastructure projects?

Multi-select option	Count	Response Percent
Primary financing source	72	60%
Risk-sharing with other stakeholders	62	51%
Secondary or supplementary financing source	62	51%
Providing expertise and governance support	44	36%

The majority of participants (60 percent) view private equity or institutional investors as the primary financing source. Around half (51 percent) of the respondents perceive private equity or institutional investors to play a role in risk-sharing with other stakeholders and serving as a secondary or supplementary financing source.

Table 2.8 explores potential incentives to attract private sector investment in infrastructure projects.

Table 2.8 What incentives or guarantees are most effective in attracting private sector investment?

Multi-select option	Count	Response Percent
Tax benefits or exemptions	86	71%
Government-backed guarantees	68	56%
Revenue-sharing models	57	47%
Long-term contracts with assured returns	36	30%

Overall, 71 percent of the respondents view tax benefits or exemptions as the most effective incentive in attracting private sector investment. Government-backed guarantees (56 percent) and revenue-sharing models (47 percent) are also considered to be important incentives. These results suggest that the structure of relationships between stakeholders may determine whether private investors would be interested in an infrastructure project, further supporting the view that more transparent and fair structures, such as tokenization-based financing , could be attractive to outside investors.

2.4.3 Tokenization: linking on-chain and off-chain information

The next framework component to be considered is the link between available funds and token prices, which would be achieved through as escrow account linked to smart contracts through a blockchain oracle. The attractiveness of this structure from the experts' point of view is explored in the following questions.

The general attitude towards tokenization as a financing tool for infrastructure projects is positive (Table 2.9).

Table 2.9 How promising do you find tokenization as a financing tool for infrastructure projects?

Single select option	Count	Response Percent
Not promising	3	2%
Slightly promising	13	11%
Promising	30	25%
Fairly promising	41	34%
Very promising	34	28%

Overall, a significant proportion of the respondents found tokenization to be moderately or very promising. In particular, 34% responded that tokenization was "Fairly promising", while 28% viewed that it was "Very promising". Wilcoxon test was used to determine whether the respondents viewing tokenization as being very or fairly important reflects the average view. The results suggest that this effect is significant at the 0.001 level (Table 2.10).

Table 2.10 Wilcoxon signed rank test and effect size

Wilcoxon signed rank test with continuity correction			
Item	**Statistic**	**p-value**	**Effect size**
Q14	3609.5***	0.000	0.578
Q21	4074.5***	0.000	0.737
Q29	3296.0***	0.000	0.671
Q30	3453.0***	0.000	0.660
Q31	3148.0***	0.000	0.629
Q32	3448.0***	0.000	0.659
Q33	361.0	1.000	0.626
Q34	2968.0***	0.000	0.541
Q35	3174.5***	0.000	0.648
Q36	242.5	1.000	0.682
Q37	3052.0***	0.000	0.623
Q38	2881.0***	0.000	0.523
Q39	3792.5***	0.000	0.658
Q40	267.5	1.000	0.610

Notes: Wilcoxon signed rank test with continuity correction:

Null hypothesis: data is distributed with median $\mu=3$

Alternative hypothesis: data is distributed with median $\mu>3$ (corresponding to "Fairly Important" and "Extremely Important" choices)

*** $p<0.001$

Regarding the strength of the effect, the estimated effect size is 0.578, which corresponds to a large effect. To sum up, the results of statistical hypothesis testing support the view that tokenization is sufficiently promising to be used as a basis for the proposed framework. Comparisons between tokenization and its alternatives are summarised in Table 2.11.

Table 2.11 Would you consider tokenization a viable alternative to traditional methods for raising funds?

Single select option	Count	Response Percent
Yes, it offers significant advantages	55	45%
Yes, but only for specific types of projects	39	32%
No, traditional methods are more reliable	12	10%
No, tokenization is not practical for large projects	7	6%
Unsure	8	7%

Overall, the majority of the sample (77 percent) views tokenization as a viable alternative either for specific types of projects or for all projects. This further supports the viability of rooting the proposed framework in asset tokenization.

While the respondents agree that tokenization is a promising means of financing new infrastructure projects, they also acknowledge its drawbacks (Table 2.12).

Table 2.12 What are the primary challenges you foresee in implementing tokenization for infrastructure financing?

Multi-select option	Count	Response Percent
Regulatory and legal uncertainties	51	42%
Lack of investor awareness or trust	57	47%
Difficulty in integrating with existing financial systems	52	43%
Technological complexity	42	35%
All of the above	17	14%

Key challenges related to asset tokenization include lack of investor awareness or trust (47 percent), difficulty in integrating with existing financial systems (43 percent), and regulatory and legal uncertainties (42 percent). Regarding regulatory challenges, key issues are expected to arise from financial regulations and data protection laws (Table 2.13).

Table 2.13 What challenges do you foresee in complying with regulatory requirements for tokenized assets?

Multi-select option	Count	Response Percent
Financial regulations	57	47%
Maintenance regulations	32	26%
Data protection laws	47	39%
All of the above	34	28%

Having established the general attractiveness of asset tokenization as a possible alternative for financing infrastructure projects, it is important to consider whether the proposed framework of linking on-chain and off-chain information is positively viewed by the experts. This problem is examined in Table 2.14.

Table 2.14 How would you rate the importance of having an escrow account linked to smart contracts to ensure that the value of the token always reflects the pool of funds used for financing the infrastructure project?

Single select option	Count	Response Percent
Not Important	1	1%
Slightly Important	7	6%
Important	37	31%
Fairly Important	50	41%
Extremely Important	26	21%

The participants were asked about the importance of having an escrow account linked to smart contracts to ensure that the value of the token always reflects the pool of funds used for financing the infrastructure project. Overall, a significant portion of the respondents considered this practice important. In particular, 41% responded that it was “Fairly important”, while 31% viewed it as “Important”. The results of the sign-rank Wilcoxon test suggest that this effect is significant at the 0.001 level. Put differently, having an escrow account linked to smart contracts was deemed very or extremely important. Regarding the strength of the effect, the estimated effect size is 0.671, which corresponds to a large effect. To sum up, the results of statistical hypothesis testing support the view that this mechanism is sufficiently important to be included in the framework.

2.4.4 SPV management

The next group of framework components is related to the proposed special purpose vehicle (SPV) for reducing risk, meeting regulatory requirements, and managing infrastructure assets. Table 2.15 summarises the experts' views on the general viability of SPVs for activities such as hiring engineers and entering agreements with contractors.

Table 2.15 How would you rate the importance of having a special purpose vehicle (SPV) for managing the infrastructure assets (e.g. hiring engineers, entering agreements with contractors, etc.)?

Single select option	Count	Response Percent
Not Important	1	1%
Slightly Important	9	7%
Important	35	29%
Fairly Important	39	32%
Extremely Important	37	31%

Overall, a large number of respondents found this practice to be important. In particular, 32% responded that it was "Fairly important", while 31% viewed it as "Extremely important". Thus, these results suggest that using an SPV for asset management was generally considered important. A Wilcoxon test was used to determine whether the respondents tended to view having a special purpose vehicle (SPV) for asset management as being very or extremely important is statistically significant. The results suggest that this effect is significant at the 0.001 level. Regarding the strength of the effect, the estimated effect size is 0.660, which corresponds to a large effect. This supports the view that the SPV approach is sufficiently important to be included in the framework.

Another potential advantage of SPVs is they may help meet regulatory requirements. This would address the regulatory concerns that the participants had, as was discussed above with regards to general views on tokenisation. Table 2.16 presents the results on the perceived role of SPVs in meeting regulatory requirements.

Table 2.16 How would you rate the importance of an SPV for meeting regulatory requirements?

Single select option	Count	Response Percent
Not Important	2	2%
Slightly Important	8	7%
Important	38	31%
Fairly Important	42	35%
Extremely Important	31	26%

Overall, a substantial portion of the respondents found this practice to be important. In particular, 35% responded that it was “Fairly important”, while 31% viewed it as “Important”. The results of the Wilcoxon test suggest that this effect is significant at the 0.001 level. Put differently, utilising an SPV for regulatory compliance was perceived as very or extremely important. Regarding the strength of the effect, the estimated effect size is 0.629, which corresponds to a large effect. Overall, the results further support the view that an SPV-based approach is sufficiently promising to be included in the framework.

Finally, SPVs may also help safeguard the investors in the parent company from being responsible for compensating losses in case of project failure (Table 2.17).

Table 2.17 How would you rate the importance of an SPV in safeguarding the investors in the parent company from being responsible for compensating losses in case of project failure?

Single select option	Count	Response Percent
Not Important	1	1%
Slightly Important	9	7%
Important	35	29%
Fairly Important	40	33%
Extremely Important	36	30%

A significant number of respondents considered this a vital practice. In particular, 33% responded that it was “Fairly important”, while 30% viewed it as “Extremely important”. This effect was found to be significant at the 0.001 level, with the estimated effect size of 0.659, which corresponds to a large effect. To sum up, the results of statistical hypothesis testing support the view that an SPV approach is sufficiently important to be included in the framework.

2.4.5 Simple Agreement for Future Tokens (SAFTs)

A big part of the proposed framework is how it treats primary and secondary investors, naturally leading to the use of both NFTs and fungible tokens. To achieve this, Simple Agreement for Future Tokens (SAFTs) are used for primary investors. However, it is possible that other alternatives, such as ICOs and issue of only fungible tokens, may be appropriate. Firstly, the attractiveness of ICOs for financing infrastructure projects is examined (Table 2.18).

Table 2.18 How would you rate the importance of initial coin offerings (ICOs) in financing infrastructure projects with asset tokenization?

Single select option	Count	Response Percent
Not Important	33	27%
Slightly Important	41	34%
Important	35	29%
Fairly Important	11	9%
Extremely Important	1	1%

Overall, a mixed view emerged regarding the utility of ICOs. In particular, 34% responded that they were only “Slightly important”, with 29% viewing them as “Important”, and 27% viewing them as “Not important”. This indicates a somewhat divided opinion amongst respondents on the usefulness of ICOs for financing infrastructure projects. A Wilcoxon test was used to determine whether the respondents tended to view ICOs as being very or extremely important. The results suggest that this effect is not significant ($p > 0.1$). As such, ICOs are not included as a framework component, reflecting the need to adopt a more complex approach utilising a combination of fungible tokens and NFTs.

One possible reason for the divisiveness of ICOs is that they may put primary and secondary investors on different grounds with regards to transparency and future profits. Table 2.19 summarises the respondents' views on this matter.

Table 2.19 How would you rate the importance of bridging the gap in the rights of primary and secondary investors in infrastructure projects with asset tokenisation?

Single select option	Count	Response Percent
Not Important	2	2%
Slightly Important	13	11%
Important	38	31%
Fairly Important	44	36%
Extremely Important	24	20%

Overall, a considerable portion of the respondents found this to be a crucial consideration. In particular, 36% responded that it was "Fairly important", while 31% viewed it as "Important". Thus, these results suggest that ensuring equitable rights for both primary and secondary investors was generally considered important, which was supported by the Wilcoxon test showing a statistically significant effect ($p < 0.001$). Regarding the strength of the effect, the estimated effect size is 0.541, which corresponds to a large effect. As such, it is important to incorporate into the framework a way to make financing infrastructure projects more attractive to secondary investors.

SAFTs are one possible solution for making primary investors to be treated less preferentially. The results for the corresponding question are summarised in Table 2.20.

Table 2.20 How would you rate the importance of having Simple Agreement for Future Tokens (SAFTs) to guarantee that investors will be given tokens at a later date when the project has been commenced?

Single select option	**Count**	**Response Percent**
Not Important	1	1%
Slightly Important	8	7%
Important	38	31%
Fairly Important	51	42%
Extremely Important	23	19%

Overall, a strong consensus emerged regarding the usefulness of SAFTs. In particular, 42% responded that they were “Fairly important”, while 31% viewed them as “Important”. This indicates a widespread belief in the value of SAFTs for ensuring investor commitments. A one-sided sign-rank Wilcoxon test showed that this effect was significant at the 0.001 level. Put differently, utilising SAFTs to secure future token allocation was perceived as very or extremely important. Regarding the strength of the effect, the estimated effect size is 0.648, which corresponds to a large effect. To sum up, the results of statistical hypothesis testing support the view that SAFT-based financing is sufficiently important to be included in the framework.

Another possible choice in designing the framework is the decision to include NFTs. As mentioned in the literature review, previous tokenization projects tended to limit themselves to fungible tokens, which might have harmed the attractiveness of these projects to secondary investors. Table 2.21 explores this issue from the viewpoint of the surveyed experts.

Table 2.21 How much do you agree with the following statement: "Asset tokenization involving the issue of only fungible tokens through security token offerings (STOs) is appropriate for financing construction projects"?

Single select option	Count	Response Percent
Strongly Disagree	35	29%
Disagree	42	35%
Neutral/Uncertain	36	30%
Agree	7	6%
Strongly Agree	1	1%

Overall, opinions were divided regarding whether issue of only fungible tokens STOs would be appropriate for financing construction projects. In particular, 35% responded that they "Disagree", while 30% selected "Neutral/Uncertain". This indicates a mixed perspective on the appropriateness of exclusively fungible token offerings for construction project financing. The sign-rank Wilcoxon test showed that this effect was not significant ($p > 0.10$). As such, it can be argued that relying solely on fungible tokens is not sufficient, supporting the proposed framework.

Next, it is directly examined whether the use of a combination of fungible tokens and NFTs is viewed as appropriate for financing construction projects (Table 2.22).

Table 2.22 How much do you agree with the following statement: "Asset tokenization involving a combination of fungible tokens and NFTs is appropriate for financing construction projects"?

Single select option	Count	Response Percent
Strongly Disagree	1	1%
Disagree	9	7%
Neutral/Uncertain	39	32%
Agree	52	43%
Strongly Agree	20	17%

A strong consensus emerged regarding the potential of this hybrid approach. Specifically, 43% responded that they “Agree”, 32% responded “Neutral/Uncertain”, and 17 percent responded “Strongly Agree”. This generally indicates a belief in the value of combining fungible tokens and NFTs for construction project financing. The results of hypothesis testing showed that the median response corresponds to “Agree” and “Strongly Agree” choices, with the effect being significant at the 0.001 level. Put differently, utilising a combination of fungible tokens and NFTs for project financing was perceived as very or extremely appropriate. Regarding the strength of the effect, the estimated effect size is 0.623, which corresponds to a large effect. To sum up, the results of statistical hypothesis testing support the view that this aspect is sufficiently appropriate to be included in the framework.

2.4.6 Post-token generation event (TGE) stage

The goal of the framework in the post-TGE stage is to ensure fairness in the treatment of different stakeholders, in particular primary and secondary investors. One important consideration is limiting what investors can do with their tokens. Table 2.23 considers the first issue, namely possible “pump and dump” schemes.

Table 2.23 How would you rate the importance of including a mechanism preventing pump and dump schemes in financing infrastructure projects with asset tokenization?

Single select option	Count	Response Percent
Not Important	1	1%
Slightly Important	16	13%
Important	40	33%
Fairly Important	30	25%
Extremely Important	34	28%

Overall, there was a strong feeling that safeguards against manipulative trading practices were essential. In particular, 33% responded that it was “Important”, while 28% viewed it as “Extremely Important”. This highlights the concern among respondents regarding the potential for market manipulation in tokenised infrastructure projects. A Wilcoxon test was used to determine whether such safeguards were viewed as being at least fairly important. The results suggest that this effect is significant at the 0.001 level, with the estimated effect size is 0.523, which corresponds to a moderate effect.

A related issue is the ability of primary investors to stake their NFTs to generate fungible tokens if they want to increase their earnings. In contrast to pump and dump schemes, this approach allows a transparent way for primary investors to capitalise on their position in the financing structure. Table 2.24 contains relevant data on experts' views.

Table 2.24 How much do you agree with the following statement: "Primary investors should be restricted in staking their NFTs to generate fungible tokens if they want to increase their earnings"?

Single select option	**Count**	**Response Percent**
Strongly Disagree	25	21%
Disagree	42	35%
Neutral/Uncertain	45	37%
Agree	8	7%
Strongly Agree	1	1%

Opinions were quite varied on this matter, suggesting a nuanced perspective on investor incentives. In particular, 35% responded that they "Disagree" with restricting primary investors in this context, while 37% selected "Neutral/Uncertain". This indicates a general reluctance to impose limitations on primary investor earnings through NFT staking. The results of hypothesis testing suggest that this restriction should not be included in the framework ($p > 0.10$).

Another consideration is the ability of primary investors to convert their SAFTs to NFTs to give them voting rights on future capital expenditures, which is explored in Table 2.25.

Table 2.25 How would you rate the importance of the primary investors being able to convert their SAFTs to NFTs to give them voting rights on future capital expenditures?

Single select option	Count	Response Percent
Not Important	2	2%
Slightly Important	9	7%
Important	30	25%
Fairly Important	45	37%
Extremely Important	35	29%

Overall, a considerable proportion of respondents considered this feature to be valuable. In particular, 37% responded that it was "Fairly important", while 29% viewed it as "Extremely important". This suggests a belief that providing primary investors with enhanced governance rights through token conversion is a desirable characteristic. The results from the sign-rank Wilcoxon test supported this view ($p < 0.01$), with the estimated effect size of 0.658 suggesting a large effect. To sum up, the results of statistical hypothesis testing support the view that this aspect is sufficiently important to be included in the framework.

Finally, the importance of including other stakeholders is considered (Table 2.26).

Table 2.26 How would you rate the importance of stakeholder consultation in infrastructure projects?

Single select option	Count	Response Percent
Slightly important	6	5%
Fairly important	38	31%
Not Important	1	1%
Moderately Important	29	24%
Extremely Important	47	39%

Overall, the majority of the respondents found stakeholder consultation to be very important. In particular, 39% responded that stakeholder consultation was "Extremely important", while 31% viewed that it was "Fairly important". Hypothesis testing suggests that this effect is significant at the 0.001 level, with the estimated effect size is 0.737 corresponding to a large effect. As such, other stakeholders should be incorporated, in particular through consultants funded from the project's revenue.

2.5 Discussion

2.5.1 Present Results and Previous Work

The survey results provide strong validation for the proposed layered financing framework. The observed shift from predominantly public sector financing toward increased reliance on private capital aligns with findings by Grimsey et al. (2017). This transition reflects structural limitations and shortcomings inherent in traditional public financing models. While Public-Private Partnerships (PPPs) redistribute risk between public and private sectors (Rybnicek et al., 2020), our findings indicate further structural reforms are necessary to address common PPP challenges such as risk-sharing disputes, governance complexities, and inflexibility (Almeile et al., 2024). Consistent with Schooling et al. (2023), the survey suggests that novel financial resource mobilization and allocation approaches are needed such as approaches that incorporate innovative instruments to deliver flexibility, transparency, and inclusiveness in infrastructure capital mobilization. Our empirical data supports the view that blockchain-enabled layered models are better positioned to accommodate such attributes, especially regarding governance adaptability and enhanced investor participation.

Positive attitudes toward asset tokenization corroborate observations by Kreppmeier et al. (2023), who emphasized that tokenizing real assets reduces minimum investment thresholds and fosters secondary market liquidity. Baum (2021) similarly noted that tokenization expands the investor base by enabling retail participation in infrastructure projects traditionally limited to institutional investors. Our findings align with these perspectives, highlighting a trend tied to blockchain's facilitation of new asset classes, including real estate tokens that promote direct property ownership.

The survey outcomes also concur with Louis et al. (2023), emphasizing the importance of encouraging integration of asset tokenization with blockchain technology within infrastructure financing. Additionally, concerns about investor disengagement and accountability gaps, identified by Tian et al. (2022) in passive-token models, underscore the need for new frameworks that support active investor participation in large, tokenized infrastructure projects. A layered financing approach, as proposed by Betz (2014), appears particularly relevant because its structure accommodates diverse token classes with distinct rights and obligations, resembling traditional equity and debt tranches.

Respondents notably favored a combination of fungible and non-fungible token rights enhanced by staged governance mechanisms, reinforcing the modular and flexible design of the proposed framework.

A key insight from the data is the critically perceived importance of stakeholder management, consistent with Subramanyam (2024), who links robust stakeholder engagement with reduced political and reputational risks and overall project viability. Similarly, Kreppmeier et al. (2023) identified misaligned incentives and communication shortfalls as major sources of stakeholder conflict in projects with significant social or environmental consequences. This aligns with the emphasis of our proposed framework on embedding fairness, transparency, and stakeholder inclusiveness. Our respondents highlighted stakeholder-funded consulting, layered governance, and real-time transparency as essential elements for safeguarding interests in tokenized financial frameworks.

2.5.2 Implications for the Infrastructure Investment Gap

The findings support the hypothesis that going beyond traditional financing such as direct equity and bank loans could increase infrastructure investment by opening access to a broader investor base. This broader participation enables risk diversification across more stakeholders and unlocks substantial underutilized capital market resources. While infrastructure bonds and funds remain significant vehicles, diverse instruments enabled by tokenization can attract fresh investor interest and provide more resilient risk diversification. Currently, infrastructure risk disproportionately falls on banks and public sector guarantees, but the proposed modular framework may reduce concentration by appealing to private sector investors.

Private sector investment can enhance operational effectiveness in infrastructure, where investor behavior directly relates to risk-reward allocations. Poorly structured risk transfers contribute to cost overruns and project failures. For instance, complete government guarantees that fully shield private investors will reduce incentives to control costs and ensure quality. Conversely, too much risk transferred to private actors can misalign incentives, leading to higher construction and maintenance costs due to elevated required returns. Moreover, risks difficult for private investors to insure, such as political instability, increased funding costs or deter investment. Equity sponsors with higher risk tolerance often provide capital during construction or operation, but their premiums affect overall project costs.

Realizing the promise of alternative financing hinges on long-term investors recognizing infrastructure as a distinct asset class. This recognition requires accounting for infrastructure's unique attributes to optimize risk-return trade-offs. A major barrier is the heterogeneity in project structures and the scarcity of standardized data, complicating investor evaluation across jurisdictions and projects. Variation in contractual and regulatory environments further challenges expertise development. Blockchain-enabled asset tokenization, as proposed, could foster data standardization and facilitate easier and more reliable investor assessments and comparisons.

2.5.3 Possible Limitations

It is important to note that the question of the most suitable financing source such as government, banking sector, or capital markets is an oversimplification. Infrastructure projects evolve through multiple phases, each with unique risk-return profiles and incentives. Hence, heterogeneous investor roles and financial instruments are appropriate at different stages. Further research should explore tailoring the layered framework to address stage-specific investor types and risks. For example, planning stages benefit from incentives monitoring, where private participation through tokenization could enhance oversight. Construction stages entail higher risks, requiring equity investors capable of supplemental funding to absorb adverse events. Operational stages generally yield stabilized cash flows and reduced default risk, favoring refinancing bank loans into bonds.

A guiding principle for risk allocation in the framework is to transfer responsibility to private investors only where they have management capacity or insurance options. Political risks, including contract changes by governments, pose challenges given infrastructure's long return horizons. These risks heighten perceived default risk, adversely affecting credit ratings and financing costs. Governments should therefore implement robust mitigation strategies or provide insurance mechanisms to ensure steady cash flow transfers to private investors.

2.6 Conclusion

Infrastructure development remains a critical driver of sustained economic progress globally. Despite significant capital available in financial markets, lagging infrastructure investment continues to pose a substantial challenge for large-scale projects. This gap primarily stems from constraints in reliable and sustainable sources of funding such as user fees, dedicated taxes, or government grants rather than from the availability of financing instruments or investor capital per se. In addition, inefficiencies and limitations in existing financing mechanisms, including skewed risk allocation and limited investor engagement, may exacerbate the problem.

Recognizing these challenges, the present study explored emerging blockchain technology and asset tokenization as innovative financing structures aimed at improving the management and funding of large-scale infrastructure projects. Asset tokenization enables the fractional ownership of traditionally illiquid, high-value assets, thereby broadening access to a more diverse investor base. Blockchain-enabled smart contracts facilitate transparency, security, and transferability of ownership interests, reducing intermediation costs and potentially enhancing trust.

This research sought to bridge the gap between theoretical frameworks and practical application through empirical validation of a previously developed layered model for tokenized infrastructure financing. Survey data from industry stakeholders including investors, regulators, project developers, and blockchain service providers which provided insights into the relevance and feasibility of core model components such as token convertibility, governance tiers, and layered risk allocation. The layered approach was found to facilitate a more resilient distribution of risks and rewards among stakeholders.

The results indicate that tokenized layered financing is perceived as both conceptually sound and implementable by a knowledgeable professional audience. However, this study underscores the need for further applied research, particularly in the form of pilot implementations and regulatory sandbox initiatives, to evaluate real-world performance, scalability, and integration with existing project finance structures.

Future work should also address the dynamic nature of infrastructure project financing across different lifecycle stages, governance challenges inherent to fractionalized ownership, and evolving regulatory frameworks to fully realize the transformative potential of blockchain-enabled infrastructure finance.

CHAPTER 3

ASSET TOKENIZATION IN PUBLIC INFRASTRUCTURE: A STRATEGIC FRAMEWORK FOR BLOCKCHAIN-DRIVEN FINANCING

A. E. Helou [a], G. J. Assaf [a]

[a] Department of Construction Engineering, École de technologie supérieure,
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

Article submitted for publication in *Journal of Ledger Journal*, October 2025

3.1 Introduction

Blockchain technology offers a transformative approach to asset management through asset tokenization, a process that encodes ownership claims of financial assets into digital tokens on a blockchain (OECD, 2020). This enhances transparency, security, and accessibility while enabling fractional ownership, thereby democratizing investment in high-value assets such as public infrastructure projects (Tian et al., 2020). Due to fractional ownership, the relatively high-value assets like big infrastructure projects can be largely financed by several investors whereby such kind of funding opportunities were in the past mostly dominated by institutions and affluent investors (Mougayar, 2016). Asset tokenization makes investment access not centralized, thus increasing pool participation within the capital markets (Silva et al., 2024).

Additionally, asset tokenization goes beyond accessibility by offering significant advantages with respect to the liquidity of financing, allowing for tokens to be exchanged or sold on blockchain markets. This in the long run will attract more investors to finance large-scale projects, increasing flexibility compared to traditional financing structures (Tapscott and Tapscott, 2016). As a result, public infrastructure projects can receive funding more quickly, enhancing capital flow management and supporting the success and longevity of these initiatives (Yu et al., 2024).

Nonetheless, this idea tends to encounter certain challenges when it comes to the actualization of asset tokenization in public infrastructure. In regard to challenges, it is essential to examine the specific problem of the numerous regulations and restrictions under which the tokenized-asset management company operates. Regulatory bodies often classify tokenized assets as securities, subjecting them to stringent compliance requirements (OECD, 2021). While these regulations aim to protect investors, they impose operational and financial challenges, particularly for smaller firms or startups. Addressing these barriers requires clearer legal frameworks that balance investor protection with fostering innovation (Zohar, 2015). This has the effect of constraining innovation, and hence the speed of implementing tokenization in public infrastructure (Carapella et al., 2023).

Besides the foregoing challenges having a regulatory background, the relationships between the parties involved in the provision of funding, especially the developers, funding parties, and the regulatory bodies enhance the complexity of tokenization (BIS, 2024). Every stakeholder possesses specific demands, concerns and tolerance for an acceptable level of risk that may affect his or her activities (Catalini and Gans, 2016). For instance, while investors would care most about the returns on their investments, the project developers may also be interested in the social and environmental impacts of their projects (Tian et al., 2022). Managing these conflicting objectives entails a careful analysis of social relations, which is always helpful in the correct definition of interaction and cooperation between all the participants of the process. On balance, it is crucial to identify the complex nature of the barriers that might hinder the introduction of asset tokenization for infrastructure projects to create a strategy to promote the adoption of the technology. Overcoming regulation challenges and managing relations with stakeholders will help stakeholders build a better context for tokenizing and selling assets for financing public infrastructures. Forthcoming endeavors and discussions, in particular those by means of this paper will be significant to move the discussion forward and deliver the full potential of the existing distributed ledger technology in restructuring public infrastructure financing.

3.2 Background

3.2.1 Asset tokenization

Asset tokenization is defined as the process of tokenizing the ownership of a particular asset either physical or digital and settling it on a blockchain (OECD, 2025). Tokenization can greatly improve liquidity of financing, because tokens can be exchanged at various markets without the participation of third parties (Chung et al., 2023). Tokenization also enhances the overall transparency as through the blockchain: there will be record of ownership as well as the transaction in case of any assets and it is easier to prove the ownership of an asset (Wang et al., 2024). Another advantage of asset tokenization is the fractional ownership, whereby instead of many investors investing individually in an asset, several investors can jointly own an asset (Silva et al., 2024). This can be specifically useful to high end valuables like real estates or infrastructure projects which may lead to total investment being high for the individual investors (Catalini and Gans, 2016). Through this process, asset tokenization makes more investment opportunities possible, allowing many investors to invest in public infrastructure projects (Alamsyah et al., 2024).

As a result, tokenization of assets can improve the access to investments. Conventional investment products always expect high investment and have complex procedures while tokenized assets can be traded anytime on several blockchains, which make them more efficient and convenient in terms of financing liquidity (Chung et al., 2023). Such shift can lead to higher participation from lower-tier investors via retail workers and small companies who did not have a chance earlier (Alamsyah and Syahrir, 2024).

However, the given approach towards the implementation of asset tokenization is not without certain difficulties. Legal matters that include the questions of, how tokens should be classified, how to work with regulations of securities laws and the necessity of a secure and stable technological platform can present challenging obstacles (Avci & Erzurumlu, 2023). Besides, addressing relationship dynamics and achieving clarity about participants' obligations in tokenization becomes a concern for the stakeholders implicated in public infrastructure projects.

3.2.2 Public Private Partnership

Infrastructure funding cannot be overemphasized since more reforms are needed to finance the backlog as well as functioning of social amenities such as transport, water and health facilities (Silva et al., 2024). Yet, these projects face serious financing problems and complicated bureaucratic frameworks, implementing which may take more time and require more money (Grimsey and Lewis, 2004). Therefore, conventional sources for financing transport infrastructure projects in the global economy embrace government funding, with PPPs, and bonds (Singh et al., 2024). As a primary funding source, government funding often relies on public funds and political agendas. For some time, money is spent with reference to political imperatives rather than with reference to the real requirements of infrastructure (Singh et al., 2023). Consequently, the effective and timely funding for crucial activities can fail, which results in degrading infrastructure and missed chances for the economy (Shahmohammad et al., 2024).

There is also the case of public-private partnership which has been favored as a mode of financing. While they offer an opportunity for access to private capital as well as specialized knowledge, these structures are rather intricate and demands time to arrange, which may hamper the launch of initiatives (Yescombe, 2017). Furthermore, the financial risks of PPPs may dissuade some private companies, especially where the regulatory circumstances are uncertain or the expected profits of an investment are unclear (Roehrich & Kivleniece, 2022). Municipal bonds are still used to fund infrastructure projects, as they enable municipalities to sell securities to investors. However, they may be time consuming with substantial transaction costs (Ye et al., 2022). Furthermore, there is uncertainty linked to bond markets because economic crises result in decline in investor interest, and the yields on these bonds become higher for public corporations (BIS, 2024). As such, there is a need to explore more effective implementing instruments in regard to financing of public infrastructure projects. Asset tokenization is one of such solutions as it can open new opportunities to attract more investors (Nassr, 2021). Through tokenization of infrastructure assets, public entities can likely finance their projects at a lower cost than it is possible through traditional sources of funding. Generally, in traditional public infrastructure financing models there are challenges which are difficult to overcome (Weber and Baisch, 2023); at the same time, the cases like asset tokenization likely contain potential in enhancing access to capital and delivery of projects.

3.2.3 Asset tokenization as a solution

The financing of infrastructure projects has traditionally presented a unique set of challenges, including illiquidity, high costs of capital, and limited avenues for broader participation from retail investors (Hamledari and Fischer, 2021). Traditional financing models primarily rely on project finance, public debt, and institutional investment. While this has facilitated numerous large-scale projects, such an approach often struggles to overcome the persistent challenges above (Wu et al., 2025). Asset tokenization offers a potentially transformative approach to infrastructure financing.

One of the most significant obstacles to efficient infrastructure financing is the inherent illiquidity of the underlying assets (OECD, 2020). Infrastructure projects often involve long-term illiquid assets such as roads, bridges, and renewable energy plants, whose value is realized over extended periods (Silva et al., 2024). This lack of immediate liquidity discourages investment, and can significantly inflate the cost of capital (BIS, 2024). While asset tokenization does not directly enhance liquidity of physical assets, it allows for fractionalizing ownership of these assets. These tokens can be traded on secondary markets, providing investors with the flexibility to exit their positions and freeing up capital for reinvestment (Catalini and Gans, 2016). This fosters price discovery and improves market efficiency, potentially attracting a wider range of investors, and reducing the overall cost of financing (Wang et al., 2024).

The high cost of financing infrastructure projects reflects the perceived risk associated with long-term commitments and the complexities of project finance structures (Silva et al., 2024). Asset tokenization offers the potential to reduce this cost by streamlining the investment process and expanding the investor base. Traditional project finance involves a significant layer of intermediaries and complex contractual arrangements, each adding to the overall cost (Tian et al., 2020). Tokenization facilitates direct investment and reduces intermediary involvement, which can lower transaction costs and improve efficiency. Furthermore, the prospect of attracting a broader range of investors, including retail investors, can increase competition for investment opportunities, and put downward pressure on financing rates (Carapella et al., 2023).

Asset tokenization further opens avenues for bringing in retail investors into infrastructure financing, a sector which has been historically dominated by institutional players (Mougayar, 2016). The high minimum investment thresholds and complex structures associated with traditional project finance have effectively excluded smaller investors (Silva et al., 2024). Tokenization dramatically lowers these barriers, enabling individuals to invest in fractional ownership of infrastructure assets with relatively small amounts of capital (BIS, 2024). This increases the pool of potential capital available for infrastructure projects, and fosters a greater sense of public ownership and support for these public goods. The ability to participate in infrastructure projects, previously inaccessible to most individuals, can enhance public understanding of these initiatives, and contribute to their long-term success (Tian et al., 2022).

3.3 Challenges in Asset Tokenization

Despite its potential benefits in streamlining financing, including in public infrastructure projects, asset tokenization has not seen widespread adoption. As such, it is important to establish key challenges, notably legal and regulatory issues, related to Distributed Ledger Technology (DLT)-based financing. This should provide further context for the framework proposed in the present study.

3.3.1 Risk and stability challenges

Asset tokenization introduces new challenges related to systemic risk and financial stability (BIS, 2024), particularly when considering its potential role in financing large-scale public infrastructure (Silva et al., 2024). A primary concern stems from the potential for stress transmission vulnerabilities, which may be more pronounced when the underlying reference assets underpinning the tokenized instruments lack inherent liquidity (Carapella et al., 2023). Assets such as real estate exhibit limited liquidity, making them susceptible to rapid price adjustments during periods of market stress (Carapella et al., 2023). In principle, the increased liquidity within cryptocurrency markets could improve liquidity in financing underlying reference assets (BIS, 2024). However, a reciprocal risk exists where volatility might propagate from the volatile cryptocurrency sphere into the comparatively less liquid markets for financing the project (OECD, 2025). This bidirectional flow of volatility represents a significant challenge for the reliable financing of public infrastructure, where predictable funding and asset valuation are particularly relevant.

A related stability concern arises from the potential for runs on the issuer of tokenized assets (BIS, 2024). This risk is heightened by the inclusion of redemption options within the token structure. Such mechanisms, while intended to offer investor flexibility, introduce parallels with issues observed in collateralized stablecoins like Tether (OECD, 2020). The prospect of similar dynamics occurring within tokenized asset systems presents a challenge to widespread adoption, and especially to the provision of stable financing for infrastructure projects requiring substantial upfront capital and predictable returns (OECD, 2021). The lack of robust and readily accessible information about the issuing entity and its management of collateral may further exacerbate these concerns (Catalini and Gans, 2016).

The differing operational characteristics of cryptocurrency trading venues and traditional asset markets create additional challenges (Carapella et al., 2023). Continuous trading on cryptocurrency exchanges contrasts sharply with the limited operating hours of most traditional asset markets (Tian et al., 2020). This timing mismatch introduces unpredictable implications during periods of stress, as rapid fluctuations in cryptocurrency prices can occur outside of regular trading hours, potentially triggering cascading effects on the underlying reference assets (OECD, 2025). Furthermore, automated margin call mechanisms prevalent in decentralized finance exchanges can trigger rapid liquidations of cryptocurrency tokens, which may then exert downward pressure on the value of the underlying reference assets. The potential for such automated, rapid-fire responses to market shifts poses a significant challenge for the stable financing of public infrastructure, where considered assessment and measured responses are typically preferred (Carapella et al., 2023).

More mature tokenization techniques could lead to tokenized assets themselves becoming reference assets, embedded within both cryptocurrency and traditional financial markets (Silva et al., 2024). If cryptocurrency prices consistently demonstrate higher volatility than their real-world counterparts, these secondary tokenizations could introduce volatility into traditional financial markets, broadening the scope of potential systemic risk (BIS, 2024). The recent examples of tokenized grain used as collateral by Santander, and the initiatives to tokenize the U.S. government money market funds by Ondo Finance, demonstrate the increasing integration of tokenized assets within mainstream financial systems (OECD, 2025). The expanding role of traditional financial institutions, either through direct ownership of tokenized assets or through their use as collateral, may further amplify these effects (OECD, 2021), suggesting that there is a need for a framework that would help mitigate potential destabilizing effects in such areas as public infrastructure projects.

3.3.2 Legal and regulatory challenges

Studying regulations in other industries offers recommendations for successful and unsuccessful approaches to asset tokenization (Pereira et al., 2019). Some jurisdictions like that of the Swiss have embraced the tokenization approach and passed a law that recognizes tokenized assets as such and the rights that come with it. The existing legal framework for ICOs is also the most comprehensive and nuanced: the Swiss Financial Market Supervisory Authority (FINMA) has issued practical guidelines for categorizing tokens into payment tokens, utility tokens, and asset tokens, so that different types can be regulated differently (Lising, 2026). It has defined Switzerland as the center of the blockchain industry, where many startup companies and projects convene. Nonetheless, there are still many barriers to the legal deployment of trading of digital assets, even in relatively liberal locations. For example, technology advances at a much faster rate compared to the rates of law reform, thus giving rise to possible regulatory deficiencies within investors' protection arena (Arumugam et al., 2018). Moreover, legal compliance is likely to be an issue because asset tokenization crosses national borders and may be subject to the laws of several countries with individual standards for the subject projects.

A prevailing characteristic of regulatory frameworks in jurisdictions with active tokenized markets is the adoption of a technology-neutral approach to financial services regulation (OECD, 2021). This stance is exemplified by the regulatory positions of the European

Commission, the UK's Financial Conduct Authority (FCA), and US regulators (OECD, 2025). It dictates that the regulatory assessment of financial products, services, and activities is independent of the technological medium facilitating their delivery. This means the deployment of Distributed Ledger Technologies (DLTs) or alternative technologies does not inherently determine whether a particular financial product, service, or activity falls within the established regulatory perimeter. The capacity of DLTs to enable both the creation of novel tokenized securities and the tokenization of existing securities highlights the significance of this principle (BIS, 2024). In some jurisdictions, tokenized securities are effectively understood as cryptographic-enabled, dematerialized securities, recorded on decentralized ledgers powered by DLTs rather than traditional electronic book-entries held within central securities depositories (OECD, 2021). Viewed through this lens, tokenization in these regulatory environments can be interpreted as a substitution of one digital technology for another, a process occurring within a pre-existing regulatory structure designed without specific technological considerations in mind.

For instance, the FCA explicitly articulates a policy of technological neutrality, and applies this principle to its policy-making concerning crypto-assets (OECD, 2020). Similarly, the Swiss Financial Market Supervisory Authority (FINMA) considers technological neutrality as a core tenet within its framework for regulating FinTech activities, including asset tokenization (OECD, 2021). This approach is echoed by the Polish FSA, whose supervisory position emphasizes a 'substance over form' principle when assessing crypto-assets (OECD, 2021). The European Commission similarly adopts this principle, articulating a core tenet of 'the same activity is subject to the same regulation, irrespective of the way the service is delivered', in its policy guidance on FinTech (OECD, 2025). The European Securities Markets Authority (ESMA) also emphasizes the importance of a technology-neutral approach to ensure that activities and assets with similar characteristics are subject to comparable standards, regardless of their form (OECD, 2021).

The implications of this technology-neutral stance are particularly relevant to the use of tokenized assets to finance public infrastructure projects. While the underlying legal and regulatory frameworks may not be fundamentally altered by the shift to tokenization, the potential to leverage this technology for large-scale infrastructure funding introduces new complexities (BIS, 2024). For example, the ease with which tokenized assets can be created and traded raises questions about investor protection, market integrity, and the potential for regulatory arbitrage (Silva et al., 2024). The technology-neutral approach requires a careful evaluation of the economic substance of the infrastructure projects being funded and the activities of the issuers, rather than a superficial assessment of the technology employed (OECD, 2021). Further, the potential for increased financing liquidity, which is a key appeal of tokenization, must be balanced against the risks of volatility and the need for robust governance structures to ensure the long-term stability of the infrastructure assets and the confidence of investors (Tian et al., 2020). Successful integration of tokenized assets into public infrastructure finance may require application of the technology-neutral principle, combined with a proactive approach to addressing the novel risks and opportunities presented by this emerging market (OECD, 2020). It is this context that guided the development of the present framework, including the proposed approach to escrow through SAFTs.

Regulators have been further gaining experience with DLT-based securities settlement platforms through pilot or proof-of-concept projects, in particular those involving CBDCs (OECD, 2021). Notably, this includes the Helvetia project of the Swiss National Bank and the Digital Securities Sandbox (DSS) in the United Kingdom, as well as CBDC projects in Australia, Thailand, Canada, Germany, and France (OECD, 2025). Globally, regulatory bodies are actively issuing guidance to address uncertainties among market participants regarding the regulatory oversight of tokenized asset activities (OECD, 2020). This proactive approach stems from a need to provide clarity on the scope of regulatory application and authorization requirements within different jurisdictions. For example, the UK's FCA has issued a policy statement on cryptoassets, delineating the circumstances under which specific activities fall under the regulator's purview and necessitate formal authorization (OECD, 2021). Similarly, the Federal Financial Supervisory Authority of Germany (BaFin) has provided clarification concerning certain tokenized assets, determining that specific types represent a distinct asset class as a sui generis designation. This is related to the process of converting non-tradable investments into MiFID-compliant securities through tokenization mandating their classification as securities (OECD, 2025). The common trend is the focus on the economic substance of the transaction rather than the technological process employed. The US Securities and Exchange Commission (SEC), through its FinHub staff, has also published an instructive framework to assist market participants in determining whether a digital asset constitutes an investment contract and, therefore, qualifies as a security (OECD, 2021). The SEC's framework, and subsequent statements, employ the term 'digital asset' to describe assets issued and/or transferred using DLTs, encompassing a broad range of instruments including virtual currencies, coins, and tokens.

The increasing focus on clarifying the regulatory status of tokenized assets holds particular significance for the use of this technology in financing public infrastructure projects. The ambiguity surrounding the classification of tokenized assets can create barriers to investment and hinder the development of robust funding mechanisms for large-scale infrastructure initiatives (Tian et al., 2022). Regulatory clarity regarding the legal and financial characteristics of tokenized infrastructure assets is important for establishing investor confidence and attracting the capital necessary to support these projects (Silva et al., 2024). Furthermore, the determination of whether a tokenized asset represents a security has implications for compliance requirements, reporting obligations, and investor protection measures, all of which are vital considerations for any prospective infrastructure financing model (Tian et al., 2020). The ongoing efforts by regulatory bodies to provide this clarity are therefore fundamental to the successful integration of tokenization into the landscape of public infrastructure finance.

The Canadian Securities Administrators (CSA) and Quebec's Autorité des marchés financiers (AMF) apply a precautionary principle to tokenized assets, particularly those regarded as securities. Similar to the U.S. Securities and Exchange Commission (SEC), they assess whether tokens qualify as securities and if so, require comprehensive compliance with securities laws. These laws aim to protect investors but can impose high compliance costs, particularly for start-ups and smaller issuers.

For instance, the CSA has set guidelines on asset-backed security tokens emphasizing the importance of valuation transparency and disclosure of investors' rights and risks. The AMF in Quebec reinforces these standards regionally, applying specific oversight to ensure that tokenized assets meet both local and federal securities requirements. Although this regulatory approach protects investors, the lack of clear guidelines for tokenized assets sometimes creates legal ambiguities, posing challenges for companies attempting to align with both regional and national rules. These challenges can slow the fundraising process and hinder the launch of projects.

3.4 Methodology

This research employs a systematic literature review alongside a design science research (DSR) methodology to develop a comprehensive infrastructure tokenization framework. By systematically analyzing previous studies and case studies, this approach identifies key regulatory, technological, and market challenges, ensuring a robust and data-driven framework proposal. These challenges have been identified through the systematic literature review.

There are two main objectives of the present literature review. The first objective is to infer a general model of asset tokenization that can then be adjusted to address the study's research problem. This should allow for a better understanding of which components of the model one should focus on in the context of the study. The second objective is, given the current lack of solutions to the examined problem, to identify potentially overlooked directions of research that may be relevant to the problem. Specifically, the potential for primary investors to sell their tokens immediately after issuance may undermine the confidence of secondary investors. Tools that can be expected to be commonly used in the context of asset tokenization, such as smart contracts and NFTs, are not designed to resolve such concerns.

The research articles for the review were selected using criteria provided in the PRISMA flow chart. Its guidelines have been followed in applying the exclusion and inclusion criteria to the identified articles.

Overall, four databases have been searched using the key phrase "asset tokenization". These databases are ScienceDirect, EmeraldInsight, Springer, and IEEE Xplore. The search resulted in 299 articles. After removing articles in foreign languages and filtering out the publications that were not peer reviewed, the total number of articles selected for screening was 162 (Figure 3.1).

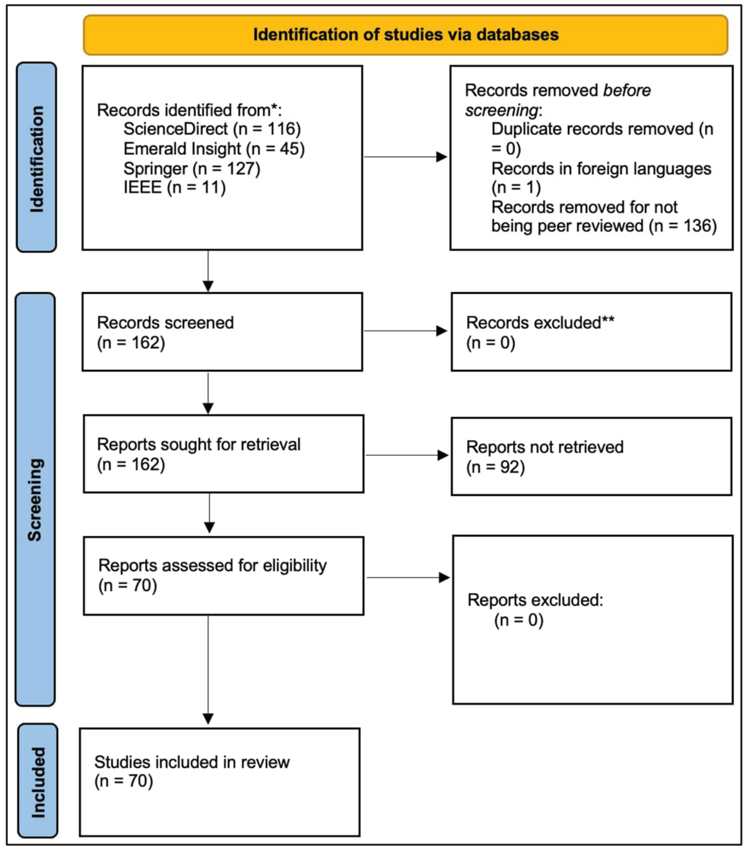

Figure 3.1 PRISMA Flow Chart

In the course of screening, it was possible to gain full access to 70 articles and retrieve them to check for eligibility. In addition to the reviewed research articles, several case studies of recent asset tokenization have been compiled and analyzed to compare how previous projects measure against the conceptual model we propose. The case study analysis along with the systematic literature review allow for addressing the previous challenges and designing a new framework for asset tokenization that would be applicable to infrastructure projects.

The first step involves defining the problems related to asset tokenization, such as funding shortfalls and regulatory complexities. Next, a conceptual framework is developed to map the interrelationships among stakeholders—investors, regulators, project developers, and the community—illustrating how their interactions influence the tokenization process.

3.5 Analysis

3.5.1 Literature Review

The analysis of the reviewed literature uncovered the following themes that help to devise a new conceptual framework for infrastructure tokenization.

Table 3.1 Results of Thematic Analysis of Literature

Theme	References
Smart Contract	68
Fungible tokens	44
NFT	42
Initial Coin Offering (ICO)	38
Oracle	21
Regulatory compliance	17
SPV	9
Escrow	7
Security Token Offering (STO)	6
Public Private Partnership	2
Simple Agreement for Future Tokens (SAFT)	1
Capital expenditure	1

Two relevant results from the literature review were obtained. Firstly, previous studies mainly focused on smart contracts and either fungible or non-fungible tokens separately. The most frequently occurring theme is related to smart contracts. It was present in 68 out of 70 studies reviewed. This is followed by fungible tokens with 44 references, non-fungible tokens (NFT) with 42 references, and initial coin offering (ICO) with 38 references. However, fewer studies have examined such topics as escrow or SAFTs. This may point towards a gap in how blockchain-based financing is typically investigated in the current literature. It is possible that the current lack of a solution to the problem of enhancing the confidence of secondary investors lies not in the lack of depth, but rather the lack of breadth in the existing body of literature. As such, it may be valuable to look into how a hybrid model utilizing such tools as SAFTs and escrow together could be of use in financing infrastructure projects.

Several explanations of this result can be considered. One possibility is the focus of academic research in the field of blockchain on computer science and engineering perspectives. The design, optimization, and security of smart contracts, token standards, and the mechanics of token issuance are natural subjects for these disciplines. In contrast, SAFTs and escrow can be seen as legal contracts that govern the relationship between issuers and investors and the custody of assets during the pre-tokenization phase.

Another possible explanation is the lack of empirical data. The behavior of smart contracts, token prices, and transaction volumes can be extracted directly from public blockchains, providing a rich source of quantitative evidence. In contrast, SAFT agreements are private contracts negotiated between parties, and they are rarely published in a standardized format. Escrow arrangements are also typically documented in legal prose and are not recorded on the blockchain until the release of funds. The lack of publicly accessible data could make it difficult for scholars to conduct systematic analyses of SAFTs and escrow.

Alternatively, the results could be due to the regulatory status of SAFTs, which varies considerably across jurisdictions. In particular, SAFTs may be treated as securities or as investment contract depending on the jurisdiction. Escrow arrangements also differ in their legal enforceability and the conditions under which funds can be released. This heterogeneity complicates comparative studies, potentially discouraging researchers from focusing on instruments that lack a stable legal framework. In contrast, the technical standards for smart contracts and NFTs are relatively more uniform, enabling cross-border research.

In summary, SAFTs and escrow might have been overlooked due to the topic requiring a more multidisciplinary approach, which could be less feasible methodologically.

Secondly, the systematic review of literature on asset tokenization has revealed that the process can be generally divided into the following stages (Figure 3.2):

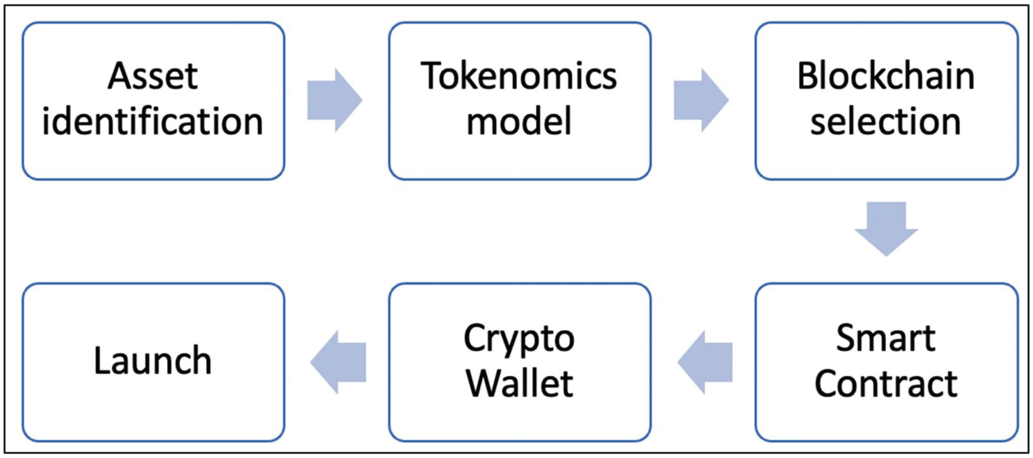

Figure 3.2 Asset Tokenization Algorithm

The model illustrated in Figure 3.2 was obtained by coding each study based on the stages of asset tokenization that were examined and then grouping the codes into specific but sufficiently broad categories that could be used for developing a framework suitable for financing infrastructure projects.

Blockchain technology allows for tokenization of both tangible assets, such as real estate and infrastructure projects, and intangible assets, such as art. While tokenization of real estate, securities, products, and even raw materials have been covered in literature, there is scarce research on the tokenization of large public infrastructure projects. One of the reasons for this is that there is no constantly updated market price of the real-world asset (RWA) that is being tokenized. For tradable assets such as currencies, stocks, bonds, real estate or real estate investment trusts (REIT), the process of tokenization is straightforward and similar to how stablecoins are created. In particular, a piece of code retrieves market prices of the RWA through application programming interface (API) and feeds the data into the blockchain, ensuring that the value of the token in the pool will always be equal to the value of the RWA it is backed by off chain.

Our analysis of the blockchain oracles shows that Chainlink (LINK) accounts for 85% of the total market (Figure 3.3).

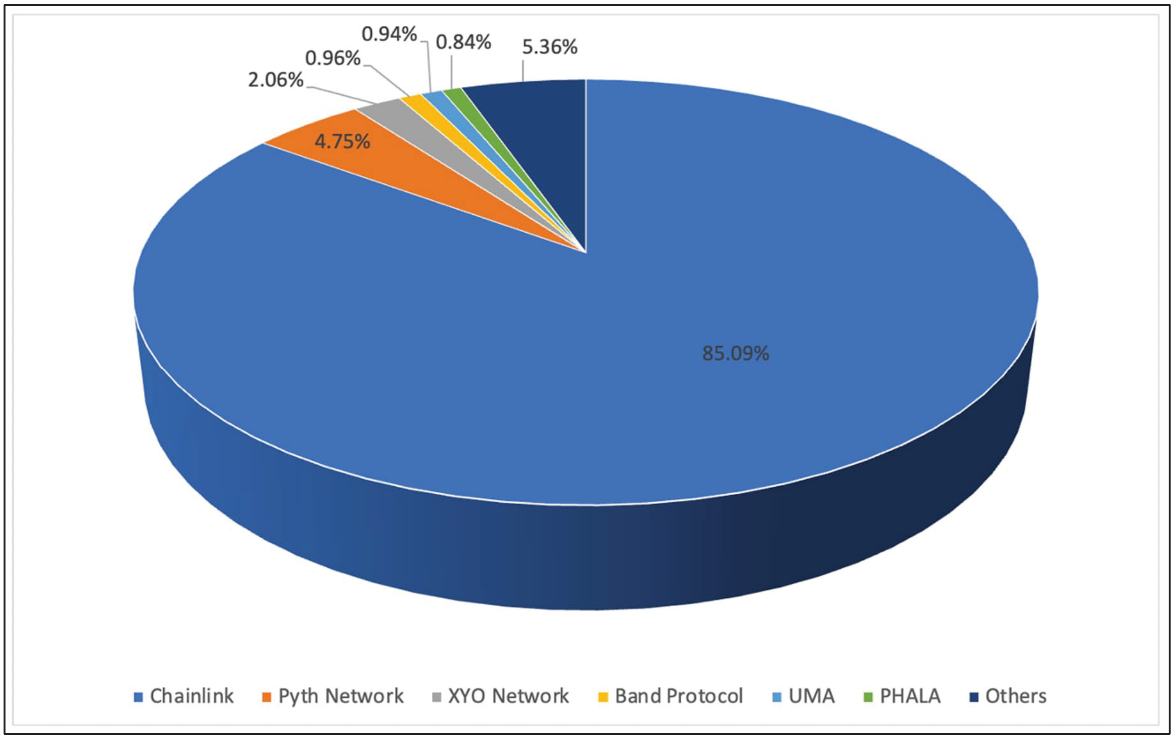

Figure 3.3 Top Blockchain Oracles by Market Capitalization
Author’s analysis based on data from Coingecko

Overall, with large infrastructure assets that do not have market prices that can be retrieved, the main challenge of tokenization is developing an algorithm by which the value of the token will be linked to the value of the RWA. One such framework is developed in the following section.

The rationale for the proposed framework is rooted in the following research gap. While the prospect of fractional ownership and increased liquidity is attractive, a primary concern revolves around the security and value stability of tokens representing RWAs. A frequent objection stems from the potential for primary investors to sell their tokens on secondary markets before the underlying asset has matured or generated sufficient returns, potentially devaluing the asset and disadvantaging subsequent investors. This risk is exacerbated by the historical association of ICOs with instances of investor exploitation and a general lack of regulatory oversight, creating a climate of distrust within the investment community.

The potential for primary investors to profit from early token sales, while leaving secondary investors exposed to the project's inherent risks, presents a fundamental challenge to building a sustainable and equitable tokenized infrastructure financing ecosystem. Secondary investors, who are typically institutional or sophisticated retail participants, demand assurance that the token's value will remain anchored to the underlying infrastructure project and that the liquidity they expect will not be eroded by early exits from the primary tranche. Without mechanisms to mitigate this disparity in rights and exposure, secondary investors may be reluctant to participate, hindering the ability of tokenization to fulfil its potential.

The hypothesis proposed in the present study is that the above concerns can be addressed by delaying token distribution and linking token value to a secured pool of funds. This approach aims to build confidence amongst secondary investors by ensuring a degree of protection against the volatility associated with early-stage token trading and fostering a more balanced relationship between primary and secondary stakeholders. By tying token supply to the actual pool of invested funds, the framework ensures that the token's value is transparently linked to the capital committed to the infrastructure project. This linkage reduces the risk that a primary investor can manipulate token value through early sales, as the token supply remains fixed until the escrow balance reflects the full investment commitment.

3.5.2 Proposed Framework

We propose that the problem of linking token and RWA values should be addressed by introducing an escrow account where the pool of invested funds will be held and a blockchain oracle will be accessing the information on the amount of funds in the escrow account. This information will then be transmitted to smart contracts on the blockchain, which will ensure that the value of the token is always linked to the pool of funds used for financing the infrastructure project. This is illustrated in Figure 3.4.

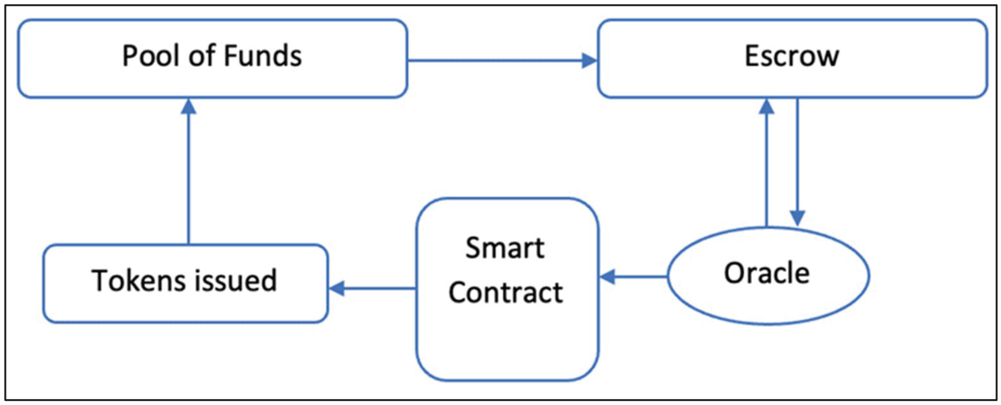

Figure 3.4 Connection between the on-chain and off-chain information

The actual infrastructure assets underlying the tokens are usually managed by a special purpose vehicle (SPV). These are legal entities formed by parent companies for particular projects in order to isolate the risks of the project from the cash flows of the parent company. In other words, if the project fails, the parent company will not be responsible for compensating the losses with its own assets. This safeguards investors in the parent company. However, SPVs are not formed only for risk management purposes. Sometimes, they are required to address specific regulations and are very common in the traditional securitization process. The introduction of the SPV adds another layer in the proposed conceptual model, where an SPV will be managing the infrastructure assets such as hiring engineers, entering agreements with contractors, and engaging in other related ventures that facilitate the completion of the infrastructure project (Figure 3.5).

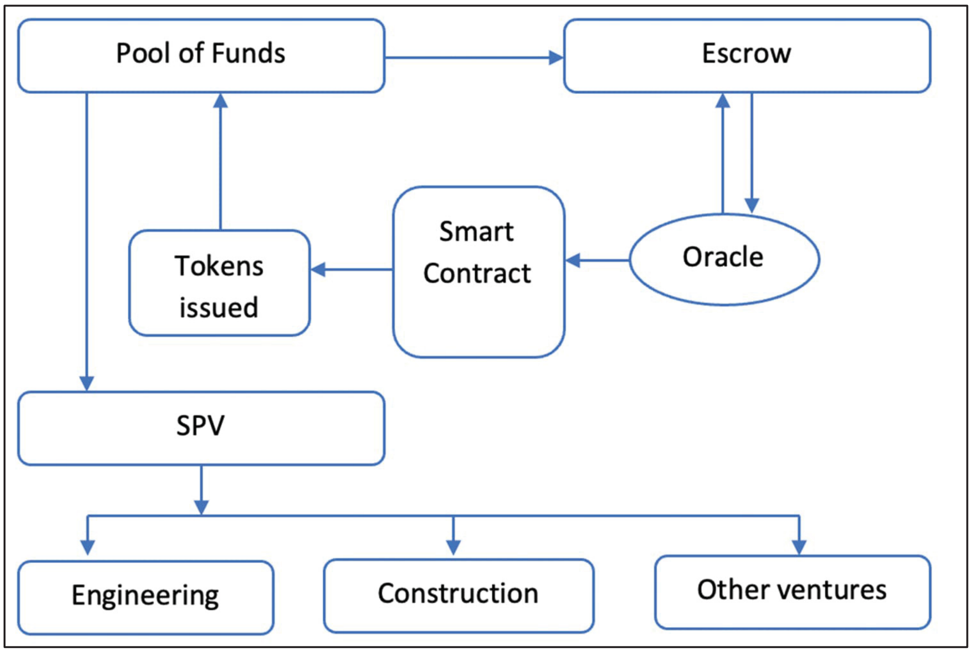

Figure 3.5 Project management by SPV

This design involving SPVs is justified based on the analysis of previous case studies of asset tokenization, such as Smartlands and BrickMark.

Smartlands was one of the early attempts to tokenise large RWAs, namely: real estate and agricultural projects. In May 2019, it tokenized a student accommodation complex, which the company claims was the first piece of property ever tokenized in the United Kingdom that was fully compliant with regulations such as Financial Conduct Authority (FCA) (Smartlands, 2025). However, the company changed its name to Definder in 2021, and its token has not gained significant attention from investors. One of the reasons for the failure could be attributed to the choice of the less popular blockchain Stellar instead of Ethereum and difficulty to achieve compliance with global regulations, which limited the scope of the project.

Another case study applicable to tokenization of large RWAs is BrickMark, which successfully tokenized one of the largest infrastructure projects worth $150 million, allowing for fractional ownership. This piece of real estate was purchased in Zurich, Switzerland. BrickMark used security token offering (STO), similar to Smartlands, as a way to raise capital. This method of financing took into account the local regulatory compliance, unlike unregulated initial coin offerings (ICOs). In contrast to Smartlands, BrickMark used the most popular Ethereum ERC-

20 standard instead of original solutions, which resulted in faster attraction of funding. The investors in the tokens were entitled to fractional ownership in the property as well as the associated rental income and capital gains from price appreciation. While, conceptually, this was no different from traditional asset-backed securities (ABS) as an SPV was created to pool the funds and manage cash flows, it did not require direct management, as all contractual payments were automated through smart contracts. Also, even though BrickMark claims that the deal is one of the largest infrastructure tokenization cases, technically, the traditional securities issued by the SPV were tokenized, suggesting that it is not much different from tokenization of financial assets such as bonds and equities.

A recurring pattern in asset tokenization case studies is the prioritization of primary investors, with secondary investors gaining access only after liquidity pools are established on decentralized exchanges (DEX) or listing occurs on centralized exchanges (CEX). This sequential process creates asymmetries, potentially disadvantaging secondary investors and limiting market inclusivity. Addressing these concerns through fairer distribution mechanisms could improve investor confidence and long-term viability. Secondary investors are skeptical of projects in which primary investors already have large holdings. Therefore, the claimed intentions of asset tokenization to provide affordable fractional ownership to retail investors could be interpreted as a means by which primary investors will have a guaranteed way to exit their investment and reap a profit at the expense of secondary investors. Therefore, a primary problem that should be solved in asset tokenization of large RWAs is equalizing the rights of primary and secondary investors. We propose that this can be addressed by issuing a Simple Agreement for Future Tokens (SAFT). In contrast to ICO, which gained a bad reputation for exploiting investors, SAFTs do not imply the immediate distribution of tokens. Instead, primary investors pool their money in the SPV and receive SAFTs in return, which guarantee that they will be given tokens at a later date when the project has been commenced. In order to prevent the early dumps of the tokens that could destroy the value for secondary investors, SAFTs should be arranged with vesting periods during which the tokens will be locked up. However, we propose that the early-stage primary investors receive SAFT non-fungible tokens (NFTs), which will have unique contract terms for each large investor. On the one hand, this will imply that the investors who invest more funds into the project, rather than being just the first among others, will have exclusive rights. On the other hand, NFTs will be less liquid and should not disrupt the market for fungible tokens distributed to secondary investors. The main reason why NFTs will be rather illiquid is because the regulatory compliance will be more complex compared to the standardized approach used in fungible tokens, and the new owner of the NFT, if an exchange between primary and secondary investors happens, will be subject to regulatory checks, as SAFT NFTs are treated as securities. The conceptual model we propose will then be extended as follows (Figure 3.6).

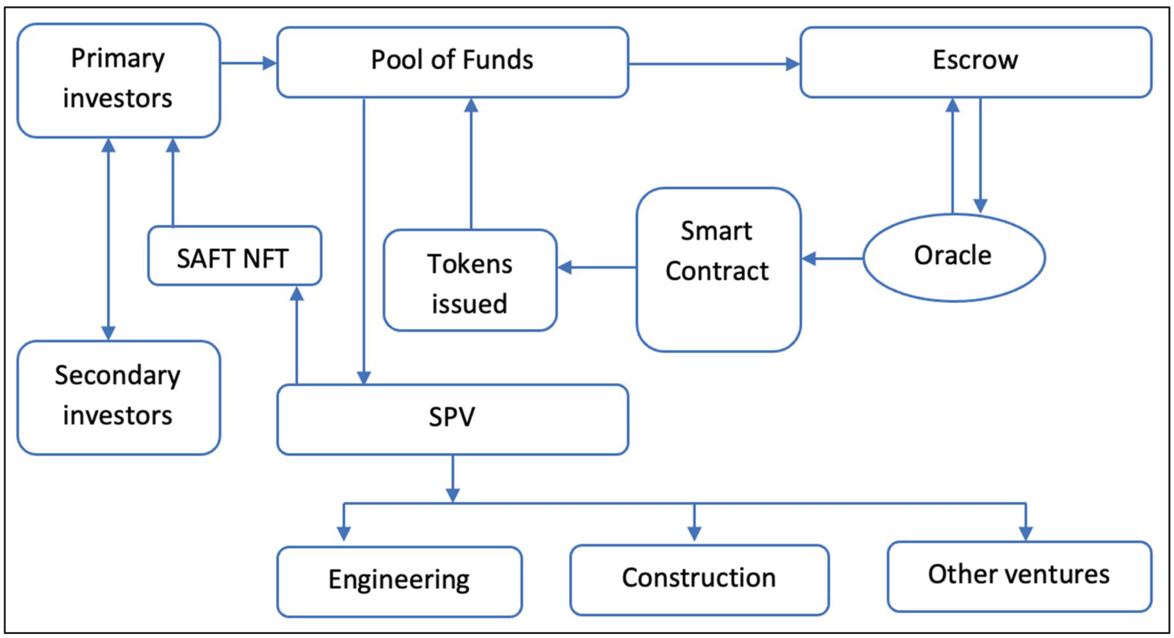

Figure 3.6 Structure of the Initial Round of Financing an Infrastructure Project

This figure illustrates the first round of financing an infrastructure project before it has been commenced. Since many infrastructure projects will involve public-private partnerships, as shown in the literature review, the unique interests of different stakeholders have to be addressed by NFTs, rather than fungible tokens, as each primary investor will make a different contribution to the project and will require different governance rights or profit-sharing rights in return. At the same time, the issuance of fungible tokens will be needed at the next stage to provide fractional ownership to secondary investors. SAFT NFT agreements are signed between the SPV and primary investors. The latter provide their funds to the SPV, and these funds are held in escrow. An oracle connected to the escrow account monitors how the funds of the primary investors are spent on the project construction, and the information is transmitted on the blockchain, where tokens will be issued at the token generate event (TGE). While the participation of secondary investors before the TGE is theoretically possible, as primary investors can exchange their SAFT NFT with secondary investors, in practice their participation is expected to be rare due to regulatory complexities associated with such an exchange. This leads to the second phase of the project after TGE (Figure 3.7).

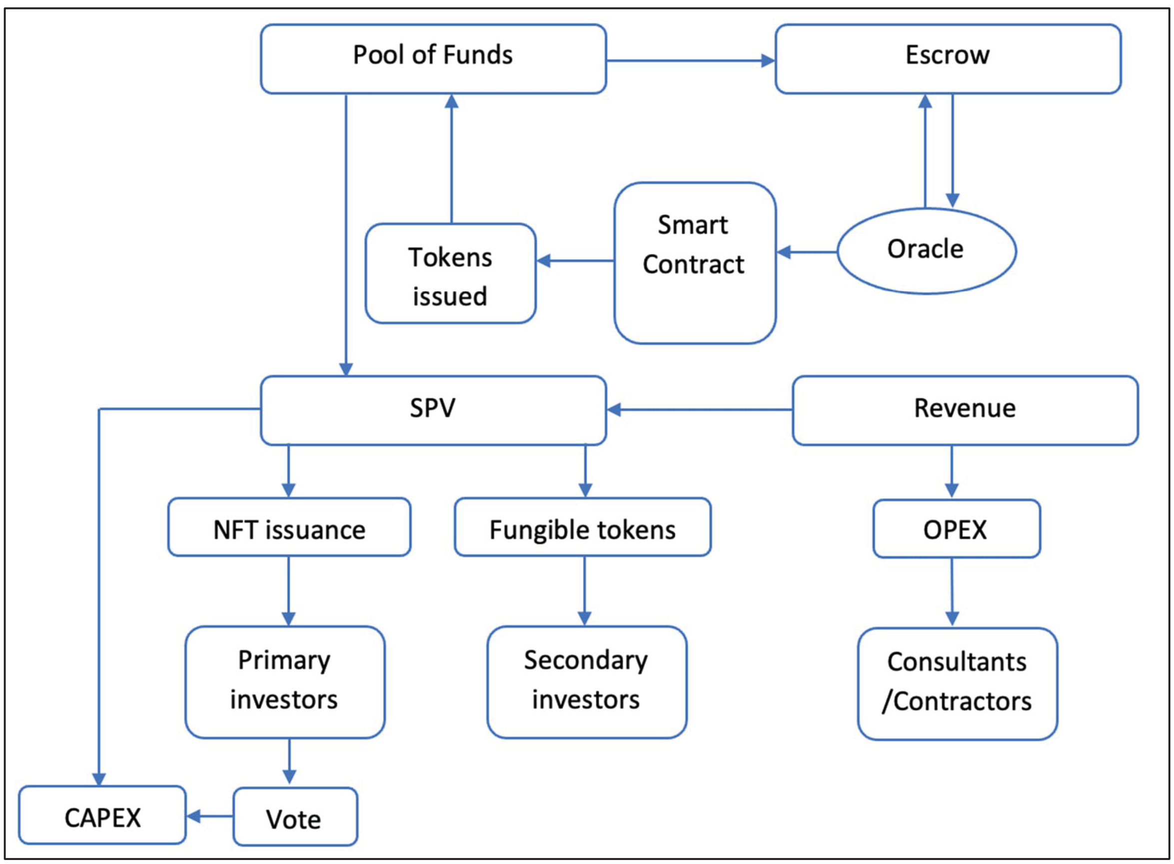

Figure 3.7 Post-TGE Stage

At the TGE, primary investors can convert their SAFTs to NFTs, which give them voting rights on future capital expenditures (CAPEX) of the project and the right to get a share of the company's profit, which is the difference between revenue generated by the project and operating expenses (OPEX). These profits generated are added to the pool of funds and kept in the escrow account, and the information on the changes in the escrow account are transmitted by the oracle through a smart contract to the blockchain. Investors who hold both fungible tokens and NFTs receive a respective share of these profits in the form of tokens. Even though secondary investors do not have the voting rights, they have a fair share in the profit of the project, and the rights of all secondary investors are equal, as their fractional ownership is represented by fungible tokens. Primary investors also do not have the opportunity to dump fungible tokens to manipulate its price and thus exploit secondary investors. At the same time, the smart contract allows primary investors to stake their NFTs to generate fungible tokens if they want to increase their earnings. This will sustain the price of the tokens and benefit both primary and secondary investors, where each party will receive a fair share of the business.

This proposed model has been tested against previous case studies collected for this research, and the results are reported in Table 3.2.

Table 3.2 Project Evaluation Against Previous Cases

Project Name	**Type of Issue**	**Type of Tokens**
Our Model	**SAFT**	**NFT + Fungible**
Centrifuge	ICO	NFT only
Polymath	STO	Fungible
Securitize	STO	Fungible
Tokeny Solutions	STO	Fungible
St. Regis Aspen Resort	STO	Fungible
Lofty	Not disclosed	Fungible
RealT	Not disclosed	Fungible
HouseBit	Not disclosed	Fungible
PO8	Not disclosed	NFT only
Ondo Finance	Not disclosed	Fungible
Tokensoft	STO	Fungible
ADDx	Not disclosed	Fungible
tZERO	STO	Fungible

Among all the recent case studies of asset tokenization reviewed, around half did not disclose the type of token issue, which created information asymmetry between primary investors and secondary investors. Fewer than 10% of the projects raised funding through an ICO, which can be explained by the bad reputation this method gained. However, almost all projects reviewed raised funds through STOs and no project addressed the concerns of investors using SAFT as we propose herein. Also, more than 80% of the case studies reviewed showed that asset tokenization involved the issue of fungible tokens through STOs, and no projects chose a combination of the NFT and fungible tokens as our model suggests. This suggests that our proposition is a novel approach to asset tokenization, which can help projects generate more trust among both primary and secondary investors, ensure strong regulatory compliance through SAFT being treated as securities, and achieve a fair distribution of profits among investors with the mechanism preventing the pump and dump schemes.

3.6 Discussion: Roles and Responsibilities

3.6.1 Understanding the Development Framework for Asset Tokenization

SPV architecture involves several actors with essential roles in asset tokenization implementation and endogenous success factors. Every actor plays a part in overseeing the distinct stages of project implementation, financing, legal requirements analysis, and interaction with the public. It is noteworthy that such cooperation is crucial to achieve the desired climate that supports innovation and sustainable development of public infrastructure.

3.6.2 Project Initiators

Project initiators are usually the public and private organizations that are supposed to implement infrastructure projects. Some of their functions are to define project requirements, obtain funds, and control projects delivery (Kifokeris and Koch, 2020). When it comes to the asset securitization, project initiators play a role to explain new financing concepts such as asset tokenization to potential financiers. They must convincingly explain how tokenization can improve project solvency; expunge funding limitations, and present fractional ownership propositions. Also, the project initiators are responsible for the proper coordination of the action so that the infrastructure projects meet the needs of the market, which depends on the awareness of the community and investors (Le and Hsu, 2021). In fact, they act as a connecting link by narrowing down the gap between the vision behind the project and financial feasibility of tokenized infrastructure projects.

3.6.3 Investors

Another participant for asset tokenization is investors as they bring the necessary funds for funding an infrastructure project. Their participation can include institutions like pension funds, hedge funds, banks and in addition be individual retail investors seeking other investment options. Investors get a chance to invest in infrastructure projects, which would have otherwise been out of their reach due to high capital costs given access to tokenized asset offerings (Laschinger et al., 2024). Such democratization of investment opportunities gives as many people as possible a chance to have an involvement with the financing of infrastructure which could lead to better financing liquidity and therefore better returns. The changes of the investors are not only useful to provide necessary capital for the project, but they also make the project owner feel as if the investor community is involved in the project and should be beneficial for the development of a long-term sustainable infrastructure.

3.6.4 Regulatory Bodies

To address the emphasis on regulations, it is important to balance the discussion by highlighting the benefits and innovations of asset tokenization beyond compliance. While regulatory bodies like the SEC in the USA and AMF in Quebec, Canada play a vital role in establishing legal structures to protect investors, asset tokenization also offers technological and operational advancements that promote accessibility and market efficiency. By providing decentralized ownership, tokenization attracts a diverse range of investors and allows for fractionalized investment in traditionally high-barrier assets. Recognizing both the regulatory safeguards and the transformative potential of tokenization can foster a more comprehensive understanding of its value in modern markets.

3.6.5 Community Representatives

The local people need to be involved in the process of implementation of infrastructure projects. The community representatives act as both the eyes and ears of the community; and represent the interests of the community to the project initiators to ensure that value is delivered to the community (U.S. Department of the Treasury, 2021). The community's participation is essential in addressing those concerns, mobilizing community support, and managing some risks due to project interferences. Community representatives thus stand to make major contributions to open line of communication between projects teams and residents that keep checking that such infrastructural projects are socially constructive and financially sustainable. Their function is vital in the improvement of social acceptability hence increasing the local acceptability to projects hence making it easy to have a more significant number of local stakeholders not to resist the tokenized infrastructure projects hence their long-term success. Knowledge of these roles is vital to knowing how each of them contributes towards the achievement of the SPV's goals as well as the success of the asset tokenization of public infrastructure.

3.7 Discussion: Drivers for Token Holders

3.7.1 Incentives

Token holders are encouraged by several incentives that make participation in tokenized public infrastructure projects desirable. The first of these motivations is the capacity to make profits which is the primary reason that feeds into stakeholder theory. Tokenization makes possible the buying of small portions of large and costly infrastructure projects of a size and value that otherwise would not be accessible in the market. Since these projects create the direct product and service delivery systems, like toll roads, parking lots, service stations, or rental properties, token shareholders can get dividends or profit distributions in direct ratios of their token holdings (Weber and Baisch, 2023). Besides, this financial model brings investment opportunities towards the general public and offers the diverse investors to acquire the positive outcome from the infrastructure development.

Besides the financial returns, the improved liquidity is another factor that encourages token holders. The conventional investment model may involve investments with relatively low financing liquidity, a factor that locks down capital for lengthy durations. However, tokenization improves liquidity through the sale of tokens, by providing a market in which investors can easily sell and buy their stakes (Le and Hsu, 2021). This actively enhances the flexibility of this choice for those investors who enjoy active management of their portfolios, especially granting them the opportunity to change their decisions and accordingly their investments based on the changes in the market conditions.

Community engagement also provides other strong motivation for many the token holders as well. The tokenized projects always seek to engage the local actors in a way that is consistent with the general trend of seeking extra-financial value. Pension funds may also get a morale boost from being able to fund projects that would positively impact society sectors such as transport or energy. Such an implication in community participation can positively impact the investor base and create virtuous cycle leading to incremental investment. Furthermore, a particular investment in certain public infrastructure projects thereof may benefit from tax credits. That is why such benefits can greatly increase the total ROI, thereby making the participation in these tokenized offerings even more interesting for the potential investors (Roehrich & Kivleniece, 2022).

3.7.2 Governance participation

Token ownership participation in governance serves as the most significant motivation for the asset tokenization framework. The most used primary, attending to governance, is the right to vote by the holders of tokens. Most tokenized models have implemented elements of governance by which these holders can affect the future decisions of the project by way of a vote. For instance, token holders can also decide on critical fields such as the amount of money to be spent in the project, the duration of the project, or a change in the project operations. This participatory system enhances the feelings of investors and gives them a greater sense of the projects in which they invest their money to guarantee that their opinions are considered in the decision-making process.

Furthermore, it is also important to understand that the use of the decentralized management system can increase the level of activity of token holders even more. In such models, all decisions are reached through consensus mechanisms involving smart contracts. This structure eliminates interference from any massive stake and delivers fairness and equal representation of interests for clients participating in the project's governance (Tapscott and Tapscott, 2016). Further, the governance participation may help enhance openness and probity in public infrastructure works.

As a result of owning tokens, contributors may request more frequent updates and reports on the implementation of projects' strategies and operations and financial results, which make it more transparent. This makes investors and stakeholders develop confidence in the tokenized initiatives, which is of paramount importance for the success of these initiatives in the long run (Arumugam et al., 2018). Mainly, tokenized PIPs can focus on the financial incentive and governance participation of different investors, which will significantly enhance their sustainability and effectiveness in the end.

3.8 Implications

3.8.1 Appeal to Secondary Stakeholders

Secondary investors may find the proposed framework attractive because it introduces several mechanisms that directly address the principal concerns that have historically limited their participation in infrastructure tokenization. Firstly, the use of an escrow account ensures that the capital contributed by primary investors is held in a secure, transparent repository until the project reaches a defined milestone. By coupling this escrow with a blockchain oracle that reports the balance to on chain smart contracts, secondary investors can verify in real time that the token supply is fully collateralized by the underlying pool of funds. This real time auditability reduces the risk that tokens will be issued without adequate backing, a scenario that has eroded confidence in earlier token sales.

Secondly, the SAFT structure separates the investment phase from the token distribution phase. Primary investors receive a contractual right to tokens rather than the tokens themselves, and the actual issuance is deferred until the project is operational. This deferral mitigates the risk of token dilution that secondary investors might face if primary investors were able to sell tokens immediately upon issuance. Because the SAFT guarantees that primary investors will receive tokens only after the infrastructure project has commenced, secondary investors can be reassured that the token value will be linked to a completed asset rather than to speculative expectations.

Thirdly, the smart contract logic that governs token supply is designed to enforce a one to one ratio between the escrowed funds and the circulating tokens. Should a primary investor attempt to sell tokens before the project is fully funded, the contract can automatically lock or burn the tokens, preventing a sudden influx that could depress the market price. This built in protection against premature token sales creates a more stable secondary market, which is a key determinant of investor confidence.

Finally, the transparency of the entire process from escrow balance to token issuance provides secondary investors with a clear audit trail. The combination of off chain escrow monitoring, on chain oracle reporting, and immutable smart contract rules means that secondary investors can independently confirm that the tokenization process is proceeding as promised. Such verifiable compliance with the agreed terms is likely to reduce the perceived need for extensive due diligence, thereby lowering the barrier to entry for institutional investors who typically require robust risk mitigation mechanisms before committing capital to infrastructure projects.

3.8.2 Potential Conflicts and Dispute Resolution

Though there can be some expected benefits of integration in terms of effective resource sharing, efficient and effective coordination between stakeholders may face hurdles because of conflicting interest targets. For instance, in investing, the major concern is financial rate of return, that is the investment’s ability to generate profit. However, to project initiators, the focus could be on the actualization of social and environmental gains, where the goals are to address community needs and improve on public utility (Atzori, 2015). Such conflict of interest is evident in that project initiators with a social agenda can feel forced to bend the rules to suit investors in search of higher levels of returns.

Regulatory authorities set conditions that reduce the range of possible investments. Such rules while important in safeguarding investors and enhancing the structure of the market hinder investors who want to engage in more flexible investments. These are general regulatory limitations that can limit the possibilities of tokenized assets or put forward strict requirements: here they can potentially decrease the very investment inflows that are meant to be attracted through the tokenization process. It is significant to understand these conflicts in much detail during outlining strategies that not only solve disagreement but also foster synergy between stakeholders.

In the present matter, the core aspects of this dispute resolution framework in the formulation of milestone-based releases of fund. Certain predefined check points would be agreed while entering a project contract which must be completed before any funds are released. In this way, the planning and schedule is developed in such a manner that makes it clear to all stakeholders of a project. The same idea will apply in the project company whereby as each of the above milestones will be reached, a third party like a project auditor or a regulatory authority will validate it as complete before releasing the funds needed for the subsequent milestones. Another layer of supervision is added, which helps in increasing accountability and minimizes the probability of misuse of funds or controversy over its usage. Apart from being clear and free from political influence, such a link between monetary releases and deliverables acts as a disincentive to project promoters who are under pressure to utilize funds as agreed.

Timely and efficient communication with other stakeholders of the dispute regulation system is very crucial. It is expected that the project participants provide frequent updates on the needs of the projects, performance achievements of milestones, and financial transactions. With this commitment, there is the need to ensure that misunderstandings do not happen the way they would when dealing with other stakeholders (Singh et al., 2023). When everybody receives the information, it is hard for controversy to develop in the first place and stakeholders are more likely to be involved. Further, successful transparent communication fosters an environment of responsibility. With this, the performance is disclosed to stakeholders to notify them of both accomplishment and issues throughout the project's lifecycle (Arumugam et al., 2018). This increases the chances of stakeholders avoiding confrontations and promoting negotiations to solve their differences. Consequently, it is imperative to design an appropriate scaling and conflict resolution system, divide the asset tokenization into milestones, and emphasize the importance of disclosure and communication in legal and business relationships for the implementation of public infrastructure projects with asset tokenization. Consequently, through the timely identification of areas of conflict and open communication, all stakeholders can promote the successful attainment of project goals and thus positively advance the overall concept of public infrastructure financing.

3.9 Challenges and Risks

Cross-border compliance. Tokenized claims that convey economic rights in the project should be treated as securities and issued through a project SPV, with a conventional register mirrored on-chain and transfer-restriction logic enforcing offering limits and resale conditions. Compliance is then applied jurisdiction by jurisdiction to primary and secondary distribution (offering exemptions, investor eligibility, resale periods), alongside standard AML/CFT controls, KYC, and secure originator/beneficiary data exchange. This technology-neutral approach recognizes that tokenization changes the settlement rails, not the legal obligations, and lets the SPV interoperate with local regulators, custodians, and market infrastructures.

It is crucial to note that asset tokenization has potential drawbacks and risks for proper evaluation of the possibility of work in the public infrastructure industry. One of the biggest technological challenges that come with using blockchain technology is its compatibility with other systems and functioning (U.S. Department of the Treasury, 2021). Most of the structures for delivering public infrastructure services still use systems that may not necessarily be compatible with the decentralization of blockchain.

The change from a centralized environment to a tokenized environment is about much more than technology – it means a complete change in the organizations' culture and processes. According to Zohar (2015), this kind of transitions is faced with resistance from stakeholders who have always practiced the conventional ways hence the possibility of project alteration and slow implementation is highly probable.

Additional pressures specifically increase the risk related to regulatory obstacles in asset tokenization. Different regulatory authorities, especially those in North America, have strict laws with regards to tokenized assets. The ability of tokens to be classified as securities may result in massive compliance costs and various operational challenges for companies. This issue can prove very cumbersome and requires legal and financial input, an aspect that can be expensive especially for small players or start-ups. These organizations are also challenged by the realities of the regulatory environment especially due to the limited capacity they have in handling compliance issues (Weber and Baisch, 2023). This is because fluctuating regulatory environment creates more risks thereby preventing capable investors from participating in projects with tokenized public infrastructure, thus limiting growth of other tokenization projects.

Market risks on asset tokenization are also factor that should not be underestimated. Fear of loss is always a possibility with cryptocurrencies and tokenized assets as well as their influence may affect the risk perception of a project. Tokenized assets are comparatively more volatile than conventional tools of investment since there exists no benchmark on how an investment should fare or regulatory constrains when issuing securities. Such fluctuation causes a lot of financial risk for investors hence it becomes important for project initiators and investors establish and implement measures aimed at reducing the financial risks involved.

Cybersecurity problems present another particularly daunting threat in asset tokenization. The decentralization itself, which grants the blockchain multiple advantages, can play in favor of malefactors. Both the block chain itself and the surrounding architecture are at risk when it comes to hacking and phishing (Pereira et al., 2019). The nature of the access to data or funds brings concerns among investors and stakeholders as the tokenization of assets require the implementation of sufficient security solutions.

Generally, asset tokenization in public infrastructure projects encounters several obstacles and threats of various nature technological, regulatory, market, and cybersecurity in particular. The idea is to properly solve these problems and create a solid foundation that would work on the development of blockchain technology’s opportunities and, at the same time, maintain the investors’ safety, and project’s credibility. Through active management of these challenges, stakeholders want to increase the probability of positive results in the process of asset tokenization.

3.10 Conclusion

The future of asset tokenization in public infrastructure hinges on advancements in technology, regulatory harmonization, and enhanced investor protections. Future research should further explore decentralized finance (DeFi) integration, adaptive regulatory frameworks, and governance mechanisms that balance accessibility with compliance. These innovations can expand the adoption of tokenized infrastructure financing, making it more sustainable and scalable. For example, innovative developments in the space of DeFi can open new possibilities for both liquidity and financial services oriented to the tokenized public infrastructure projects (Lising, 2026). Through the incorporation of Decentralized finance platforms, stakeholders can develop solutions that enhance auto trading, lending, and yield farming that may attract investors to participate.

There is scope for further research in identifying intermediate regulatory models that could apply to tokenized assets. Thus, the development of the variable mechanisms of regulation that would allow worldwide regulatory bodies to accommodate innovations in the field meeting their interests and maintaining investor protection at a satisfactory level will remain one of the key tasks. Challenges that restrict innovation in tokenized asset markets need to be addressed through cooperation between regulators and industry stakeholders to create a regulatory environment that enables responsible experimentation.

Therefore, additional research in asset tokenization including social aspects of the process in connection with citizens should be conducted. It can help tokenization's stakeholders enhance the overall perception, identify strategies to endorse tokenization for empowering local communities as well as for boosting the public's trust towards the infrastructure projects. Besides, with increased concentration of incentives offered by tokenization on the access to investing, assessing the effect of tokenization on social justice and equality, particularly as it bears on the intended programs and projects, is instrumental in guaranteeing that these initiatives offer favorable effects on society.

Lastly, finance and technology along with public policies will be crucial for future configuration in public infrastructures, asset tokenization particularly. When this interdisciplinary team of academics, professionals, and policymakers become coordinated, asset tokenization can attain its potential for enabling enhanced conditions for public infrastructure financing efficiency, accountability, and accessibility.

CHAPTER 4

APPLYING ASSET TOKENISATION TO THE RAIL INDUSTRY: A CASE-BASED COMPARATIVE ANALYSIS OF THE REM PROJECT

A. E. Helou [a], G. J. Assaf [a]

[a] Department of Construction Engineering, École de technologie supérieure,
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

Article submitted for publication in Journal of International Money and Finance, November 2025

4.1 Introduction

Traditional methods of funding, including government grants, municipal bonds, and public-private partnerships, have historically been considered essential for successful infrastructure development (Rybnicek et al., 2020). However, these approaches often face difficulties related to limited capital, lengthy administrative processes, mismanaged risk, and low levels of investor involvement (Lubu et al., 2023). Large-scale infrastructure projects, or megaprojects, require substantial resources and significant initial capital expenditure. Government efforts to allocate budgets effectively have not eliminated the challenges associated with building and maintaining these projects. Changes in the economic environment have made it difficult for public bodies to manage high costs within restricted budgets. Consequently, more public agencies are seeking alternative, cost-effective financing options.

The Réseau express métropolitain (REM) represents one of the largest urban rail projects currently underway in North America. Its financing structure is complex, involving a mix of equity from the Canadian Infrastructure Investment Corporation (CDPQ Infra) and the Government of Québec, a senior loan from the Canadian Investment Bank (CIB), and ancillary contributions from Hydro Québec and the Autorité régionale de transport métropolitain (ARTM). While this arrangement has enabled the project to move forward, the resulting cost of equity and the limited availability of traditional institutional capital may suggest that this model could be improved upon.

Digital asset technology has emerged as a potential mechanism for broadening access to infrastructure investment (Laschinger et al., 2024). Tokenisation, the process of representing an asset or a share of an asset on a blockchain, offers the possibility of attracting a wider range of investors, including retail participants, and of providing greater liquidity for holders (Carapella et al., 2023). In the context of large infrastructure projects, tokenisation could reduce the cost of capital by diluting the ownership of existing investors and by introducing a new class of investors that is priced at a lower required return (OECD, 2020).

However, the implementation of asset tokenisation in public infrastructure faces obstacles. A key issue is the complex regulatory environment in which tokenised asset management companies operate. Regulatory bodies often consider tokenised assets to be securities, which means they are subject to strict rules (OECD, 2021). While these rules are intended to protect investors, they can create difficulties for companies, especially smaller firms and new businesses. To overcome these problems, clearer legal guidelines are needed, balancing investor protection with the encouragement of new ideas (OECD, 2025). These limitations can slow down the introduction of tokenisation in public infrastructure.

Despite the growing interest in tokenised infrastructure finance, there is a lack of systematic analysis of its economic impact on projects of the REM's scale. Existing studies tend to focus on the regulatory or technical aspects of tokenisation, rather than on its financial implications (Helou and Assaf, 2024). This study seeks to fill that gap by applying a discounted cash flow framework to evaluate different tokenisation scenarios for the REM. Specifically, the present study aims to assess the potential of asset tokenisation to improve financing options for the REM project. The research explores whether tokenisation can offer a more efficient and attractive funding model for large-scale infrastructure developments. The study employs discounted cash flow (DCF) analysis to compare traditional financing approaches with two tokenisation scenarios. Furthermore, the research incorporates qualitative data gathered through interviews with industry experts. This provides valuable insights into the practical considerations and potential challenges associated with implementing asset tokenisation in the rail sector.

4.2 Literature Review

4.2.1 Financing large infrastructure projects

Securing adequate funding is a key element in the successful planning and completion of major infrastructure developments. Financing details reveal where the money for construction and operation will come from and provide project leaders with an understanding of available resources (Roehrich & Kivleniece, 2022). Financing also involves the methods used to manage cash flow to build the infrastructure and provide services to users. Historically, these large projects have relied on both government and private investment. However, there has been a noticeable change in how infrastructure is financed. Previously, projects were largely funded by the public sector; now, private capital plays a more significant role.

Despite the increasing use of private investment, traditional public-private partnership (PPP) models have certain drawbacks. This includes complicated negotiations, disagreements over risk-sharing, governance problems, and difficulties in allocating risk (Almeile et al., 2024). Transaction costs and a lack of flexibility have also been identified as limitations (Grimsey and Lewis, 2004). Private investors often view infrastructure projects as risky due to the time it takes to recover their investment, potential political interference, and unclear regulations. This reluctance limits their involvement in large infrastructure projects across both wealthier and less developed nations.

4.2.2 Infrastructure financing and digital transformation

The shift towards digital financial markets presents new possibilities for funding infrastructure projects (Singh et al., 2023). Developments in financial technology have noticeably affected how infrastructure projects are financed. Digital finance may improve the efficiency and accuracy of financial processes through better systems and data management. It can provide new sources of funding and help make more informed financial decisions. Integrating digital finance may also help overcome difficulties related to expanding sustainable finance, such as a lack of information sharing between investors and local communities (Singh et al., 2024).

Within digital finance, distributed ledger technologies (DLTs), and particularly blockchain, are seen as possible drivers of innovation (Alamsyah and Syahrir, 2024). DLTs typically use a peer-to-peer system, which allows for the simultaneous recording of transactions in several locations. This allows computers to share information directly, without needing a central authority (Kifokeris and Koch, 2020). Blockchain, the most well-known technology in this area, uses DLT to create a secure, reliable, and open system that can lead to new business solutions (Alamsyah et al., 2024). Blockchain can create new financial tools and methods to resolve traditional market problems by increasing openness and reducing the need for intermediaries, which lowers costs (Le and Hsu, 2021). Because of these qualities, blockchain has attracted considerable interest from financial organisations, energy companies, technical experts, governments, and researchers.

4.2.3 Asset tokenisation

Asset tokenisation involves converting ownership rights of an asset into digital tokens recorded on a blockchain (Avci & Erzurumlu, 2023). This process can significantly increase the ease with which assets can be bought and sold. Tokens can be traded across different markets without needing intermediaries. The process of converting assets into digital tokens can broaden access to investment opportunities (Carapella et al., 2023). Traditional investment options often require substantial capital and involve complicated processes. Tokenised assets, however, can be bought and sold at any time on various blockchain networks. This makes them a more effective and accessible means of raising funds (OECD, 2020). This change has the potential to encourage participation from a wider range of investors, including those working in retail and smaller businesses who previously lacked opportunities.

4.2.4 Asset tokenisation in infrastructure finance

Infrastructure projects frequently involve assets, such as roads, bridges, and renewable energy facilities, that generate value over many years (Singh et al., 2023). This lack of immediate liquidity can discourage investment and increase borrowing costs. Asset tokenisation does not make the physical assets themselves more liquid. However, it allows ownership to be divided into smaller units, represented as tokens (Carapella et al., 2023). These tokens can then be bought and sold on secondary markets. This gives investors more options and allows them to sell their investments when needed, releasing capital for new projects (Pereira et al., 2019). This process can also help establish fair prices and improve market efficiency, potentially attracting a broader range of investors and lowering overall financing costs.

The expense of funding infrastructure projects is often high because of the perceived risk involved in long-term agreements and the complicated nature of project finance. Asset tokenisation may help to lower these costs by making the investment process simpler and attracting a wider group of investors (Silva et al., 2024). Traditional project finance typically involves many intermediaries and intricate contracts, all of which add to the overall cost. Tokenisation allows for more direct investment and reduces the need for intermediaries, potentially lowering transaction costs and improving efficiency. A larger group of investors, including individual investors, may be attracted to infrastructure projects through tokenisation. This increased competition for investment opportunities could lead to lower financing rates (Tian et al., 2020).

Historically, infrastructure financing has been largely controlled by large institutions (Hamledari and Fischer, 2021). However, traditional project finance often requires high minimum investments and has complex structures, effectively preventing smaller investors from participating. Tokenisation significantly reduces these barriers (Avci & Erzurumlu, 2023). Individuals can now invest in small portions of infrastructure assets with relatively small amounts of money. This expands the potential pool of available capital for infrastructure projects. It may also encourage a greater sense of public involvement and support for these important public services. The ability for individuals to participate in infrastructure projects, previously unavailable to most, can improve public understanding of these initiatives and help ensure their long-term success (OECD, 2025).

4.2.5 Challenges and risks of tokenisation

Asset tokenisation creates new issues regarding systemic risk and financial stability, especially when considering its use in large-scale public infrastructure projects (Tian et al., 2022). A key worry is the possibility of problems spreading quickly. This risk is greater when the assets that back the tokenised instruments are not easily bought or sold (Carapella et al., 2023). While cryptocurrency markets can sometimes offer greater liquidity, there is also a risk that volatility from these markets could affect the less liquid markets used to finance projects.

Another concern relates to the possibility of investors withdrawing funds from the issuer of tokenised assets. This risk is increased if the token structure includes options for investors to redeem their assets (Baum, 2021). While these options are designed to give investors flexibility, they create similarities to problems seen with collateralised stablecoins. The possibility of similar problems occurring with tokenised assets could limit their adoption, particularly for infrastructure projects that require large amounts of initial capital and consistent returns (OECD, 2020).

The growing attention being given to defining the legal status of tokenised assets is particularly important for their use in finance and public infrastructure projects (OECD, 2021). Uncertainty about how these assets are classified can prevent investment and make it difficult to develop reliable ways to fund large infrastructure projects. Clear regulations that outline the legal and financial aspects of tokenised infrastructure assets are needed to build trust among investors and attract the funding required for these projects (OECD, 2021).

4.2.6 Literature gap and tokenisation in the rail sector

Asset tokenisation presents a potentially valuable opportunity in infrastructure finance. Representing ownership of infrastructure assets as digital tokens on a blockchain could greatly improve liquidity. These tokens can be divided into smaller units, allowing a wider range of investors to participate in projects that previously required large initial investments. The transparency and security of blockchain technology may also build investor trust and reduce differences in information availability, which could lead to more accurate pricing.

While research on asset tokenisation is expanding, there remains a limited focus on its application within the rail sector. Existing literature often explores tokenisation in more liquid asset classes, such as real estate or financial instruments. This study addresses this gap by specifically examining the feasibility and benefits of tokenisation within the context of a large-scale infrastructure project, namely the REM. Furthermore, this research provides a quantitative assessment of the financial implications of tokenisation using a real-world case study.

4.3 Methodology

4.3.1 Research objectives

This study investigates the potential of asset tokenisation to improve financing options within the rail industry. Specifically, it examines the Réseau express métropolitain (REM) project in Montreal, Canada, as a case study. The research aims to assess whether tokenisation can offer a more efficient and attractive funding model for large-scale infrastructure developments. To achieve this, the study follows three objectives:

(1) To assess the financial viability of asset tokenisation in the REM project;
(2) To compare equity-based tokenisation and revenue-based tokenisation models for the REM;
(3) To evaluate perceptions of industry experts with regards to tokenisation in large infrastructure projects.

4.3.2 Research design

This study employs a mixed-methods research design, combining quantitative analysis with qualitative data collection to provide a comprehensive assessment of asset tokenisation within the rail industry. The research focuses on the Réseau express métropolitain (REM) project as a case study, allowing for a detailed examination of the potential benefits and challenges. A mixed-methods approach is appropriate because it allows us for exploring both the financial implications of tokenisation through quantitative analysis, and the perspectives of industry professionals through qualitative interviews.

The quantitative component of the study uses Discounted Cash Flow (DCF) analysis to evaluate the financial impact of tokenisation. To complement the quantitative findings, qualitative data is gathered through semi-structured interviews with industry experts. These interviews aim to explore their views on the feasibility and acceptability of asset tokenisation in large infrastructure projects. Participants were selected to represent a range of perspectives, including investors, project developers, and regulatory bodies. The interviews explore themes such as the potential for increased liquidity, the regulatory hurdles, and the impact on risk allocation. Interview transcripts are analysed using thematic analysis to identify recurring patterns and insights.

Interviews and saturation. We conducted 12 semi-structured interviews spanning investors, project developers, regulators, and technology providers. Interviews averaged 20 minutes and were transcribed verbatim. We applied iterative coding and tracked thematic saturation defined as the point at which no new codes emerged across two consecutive interviews. Saturation was reached at interview 10, with additional interviews confirming theme stability.

4.3.3 DCF analysis

The present study employs a discounted cash flow (DCF) framework to evaluate the financial performance of the REM under two distinct capital structures, namely the existing real-world arrangement and a tokenised alternative. The DCF methodology follows the standard approach of projecting operating cash flows, applying a cost of capital to discount those cash flows to present value, and summing the discounted values to obtain a net present value (NPV). Operating cash flows are derived from projected revenue, operating costs, depreciation, and taxes. After deducting debt service in the form of interest and principal repayments as applicable, the residual cash flow is allocated to equity holders according to the waterfall. The equity cash flow is then discounted using the equity cost of capital, which is derived from the weighted average cost of capital (WACC) for the project. The terminal value is estimated using a perpetual growth model, with the growth rate set equal to the long-term inflation rate.

4.3.4 Baseline scenario

In the baseline arrangement, the capital structure consists of 70% equity held by CDPQ Infra ($4.58B) and 30% equity held by the Government of Québec ($1.28B), a 15 year senior loan provided by the Canadian Investment Bank ($1.28B), fixed capital contributions from Hydro Québec ($0.295B), and a fee from the Autorité régionale de transport métropolitain ($0.512B) (REM, 2021). The waterfall operates as follows. Debt service is paid first. CDPQ Infra then receives a priority return of 8% on its equity until the cumulative return reaches the target (CDPQ, 2017a). Once CDPQ's priority return is satisfied, 72% of the remaining equity cash flow is allocated to the minority shareholders until their cumulative return reaches 3.7%. After both targets are met, the remaining equity cash flow is split pro rata according to the 70/30 ownership ratio. The cost of debt is the average interest rate on the CIB loan, ranging from 1% to 3% over the 15-year term.

The following information was used to estimate annual cash flows. CDPQ Infra is assumed to use actual REM ridership figures to adjust its revenues per passenger-km. Specifically, it is assumed that revenue is $0.72/passenger-km if ridership is up to 15% higher than the baseline scenario, and $0.58/passenger-km for ridership above the 15% threshold (CDPQ, 2017b). Annual ridership is assumed to be around 42 million (608 million passenger-km) in 2021, scaling linearly to the projected annual ridership of about 45 million (654 million passenger-km) by 2031 (Hanscomb, 2017).

4.3.5 Tokenisation scenarios

Two tokenisation scenarios are examined:

(1) Equity tokenisation (Scenario A);

(2) Revenue tokenisation (Scenario B).

Scenario A corresponds to tokenised equity. In this scenario, 10% of the total equity is tokenised and sold to a broad investor base. The token holders are treated as a new minority equity group with a priority return of 6%. The waterfall is extended to include the token holders before Quebec. Debt service is paid first. CDPQ Infra receives its 8% priority return. Token holders receive a 6% priority return until the cumulative target is met. Quebec receives a 3.7% return until the target is met. Remaining equity cash flow is split pro rata among CDPQ Infra (63%), Quebec (27%), and token holders (10%). The dilution of CDPQ Infra and Quebec is reflected in the reduced ownership percentages, which in turn affects the equity weight in the WACC calculation.

The justification for the lower return for token investors is as follows. The tokenised slice would be priced to reflect the risk profile of the new investor group, which is typically lower than that of the existing majority shareholder. Retail and institutional token holders spread their exposure across many projects, reducing idiosyncratic risk. Tokens can be traded on secondary markets, offering liquidity that is absent for traditional equity. The liquidity premium is priced as a discount to the required return. The cost of managing a large, dispersed investor base is lower than that of a small, concentrated group of institutional investors. Consequently, a tokenisation model would set the tokenised equity return at a lower rate compared to CDPQ's priority return.

Scenario A describes the most direct way to enlarge the investor base. By issuing a tokenised slice of the project's equity, the REM can engage retail and institutional investors who might otherwise be excluded from a large, regulated infrastructure project. The primary benefit is the potential to lower the WACC, as the new investors bring a lower required return than the existing majority shareholder. Even if the tokenised slice is priced at only a slightly lower return than CDPQ's 8%, the overall equity cost can fall, because the new investors dilute the high-return requirement of the original equity holders. Scenario A therefore serves to demonstrate the value-creation potential of tokenisation.

Scenario B corresponds to tokenised revenue sharing. In this alternative, the token holders receive a fixed 5% share of the annual fare revenue. The revenue sharing token is not part of the equity pool, so CDPQ Infra and Quebec retain their 70/30 ownership. However, the initial equity investment may be partially covered by token investments, potentially reducing the need for more expensive equity financing. The amount represented by token investors is kept at the same level as in Scenario A. The waterfall for equity cash flows remains identical to the baseline. The tokenised revenue share is deducted from the operating cash flow before the equity waterfall is applied. The cost of capital for the tokenised revenue stream is modelled as a 5% return on revenue, and the WACC is recalculated to include the revenue sharing component as a separate risk adjusted discount rate.

Scenario B introduces a new risk-adjusted cash flow stream that is independent of the equity and debt waterfall. It can attract investors who prefer a revenue-based return rather than equity exposure, which makes it valuable to consider two separate scenarios for possible tokenisation approaches. Tokenisation of debt is not considered. The cost of debt for the project is already low at between 1% and 3%, and as such the incremental benefit of tokenising it is limited.

4.3.6 Parameters and assumptions

Justification of token investor return assumptions. The 6% priority return for tokenized equity (Scenario A) and 5% revenue-share (Scenario B) were set with reference to: (i) market evidence that core/brownfield infrastructure equity returns cluster in the mid- to high-single digits; (ii) observable listed-infrastructure income yields of ~3–6%; and (iii) on-chain risk-free baselines from tokenized T-bill vehicles (~3–5% APY in 2024–2026). A 6% equity token thus sits above tokenized cash yet below CDPQ's 8% priority hurdle, consistent with the hypothesis that broader distribution/liquidity and stronger governance signals can compress the cost of equity for a minority tokenized tranche.

Key assumptions are summarised in Table 4.1 below.

Table 4.1 DCF Analysis Assumptions for Baseline and Tokenisation Scenarios

Parameter	Baseline	Scenario A	Scenario B
Cost of equity	CDPQ: 8% Quebec: 3.7%	CDPQ: 8% Quebec: 3.7% Token holders: 6%	CDPQ: 8% Quebec: 3.7%
Ownership structure	CDPQ: 70% Quebec: 30%	CDPQ: 63% Quebec: 27% Token holders: 10%	CDPQ: 70% Quebec: 30%
Revenue distribution	Priority-based waterfall (CDPQ, Quebec) Pro rata once targets are met	Priority-based waterfall (CDPQ, Token holders, Quebec) Pro rata once targets are met	Token investors: 5% of fare revenue Priority-based waterfall for the rest (CDPQ, Quebec) Pro rata once targets are met
Cost of debt	1% to 3%	1% to 3%	1% to 3%
Debt term	15 years	15 years	15 years
Project horizon	30 years	30 years	30 years
Tax rate	26%	26%	26%
Revenue growth	2% to 4%	2% to 4%	2% to 4%
Operating cost inflation	2% to 4%	2% to 4%	2% to 4%
Terminal growth rate	2%	2%	2%

Sensitivity analysis is performed to assess the robustness of the NPV to variations in growth, discount rates, and tokenisation size. The DCF model is run for each scenario, producing an NPV and an internal rate of return.

In CAPM, the cost of equity rises with beta; higher secondary-market volatility that co-moves with public markets increases beta and thus the cost of equity, raising WACC. Design choices that dampen volatility and idiosyncratic risk (e.g., restricted transfer, staged vesting, escrow-oracle backing, or revenue-share tokens) reduce perceived beta and illiquidity/novelty premia. In Scenario B the lower-risk cash flow reduced WACC from 5.66% to 5.46%, increasing project NPV despite modest equity IRR dilution.

The reduction in WACC in tokenization scenarios is based on the premise that a diversified investor base and increased liquidity may lower the required return on equity. However, these assumptions are hypothetical and should be interpreted with caution, as real-world market dynamics and regulatory factors may affect actual investor behaviour and risk premiums.

4.3.7 Limitations

This study is subject to certain limitations. The focus on the REM project as a single case study limits the generalisability of the findings. While the REM project offers a valuable example of a large infrastructure development, the specific characteristics of the project and the regulatory environment in Quebec may not be directly transferable to other contexts. The DCF analysis relies on a number of assumptions regarding future revenue, costs, and discount rates. These assumptions are based on available data and industry forecasts, but they inherently involve uncertainty. Sensitivity analysis was conducted to assess the impact of these uncertainties, but it cannot eliminate them entirely.

The qualitative data collected through interviews is also subject to limitations. The selection of interview participants was purposive, aiming to include a range of perspectives. However, this approach may have introduced bias, as certain viewpoints may have been over- or under-represented. Furthermore, the data collected is based on the perceptions and opinions of the interviewees, which may not always reflect the reality of the situation. Finally, the study does not explore the technological aspects of asset tokenisation in detail.

4.4 Analysis

The analysis proceeds as follows. Firstly, quantitative assessment of tokenisation for the REM project is carried out by estimating a DCF model. This includes a direct comparison between the baseline capital structure and tokenisation alternatives and a sensitivity analysis of the results to key DCF parameters and assumptions. Secondly, a qualitative assessment is performed by analysing interviews of industry experts with regards to the benefits and shortcomings of asset tokenisation in large infrastructure projects such as REM.
The following sections present the results of the DCF analysis for the two tokenisation scenarios that have been introduced in the preceding chapter. The baseline case represents the current capital structure, in which 70% of the equity is held by CDPQ Infra and 30% by the Government of Québec, a 15-year senior loan is provided by the Canadian Investment Bank (CIB), and Hydro-Québec and ARTM contribute fixed capital and a tax-revenue uplift fee, respectively. The two alternative structures are (i) a tokenised equity tranche of 10% priced at a 6% return (Scenario A), and (ii) a revenue-sharing token that captures 5% of the annual fare-revenue (Scenario B).

4.4.1 DCF analysis: Scenario A

The introduction of a tokenised equity slice reduces the weighted average cost of capital (WACC) by directly lowering the equity cost. In the baseline scenario, the equity cost is at 6.71%. After tokenisation, the equity cost becomes 6.64%. The difference is marginal mainly due to the reduction in the ownership share of an investor with a considerably lower cost of equity (Quebec). In fact, sensitivity analysis shows that, if token investors require a 7% return, then the total cost of equity would increase compared to the baseline by 0.03 percentage points. This shows that the actual change in cost of equity, and therefore WACC, greatly depends on the rate of return required by token investors. The result also depends on the equity structure on which CDPQ would agree upon. Scenario A assumes that both CDPQ and Quebec lose 10%

of their equity share to accommodate token holders. However, if CDPQ agrees to fully cover the change in capital structure by dropping its share to 60%, then the total cost of equity would drop to 6.51%.

The cost of debt remains unchanged at an average of 2.5% before tax and 1.85% after tax. Consequently, the WACC falls from the baseline value of 5.66% to 5.61%, representing a marginal reduction of 0.05 percentage points. This decline in the discount rate slightly increases the present value of all future cash-flows. The drop in WACC translates into around 1.9% rise in the NPV. The internal rate of return (IRR) for the project also improves. Scenario A raises the IRR by about 0.03 percentage points from 8.91% to 8.94%.

The tokenised equity slice dilutes the ownership of the existing shareholders. CDPQ Infra's stake falls from 70% to 63%, and Quebec's stake falls from 30% to 27%. However, the dilution is offset by the lower cost of equity, as well as by the liquidity premium that a broad, diversified investor base brings. The debt-to-equity ratio is unchanged because the debt tranche remains the same. Overall, Scenario A increases the project value by a small amount while preserving the equity structure's stability.

4.4.2 DCF analysis: Scenario B

In this structure, a fixed 5% share of the annual fare-revenue is allocated to token holders before the equity waterfall is applied. The equity cash-flow is therefore reduced by 5% of revenue each year, but the project receives an additional low-risk cash-flow stream that is not subject to the equity return thresholds. The required return on the revenue-share token is set at 5%. Because the revenue-share is less risky than equity, its discount rate is lower than the 8% equity cost. When incorporated into the WACC calculation, the overall discount rate falls from 5.66% to about 5.46%, a reduction of 0.20 percentage points.

The impact on the NPV is also more considerable than in Scenario A. While the removal of a portion of the equity cash-flow partially offsets the benefit of the lower WACC, the reduction in the cost of capital dominates in the long run. The NPV is estimated to rise by around 14.8% relative to the baseline, and by 10.3% compared to Scenario A. The IRR for the project as a whole also increases to 9.00%, which is a 0.09 percentage point increase compared to the baseline, and a 0.06 percentage point increase compared to Scenario A. However, the equity IRR declines slightly because a larger share of the operating cash-flow is now directed to the revenue-share token.

Debt coverage ratios remain essentially unchanged, as the debt tranche is unaffected. The revenue-share introduces a predictable, low-risk cash-flow that can improve the overall risk profile of the project, potentially reducing the equity risk premium further. The equity ownership percentages remain at 70 %/30 %, so the equity base is preserved while an additional revenue stream is added.

4.4.3 Comparative assessment

Both tokenisation scenarios are expected to raise the NPV of the REM project relative to the baseline. The results are summarised in Table 4.2.

Table 4.2 Comparison of Baseline and Tokenisation Scenarios

Feature	Baseline	Scenario A	Scenario B
WACC	5.66 %	5.61 %	5.46 %
NPV	Reference	Increased by 4.0 %	Increased by 14.8 %
IRR (project)	8.91 %	8.94 %	9.00 %
IRR (equity)	8.20 %	8.31 %	8.08 %
IRR (token)	–	6 %	5 %
Equity dilution	70 %/30 %	63 %/27 %	70 %/30 %

Scenario A delivers a small uplift as it reduces the cost of equity, whereas Scenario B offers a larger improvement due to the lower WACC outweighing the reduction in equity cash flow. The IRR for the project improves in both cases, but the equity IRR falls in Scenario B. The dilution of equity ownership in Scenario A is modest and is compensated by the cheaper capital. Scenario B preserves the equity structure but introduces a new revenue-based risk profile. In terms of risk-adjusted value, Scenario B appears to provide the greatest benefit, while Scenario A offers a more conservative enhancement. The risk premium baseline is also lower in both Scenario A due to diversified equity, and in Scenario B due to predictable revenue share.

4.4.4 Sensitivity analysis

The discounted cash-flow model that underpins the valuation of the REM project is inherently sensitive to a number of input variables. The following discussion examines how variations in each of the principal parameters influence the net present value (NPV) and internal rate of return (IRR) for the baseline, Scenario A (tokenised equity at 6%) and Scenario B (5% revenue-sharing). The analysis is intended to inform the robustness of the conclusions drawn in the preceding section, and to highlight the parameters that warrant careful calibration.
The results are summarised in Table 4.3.

Table 4.3 Degree of Sensitivity of DCF Analysis to Model Parameters

Parameter	Baseline	Scenario A	Scenario B
WACC	High	High	High
Annual growth rate	High	High	High
Operating margin	Moderate	Moderate	Low
Cost of debt	Moderate	Moderate	Low
Cost of equity	Moderate	High	Moderate
Token return	–	Moderate	Moderate
Tokenised equity size	–	Moderate	–
Tax rate	Low	Low	Low
Terminal growth rate	High	High	High
Forecast period	Low	Low	Low

The WACC is the most influential variable in a DCF calculation because it directly scales the present value of all future cash-flows. In the baseline case, the WACC is approximately 5.66%. Directly varying this value corresponds to assumptions related to the perceived risk of the project with the introduction of token holders. The rationale is that the project is now perceived as slightly less risky due to the broader investor base and potential for increased liquidity.

However, CDPQ might also demand a premium to compensate for the dilution of their ownership. A 0.5 percentage point increase in the WACC reduces the NPV of the 30-year cash-flow stream by more than 40%. Consequently, the IRR declines by about 0.21 percentage points. A 0.5 percentage point reduction in the WACC increases the NPV by around 40% and increases IRR by 0.25 percentage points. Scenarios A and B, which benefit from a lower WACC, are slightly less sensitive to further reductions compared to the baseline. Overall, these considerations show that the estimated project value is highly sensitive to adjustments to WACC due to changes in perceived risk.

The annual growth rate of fare-revenue drives the magnitude of the operating cash-flows. A 0.5% increase in the growth rate leads to a 23% increase in the baseline NPV. Scenario A, which relies on a larger equity base, benefits more from higher growth because the additional cash-flows are first allocated to the equity tranche before the tokenised slice is paid. Scenario B, by contrast, captures a fixed 5 % of revenue, and the relative benefit of higher growth is smaller for the token holders, but larger for the equity holders. A 0.5% decline in growth reduces the baseline NPV by a similar proportion.

Operating margin determines the proportion of revenue that survives after operating costs. A 1% improvement in margin increases the operating cash-flow by the same percentage, leading to an around 5% rise in the baseline NPV. Scenario B is slightly less sensitive to changes in costs, because the revenue-share is calculated before the margin adjustment. The tokenised cash-flow rises in line with the margin improvement, but the equity cash-flow that is subject to the waterfall also increases. A reduction of the margin has the opposite effect, reducing the NPVs across all scenarios.

The cost of debt enters the WACC calculation and also determines the amount of cash-flow that must be allocated to debt service. A 1% increase in the debt rate raises the WACC by about 0.15 percentage points and reduces NPVs by roughly 10%. Scenario B is less affected because the revenue-share is independent of debt service. However, higher debt costs still raise the WACC and thereby reduce the overall discount rate applied to the remaining cash-flows. The sensitivity to debt cost is therefore moderate, but not negligible.

In Scenario A the equity cost for token holders is an important driver of the WACC. A 1% increase in the required return on the tokenised equity slice raises the WACC by roughly

0.08 percentage points and reduces the scenario's NPV by 5.7%. The baseline scenario, which relies on an 8% return for CDPQ Infra, is more sensitive to changes in the equity cost, as it has a larger equity base. Scenario B does not involve an equity cost for the tokenised component, and its sensitivity to equity cost is limited to the effect on the overall WACC.

The corporate tax rate affects the after-tax cost of debt and the after-tax operating cash-flows. A 1% increase in the tax rate reduces the after-tax cost of debt by about 0.3 percentage points and lowers the operating cash-flows by 1%. The baseline and Scenario A NPVs decline by around 3%. Scenario B's sensitivity is slightly lower because the revenue-share is calculated before the tax adjustment. The tax rate is therefore an important but secondary driver of the valuation.

The terminal growth rate determines the value of the project beyond the explicit forecast horizon. A 0.5% increase in the terminal growth rate raises the terminal value by 14%. Extending the explicit forecast period from 30 to 35 years increases NPVs by around 4%, as additional cash-flows are added before the terminal value is calculated.

Sensitivity analysis demonstrates that project NPV is highly sensitive to changes in WACC, highlighting the need for further empirical validation in future pilot implementations.

4.4.5 Qualitative analysis of interviews with industry experts

Thematic analysis of interviews revealed two major themes, namely:

(1) Tokenisation may help finance large infrastructure projects (Theme 1);

(2) Value assessment can be challenging due to the complexity of tokenisation (Theme 2).

Regarding Theme 1, participants expressed agreement on tokenisation being a promising approach for facilitating the financing of large infrastructure projects. In particular, one of the experts noted that the key advantage of tokenisation was the ability to broaden the investor base. The discussion suggested that traditional infrastructure financing relied on a handful of institutional investors, pension funds, and sovereign wealth funds. Meanwhile, tokenisation was regarded as a tool that could open the market to retail investors and smaller institutional participants, thereby increasing the pool of capital available for a project. Participants further acknowledged that this could reduce the cost of capital, which is in line with the present results for both Scenario A and Scenario B.

Another consideration regarding Theme 1 expressed by the interviewees was that the liquidity premium that a diversified investor base brings could further reduce the equity risk premium. From this perspective, the secondary market for tokens might provide a mechanism for investors to exit or trade their positions. The experts generally agreed that this was a significant improvement over the illiquidity of conventional infrastructure equity. Revenue-based models were preferred, with several participants explicitly mentioning that such tokenisation schemes were particularly suitable for infrastructure projects due to stable revenue streams.

The next theme that emerged from interview data was that value assessment could be challenging due to the complexity of tokenisation. This can be especially relevant considering the present analysis utilised a DCF model. Indeed, the majority of the participants were in agreement that evaluating the tokenisation of large projects such as REM may require more sophisticated models. While DCF analysis allows for incorporating specific capital structure, including equity waterfall, debt service, and tax considerations, the model may be too sensitive to assumptions on the discount rate and growth rates. These experts' concerns are in line with the output of the present sensitivity analysis.

Furthermore, the DCF model assumed a fixed tokenised return for equity token holders and a fixed revenue share for the revenue-sharing scenario. In practice, the pricing of tokenised securities may be influenced by market demand, liquidity, and regulatory constraints, which may lead to higher required returns, diminishing the projected benefit. The interviews further suggested that it would be a substantial simplification to treat the revenue share as a deterministic percentage of fare-revenue, ignoring potential volatility in ridership or fare adjustments that could affect its value. Furthermore, such a model may fail to fully capture the potential operational savings that a tokenised structure could bring, such as reduced transaction costs or improved capital efficiency through secondary market liquidity. In a similar vein, one interviewee argued that it was important to consider how tokenisation would affect negotiations with large investors such as CDPQ.

A related issue raised by several participants with regards to Theme 2 was that the regulatory environment for digital assets was still evolving, including the case of Canada. There may be uncertainties around compliance, anti-money-laundering requirements, and investor protection. These uncertainties can drive up the required return on tokenised securities, eroding the cost-saving benefit. Additionally, a few participants noted that the operational complexity of managing a large number of token holders, including settlement and reporting, can offset the liquidity advantage. However, it was also argued that, in the context of a large infrastructure project such as the REM, the scale of the tokenised tranche would be relatively small compared to the overall equity base. In such cases, the dilution effect would be modest, although it would still require careful governance to maintain alignment with the project's long-term objectives. In summary, the present results of DCF model analysis showed that asset tokenisation would improve the value of the REM project in both absolute and relative terms. A larger improvement is observed for the revenue-based tokenisation model, which is in line with the REM being expected to generate a stable long-term revenue stream. The interview participants generally agreed that the expected benefits of asset tokenisation in large infrastructure projects could include a broader investor base, potential cost-of-capital reductions, and improved liquidity. However, the experts also noted the shortcomings of tokenisation of such projects as the REM, including regulatory uncertainty, operational complexity, and the risk that the tokenised return may not be sufficiently attractive to offset these costs.

4.5 Discussion

4.5.1 Present results and previous work

The DCF analysis presented earlier indicates that the introduction of a tokenised equity tranche can reduce the cost of capital of the REM project. This reduction translates to a small but noticeable increase in both absolute (NPV) and relative (IRR) value of the project. From a theoretical standpoint, the results reinforce the notion that tokenisation can act as a mechanism for capital structure optimisation (OECD, 2020). By broadening the investor base, tokenised securities introduce additional sources of equity capital that are priced at a lower required return than the traditional institutional investors that dominate infrastructure finance. The lower equity cost is a direct consequence of the increased liquidity and diversification afforded by a tokenised market, which reduces the equity risk premium in the capital asset pricing model. The model's sensitivity to the discount rate confirms that the primary channel through which tokenisation enhances project value is the reduction in the cost of capital, rather than any direct effect on operating cash flows. This aligns with the theoretical framework that views tokenisation as a tool for improving the efficiency of capital allocation rather than as a substitute for conventional financing mechanisms (OECD, 2025).

Practically, the findings suggest that tokenisation can provide a viable alternative to traditional equity financing for large infrastructure projects. The ability to issue a tokenised tranche of equity allows project sponsors to tap into a wider pool of investors, including retail participants who may be attracted by the transparency and liquidity of blockchain based instruments. The resulting dilution of the existing equity holders is modest, and the reduction in the cost of capital can offset the loss of ownership. Moreover, the secondary market for tokens can provide a mechanism for investors to exit or trade their positions, potentially reducing the lock in period that is typical of infrastructure equity. These practical benefits are particularly relevant for projects with long operating lives, where the ability to manage investor expectations over extended horizons is critical.

Positive responses to tokenisation observed in this study are consistent with previous studies suggesting that tokenising physical assets could increase market liquidity (Tian et al., 2020). They argued that this effect is due to the reduced amount of money needed to invest, allowing for trading on a secondary market (Pereira et al., 2019). In line with this, Baum (2021) also proposed that tokenisation could broaden the range of investors involved in infrastructure projects, providing opportunities for individuals who previously could not participate. The findings of this study support this idea and suggest a connection to the increasing use of blockchain technology, which has allowed for the creation of real estate tokens as a way to directly own property. The results regarding tokenisation also align with the recent OECD report (OECD, 2025), which highlighted the importance of integrating tokenisation and blockchain within infrastructure finance. Concerns raised by Tian et al. (2022) about investor involvement and responsibility in current tokenisation models reinforce the need for new ways to finance large projects using tokenized assets.

Nevertheless, the analysis also highlights several practical constraints that must be addressed. The regulatory environment for digital assets remains uncertain, and the need to comply with anti money laundering regulations, securities laws, and investor protection rules can increase the cost of issuing tokenised securities. Operationally, managing a large number of token holders introduces complexity in settlement, reporting, and governance that is absent in conventional equity arrangements. These factors may erode the theoretical cost saving advantage if the required return on tokenised equity rises above the projected seven per cent. In the revenue sharing scenario, the fixed nature of the revenue share reduces the flexibility of the capital structure, and the impact on the equity holders' cash flows may limit the attractiveness of the tokenised instrument to risk averse investors.

4.5.2 Implementing tokenisation in large infrastructure projects

Special Purpose Vehicle (SPV) structures for asset tokenisation require the involvement of several parties, each with important roles that contribute to the success of the process (Helou and Assaf, 2024). Project initiators have a key role in explaining new financing methods to potential investors. They must clearly demonstrate how tokenisation can improve a project's financial stability, reduce funding difficulties, and offer opportunities for fractional ownership (OECD, 2020). Furthermore, initiators are responsible for coordinating activities to ensure projects meet market demands, which relies on awareness among both the community and potential investors.

The implementation of regulations is a significant consideration. However, it is important to also recognise the potential benefits and innovations that asset tokenisation offers beyond simply meeting compliance requirements. Regulatory bodies are important for creating legal frameworks that protect investors (OECD, 2021). However, asset tokenisation also presents opportunities for improvements in technology and operations, which can increase access to markets and improve their efficiency. Tokenisation enables decentralised ownership, which can attract a wider range of investors and allows for smaller investments in assets that were previously difficult to access (Carapella et al., 2023). A balanced understanding of both the regulatory protections and the potential for change offered by tokenisation is necessary to fully appreciate its value in contemporary markets.

4.5.3 Implications

This study's findings have several practical implications for infrastructure developers, investors, and policymakers. For infrastructure developers, the analysis suggests that tokenisation could be a viable option for attracting new sources of capital and potentially reducing financing costs. The ability to offer fractional ownership and target a wider range of investors, including retail investors, could significantly broaden the investor base for large-scale projects like the REM. This could be particularly beneficial in markets where traditional financing options are limited or expensive.

For investors, the present research highlights the potential for enhanced returns and diversification through tokenised infrastructure assets. The revenue-based model, in particular, offers a compelling investment proposition, providing direct exposure to project cash flows and potentially reducing reliance on equity market volatility. However, investors should carefully consider the regulatory uncertainties surrounding tokenised assets and conduct thorough due diligence before investing.

Policymakers also have a role to play in facilitating the responsible adoption of tokenisation in infrastructure finance. Clear and consistent regulatory frameworks are needed to address concerns about investor protection, market integrity, and financial stability (OECD, 2025). While this study identifies regulatory uncertainty as a significant barrier, proactive engagement with the technology and its potential benefits could unlock significant opportunities for infrastructure development and economic growth. Furthermore, policymakers should consider the potential impact of tokenisation on existing financial regulations and adapt them accordingly to ensure a level playing field for all market participants. The REM case study provides a valuable example for policymakers seeking to understand the practical challenges and opportunities associated with tokenising infrastructure assets.

4.5.4 Challenges and risks

The adoption of asset tokenisation presents potential difficulties and risks that require careful consideration when evaluating its suitability for public infrastructure projects. A significant technological hurdle lies in ensuring that blockchain technology can operate effectively alongside existing systems. Many current structures for delivering public infrastructure services rely on systems that may not be easily integrated with a decentralised blockchain environment (OECD, 2020). The shift towards a tokenised system involves technological changes as well as a fundamental alteration to organisational culture and established processes. Such transitions often encounter resistance from stakeholders accustomed to traditional methods, which can lead to project modifications and delays in implementation (Helou and Assaf, 2024).

Furthermore, regulatory uncertainty adds to the risks associated with asset tokenisation. Regulatory bodies, particularly in North America, have stringent rules concerning tokenised assets (OECD, 2021). The possibility of tokens being classified as securities can result in substantial compliance costs and operational difficulties for businesses. This situation can be particularly burdensome, requiring specialist legal and financial expertise, which can be expensive, especially for smaller organisations and new ventures. These businesses also face challenges in navigating the regulatory environment due to their limited resources for managing compliance (OECD, 2025). The constantly changing nature of regulations creates additional risks, potentially discouraging investment in tokenised public infrastructure projects and hindering the wider development of tokenisation initiatives. Cybersecurity poses a significant challenge to asset tokenisation (Le and Hsu, 2021). The decentralised nature of blockchain technology can be exploited by malicious actors. Both the blockchain itself and the systems around it are vulnerable to hacking and phishing attacks. Concerns about data security and access to funds are common among investors and stakeholders. Adequate security measures are essential when tokenising assets.

4.6 Conclusion

This study investigated the potential of blockchain technology and asset tokenisation to improve the financing of large infrastructure projects. Asset tokenisation could allow for smaller investments in assets that are usually difficult to trade by offering fractional ownership. Blockchain-enabled smart contracts could also make it easier for investors to access secure and transferable interests, while increasing transparency.

This study investigated the potential benefits of asset tokenisation for financing large-scale infrastructure projects, using the Réseau express métropolitain (REM) project as a case study. The analysis, utilising Discounted Cash Flow (DCF) modelling, suggests that both equity-based and revenue-based tokenisation scenarios can improve the financial viability of the REM project. The revenue-based tokenisation scenario consistently outperformed the equity-based approach, indicating a potentially more attractive investment opportunity for token holders.

These findings align with theoretical arguments suggesting that tokenisation can broaden the investor base for infrastructure assets. By offering fractional ownership and potentially more accessible investment options, tokenisation can unlock capital that might not otherwise be available. The superior performance of the revenue-based model supports the idea that linking returns directly to project revenues can be a compelling value proposition for investors. This approach reduces the reliance on equity appreciation, potentially mitigating some of the risks associated with infrastructure investments.

Beyond the quantitative results, the expert interviews provided valuable qualitative insights. Industry professionals largely agreed that tokenisation, particularly the revenue-based model, could be a useful tool for financing significant infrastructure projects like the REM. However, they also highlighted important practical considerations. Regulatory uncertainty surrounding tokenised assets remains a significant barrier to widespread adoption. Furthermore, the experts raised concerns about the potential oversimplification of the DCF assumptions used in our modelling. While DCF provides a useful framework, the complexities of a project as large as the REM may not be fully captured by simplified assumptions.

Further research is needed to explore the impact of different regulatory frameworks and to develop more sophisticated modelling techniques that can account for the unique characteristics of infrastructure assets. This study provides a valuable initial assessment of asset tokenisation in the rail industry, but it also identifies areas for future investigation to fully understand its potential and limitations.

CONCLUSION AND RECOMMENDATIONS

The present thesis investigated the potential of asset tokenization to improve funding for public infrastructure projects. The study's objectives focused on assessing opportunities, developing a methodology, and validating its effectiveness against conventional approaches. Overall, the findings suggest that asset tokenization offers a worthwhile opportunity to supplement existing funding models. It is not intended to replace them entirely, but rather to provide an additional layer of investment.

While the results suggest that asset tokenization can complement traditional funding models, these conclusions are based on theoretical modeling and expert interviews. The absence of large-scale real-world implementations means that generalizability remains limited. Further pilot projects and regulatory sandboxes are needed to validate these findings in practice.

Investment in infrastructure is a key factor in long-term economic growth worldwide. However, despite the availability of funds in financial markets, a lack of investment in infrastructure continues to be a significant obstacle to large projects. This shortfall is largely due to difficulties in securing dependable and long-lasting sources of income, such as user charges, specific taxes, or government support. It is not primarily a problem of a lack of financial tools or investor funds. Furthermore, problems with current financing methods, including unfair risk distribution and limited investor involvement, can worsen the situation.

The opportunity of asset tokenization in financing public infrastructure. This study investigated blockchain technology and the process of asset tokenization as potential new ways to finance and manage large infrastructure projects. Asset tokenization allows for the division of ownership of assets that are typically difficult to trade and have high value. This can open up investment opportunities to a wider range of investors. Blockchain technology, through the use of smart contracts, can improve transparency, security, and the ease of transferring ownership. This may also help to build greater confidence and reduce costs associated with intermediaries.

This research aimed to connect established theories with real-world use. It did this by testing a previously created model for financing infrastructure using tokens. Data was gathered through surveys of people working in the industry. These included investors, regulators, project developers, and companies providing blockchain services. The surveys explored how useful and possible the model's key parts are. These parts included the ability to change tokens, different levels of control, and how risk is shared.

The research found that a layered approach helps to distribute risks and rewards more effectively between those involved. The results suggest that professionals with expertise in the field consider tokenized, layered financing to be both logical and possible to put into practice. However, more research is needed to understand how this approach works in reality. This should include small-scale projects and tests within regulatory environments. These would help to assess performance, the ability to grow the system, and how it fits with current project finance methods. Future studies should also consider how infrastructure project financing changes over time. It is also important to investigate the challenges of shared ownership and the impact of changing rules and regulations. Addressing these areas will help to fully understand the potential benefits of using blockchain technology in infrastructure finance.

The long-term success of asset tokenization within public infrastructure projects depends on several factors. These include improvements in technology, agreement on regulations across different jurisdictions, and stronger safeguards for investors. Further investigation is needed to examine how decentralized finance (DeFi) can be integrated, how regulations can adapt to innovation, and how governance systems can ensure both accessibility and adherence to rules. These developments have the potential to broaden the use of tokenized infrastructure financing, making it more reliable and capable of growth. For instance, new developments in DeFi could create opportunities for improved liquidity and financial services specifically designed for tokenized public infrastructure. DeFi platforms could allow stakeholders to develop systems for automated trading, lending, and earning interest, which may encourage investment.

Framework for optimizing conventional capital investment strategies of public infrastructure projects with asset tokenization. A key strength of the proposed framework is that it may appeal to secondary investors. The use of an escrow account coupled with a blockchain oracle allows secondary investors to independently check that funds support the number of available tokens. Incorporation of a Simple Agreement for Future Tokens (SAFT) structure separates the initial investment stage from the distribution of tokens. The actual issuance of tokens is delayed until the infrastructure project is operational, which helps reduce the risk of token dilution. If primary investors were able to sell tokens immediately after they were issued, secondary investors might experience a reduction in the value of their investment. Because the SAFT ensures that primary investors only receive tokens once the infrastructure project is underway, secondary investors can be more confident that the value of the tokens is connected to a completed asset, rather than simply based on expectations.

The smart contract code that manages the token supply includes a mechanism to maintain a direct relationship between funds held in escrow and the number of tokens in circulation. If a primary investor tries to sell tokens before the project receives full funding, the contract can automatically restrict or destroy those tokens. This prevents a sudden increase in the token supply, which could negatively affect the market value. This protection against early token sales contributes to a more predictable secondary market, which is important for maintaining investor trust. Furthermore, the entire process, from the amount held in escrow to the creation of tokens, is open and easily checked. A combination of monitoring external accounts, reporting from external data sources, and unchangeable smart contract rules allows secondary investors to verify that the token creation process is happening as planned. This clear demonstration of adherence to the agreed terms may reduce the need for detailed investigations, making it easier for larger investors to commit funds to these kinds of projects. Additional research should focus on identifying appropriate regulatory approaches for tokenized assets. It is important to develop flexible regulatory systems that allow global bodies to manage innovation while still protecting investors. Addressing the challenges of regulating this new area will require collaboration between regulators and other involved parties, creating an environment where experimentation can occur. Further investigation is needed to understand the social elements involved in asset tokenization, especially concerning the views of the public. This research could help those involved in tokenization projects improve how they are viewed. It could also help them find ways to promote tokenization to benefit local communities and increase public confidence in infrastructure projects.

It is also important to examine the effect of tokenization on social fairness and equality. Tokenization often makes investment opportunities more accessible. Therefore, it is necessary to evaluate how these programs affect society and ensure they have a positive impact. The future development of public infrastructure, including asset tokenization, will depend on collaboration between finance, technology, and public policy. When experts from these fields, alongside academics and policymakers, work together, asset tokenization can achieve its potential. This collaboration can lead to improvements in how public infrastructure is financed, making it more efficient, accountable, and accessible.

Asset tokenisation and large-scale infrastructure developments. This research further explored how blockchain technology and the process of asset tokenisation could enhance the financing of major infrastructure developments. Asset tokenisation allows for smaller investments in assets that are typically difficult to trade, as it provides opportunities for fractional ownership. Furthermore, blockchain-based smart contracts could simplify the process for investors to gain secure and transferable rights, while also increasing openness and clarity. The study examined the potential advantages of asset tokenisation for funding large infrastructure projects, using the Réseau express métropolitain (REM) project as an example. Financial modelling, utilising a Discounted Cash Flow (DCF) approach, suggests that both models of tokenisation – those based on equity and those based on revenue – could improve the financial success of the REM project. The revenue-based model consistently showed better results than the equity-based model, suggesting it may be a more appealing investment for those holding tokens.

The findings support existing ideas that tokenisation can broaden the range of investors interested in infrastructure assets. Providing fractional ownership and potentially easier investment options can release capital that might not otherwise be available. The stronger performance of the revenue-based model suggests that linking returns directly to project income can be a persuasive benefit for investors. This method reduces the need to rely on increases in equity value, which could lessen some of the risks associated with infrastructure investments.

The expert interviews offered important qualitative information, supplementing the quantitative findings. Participants in the rail industry generally felt that tokenisation, especially a revenue-sharing approach, could be a helpful method for funding large infrastructure developments, such as the REM project. However, they also pointed out practical issues that need attention. A major obstacle to wider use of tokenised assets is the lack of clear regulations. The experts also expressed worries that the discounted cash flow (DCF) methods used in the modelling might be too simple. While DCF provides a useful structure, the scale and complexity of a project like the REM may not be entirely reflected in simplified assumptions. Further study is needed to examine how different regulatory systems might affect outcomes and to create more advanced modelling approaches. These approaches should be able to take into account the specific features of infrastructure assets. This study offers a first look at asset tokenisation within the rail sector. It also identifies areas where more research is needed to fully understand both the potential benefits and the limitations of this approach.

Cybersecurity Risks. Asset tokenization platforms for infrastructure projects rely heavily on blockchain and digital infrastructure, making cybersecurity a critical concern. As discussed in Chapters 3 and 4, the decentralized nature of blockchain introduces vulnerabilities such as hacking, phishing, and smart contract exploits. To address these risks, it is essential to implement robust cybersecurity protocols, including regular security audits, penetration testing, and comprehensive incident response plans. Ensuring the security of smart contracts and ongoing monitoring for vulnerabilities will help maintain investor trust and safeguard both assets and stakeholders.

Retail Participation & Protection. Where retail access is contemplated by law, we will implement the following guardrails, aligned to IOSCO's 18 policy recommendations and national rules: (i) appropriateness/suitability testing and prominent risk labels (non-deposit, market risk, potential illiquidity); (ii) investment caps and cooling-off periods; (iii) high-quality disclosures (rights, waterfalls, oracles/escrow mechanics, fees), with plain-language summaries; (iv) conflicts-of-interest governance (vertical integration, related-party O&M, transfer-pricing); (v) custody safeguards, asset segregation, and independent assurance; (vi) market-abuse controls (transfer-restriction logic, anti-"pump and dump" measures, trading surveillance); (vii) complaint handling and ombuds access; and (viii) ongoing periodic reporting (cash flows, construction milestones, covenant compliance) to token holders and regulators.

Emerging Markets and Developing Economies EMDEs. The REM case reflects a high-governance, investment-grade context. In EMDEs, the direction of impact is similar but magnitudes differ due to FX/country risk, legal enforceability, capital controls, and payment rails. Tokenization can broaden investor reach (e.g., mobile-first distribution) and reduce intermediation frictions if paired with local-currency denominations, FX-hedge overlays, and credit enhancement (e.g., MDB guarantees). Examples like Kenya's M-Akiba mobile bond show feasibility of fractional, mobile-native public finance. EMDE tokenizations should pair the layered SPV + escrow-oracle design with sovereign/DFI wraps and local-law enforceability to preserve cost-of-capital benefits.

Retail Investor Protection. The democratization of infrastructure investment through tokenization offers new opportunities for retail investors but also introduces unique risks. As highlighted in the regulatory discussions, protecting less sophisticated investors is crucial for sustainable market growth. This can be achieved by ensuring transparent disclosure of all investment risks, strict adherence to regulatory compliance (including KYC and AML procedures), and the implementation of mechanisms to prevent market manipulation. Collaboration with regulators to develop clear guidelines for retail participation, including educational resources and accessible dispute resolution, will further enhance investor protection and market integrity.

APPENDIX A

CODE USED IN THE ANALYSIS – CHAPTER 2

Algorithm 1.1 R Code

Below is the R code used to conduct the analysis presented in Section 2.4 (Chapter 2).

```
> library(xlsx)
>
> data <- read_excel(path = 'data.xlsx', sheet = 1)
> N <- nrow(data)
> wb = createWorkbook()
> sheet = createSheet(wb, "Freq")
> startRow=1
>
> for (j in seq_len(ncol(data))){
+   name <- colnames(data)[j]
+   print(name)
+    df<-data.frame("Single-select option"=c("Not Important","Slightly Important","Important","Fairly Important","Extremely Important"),
+                  "Count"=N*prop.table(table(data[name])),
+                  "Response Percent"=prop.table(table(data[name])))
+   df<-df[,c(1,3,5)]
+     colnames(df) <- c("Single select option", "Count", "Response Percent")
+   print(df)
+   test <- wilcox.test(data[,j][[1]], mu = 3, alternative = "greater")
+   print(test)
+   effsize <- wilcox_effsize(data, as.formula(paste(name, "~ 1")), mu = 3, alternative="greater")
+   print(effsize)
+       addDataFrame(data.frame(c(name)), sheet=sheet, row.names=F, col.names=F, startRow=startRow)
+        addDataFrame(df, sheet=sheet, row.names=F, col.names=T, startRow=startRow+1)
+   startRow=startRow + nrow(df)+3
+ }
[1] "Q14"
  Single select option Count Response Percent
1        Not Important     3       0.02479339
2   Slightly Important    13       0.10743802
3            Important    30       0.24793388
4     Fairly Important    41       0.33884298
5  Extremely Important    34       0.28099174
```

Algorithm 1.1 R Code (Cont'd)

```
    Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 3609.5, p-value = 2.569e-10
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q14   1      null model   0.578   121 large
[1] "Q21"
  Single select option Count Response Percent
1        Not Important     1      0.008264463
2   Slightly Important     6      0.049586777
3            Important    29      0.239669421
4     Fairly Important    38      0.314049587
5  Extremely Important    47      0.388429752

    Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 4074.5, p-value = 3.657e-15
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q21   1      null model   0.737   121 large
[1] "Q29"
  Single select option Count Response Percent
1        Not Important     1      0.008264463
2   Slightly Important     7      0.057851240
3            Important    37      0.305785124
4     Fairly Important    50      0.413223140
5  Extremely Important    26      0.214876033

    Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 3296, p-value = 9.482e-13
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
```

Algorithm 1.1 R Code (Cont'd)

```
1 Q29   1      null model   0.671   121 large
[1] "Q30"
  Single select option Count Response Percent
1        Not Important     1      0.008264463
2   Slightly Important     9      0.074380165
3            Important    35      0.289256198
4     Fairly Important    39      0.322314050
5  Extremely Important    37      0.305785124

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 3453, p-value = 9.565e-13
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q30   1      null model   0.660   121 large
[1] "Q31"
  Single select option Count Response Percent
1        Not Important     2       0.01652893
2   Slightly Important     8       0.06611570
3            Important    38       0.31404959
4     Fairly Important    42       0.34710744
5  Extremely Important    31       0.25619835

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 3148, p-value = 1.935e-11
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q31   1      null model   0.629   121 large
[1] "Q32"
  Single select option Count Response Percent
1        Not Important     1      0.008264463
2   Slightly Important     9      0.074380165
3            Important    35      0.289256198
4     Fairly Important    40      0.330578512
5  Extremely Important    36      0.297520661

   Wilcoxon signed rank test with continuity correction
```

Algorithm 1.1 R Code (Cont'd)

```
data:  data[, j][[1]]
V = 3448, p-value = 1.089e-12
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q32   1      null model   0.659   121 large
[1] "Q33"
  Single select option Count Response Percent
1        Not Important    33      0.272727273
2   Slightly Important    41      0.338842975
3            Important    35      0.289256198
4     Fairly Important    11      0.090909091
5  Extremely Important     1      0.008264463

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 361, p-value = 1
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q33   1      null model   0.626   121 large
[1] "Q34"
  Single select option Count Response Percent
1        Not Important     2       0.01652893
2   Slightly Important    13       0.10743802
3            Important    38       0.31404959
4     Fairly Important    44       0.36363636
5  Extremely Important    24       0.19834711

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 2968, p-value = 2.971e-09
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q34   1      null model   0.541   121 large
[1] "Q35"
```

Algorithm 1.1 R Code (Cont'd)

```
  Single select option Count Response Percent
1        Not Important     1      0.008264463
2   Slightly Important     8      0.066115702
3            Important    38      0.314049587
4      Fairly Important    51      0.421487603
5  Extremely Important    23      0.190082645

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 3174.5, p-value = 4.365e-12
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q35   1      null model   0.648   121 large
[1] "Q36"
  Single select option Count Response Percent
1        Not Important    35      0.289256198
2   Slightly Important    42      0.347107438
3            Important    36      0.297520661
4      Fairly Important     7      0.057851240
5  Extremely Important     1      0.008264463

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 242.5, p-value = 1
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q36   1      null model   0.682   121 large
[1] "Q37"
  Single select option Count Response Percent
1        Not Important     1      0.008264463
2   Slightly Important     9      0.074380165
3            Important    39      0.322314050
4      Fairly Important    52      0.429752066
5  Extremely Important    20      0.165289256

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
```

Algorithm 1.1 R Code (Cont'd)

```
V = 3052, p-value = 2.092e-11
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q37   1      null model   0.623   121 large
[1] "Q38"
  Single select option Count Response Percent
1        Not Important     1      0.008264463
2   Slightly Important    16      0.132231405
3            Important    40      0.330578512
4      Fairly Important    30      0.247933884
5  Extremely Important    34      0.280991736

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 2881, p-value = 1.429e-09
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q38   1      null model   0.523   121 large
[1] "Q39"
  Single select option Count Response Percent
1        Not Important     2       0.01652893
2   Slightly Important     9       0.07438017
3            Important    30       0.24793388
4      Fairly Important    45       0.37190083
5  Extremely Important    35       0.28925620

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 3792.5, p-value = 1.641e-12
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q39   1      null model   0.658   121 large
[1] "Q40"
  Single select option Count Response Percent
1        Not Important    25      0.206611570
```

Algorithm 1.1 R Code (Cont'd)

```
2   Slightly Important    42      0.347107438
3            Important    45      0.371900826
4     Fairly Important     8      0.066115702
5  Extremely Important     1      0.008264463

   Wilcoxon signed rank test with continuity correction

data:  data[, j][[1]]
V = 267.5, p-value = 1
alternative hypothesis: true location is greater than 3

# A tibble: 1 x 6
  .y.   group1 group2     effsize     n magnitude
* <chr> <chr>  <chr>        <dbl> <int> <ord>
1 Q40   1      null model   0.610   121 large
> saveWorkbook(wb, "Freq.xlsx")
```

LIST OF BIBLIOGRAPHICAL REFERENCES

Adigwe, P.K. (2012). “Project finance for small and medium scale enterprises (SMEs) in Nigeria.” African Research Review. 6(1). pp.91-100.

Alamsyah, A., and Syahrir, S. (2024). A taxonomy on blockchain-based technology in the financial industry: drivers, applications, benefits, and threats. In El Madhoun, N., Dionysiou, I., Bertin, E. (eds) *Blockchain and Smart-Contract Technologies for Innovative Applications*. Cham: Springer, 91-129. https://doi.org/10.1007/978-3-031-50028-2_4

Alamsyah, A., Kusuma, G. N. W., and Ramadhani, D. P. (2024). A review on decentralized finance ecosystems. *Future Internet*, *16*(3), 76. https://doi.org/10.3390/fi16030076

Alinezhad, M., Saghatforoush, E., Kahvandi, Z. and Preece, C. (2020). Analysis of the benefits of implementation of IPD for construction project stakeholders. *Civil Engineering Journal*, *6*(8), pp.1609-1621.

Allen, S., Capkun, S., Eyal, I., Fanti, G., Ford, B., Grimmelmann, J., Juels, A., Kostiainen, K., Meiklejohn, S., Miller, A., Prasad, E., Wüst, K., & Zhang, F. (2020, 23 July). Design choices for Central Bank Digital Currency: Policy and technical considerations. Brookings Institution. https://www.brookings.edu/wp-content/uploads/2020/07/Design-Choices-for-CBDC_Final-for-web.pdf

Almeile, A.M., Chipulu, M., Ojiako, U., Vahidi, R. and Marshall, A. (2024). Project-focussed literature on public-private partnership (PPP) in developing countries: a critical review. Production Planning and Control, 35(7), pp.683-710.

Anderson, R., Mack, B., & Selig, T. (2000, September). „CSX Track Chart and Engineering Information System “. In *AREMA Proceedings of the 2000 Annual ConferenceAmerican Railway Engineering and Maintenance-of-Way Association*.

Anshori, F.A., Salomo, V. and Kusumastuti, R. (2023). Understand Blended Finance: How Different Definitions of Blended Finance Result in Different Inputs and Outputs and What to Expect. *Technium Soc. Sci. J.*, *44*, p.15.

Arumugam, S. S., Umashankar, V., Narendra, N. C., Badrinath, R., Mujumdar, A. P., Holler, J., & Hernandez, A. (2018, August). IOT enabled smart logistics using smart contracts. In 2018 8th International conference on logistics, informatics and service sciences (LISS) (pp. 1-6). IEEE.

Atlas Magazine (2018). Standard & Poor's rating scale. https://www.atlas-mag.net/en/articles/standard-poors-rating-scale-0

Atzori, M. (2015). Blockchain technology and decentralized governance: Is the state still necessary?. Available at SSRN 2709713. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2709713

Avci, G., & Erzurumlu, Y. O. (2023). Blockchain tokenization of real estate investment: a security token offering procedure and legal design proposal. *Journal of Property Research*, *40*(2), 188-207. https://doi.org/10.1080/09599916.2023.2167665

Batiz-Benet, J., Santori, M., and Clayburgh, J. (2017). The SAFT Project: Toward a Compliant Token Sale Framework. https://saftproject.com/static/SAFT-Project-Whitepaper.pdf

Baum, A. (2021). Tokenization—The future of real estate investment. *The Journal of Portfolio Management*, *47*(10), pp.41-61.

Beecher (2021). "Funding and Financing to Sustain Public Infrastructure: Why Choices Matter". https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3766953

Berryhill, J., Bourgery T. and Hanson A. (2018). Blockchains Unchained: Blockchain Technology and its Use in the Public Sector. OECD Working Papers on Public Governance, No. 28, OECD Publishing, Paris. Retrieved from https://doi.org/10.1787/3c32c429-en.

Betz, F. (2014). Modeling a layered financial structure in a knowledge economy. *Journal of the Knowledge Economy*, *5*, pp.841-862.

BIS. (2024). Novel risks, mitigants and uncertainties with permissionless distributed ledger technologies. *Basel Committee on Banking Supervision Working Paper*. https://www.bis.org/bcbs/publ/wp44.htm

Burguet R, and Che Y K (2004). Competitive procurement with corruption. Rand Journal of Economics, 35(1): 50–68

Buterin (2021). Why sharding is great: demystifying the technical properties. https://vitalik.ca/general/2021/04/07/sharding.html#:~:text=The%20scalability%20trilemma%20says%20that,get%20two%20of%20those%20three.&text=Scalability%3A%20the%20chain%20can%20process,a%20consumer%20laptop)%20can%20verify

Carapella, F., Swem, N., and Gerszten, J. (2023). Tokenization: overview and financial stability implications. *Finance and Economics Discussion Series*. https://doi.org/10.17016/FEDS.2023.060r1.

Casady, C.B., Eriksson, K., Levitt, R.E. and Scott, W.R. (2020) (Re) defining public-private partnerships (PPPs) in the new public governance (NPG) paradigm: an institutional maturity perspective. *Public management review*, *22*(2), pp.161-183.

Catalini, C., and Gans, J. S. (2016). Some Simple Economics of the Blockchain. *NBER Working Pape*r No. 22952. Retrieved from https://www.nber.org/papers/w22952

CBDC Tracker. (2021, September). Today's Central Bank Digital Currencies Status. https://cbdctracker.org

CDPQ. (2017a). Financial Information Note. Preliminary estimates of cost and revenue projections for the REM project (Réseau électrique métropolitain) https://www.cdpqinfra.com/sites/cdpqinfrad8/files/2019-10/note_financiere_ang_vf_0.pdf

CDPQ. (2017b). REM Forecasting Report. https://cdpqinfra.com/sites/cdpqinfrad8/files/2019-09/rem_forecasting_2017_appendices_0_0.pdf

Chen, Y. and Volz, U. (2022). Scaling up sustainable investment through blockchain-based project bonds. *Development Policy Review*, *40*(3).

Chishti, S., and Barberis, J. (2016). The fintech book: The financial technology handbook for investors, entrepreneurs and visionaries. John Wiley and Sons.

Chung, K. H. Y., Li, D., & Adriaens, P. (2023). Technology-enabled financing of sustainable infrastructure: A case for blockchains and decentralized oracle networks. Technological Forecasting and Social Change, 187, 122258. https://doi.org/10.1016/j.techfore.2022.122258

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. Hillsdale, N.J: L. Erlbaum Associates.

CoinGecko (2022). https://twitter.com/coingecko/status/1487380562171990019/photo/1

Commbank. 2019. "Project Bond-i: Bonds on blockchain in Collaboration with the World Bank." https://www.commbank.com.au/business/business-insights/project-bondi.html

CONVERGENCE (2019) The State of Blended Finance 2019, https://www.convergence.finance/resource/13VZmRUtiK96hqAvUPk4rt/view, 2019. CONVERGENCE: Blended Finance, Retrieved from https://www.convergence.finance/blended-finance

Corporate finance institute (n.d.). Double Spending. https://corporatefinanceinstitute.com/resources/knowledge/other/double-spending/

Creswell. J.W. and Creswell, J.D. (2017). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. 4th Edition, Sage, Newbury Park.

Croce, R. D., Paula J, and Laboul, A. (2015). Infrastructure financing instruments and incentives. Available at: oecd.org/daf/fin/private-pensions

Deloitte (2021). Investing in Infrastructure: Leading Practices in Planning, Funding, and Financing. http://www.deloitte.com/us/en/insights/topics/economy/spotlight/impact-of-us-infrastructure-investment.html

Demirors, M. (2020, 14 May). The Great Race for Assets. Meltem Writes Things. https://meltdem.substack.com/p/the-great-race-for-assets.

Demsetz, H., and Lehn, K. (1985). The Structure of Corporate Ownership: Causes and Consequences. *Journal of Political Economy*, 93(6), 1155-1177.

DFI WORKING GROUP (2018). DFI Working Group on Blended Concessional Finance for Private Sector Projects Joint Report Update, Retrieved from https://www.adb.org/documents/dfiblendedconcessional-finance-report-2018

Dobbs, R.; Pohl, H.; Lin, D. Y.; Mischke, J.; Garemo, N.; Hexter, J.; Matzinger, S.; Palter, R.; Nanavatty, R. (2013). Infrastructure productivity: how to save $1 trillion a year. McKinsey Global Institute.

EIB (2012). Financing PPPs with project bonds: Issues for public procuring authorities. EPEC. Luxembourg: EIB.

Elghais et al. 2022. Financial management of construction projects: Hyperledger fabric and chaincode solutions. *Automation in Construction*, 137, 104185.

ESCAP. (2017). *Innovative financing for development in Asia and the Pacific: government policies on impact investment and public finance for innovation*. United Nations. Retrieved from https://www.unescap.org/sites/default/files/publications/Innovative%20Financing%20for%20Development%20in%20AP.pdf

European Bank for Reconstruction and Development. (2019). "Why infrastructure matters." Retrieved from https://www.ebrd.com/infrastructure/infrastructure-matters.com. (May 21, 2019)

Fang, L., Ivashina, V., & Lerner, J. (2013, August). The Disintermediation of Financial Markets: Direct Investing in Private Equity. National Bureau of Economic Research. https://www.nber.org/system/files/working_papers/w19299/w19299.pdf

Fay, M., Martimort, D. and Straub, S. (2021). Funding and financing infrastructure: The joint-use of public and private finance. *Journal of Development Economics*, *150*, p.102629.

Fisch, C. and Momtaz, P.P. (2020). Institutional investors and post-ICO performance: an empirical analysis of investor returns in initial coin offerings (ICOs). *Journal of Corporate Finance*, *64*, p.101679.

FRA. (2019). Inspection of Rail. Final rule. 49 CFR, Part 213.

G20 Sustainable Finance (2024). First Sustainable Finance Working Group (SFWG) Meeting Summary Retrieved from https://g20sfwg.org/wp-content/uploads/2024/02/29042024-G20-SFWG-1st-Meeting-Summary.pdf

Gary White, Anna Zink, Lara Codecá, and Siobhán Clarke. A digital twin smart city for citizen feedback. Cities, 110:103064, 2021.

Global Infrastructure Hub (2019) Retrieved from https://ppp.worldbank.org/sites/default/files/2022-03/gih_project-preparation_full-document_final_art_web.pdf

Global Infrastructure Hub. (2020). Leading Practices in Governmental Processes Facilitating Infrastructure Project Preparation. https://outlook.gihub.org/ Accessed 15 January 2020.

Grimsey, D., and Lewis, M. K. (2004). Public Private Partnerships: The Worldwide Revolution in Infrastructure Provision and Project Finance. *Edward Elgar Publishing*.

Grimsey, Darrin, and Mervyn K. Lewis. (2017). Global Developments in Public Infrastructure Procurement: Evaluating Public-Private Partnerships and Other Procurement Options. Cheltenham: Edward Elgar.

Hamledari, H., and Fischer, M. (2021). The application of blockchain-based crypto assets for integrating the physical and financial supply chains in the construction and engineering industry. *Automation in construction*, *127*, 103711. https://doi.org/10.1016/j.autcon.2021.103711

Hanscomb. (2017). Réseau Électrique Métropolitain (REM) Project. Preliminary Design and Costestimate Gap Analysis. Final Report. https://scfp.ca/sites/default/files/ppp201700191_ppp_canada_rem_01_01_2016_part2-opt_0.pdf

Helms 2022. Goldman Sachs Sees the Metaverse as $8 Trillion Opportunity. https://news.bitcoin.com/goldman-sachs-metaverse-8-trillion-opportunity/

Helou A. E. Helou and Assaf, G. J. (2024). Asset Tokenization in Public Infrastructure: A Strategic Framework for Blockchain Driven Financing.

Herweijer, C., D. Waughray, and S. Warren. (2018). Building block (chain) s for a better planet. In World Economic Forum. http://www3.weforum.org/docs/WEF_Building-Blockchains.pdf

Hourcade, J. P., Braud, T., Zhou, P. Y., Wang, L., Xu, D., Lin, Z., ... & Hui, P. (2024). All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda. *Foundations and Trends® in Human–Computer Interaction*, *18*(2–3), 100-337.

HSBC, and SDFA. 2019. “Blockchain Gateway for sustainability linked bonds.” https://www.sustainablefinance.hsbc.com/mobilising-finance/blockchain-gateway-for-sustainability-linked-bonds (accessed 1 June 2020).

Hughes, L., Dwivedi, Y.K., Misra, S.K., Rana, N.P., Raghavan, V. and Akella, V. (2019) Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda. *International journal of information management*, *49*, pp.114-129.

IBM (n.d.). Public cryptography. https://www.ibm.com/docs/en/ztpf/1.1.0.14?topic=concepts-public-key-cryptography

IBM. (n.d.) What is a digital twin? https://www.ibm.com/topics/what-is-a-digital-twin

Inderst, G., and F. Stewart. (2014). “Institutional investment in infrastructure in emerging markets and developing economies.” World Bank Publications. http://documents1.worldbank.org/curated/en/748551468337163636/pdf/913070BR0SecM20itutional0investment.pdf.

International Association for Contract and Commercial Management Report.

Khan, N., Kchouri, B., Yatoo, N. A., Kräussl, Z., Patel, A., & State, R. (2022). Tokenization of sukuk: Ethereum case study. *Global Finance Journal*, *51*, 100539.

Kifokeris, D., & Koch, C. (2020). A conceptual digital business model for construction logistics consultants, featuring a sociomaterial blockchain solution for integrated economic, material and information flows. J. Inf. Technol. Constr., 25(29), 500-521.

Kreppmeier, J., Laschinger, R., Steininger, B.I. and Dorfleitner, G. (2023) Real estate security token offerings and the secondary market: Driven by crypto hype or fundamentals?. *Journal of Banking and Finance*, *154*, p.106940.

Küfeoğlu, S. & Özkuran, M. Bitcoin mining: a global review of energy and power demand.Energy Res. Soc. Sci. 58, 101273 (2019).

Laschinger, R., Leonhard, H., Dorfleitner, G., & Schäfers, W. (2024). Liquidity mechanisms in real-world assets: The empirical case of real estate tokenization. *Available at SSRN 5036350*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5036350

Lawrenz, S., Sharma, P. and Rausch, A. (2019). Blockchain technology as an approach for data marketplaces. In *Proceedings of the 2019 international conference on blockchain technology* (pp. 55-59).

Le, T. V., and Hsu, C. L. (2021). A systematic literature review of blockchain technology: Security properties, applications and challenges. *Journal of Internet Technology*, *22*(4), 789-802.

Lesavre et al.,2021. Blockchain Networks: Token Design and Management Overview. https://doi.org/10.6028/NIST.IR.8301

Lising, P. J. L. (2026). Reassessing blockchain in global development: Tokenization of infrastructure, social impacts, and the axie infinity case in the Philippines. *Social Sciences & Humanities Open*, *13*, 102340. https://doi.org/10.1016/j.ssaho.2025.102340

Lootsma, Y. 2017. "From Fintech to Regtech: The possible use of Blockchain for KYC. Fintech To Regtech Using block chain." Initio. https://static1.squarespace.com/static/567bb0614bf118911ff0bedb/t/5915784ef7e0abd89c297f3d/1494579283238/From_Fintech_to_regtech.pdf.

Louis, J., Sarkez, N., Dang, D., Knox, S., Yermurat, A., Gadda, M., Xu, S., Bais, A. and Pacific Northwest Transportation Consortium (2023). *Blockchain-based Smart Contracts for Transportation Infrastructure Project Funding* (No. 2022-S-OSU-1). Pacific Northwest Transportation Consortium (PacTrans)(UTC).

Lubu, G.L., Kalusambo, J.C.M., Kikola, C.T. and Ambroise, J.E. (2023). Infrastructure Spending, Political Instability and Economic Growth. *iBusiness*, *15*(2), pp.119-139.

Mahandule, V., Patil, M.H., Dinkar, M.P.P., Nitin, M.P.S., Sadashiv, M.D.S. and Subhash, M.S.K. (2024). Blockchain-Enabled Smart Contracts Revolutionizing Supply Chain Management: A Case Study. *transactions*, *4*(2).

Makovˇsek, D., & Veryard, D. (2016). The regulatory asset base and project finance models an analysis of incentives for efficiency. OECD - Organisation for Economic Co-operation and Development. International Transport Forum.

Makovšek, D.; Hasselgren, B.; Perkins, S. (2015). Public Private Partnerships for Transport Infrastructure: Renegotiations, How to Approach them and Economic Outcomes. Discussion Paper No. 2014-25. International Transport Forum at the OECD. Paris.

https://www.oecd.org/content/dam/oecd/en/publications/reports/2014/12/public-private-partnerships-for-transport-infrastructure_g17a26d5/5jrw1kn72gs0-en.pdf

Manoylov, M. (2021, 1 September). What the heck is a fractionalized NFT? The Block Crypto. https://www.theblockcrypto.com/news+/116361/how-do-you-fractionalize-an-nft

MARCO QUIROZ-GUTIERREZ (2022). A Florida home to be auctioned as an NFT has attracted more than 7,000 potential bidders. https://fortune.com/2022/02/08/nft-home-auction-florida-7000-bidders/

Megginson and Netter (2001). From State to Market: A Survey of Empirical Studies on Privatization.

Mercer (2021). Private markets infrastructure investing. https://www.mercer.com/en-nz/solutions/investments/alternatives/infrastructure/

Mougayar, W. (2016). *The Business Blockchain: Promise, Practice, and the Application of the Next Internet Technology*. Wiley.

Nassr, I. K. (2021). Understanding the tokenisation of assets in financial markets. https://www.oecd.org/en/publications/understanding-the-tokenisation-of-assets-in-financial-markets_c033401a-en.html.

Gaur, N., Cuomo, J. and Arun, J. (2019). Blockchain for Business. Addison-Wesley Professional.

OECD (2018). Roadmap to infrastructure as an asset class, retrieved from https://www.oecd.org/g20/roadmap_to_infrastructure_as_an_asset_class_argentina_presidency_1_0.pdf Access date 15 February 2020.

OECD. (2020). The tokenisation of assets and potential implications for financial markets. *OECD Blockchain Policy Series.* https://www.oecd.org/en/publications/the-tokenisation-of-assets-and-potential-implications-for-financial-markets_83493d34-en.html

OECD. (2021). Regulatory Approaches to the Tokenisation of Assets. *OECD Blockchain Policy Series*. https://doi.org/10.1787/aea35466-en

OECD. (2025). Tokenisation of assets and distributed ledger technologies in financial markets. *OECD Business and Finance Policy Papers*. https://www.oecd.org/en/publications/tokenisation-of-assets-and-distributed-ledger-technologies-in-financial-markets_40e7f217-en.html

Olken, B. A., and R. Pande. 2012. “Corruption in developing countries.” Annu. Rev. Econ., 4(1), 479-509.

Ontario Securities Commission, “Cryptocurrency Offerings,” CSA Staff Notice 46-307, 24 Aug. 2017.

Panos (2020). XRP: Disrupting SWIFT gpi and Correspondent Banking. https://panos.writeas.com/xrp-disrupting-swift-gpi-and-correspondent-banking

Pedersen, A. B., Risius, M., & Beck, R. (2019). A ten-step decision path to determine when to use blockchain technologies. *MIS quarterly executive*, *18*(2), 99-115.

Pereira, J., M. M. Tavalaei, and H. Ozalp. 2019. “Blockchain-based platforms: Decentralized infrastructures and its boundary conditions.” Technological Forecasting and Social Change. 146. pp.94-102.

Peters. (2021). Simple Agreement for Future Tokens (SAFT). https://www.investopedia.com/terms/s/simple-agreement-future-tokens-saft.asp

Rail Safety and Standards Board (RSSB). Cross-industry working group on freight derailment. London: Rail Safety and Standards Board, 2016.

Rauchs, M., Blandin, A., Bear, K., & McKeon, S. (2019). 2nd Global Enterprise Blockchain Benchmarking Study. Cambridge Centre for Alternative Finance. https://www.jbs.cam.ac.uk/faculty-research/centres/alternative-finance/publications/2nd-global-enterprise-blockchain-benchmarking-study/.

Regan, M. 2017. “Infrastructure financing modalities in Asia and the Pacific: Strengths and limitations.” ADB. https://www.adb.org/publications/infrastructure-financing-modalities-asia-and-pacific.

REM. (2021). Update: Réseau express métropolitain. https://rem.info/sites/default/files/document/PPT-Breffage-Mise%C3%80jour-2021-06-03-EN.pdf

Research Brief (2018). Availability Payments in Public-Private Partnerships: Issues and Implications.

Roehrich, J. K., & Kivleniece, I. (2022). Creating and distributing sustainable value through public-private collaborative projects. In George et al. (Eds.) Handbook on the Business of Sustainability (pp. 474-500). Edward Elgar Publishing. https://doi.org/10.4337/9781839105340.00036

ROGER 800. https://www.mermecgroup.com/measuring-trains-e-systems/recording-cars/533/roger-800.php

Rosenthal, R. (1991). Meta-Analytic Procedures for Social Research. Newbury Park: Sage Publications.

Rybnicek, R., Plakolm, J. and Baumgartner, L. (2020). Risks in public–private partnerships: A systematic literature review of risk factors, their impact and risk mitigation strategies. Public Performance and Management Review, 43(5), pp.1174-1208.

Schooling, J., Geddes, R., Frawley, D.D., Mair, R.J., O'Rourke, T.D., Powrie, W., Soga, K. and Threlfall, R. (2023). The Role of Funding, Financing and Emerging Technologies in delivering and managing infrastructure for the 21st Century. Retrieved from https://www.repository.cam.ac.uk/items/8a5c7dd6-f58a-493b-805c-750ffad3cb85

SCI. Rail transport markets – global market trends 2016–2025. 2017. Available at: https://www.sci.de/fil-eadmin/user_upload/Flyer_Rail_Transport_Markets_eng.pdf Google Scholar

SEC v. WJ Howey Co., 328 US 293, 298 (1946).

SEC, "Digital Asset Transactions: When Howey Met Gary (Plastic)." William Hinman, Director of Division of Corporate Finance. San Francisco, CA, June 14, 2018.

SEC. (2020, 14 January). Initial Exchange Offerings (IEOs) – Investor Alert. U.S.Securitiesand Exchange Commission. https://www.sec.gov/oiea/investor-alerts-and-bulletins/ia_initialexchangeofferings

Shahmohammad, M., Salamattalab, M. M., Sohn, W., Kouhizadeh, M., and Aghamohmmadi, N. (2024). Opportunities and obstacles of blockchain use in pursuit of sustainable development goal 11: a systematic scoping review. *Sustainable Cities and Society*, 105620. https://doi.org/10.1016/j.scs.2024.105620

Sheppard B. and Cook, J. (2020, September 25). Leveraging defi to fund major public infrastructure projects. Ledger Insights - Blockchain for enterprise. Retrieved from https://www.ledgerinsights.com/de-fi-to-fund-public-infrastructure-ppp/

Silva, R., Marques, R. P., and Inácio, H. (2024). A design for tokenization in governmental investment. *International Journal of Accounting and Information Management*, *32*(1), 19-39. https://doi.org/10.1108/IJAIM-03-2023-0070

Singh, A. K., Mohandes, S. R., Awuzie, B. O., Omotayo, T., Kumar, V. P., and Kidd, C. (2024). A roadmap for overcoming barriers to implementation of blockchain-enabled smart contracts in sustainable construction projects. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-10-2023-0303

Singh, A. K., Kumar, V. P., Dehdasht, G., Mohandes, S. R., Manu, P., & Rahimian, F. P. (2023). Investigating barriers to blockchain adoption in construction supply chain management: A fuzzy-based MCDM approach. *Technological Forecasting and Social Change*, *196*, 122849. https://doi.org/10.1016/j.techfore.2023.122849

Soleymani, H., Ravanshadnia, M. and Montazer, M. (2021). An Innovative Conceptual Model to Structure Financing Package of Infrastructure Projects. *Shock and Vibration*, *2021*(1), p.6711408.

Sraieb, M., Al-Mohamad, S. and Khaki, A.R. (2024). Blockchain, Asset Management and Real Estate Funds. In *Blockchain in Real Estate: Theoretical Advances and New Empirical Applications* (pp. 35-52). Singapore: Springer Nature Singapore.

Stably (n.d.). https://medium.com/stably-blog/decentralized-finance-vs-traditional-finance-what-you-need-to-know-3b57aed7a0c2

Stanislav Jovanovic (2017). Modern Railway Infrastructure Asset Management.

Stedas (2021). https://www.stedas.hr/pics/png/xrp-vs-btc-1.png

Stein, J. (2018, August). Josh Stein and Danny An: Harbor and TrustToken on why they don't mind being unsexy (L. Shin, interviewer). UnChained, Ep. 77. [podcast]. Retrieved from http://unchainedpodcast.co/podcast/harbor-and-trusttoken-on-why-they-dont-mind-being-unsexy-ep77

Subramanyam, S.V. (2024). Transforming financial systems through robotic process automation and AI: The future of smart finance. *International Journal of Artificial Intelligence Research and Development (IJAIRD)*, *2*(1), pp.203-223.

Tanveer, U., Ishaq, S., & Hoang, T. G. (2025). Tokenized assets in a decentralized economy: Balancing efficiency, value, and risks. *International Journal of Production Economics*, 282, 109554. https://doi.org/10.1016/j.ijpe.2025.109554

Tapscott, D., and Tapscott, A. (2016). *Blockchain Revolution: How the Technology Behind Bitcoin Is Changing Money, Business, and the World*. Penguin.

TCRP 151 (2020). Maintenance Planning for Rail Asset Management Current Practices.

The Economist (2014). Infrastructure financing: A long and winding road. Available at: economist.com/finance-and-economics/2014/03/22

The Institute for Asset Management at www.theiam.org, retrieved March 06, 2022.

Tian, Y., Zhang, Y., Minchin, R. E., Asutosh, A., & Kan, C. (2020). An innovative infrastructure financing instrument: Blockchain-based tokenization. In *Construction Research Congress 2020* (pp. 731-740). Reston, VA: American Society of Civil Engineers.

Tian, Y., Adriaens, P., Minchin, R. E., Chang, C., Lu, Z., and Qi, C. (2020). Asset tokenization: A blockchain solution to financing infrastructure in emerging markets and developing economies. *ADB-IGF Special Working Paper Series "Fintech to Enable Development, Investment, Financial Inclusion, and Sustainability*. https://dx.doi.org/10.2139/ssrn.3837703

Tian, Y., Lu, Z., Adriaens, P., Minchin, R.E., Caithness, A. and Woo, J. (2020). Finance infrastructure through blockchain-based tokenization. *Frontiers of Engineering Management*, *7*(4), pp.485-499.

Tian, Y., Minchin, R. E., Chung, K., Woo, J., and Adriaens, P. (2022). Towards inclusive and sustainable infrastructure development through blockchain-enabled asset tokenization: An exploratory case study. In *IOP Conference Series: Materials Science and Engineering*, 1218(1), 012040. IOP Publishing. https://doi.org/10.1088/1757-899X/1218/1/012040

Tian, Y., Minchin, R.E., Petersen, C., Moayed, E. and Adriaens, P. (2022). Financing public-private partnership infrastructure projects through tokenization-enabled project finance on blockchain. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1218, No. 1, p. 012027). IOP Publishing.

Tian, Y., Wang, C., Woo, J., Lu, Z. and Adriaens, P. (2022). The future of blockchain-enabled tokenization in infrastructure investment and development: A Delphi-based scenario analysis.

Tokenist. (2018). "Security Tokens Explained for Beginners (Everything You Need)." Retrieved from https://thetokenist.io/security-tokens-explained/. (May 25, 2019)

Tolstolesova, L., Glukhikh, I., Yumanova, N., and Arzikulov, O. (2021). Digital transformation of public-private partnership tools. Journal of Risk and Financial Management, 14(3), 121.

U.S. Department of the Treasury. (2021). *Infrastructure Investment and Jobs Act: Overview and Key Provisions*. https://www.congress.gov/bill/117th-congress/house-bill/3684

Uzsoki, D. (2019). "Tokenization of Infrastructure: A blockchain based solution to financing sustainable infrastructure." International Institute for sustainable development. https://www.iisd.org/publications/report/tokenization-infrastructure-blockchain-based-solution-financing-sustainable

Verdouw, W., D. Uzsoki, and C. D. Ordoñez. 2015. "Currency risk in project finance. International Institute for Sustainable Development Discussion Paper." Winnipeg. https://www.iisd.org/sites/default/files/publications/currency-risk-project-finance-discussion-paper.pdf.

Walter, I. (2012). Universal banking and financial architecture. *The Quarterly Review of Economics and Finance*, *52*(2), 114-122.

Walter I (2016). *The Infrastructure Finance Challenge*. Open Book Publishers

Wang, S., Ouyang, L., Yuan, Y., Ni, X., Han, X. and Wang, F.Y. (2019). Blockchain-enabled smart contracts: architecture, applications, and future trends. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *49*(11), pp.2266-2277.

Wang, X. and Cui, X. (2022). PPP financing model in the infrastructure construction of the park integrating artificial intelligence technology. *Computational Intelligence and Neuroscience*, *2022*(1), p.6154885.

Wang, Z., Yu, L., and Zhou, L. (2024). Navigating the blockchain-driven transformation in industry 4.0: Opportunities and Challenges for Economic and Management Innovations. *Journal of the Knowledge Economy*, 16, 3507-3549. https://doi.org/10.1007/s13132-024-02007-7

Weber, R. H., and Baisch, R. (2023). Cryptoassets: Taxonomy and Regulatory Approaches. *Banking and Finance Law Review*, *39*(3), 467-505.

Wood, M. (2019). Gartner's four phase blockchain spectrum. https://www.ledgerinsights.com/gartners-four-phase-blockchain-spectrum/

World Bank (2017). "Who Sponsors Infrastructure Projects? Disentangling Public and Private Contributions." https://ppp.worldbank.org/sites/default/files/2022-03/SPIReport_2017_small_interactive.pdf

World Economic Forum (2023) Annual Report 2023-2024 Retrieved from https://www.weforum.org/publications/annual-report-2023-2024/

Wu, L., Lu, W., and Chen, C. (2025). Resolving power imbalances in construction payment using blockchain smart contracts. *Engineering, Construction and Architectural Management*, *32*(3), 1875-1902. https://doi.org/10.1108/ECAM-03-2023-0194

Ye, X., Zeng, N., and König, M. (2022). Systematic literature review on smart contracts in the construction industry: Potentials, benefits, and challenges. *Frontiers of engineering management*, *9*(2), 196-213. https://doi.org/10.1007/s42524-022-0188-2

Yescombe, E. R. (2017). *Public-Private Partnerships: Principles of Policy and Finance*. Routledge.

Yu, H., Deng, X., Zhang, N., and Zhang, X. (2024). Is blockchain cost-effective in construction project management? A systematic review from the perspective of transaction cost. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-06-2023-0604

Zheng, Z., Xie, S., Dai, H.N., Chen, X. and Wang, H. (2018). Blockchain challenges and opportunities: A survey. *International journal of web and grid services*, *14*(4), pp.352-375.

Zohar, A. (2015). Bitcoin: Under the hood. *Communications of the ACM*, 58(9), 104-113. https://doi.org/10.1145/2701411