BLOCKCHAIN-BASED SMART CONTRACTS FOR TRANSPORTATION INFRASTRUCTURE PROJECT FUNDING

FINAL PROJECT REPORT

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16. Abstract

The USDOT Strategic Plan highlights the importance of improving the mobility of people and goods through its focus on infrastructure. However, a significant portion of the transportation infrastructure in the United States–up to 173,000 miles and 45,000 bridges—is in poor condition, which causes a variety of mobility-related traffic concerns that are estimated to cost the taxpayer over $160 billion dollars per year. Much of the major transportation infrastructure projects that are funded with federal monies are typically executed through public-private partnerships (PPPs) in which a consortium of private contractors in partnership with relevant public agencies form a special-purpose project company. While PPPs are an effective means of sharing project risk across public and private entities for capital transportation projects, critics have noted that they suffer from disadvantages related to the complexity of project procurement and administration, susceptibility to cost and time overruns, and failure to account for uncertain events due to the long-term nature of the projects. This project investigated the use of decentralized financing methods enabled by blockchain technology to provide efficient and effective financial control for capital transportation infrastructure projects. This project created a prototype framework for the issuance of a "transportation infrastructure token" cryptocurrency to be issued by project owners (typically government agencies) for specific capital transportation assets. This cryptocurrency would provide a transparent and efficient means of funding and recovering costs from transportation infrastructure projects by using smart contracts for collecting tolls from the traveling public and issuing dividends to owners. The resulting prototype can serve as a template for use across multiple capital projects. It will also support non-traditional methods of financing such projects by making investments available to a wider and more diverse range of investors and enabling crowd-funding—thereby also increasing the equity of transportation funding mechanisms.

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Executive Summary

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While PPPs are an effective means of sharing project risk across public and private entities for capital transportation projects, critics have noted that they suffer from disadvantages related to the complexity of project procurement and administration, susceptibility to cost and time overruns, and failure to account for uncertain events due to the long-term nature of the projects. To address these issues, this project investigated the use of decentralized financing methods enabled by blockchain technology to provide efficient and effective financial control for capital transportation infrastructure projects.

This project created a prototype framework for the issuance of a "transportation infrastructure token" cryptocurrency that could be issued by project owners (typically government agencies) for specific capital transportation assets.

This cryptocurrency would provide a transparent and efficient means of funding and recovering cost from transportation infrastructure projects by using smart contracts for toll collection from the traveling public and issuing dividends to owners. The resulting prototype could serve as a template for use across multiple capital projects. It would also allow non-traditional methods of financing such projects by making investment available to a wider and more diverse range of investors and enabling crowdfunding, thereby also increasing the equity of transportation funding mechanisms.

Chapter 1 Introduction

A major portion of the transportation infrastructure in the United States—up to 173,000 miles and 45,000 bridges—requires repairs and causes a variety of mobility-related traffic concerns that are estimated to cost taxpayers over $160 billion dollars per year. In response, the federal government has proposed an ambitious series of policies to expand the budget for infrastructure spending to modernize more than 20,000 miles of roadway infrastructure and repair more than 10,000 bridges that provide critical linkages for communities, many of which are underserved (the United States Government 2023).

Most major transportation infrastructure projects that are funded with federal monies are typically conducted through public-private partnerships (PPPs) in which a consortium of private contractors in partnership with relevant public agencies form a special-purpose project company. Financially, the project itself is executed by the PPP through a combination of equity and debt, which are recovered through direct payment from the government as well as from end-users in the form of toll payments for a (fixed or variable) period of time (Deye 2015).

While PPPs have been touted as an effective means of sharing project risk across public and private entities for capital transportation projects, critics have noted that they suffer from certain disadvantages, including the following:

1. Project procurement is much more complicated because of the need for banding together companies and organizations that have not previously worked as a team.
2. There is the potential for significant cost and time overruns because of the complex collaborations and the need to establish communication protocols.
3. Because PPP agreements are long term, they can fail to account for uncertain events, which can significantly increase the budget allotment for contingency planning.

These disadvantages specifically relate to the financial methods for funding and recovering cost from transportation infrastructure projects—causing huge delays and cost overruns during project execution. In response to the disadvantages of traditional means of implementing PPP projects, this project investigated the use of decentralized financing methods enabled by blockchain technology to provide efficient and effective financial control for capital transportation infrastructure projects.

Specifically, this project worked to create a prototype framework for the issuance of a "transportation infrastructure token" cryptocurrency that would be issued by project owners (typically government agencies) for specific capital transportation assets. This cryptocurrency would provide a transparent and efficient means of funding and recovering cost from transportation infrastructure projects by using smart contracts for toll collection from the traveling public and issuing dividends to owners. The resulting prototype could serve as a template for use across multiple capital projects. It would also allow non-traditional methods of financing such projects by making investment available to a wider and more diverse range of investors and enabling crowd-funding—thereby also increasing the equity of transportation funding mechanisms.

The rationale for the use of this emerging technology is that blockchain enables the use of decentralized and trustless paradigms for the storage and transfer of value, which could increase transparency among multiple project stakeholders and could be scalable to include the participation of the traveling public in the funding of infrastructure. Note that blockchain technology has enabled decentralized paradigms for financial operations in other kinds of cases, such as trading exchanges, that are known to be more complicated than providing funding for and recovering income from infrastructure projects (Sheppard and Cook, 2020).

This research pursued two main objectives to create a framework for utilizing blockchain technology to issue ownership of and recovery from public transportation infrastructure assets:

1. Conduct a literature review of blockchain technology and PPP infrastructure funding

The first task involved a review of enabling cryptocurrencies and the state of practice for PPP funding in the U.S. For the former, the largest blockchain-based cryptocurrency that enables "smart contracts"—Ethereum—was studied to identify existing analogous use-cases that could be modified to work for decentralizing and digitizing PPP financing models. This task served to provide the context for the development of a PPP smart contract framework. The outcomes of this task are presented in Chapter 2.

2. Create a PPP smart contract on Ethereum blockchain

After the requirements had been defined for the PPP workflow that involved issuance of tokens to project partners and recovery of value from the traveling public, a prototype cryptocurrency was created on Ethereum's test blockchain. Because of the exploratory nature of the work, this coin would only serve to validate the PPP framework and would not be issued to the public or have value associated with it for the scope of this project. Examples for creating customized cryptocurrency coins were available for the research team to emulate, such as that provided by Nachamkin (2016). The outcomes of this task are presented in Chapter 3.

At the outset, this research proposed an examination of blockchain technology features to identify the potential for solving issues related to the transparency and efficiency of PPP-based project financing for transportation infrastructure projects. The outcomes of the research will provide a framework for creating a specialty infrastructure cryptocurrency whose value will reflect the value of the infrastructure not just in terms of its construction and maintenance costs, but also in terms of the value provided to the public. Given the nascent stage of blockchain technology, this project will provide impetus and directions for future research for the adaptation of blockchain into the areas of transportation and infrastructure operations.

Chapter 2 Literature Review

This chapter provides a review of the state of the art of public-private partnerships (PPPs) for funding infrastructure projects, an introduction to blockchain technologies, and the work that has been done in using blockchain technologies to fund infrastructure and other similar capital projects.

2.1. Public Private Partnerships (PPPs)

A public-private partnership (PPP) is a business relationship between public and private partners that is created to build, operate, and/or maintain public-serving infrastructure projects. These are essentially a collaboration between the public sector (represented by various government agencies relevant to the project) and the private sector (typically a general contracting company) to work on a project to benefit the public. This partnership is implemented as a contract created by the public sector that specifies the project deliverables, milestones, and payment terms, which are agreed upon by the private party (New Zealand Social Infrastructure Fund 2009).

PPPs have been implemented for a variety of infrastructure projects, such as waste and water management, and transportation infrastructure such as highways and bridges. PPPs enable the public sector to engage the technical and management expertise and resources of seasoned private sector companies. The private party is responsible for completing project milestones while receiving funding from the public sector. While this partnership does not eliminate all the issues that inevitably come with infrastructure projects, it does improve efficiency, flexibility, and communication throughout the various project stages.

2.1.1. History of PPPs in the United States

PPP contracts originated at the state level in California in 1989 and have since expanded throughout the United States within the past 20 years (Sheppard and Cook 2020). This rise in the use of PPP contracts during this period is also evident in the U.S. government's allocation of $10 billion to PPPs between 1990 to 2006. This changed the primary paradigm of government constructed, owned, and operated infrastructure whereas only smaller portions would have been outsourced to private sector companies.

Most states in the U.S. require legislative approval to determine whether the specific project and PPP being considered are worth investing in. This is followed by a bidding process during which the public agency solicits contractors to participate in the project through a request for quote (RFQ) or request for proposal (RFP) (Smith et al 2019). Contractors are then selected for the project on the basis of the most likely financial considerations and their expertise and previous experience.

2.1.2. Cases of PPPs Globally

Apart from the United States, several other countries have used PPPs for capital infrastructure projects. For example, China has invested significant money to develop local infrastructure through PPP contracts. The United Kingdom has also followed the U.S. in investing billions of dollars into PPPs.

However, the application of rules and definition of privatization concepts can be different for every country. Since Spain started to implement PPPs in 1996, the legal framework has shifted to incorporate more risk sharing between public and private sectors and has provided the public sector more control over the contract and modeling of the infrastructure (Domingues and Zlatkovic 2014). Greece implemented a PPP law in 2005 allowing the government to manage large-scale projects and has a PPP structure targeted toward medium- to small-scale projects (Domingues and Zlatkovic 2014).

2.1.3. Current State of the Art of PPP Project Management

Most PPP contracts typically last 20 to 30 years, depending on the scale of the project, and enable the private partners to recover their cost from the public during operation of the infrastructure. Typically, the private sector is responsible for taking on more risk and ownership over the project than the public sector (New Zealand Social Infrastructure Fund 2009). This is because the private sector derives funds from equity investors, debt providers, and lenders. Equity investors carry a higher risk investment than lenders but receive a higher return on investment. Investors can also opt for the rights or assets of the project as an alternative form of repayment. Investment is only part of the process, as the entire PPP process can be split into four phases: (1) pre-investment, (2) investment, (3) operation, and (4) post-investment (Tolstolesova et. al 2021).

1. <u>Pre-investment Phase:</u> The pre-investment phase is the stage in which the project initiator's (typically a public agency's) funds and savings are used. This stage involves the conceptualization of the project and documentation that is used to solicit private partners in later stages.
2. <u>Investment Phase:</u> The investment phase involves the transition to a project finance structure in which resources such as grants and funds are pooled from commercial investors, and the risks of the project are shared with lenders. While the public sector partner also invests funds, this is typically done for larger-scale projects to achieve a reasonable payoff, given transaction and interest costs (Public Private Partnership Legal

Resource Center 2022). This stage involves the detailed examination of project goals and feasibility and the development of the design and plans for project execution.

3. Operational Phase: The completion of the construction of the project leads to the operational phase, as the infrastructure is now considered operational. This stage corresponds to the construction and maintenance of the project. During this stage, the funds spent in construction can be recovered through collection of funds from users of the infrastructure.
4. Liquidation Phase: During this stage, the project results are evaluated by the initiator and experts; this stage is funded primarily by participants' own internal funds.

2.1.4. Advantages of PPPs

The advantages of using PPPs for building and operating capital infrastructure can be understood by comparing them with more traditional forms of contract management such as self-performance by public agencies or outsourcing of specific aspects by public agencies to private contractors. Some of the primary benefits of PPPs are described below.

1. Diversity and availability of funding sources: PPPs enable access to capital from a broader range of funding sources. This can prove to be especially beneficial for regions that have few resources for infrastructure development, which can in turn spur economic growth (Smet et al. 2019).
2. Improved design for constructability: The collaborative nature of PPP projects brings the owners, designers, and contractors together during the early stages of the project so that the owner's requirements can be met with adequate input from the contractor regarding the project's constructability. This collaboration can lead to increased potential for design innovation, with each sector planning together. During the conceptualization and design

stages, the private sector is likely to provide a more realistic point of view regarding project expectations than the public sector's view (International Civil Aviation Organization n.d.; eSUB Construction Software 2019).

3. Reduction of risk for public: While construction and implementation risks are not fully eliminated, they are transferred for a fee to the private company, and this may be beneficial to the public in certain situations. Because the private company is primarily concerned with its bottom line, it has the incentive to manage and mitigate the occurrences of project cost and time overruns (Smet et al. 2019; Siemiatycki and Farooqi 2012).
4. Increased potential for innovation in methods and financing: PPP projects utilize the expertise, experience, and efficiencies of the private sector for public infrastructure projects. Because typical PPP projects focus on the project deliverables, this can afford the private companies executing the project some level of flexibility and independence to determine the means and methods to accomplish the project's goals. This enables them to utilize their experience and even innovate to be more efficient with project delivery to improve their own bottom line (APMG International n.d.; eSUB Construction Software 2019).

2.1.5. Disadvantages of PPPs

Despite the prevalence and advantages of PPPs for infrastructure projects, their sheer size and complexity can pose disadvantages that negatively impact project performances. Some of these important disadvantages and limitations are listed below:

1. Accountability and transparency issues: Because multiple parties are involved in the PPP and some of them are private, the contracting process and documents can be very

complex. This can also allow private companies to hide financial details under commercial confidentiality provisions within contracts that are redacted when presented to the public (Whiteside 2020; Siemiatycki and Farooqi 2012).

2. Potential for cost overruns: Numerous PPP projects have had severe cost-overruns. These could have been due to any combination of the following reasons. Because of the use of private and institutional lenders by private contractors, the cost of borrowing capital for the project tends to be higher than if it were borrowed solely by the government. This higher cost of borrowing capital can adversely affect the return on investment for the public. In addition, the negotiation of contracts and agreements between multiple parties can require numerous fees and legal costs, which, along with the expectation of profit from private partners, can bloat the project budget (McKenna 2012; Siemiatycki and Farooqi 2012).
3. Funder-related limitations: The involvement of third-party funding from banks for financing can also contribute to punitive fees and delays in transactions that can create difficulties and delays on the private sector's end (Morris 2022). Tian et al. (2022) also noted that because of the size of projects and the funding required, the funders may be limited to only certain asset classes and a narrower range of institutional investors such as pension funds and insurance companies. This lack of funding options may adversely affect the finances of the project and its progress.
4. Relationship between partners in the PPP: Because of the contractually binding nature of formal PPP contracts and the fact that these projects typically last 20 to 30 years, it is very important that the partners in the PPP have a professional and cordial working relationship. When there is miscommunication or disagreements that sour the

relationship, the project can suffer, potentially leading to protracted legal issues that can severely affect the success and even completion of projects. Hence it is key to ensure the transparency of the partners' objectives and responsibilities, and to define appropriate strategies for communication and dispute resolution among the PPP team.

5. Political implications for PPP: Because public agencies are involved and because the ultimate payers for PPP projects are the tax-payers, the public has a role to play in the adoption of PPP projects. Thus, political pressure can affect these projects as political policy can prevent or encourage the formation of PPPs for infrastructure. For this reason, any previous failure of a PPP can negatively impact the public's perspective of future projects (Maltin 2019).

Some of the disadvantages of PPPs can be overcome by adopting innovative financing structures and methods, such as blockchain. This is discussed in the next section.

2.2. Blockchain Technology

Some of the disadvantages of PPP contracts can be alleviated by using blockchain technology. These disadvantages specifically relate to contract-related issues, some of which could possibly be mitigated by smart-contracting features available with certain blockchains. Other disadvantages relate to transparency and accountability issues, which could be overcome by using the core feature of blockchains as a public and distributed, yet encrypted, ledger. This section describes the core functionality of blockchain technology, its advantages and disadvantages, and its potential for alleviating some of the disadvantages of PPPs. Example implementations of blockchains for PPP projects are also provided.

Blockchain technology is a means for recording and transferring value on a ledger without the use of trusted third parties in which each transaction is recorded under a data structure known as a “block.” It functions as a decentralized and distributed ledger in which transactions are publicly visible (Paula and Bishop 2019). No single entity (which controls less than 50 percent of nodes in a blockchain network) can alter or erase transactions within the ledger because of the automated proof of activity algorithms that are embedded in the ledger. These can either be computationally (and thus energy) expensive proof-of-work (POW) or proof-of-stake (POS) algorithms.

One of the currently primary uses of blockchain is as the underlying infrastructure that enables the creation, transfer, and storage of digital currencies (cryptocurrencies) such as Bitcoin and Ethereum. Other uses include the creation, storage, and transfer of non-fungible tokens (NFTs) on the blockchain, which provides proof of ownership of unique digital assets. A feature that was utilized in this research is the tokenization of digital assets that represent a real-world asset, as described in the following subsections.

The collective name given for financial applications of the blockchain is decentralized finance. Decentralized finance (DeFi) is a financial system built on blockchain technology that aims to provide more accessible, transparent, and secure financial services to users without the need for intermediaries such as banks or financial institutions. DeFi allows anyone with an internet connection to access various financial services, such as lending, borrowing, trading, and investing, by interacting with smart contracts on decentralized platforms.

DeFi has the potential to improve the process of public-private partnerships (PPPs) by enabling a more transparent and secure way to manage and distribute funds. PPPs involve collaboration between public and private entities to finance and deliver public services, such as infrastructure projects. However, the traditional PPP model often involves complex and opaque financing arrangements, which can lead to inefficiencies, corruption, and lack of accountability.

With DeFi, PPPs could be managed through smart contracts that automatically executed the terms of the agreement, including the distribution of funds to various parties involved in the project. Smart contracts could also enable more transparent and auditable financial reporting, as all transactions are recorded on a public blockchain ledger. Additionally, DeFi could provide more accessible and flexible financing options, such as peer-to-peer lending or crowdfunding, which could help to democratize the process of PPPs and reduce reliance on traditional financing sources.

2.2.1. Blockchain's Advantages in Tokenization

The following points describe the advantages offered by blockchain that make it suitable for use in PPP project settings:

1. Digitizing ownership for improved liquidity for investors: As mentioned previously, tokenization is the process of digitizing funds or assets on the blockchain. Thus, the ownership of an infrastructure asset could be digitized on the blockchain and could take the form of different tokens, such as security, utility, or payment tokens (Tian et al 2022). Security tokens take the form of equity or funds, utility tokens hold private sector services or products, and payment tokens cn represent any cryptocurrency. Once such digital tokens were created for infrastructure, various features would be available for cryptocurrencies, such as the ability to be bought and sold on online exchanges and to be tethered to a real-world tangible asset to mitigate market manipulation of coin price.
2. Diversifying funding sources: As described in the previous section, one of the disadvantages of PPP is the reliance of institutional investors and large banks to fund the initial project while the public pays off the project with taxes or tolls over a longer period of time. These traditional methods of financing are not accessible to smaller investors,

and blockchain's tokenization capabilities have the potential to change this. Blockchain could change the financing of infrastructure by diversifying the pool of investors from just traditional investors such as banks to initial coin offerings (ICOs) on the blockchain available to anyone with an internet connection. (Tolstolesova 2021). This could be done by developing specific tokens for an infrastructure and promoting them on the blockchain to a more diverse array of investors. Methods such as customer registration, identity validation, and other tested anti-money laundering procedures could be used to prevent customer fraud and ensure ethical transactions (Tolstolesova 2021).

3. Efficient contract management: From the perspective of contract management, blockchain could facilitate automated procurement and payments. This could be done by executing smart contracts on the blockchain, which could potentially eliminate payment and cash-flow issues in a very transparent manner to improve the efficiency of the contract administration process and promote trust in contractual relationships. The use of transparent smart-contracts could also help mitigate deviation from agreed terms in the contract, which typically leads to protracted legal issues on PPP projects (Wang et al. 2017).
4. Improved security of contract management: The security features built into a blockchain suitable for executing contracts would allow it to potentially reduce the time to verify the authenticity of documents and contract management. Blockchain technology could be used in notarization-related applications to track the creation, deletion, and updating of contract documents while ensuring their authenticity (Wang et al. 2017).
5. Improved transparency and trust in contract management: Blockchain could also improve the transparency and traceability of construction supply chains and project management

operations because of its ability to capture and document every transaction, trace it backward, and assess it from a compliance and quality assurance perspective (Wang et al. 2017).

2.2.3. Challenges for Blockchain Adoption

Two major obstacles currently prevent the widespread adoption of blockchain: (1) lack of operational knowledge and (2) the energy requirements of blockchain. The first obstacle relates to the fact that blockchain technology is still in its nascent stages even though it has caught public attention because of the volatile prices of cryptocurrencies that have become an investment medium. There are not many examples of blockchain used for project management on a regular basis, and much remains to be learned about best practices for its adoption. Therefore, even though blockchain is projected to revolutionize the way that society conducts transactions, the shortcomings of the technology stem from people's inexperience with managing the software in a real setting.

The second limitation that has hindered the widespread adoption of blockchain is the massive amount of energy needed to validate transactions on the blockchain. As mentioned earlier, blockchain utilizes proof-of-activity algorithms (POA) to ensure the integrity of miners by creating a consensus that miners are all operating on the same verification system (Seth 2021). Such systems can operate primarily as either proof-of-work (POW) or proof-of-stake (POS) systems. Proof-of-work systems result in the need to solve increasingly complex problems that require intensive computational power, which in turn uses large amounts of energy, resulting in high carbon dioxide emissions (Paula and Bishop 2019, Shi et al 2023). The U.S. White House has noted that global electricity generation for the largest crypto-assets on the blockchain has produced a combined 140 million metric tons of carbon dioxide per year, which is equivalent to about 0.3 percent of annual global greenhouse gas emissions. This has raised criticisms and concern about whether the energy costs outweigh the benefits of digital assets (The United States Government 2022). This emission level is based on blockchain's progression over time in which the difficulty of mining blocks has increased, thereby leading to higher demands in grid energy usage. Critics of the blockchain have also noted that excessive energy consumption has resulted in air, water, and waste pollutants in local communities (Clarke 2022).

However, there are alternative solutions that could mitigate these environmental effects. One solution is to switch to a POS (proof-of-stake) over a POW mechanism. With proof-of-stake, participants on the blockchain commit their coins to the validation process (Frankenfield 2023) instead of solving a computationally expensive problem. Based on the number of staked coins from each participant, they receive cryptocurrency through validation of the transaction. Most importantly, the POS system is more energy efficient than the POW system. The POS system also makes the blockchain more decentralized because of the decreased difficulty in verifying transactions. There is also an opportunity to utilize renewable energy to verify transactions under POW systems on the blockchain (Clarke 2022).

2.3. Intersection of PPP with Blockchain Technology

The features discussed above make evident the advantages of using blockchain for managing PPP contracts. The following points identify areas in which PPP contract administration could be helped by utilization of blockchain technology.

1. Broader source of project funding sources: The decentralization features that blockchain offers would broaden the list and type of available funding for projects.
2. Smart contracts that can reduce wait times and improve transparency: The availability of smart contracts could enable faster cash payments to contractors based on work

performed, without the need for bureaucratic approvals. A smart contract is an automated, digitized version of a contract that is programmed to execute agreements on the contract. This could eliminate time delays, thereby enabling private sector contractors to move forward on projects more efficiently.

3. Improved collaboration and communication: The use of such smart contracts could reduce miscommunication and misunderstandings about how funds were being distributed, leading to increased inclusivity and more effective project management. These contracts would contribute to large improvements in the transparency, accessibility of information, and coordination between sectors and stakeholders (Tian et al 2022).
4. Transparency in finances: Smart contracts could also transparently show how the funds collected by the project were disbursed to investors, thereby potentially increasing public confidence in projects. Financial instruments related to the funding of PPPs, such as debt and equity, would be held as cryptographic tokens under the blockchain, providing an organized way of displaying funds to users (Tian et al 2022).
5. Improved public accountability: In a similar vein, trust between the public and private sectors could improve because of the visibility of every transaction on the blockchain. Within the construction project environment, the blockchain could keep a record of the project's progress from the owner to the superintendents, and this could improve traceability of issues and help mitigate conflicts (Bousquin 2020).

As a whole, the blockchain's automated ledger system would provide a unique convenience in storing information that would offer the potential to avoid major problems and save time in large capital projects.

2.4. Examples of Blockchain Implementation

The features of blockchain have motivated various agencies to investigate its use for projects, and two such case studies in Dubai and Singapore are summarized here.

The city of Dubai in the United Arab Emirates investigated the potential for blockchain when an adviser in the UAE prime minister's office concluded that private companies in Dubai lacked a proper plan for implementing blockchain. The need for a platform for exchanging information in this regard was highlighted (Berryhill and Hanson 2018). The administration in turn created a Global Blockchain Council, meant to serve as a space in which public and private agencies could collaborate and formulate PPP projects to utilize blockchain's capabilities. The resulting expansion of the Council allowed for experimentation with blockchain in 15 PPP projects in Dubai, and the city prepared to conduct nearly all transactions through the blockchain (Blockchain Council 2023).

A similar example is the case of Project Ubin in Singapore, where collaboration between the Monetary Authority of Singapore (MAS) and Deloitte implemented blockchain for infrastructure projects. The MAS indicated that international, cross-border, and bank transactions would become cheaper and more efficient through the blockchain (Berryhill and Hanson 2018). The MAS created a decentralized finance (DeFi) system with the aim of removing the transaction fees and delays typically associated with banks and replacing them with a decentralized, real-time transaction system that would not require any human verification (Sheppard and Cook 2020). Using the Ethereum platform also allowed for smart contracts to be integrated, and this implementation of blockchain could improve the interaction between the private sector and banks for funds. Berryhill and Hanson (2018) anticipated the long-term impacts of the Ubin project to be a 24-hour operational blockchain network that would provide new availability, transparency, and efficiency for financial institutions and PPPs.

These projects show the real-world implementation of blockchain for infrastructure project management.

2.5. Summary of Literature Review

The above sections illustrate the potential of using blockchain technology for PPP projects and how the features of smart contracts and decentralization could improve project management. Despite the challenges of transitioning to such a novel technology, the benefits offered by blockchain in terms of fraud mitigation, real-time transactions, and tokenization of assets could potentially make its adoption worthwhile. Shifting from rigid contracts to smart contracts could deliver better communication among both sectors and opportunities for adjusting contract shortcomings. In essence, blockchain's emerging potential for PPP projects could eliminate existing barriers in the current system of PPPs that could revolutionize the industry for the better.

The above features of blockchain were utilized in this project's implementation for PPP, and these are described in Chapter 3.

Chapter 3 Methodology and Use-Case Demonstration

Given the features of blockchain and the needs of PPP project and contract administration, the goal of this project was to demonstrate the use of blockchain-based smart contracts to streamline the management of funding and ownership of an infrastructure asset that would typically be executed through a PPP mechanism. For the case study, we selected the use-case of a bridge project. It is anticipated that implementation of the developed framework could harness the power of blockchain technology to significantly enhance the transparency and accountability of transactions among the project team and external agencies and thus foster trust among all stakeholders, including investors, developers, and end-users.

This was accomplished in this project by developing a cutting-edge prototype of an Ethereum-based token that enables the creation of smart contracts to automate various operations associated with a bridge project. These asset-tokens were meant to serve as digital representations of ownership stakes in the bridge project, and their value would be tied to the revenue generated by the tolls collected from commuters during the operation of the bridge. It is anticipated that this approach will enable investors to actively participate in the growth of the infrastructure projects they have funded while it also ensuring a seamless, automated distribution of revenue through the use of smart contracts.

In this chapter, the envisioned project environment is described first, followed by details of the smart contract that were implemented for the project environment. Additional technical details are also provided in this chapter.

3.1 Envisioned Blockchain-Enabled Project Environment

This section provides a description of how blockchain was used to digitize the financial management for the case study of a bridge project. Figure 3.1 provides an overview of the use case for which this project developed smart contracts.

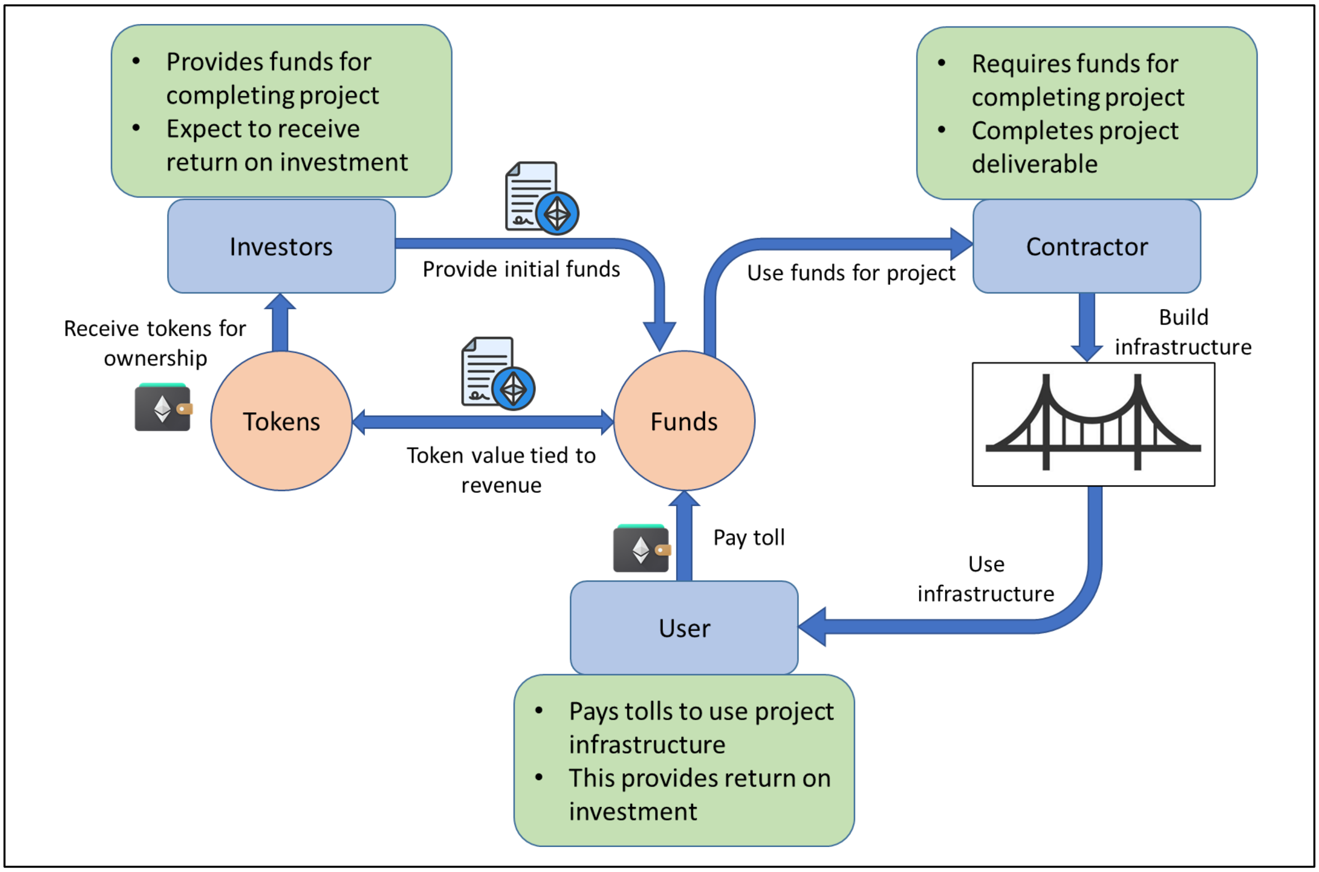

Figure 3.1: Overview of proposed blockchain-enabled PPP project environment

As can be seen in Figure 3.1, three primary types of stakeholders are involved: (1) Investors, (2) Contractors, and (3) Users. The roles of each of these stakeholders are described below.

1. Investors: This type of stakeholder is any party that invests money into the project. While these have typically been large, institutional investors, the tokenization and digitization of ownership enabled by the blockchain is expected to broaden the type of investor for PPP

projects and ease their participation. Investors would provide initial funding for the projects and receive ownership tokens for the infrastructure enabled by DeFi and blockchain. This aspect of the project funding would be enabled through smart contracts, and their functionality is described later in this chapter. Investors would require a wallet for accessing their token and for trading tokens for fiat currency as needed, which is indicated by the black wallet icon in Figure 3.1. The benefit of using tokens is that they would provide the functionality of cryptocurrency to investors, allowing them to transfer tokens through the blockchain, liquidate them as needed, and even trade with them on cryptocurrency exchanges. These are features that could be pursued if needed.

2. Contractors: Contractors are any member of the project management team that is responsible for executing and completing the deliverables of the project. These include designers, general contractors, specialty subcontractors, inspectors, and any consultants that may be used to optimize and complete the project's objectives and deliverables in a timely manner. Contractors would use the funds that had been collected from the investors for completing the project. Contractors would not be involved in the blockchain and would only require access to the funds. They would complete the infrastructure and then transfer ownership to the investors or public agency as stipulated in the contract.
3. Users: Users are the public that will use the infrastructure project that has been constructed. For the bridge project that we considered, this refers to the motorists who would use the bridge and would, as is often the case with such projects, pay a toll for doing so. The amount of money collected by the tolls would be disbursed to the initial investors as a means for them to recover their initial investment and to provide them the financial benefit for doing so. Currently, automated toll collection methods have been

implemented in various states, such as EZPass in the U.S. (Shipe n.d.). The functionality of such electronic and automated toll collected systems could be extended on the back end to enable communication with the blockchain to implement smart contracts.

3.2 Smart Contract Breakdown

This section describes the details of the developed smart contract that would enable automated financial transactions and disbursements among investors, contractors, and end users. The following three cases were encoded into the smart contract:

1. Enable investors to invest money by lending to contractors in the project. This contract type is known as "lender's contract."
2. Increase the return on investment of investor funds based on the interest rate. This contract type is known as "staking contract."
3. Use funds collected from users at toll booths to influence the price of the investor token. This contract type is known as a "toll-based contract."

The functions of these three contract types in the smart contract are described below using the Solidity language for programing on the Ethereum blockchain (Wu et al. 2019).

3.2.1. Lender's Contract

The lender's contract contains multiple public and private functions to manage lenders (primarily investors), lendees (primarily contractors), and loans. Users could use the contract to check the remaining loan balance, create a loan, check the remaining time on the loan, and pay debt. There are also multiple functions that check whether a user requested a loan, if a user was in debt, and to get a list of all investors. An overview of the contract is shown in Figure 3.2.

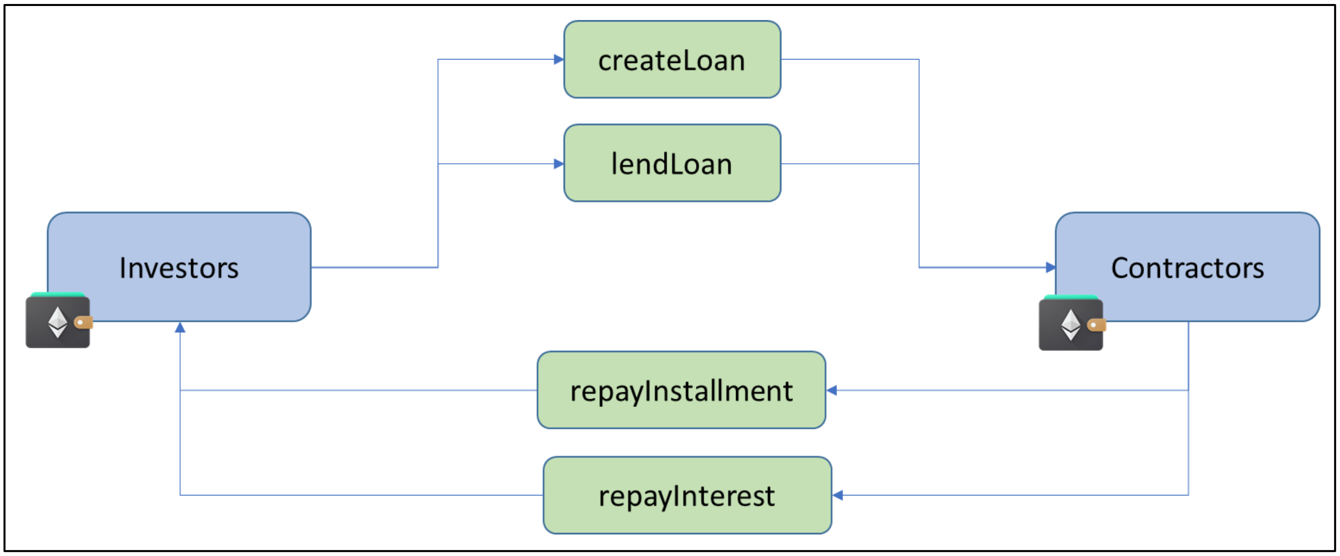

Figure 3.2: Overview of lender's contract and primary functionality

The following primary functions enable the functioning of the lender's contract:

1. createLoan: The "createLoan" function is a Solidity function that allows a lender to create a new loan. It requires several details of the loan, such as the lendee's address, the loan amount, the interest rate, the loan period, and the loan installment period. The "createLoan" function allows a lender to create a new loan by creating a new "loan" struct (a group of variables) with the provided information and add it to the end of the "loans" list. The function also updates the lender and lendee information and emits an event with the loan details.
2. lendLoan: The "lendLoan" function enables a lender to lend an existing loan by transferring the loan amount to the lendee's address. The function ensures that the caller is the lender, the value sent is sufficient, and the lender deposit flag is true before transferring the loan amount. It also emits an event with the loan details.
3. repayInstallment: The "repayInstallment" function first checks whether the lendee has access to the loan by calling the "checkIfLendeeHasAccessToLoan" function. If the

lendee has access, then the function checks whether the value sent is greater than or equal to the installment amount and performs the following additional checks and subsequent actions.

a. If the current time between installments is greater than the days between installments or the current time exceeds the loan end date, then the function checks whether the value sent is greater than or equal to the installment amount plus the late fee. If this condition is satisfied, then the function transfers the installment amount plus the late fee to the lender's address by using the ‘transfer’ function.

b. If the current time between installments is less than or equal to the days between installments and the current time does not exceed the loan end date, then the function transfers only the installment amount to the lender's address. After the installment amount has been transferred, the function updates the loan details such as the loan amount left, the total received amount, the principal loan paid, and the previous loan installment date.

c. If the loan amount balance and interest owed are zero, then the function sets the “loanRepaid” flag to true and emits an event called “LoanRepaidInFull.” If not, then the function emits an event called “InstallmentRepaid” with the updated loan details.

d. If the current time between installments exceeds the days between installments or the current time exceeds the loan end date, then the function emits an event called “LoanDefaulted” and calls the “defaultLoan” function to handle the defaulted loan. The "repayInstallment" function allows a lendee to repay an installment of an existing loan. The function checks whether the lendee has access to the loan, whether the value sent is sufficient, and whether the loan is defaulted or repaid in full. The function also updates the loan details and emits events with the updated loan details.

4. repayInterest: The "repayInterest" function first checks whether the lendee has access to the loan by calling the "checkIfLendeeHasAccessToLoan" function. If the lendee has access, then the function checks whether the value sent is greater than or equal to 0. If the value sent is less than or equal to the interest left on the loan, then the function transfers the value sent to the lender's address using the "transfer" function. The function updates the loan details such as the interest paid, the interest left, and the total received amount. The "repayInterest" function allows a lendee to repay the interest on an existing loan. The function checks whether the lendee has access to the loan, whether the value sent is sufficient, and whether the loan has been defaulted or repaid in full. The function also updates the loan details and emits events with the updated loan details.

Apart from these core functions, the following supporting functions are also provided:

1. balanceOf: This function provides the balance of a specific user when requested.
2. remainingLoanBalance: This function first checks whether the lendee or the lender has access to the loan by calling the "checkIfLendeeHasAccessToLoan" and "checkIfLenderHasAccessToLoan" functions, respectively. If the caller has access, then the function emits an event called "amountLeft" with the remaining loan balance. The "remainingLoanBalance" function allows the lender or the

lendee to check the remaining balance on an existing loan. The function checks whether the caller has access to the loan and emits an event with the remaining loan balance.

3. remainingInterestBalance: The "remainingInterestBalance" function allows the lender or the lendee to check the remaining interest balance on an existing loan. The function checks whether the caller has access to the loan and emits an event with the remaining interest balance. The function first checks whether the lendee or the lender has access to the loan by calling the "checkIfLendeeHasAccessToLoan" and "checkIfLenderHasAccessToLoan" functions, respectively. If the caller has access, then the function emits an event called "amountLeft" with the remaining interest balance.
4. remainingTimeForLoan: This function calculates and returns the remaining time for a loan to reach its end date. It checks whether the caller is either the lendee or the lender associated with the loan. If the caller has access to the loan, then it emits an event with the remaining time in seconds until the loan end date.
5. checkPaidBalance: This function checks whether the caller has access to the loan by verifying whether they are either the lendee or the lender. If they have access, then it returns the total amount of money that has been paid back toward the loan.
6. repayCustAmountLoan: This function allows the lendee to repay a specific amount of the loan by sending ether (cryptocurrency) to the contract. It checks whgether the lendee has access to the loan, whether the value sent is greater than or equal to zero, and then subtracts the amount sent from the remaining loan

balance. It also updates the total amount received from the lendee and the amount of principal loan paid, and it transfers the ether to the lender.

7. getMyActiveLoans: This function retrieves the active loans associated with the caller's address by checking whether the address is registered as a lender or lendee in the database. If the address is registered as a lender, then it returns the loan IDs associated with that lender. If the address is registered as a lendee, then it returns the loan IDs associated with that lendee. If the address is registered as both a lendee and a lender, then it returns two sets of loan IDs, one for the lendee and one for the lender. The function emits an event with the loan IDs as output.

3.2.2. Staking Contract

The staking contract has two primary public functions that pay investors that have funded a project. The payout function distributes the payout to every investor. It transfers the payout amount to each address, and updates that last payout time to each investor. Figure 3.3 provides an overview of the primary functionality of the staking contract.

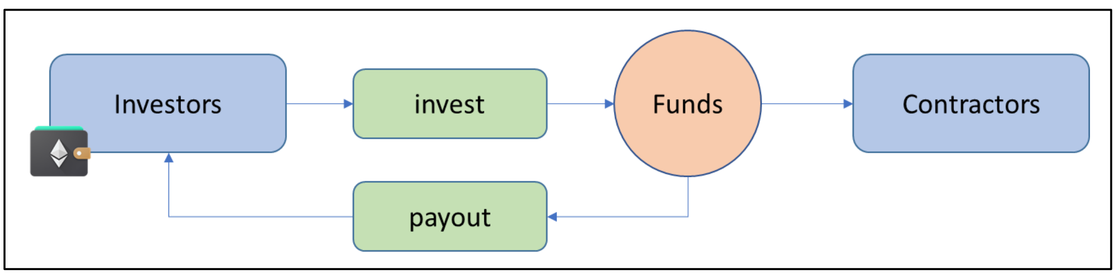

Figure 3.3: Overview of primary functionality of staking contract

The following two public functions are exposed by the staking contract:

1. invest**:** This function allows an investor to invest a certain amount of funds by adding a new entry to the investments mapping with the investor's address as the key. The amount invested is stored in the amount field of the "investment" struct. The lastPayout field in the struct is set to the current block timestamp, indicating that the investor has not yet received any payouts. Finally, the investor's address is added to the investors array to keep track of all investors.

2. payout**:** This function performs a payout to all investors in a smart contract. It iterates through a list of all investors and calculates the payout amount for each one based on their investment amount and the current time. Then it transfers the payout amount to the investor's address and updates the investment's last payout and payout amount in the contract storage.

3.2.3. Toll-Based Contract

The toll-based contract is used to create a new project and list it to receive payments from end users through tolls paid. This contract provides the ability to add investors to the project. Currently, it is possible to deposit a test token, add infrastructures, and add investors to a database. When the contract is complete, investors will be able to see what infrastructure they are invested in and how much of a stake they have in the project. The following functions are available from the toll-based contract:

1. addInfStructure: The "addInfStructure" function adds a new infrastructure wallet to the database by creating an "infrastructure" struct with the provided information and adding it to the end of the "infStructArray" list. The function requires the caller to be the owner of the contract and checks whether the infrastructure name is already in use before adding the new infrastructure wallet.
2. addUserToDataBase: The "addUserToDataBase" function adds a new user to the database by creating an "individualUser" struct with the provided information and adding it to the end of the "userStructArray" list.

3. withdrawRevenue: The "withdrawRevenue" function allows infrastructure wallets to withdraw their revenue from the contract, subject to the available withdrawable amount. If the requested amount is greater than the available withdrawable revenue, then an event is emitted and the withdrawal fails. Otherwise, the requested amount is transferred to the infrastructure wallet, and the available withdrawable amount is updated.
4. checkHowMuchIOwe: The "checkHowMuchIOwe" function enables individual users to check how much they owe for the infrastructure services provided by a particular infrastructure wallet. To achieve this, the function first finds the individual user making the payment and the infrastructure wallet by calling the "findUserInDataBase" and "findInfWallet" functions, respectively. It then checks whether the user and infrastructure exist in the database. Next, the function calculates the cost for the user by calling the "getUserCost" function with the user and infrastructure as arguments. It emits an event called "sendCost" with the string "The amount you owe is presented below:" and the user's cost as arguments. It is important to note that this function does not transfer any funds or update any information in the database. It only retrieves information and displays it to the user.
5. IndUsrpayInfrastructureWallet: The "IndUsrpayInfrustuctureWallet" function is designed to enable individual users to pay for infrastructure services provided by a particular infrastructure wallet. To achieve this, the function first finds the individual user making the payment and the infrastructure wallet by calling the "findUserInDataBase" and "findInfWallet" functions, respectively. It then checks whether the user and infrastructure exist in the database. Next, the function calculates

the cost for the user by calling the “getUserCost” function with the user and infrastructure as arguments. It checks whether the amount of ether sent by the user matches the calculated cost. If the payment amount is correct, then the function updates the revenue of the current infrastructure by calling the “updateCurrInfRevenue” function with the amount of ether sent and the infrastructure as arguments. It then transfers the ether to the contract address by calling the “deposit” function with the address of the contract as the argument. The function then updates the user's type and the total amount paid by the user by calling the “updateUserType” and “updateUserTotalPayed” functions, respectively, with the user and infrastructure as arguments. Finally, the function emits an event called “userPaymentSuccess” with the cost, user's first and last name, and infrastructure name as arguments.

3.3 Project Implementation and Future Development

During this project, the above smart contracts were coded with Solidity and test-run locally. The project code is available along with instructions from GitHub at the following link: https://github.com/jlouis2k4/cs46x-eth-smart-contracts-scaffolding

“Project-Docs/” contains project designs and requirements, research information, and the whitepaper describing intended features. Smart contracts are located in “packages/hardhat/contracts.” “Crowdfunding.sol” manages new projects deployed by a "contractor" and routes user investments to specified project addresses. “Project.sol” manages a specific project’s current information. The front-end interface is at “packages/nextjs/pages”. Contracts were deployed via hardhat with scripts in “packages/hardhat/deploy.” The Project.sol contract contains multiple public and private functions within it and is the majority of the decentralized application’s (dApp's) logic. The code contains several functions that are used to manage the roles of lenders (creditors vs. "normal" investors), lendees (the owners of each project loan reqest), and funds of corresponding loan payments.

Within the contract, users can check the current loan balance, initialize a loan (the "parent" contract, Crowdfunding.sol, calls the constructor), check the remaining time on the loan, and pay debt. There are also multiple modifier functions that check the project’s current state, whether a project owner has requested a loan withdrawal, the authorization level of any given user, and gets a list of all investors and payments. The “crowdfunding” contract mainly tracks all created project contract addresses in “Project[] private projects” and sends information about investors transactions to the “project” in “mapping(address => uint256) public contributors.”

The GitHub folder also provides important information to developers for modifying and further developing the smart contracts developed during this project; and also provides guidelines on implementing local dApps and testing them on local Ethereum blockchain. Information related to deploying smart contracts to a live Ethereum test-net is also provided in the GitHub page.

Chapter 4: Conclusions

This report describes the creation of a blockchain-based application to handle the financial management of large-scale infrastructure projects that use public-private partnership means of funding. A PPP is an agreement between a government or public agency and a private entity to deliver a service for the public benefit. PPPs are typically used for infrastructure projects such as highways, airports, and bridges. PPPs have certain fundamentals that define the process. Both public and private parties bear the risk and the reward of the project's success. Each party also has clearly defined roles and responsibilities; governments or public agencies typically set project goals and objectives, while the private sector is responsible for designing, building, and financing the project.

Cryptocurrencies can improve the current PPP process by increasing transparency, accountability, and efficiency through blockchain technology. The blockchain would be useful for this process because it can provide a record of all transactions and activities within a project. This would allow all parties to have immediate access to all information of a project in real time. Applying governance tokens would enable investors to vote and change infrastructure if needed. The use of smart contracts in PPPs could automate most if not all of the contractual obligations and payments, reducing the need for intermediaries. Cryptocurrencies could also be used to facilitate payments between parties, which could lower transaction costs. Overall, the use of cryptocurrencies in PPPs could drastically reduce costs, increase transparency, and improve efficiency.

The blockchain-based smart contracts platform that was developed in this project could be used to produce tremendous change in the way that infrastructure development contracts are executed by minimizing delays, reducing cost overruns, and improving overall transparency.

This innovative approach has the potential to not only attract more investors to the sector but also contribute to the growth of sustainable, efficient infrastructure that benefits society as a whole.

This project designed a smart contract project with the Ethereum blockchain that developed token requirements and dApps for implementing protocols for the lending process between investors and public contractors. Basic functionality for modeling the way that investors can recoup their investments was also provided. Further information is available in a GitHub page that includes the details of these implementations and how they may be further developed.

While no formal unit tests were conducted for this project, this is highly recommended for future work because of the security risks associated with smart contracts, especially when they deal with real money if such smart contracts are implemented within real projects in the future. For future work, it is also recommended that tokens be transacted through our dApp network to access various types of tolled infrastructure, such as roads, bridges, and ferries for users. It is also recommended that the use of additional decentralized finance loan protocols such as OpenZeppelin investigated and integrated into the project. Finally, methods to implement cross-chain investment protocols should be explored to increase access to such smart contracts on blockchain networks in the future.

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