POLITECNICO DI TORINO

Master Degree course in ICT FOR SMART SOCIETIES

Master Degree Thesis

Decentralized Asset Tracking and Maintenance for Railway Systems Using Blockchain Technology.

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Chapter 1

Introduction

1.1 Research Background

The railway industry is one of the most important parts of the global economy and transportation. It moves billions of passengers and huge amounts of cargo every year. This industry is a very complex system. It is not one single company, but a large network of stakeholders. These include the train operators, the national infrastructure managers, private maintenance crews, part suppliers, and government regulators.

All of these different groups must work together to manage a very large and very valuable inventory of physical assets. A single train is made of thousands of individual components, from the main engine and wagons, down to single pieces of equipment like braking systems, wheelsets, and safety sensors. The process of managing this is called **Asset Management**. This means tracking the complete life cycle of every single part, from the day it is manufactured, to its installation, all of its maintenance cycles, and finally its retirement.

This is not just an accounting problem, it is one of the biggest challenges for the industry. The safety and reliability of the entire railway network depends on knowing the exact condition and history of these assets.

1.2 Problem Statement

The main problem with traditional asset management in the railway industry is the lack of a single, trusted source of truth. The data is fragmented, disconnected (siloed), and not transparent. This creates several big problems:

- **Data Silos:** Each stakeholder in the network (the operator, the maintenance crew, the part supplier) keeps its own private, centralized database. When a part is serviced, this information is not automatically or easily shared with everyone else. This is a known challenge in the industry, where this lack of data interoperability makes it very hard to get a full picture of an asset's health [1].

- **Lack of Trust and Transparency:** Because the data is in silos, there is no trust. How can a train operator be 100% sure that the maintenance crew *really* used the

correct, official part? How can a government regulator easily audit the full history of a safety-critical part?

- **Data Integrity Issues:** The current systems are not immutable. A record in a centralized database can be changed, hacked, or just lost. Paper records, which are still very common, can be faked, damaged, or lost in a fire. This makes it impossible to guarantee the integrity of the maintenance log.

- **Inefficiency and High Costs:** This old system is very slow and expensive. To find the history of one wagon, a person might have to check three different systems or even make phone calls. This leads to high administrative costs and long delays.

1.3   Motivation

The motivation for this thesis comes from these big, real-world problems. These challenges are not just about saving money, they have very serious consequences.

1. **Safety:** This is the most important motivation. If maintenance records are lost, faked, or untrusted, a train with a faulty part could be put into service. This can lead to derailments and put human lives at risk. A trusted, auditable log of every single part is necessary for modern safety.

2. **Economic Cost:** The current system is very expensive. Companies must spend a lot of money on "preventive" maintenance (e.g., replacing parts every 6 months, "just in case"). They do this because they cannot trust the data to perform "predictive" maintenance (e.g., replacing a part only when it is needed). This wastes a lot of time and money.

3. **Regulatory Compliance:** Railway companies are under very strict rules from governments. They must be able to *prove* they are following safety rules. An immutable and auditable record of all maintenance actions would make this process much simpler and more reliable.

   We need a new system. We need a platform where all the partners can share data, where the data cannot be secretly changed, and where the history of any asset can be trusted by everyone.

1.4   Proposed Solution: A Hybrid Blockchain System

This thesis proposes a new system to solve these problems. The proposed solution is a **Decentralized Asset Tracking and Maintenance Platform for Railway Systems**.
   The core of our solution is the use of **blockchain technology**. A blockchain is a shared, distributed database. Its special feature is that it is "immutable," which means once data is written, it cannot be changed or deleted. This technology has been widely studied as a way to improve transparency and traceability in complex supply chains [2].

We believe this is a perfect technology for our problem. By storing the record of every train, wagon, and maintenance action on a blockchain, we can create the single, trusted source of truth that the industry needs.

But, a "pure" blockchain application (DApp) is often slow, very expensive (it costs "gas" for every action), and not user-friendly. It is also a very bad for storing private data like user accounts.

Therefore, our main proposal is a **hybrid, three-tier architecture**. This system is the main contribution of our work. It combines the trust of the blockchain with the speed and privacy of a normal web application. Our system, which we built, is made of three layers:

1. **The Data Layer (The Blockchain):** A Solidity smart contract that lives on the blockchain. This contract defines the assets (`Train`, `Wagon`, `Equipment`) and acts as the trusted, immutable ledger for all asset history.

2. **The Logic Layer (The Backend API):** A centralized backend server (which we built with Python and FastAPI). This server acts as the "middleware". It manages user accounts and passwords in a private SQLite database (this is the "off-chain" part). It is the only part of the system that talks to the blockchain. This makes the system secure and easy to use.

3. **The Presentation Layer (The Frontend):** A user-friendly web application (which we built with React). As we can see in our frontend project, this is a **Progressive Web App (PWA)**, so it can be "installed" on a mobile phone for mechanics to use in the field, even with a bad internet connection.

This hybrid design gives us the best of both worlds. We get the speed of a normal database for user logins, but we get the trust and immutability of the blockchain for the important asset data.

1.5 Aims and Objectives

To build this solution, this thesis has several main goals, or objectives:

- **To design** a hybrid, three-tier system architecture that balances decentralization, performance, and security.

- **To implement** a gas-efficient Solidity smart contract for managing the lifecycle of railway assets and their hierarchical relationships.

- **To develop** a secure backend API that acts as a middleware, handling user authentication off-chain and managing all blockchain transactions.

- **To create** a user-friendly, mobile-first Progressive Web App (PWA) that allows staff to manage assets and update maintenance records from any device.

- **To evaluate** the practicality of the system by measuring its performance, including the gas costs of smart contract functions.

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1.6 Thesis Contribution

The main contribution of this work is not just one thing, but the design and implementation of the whole, integrated system. While many papers *talk* about using blockchain for asset tracking (as we will see in Chapter 2), this thesis presents a complete, practical, and full-stack solution. Research in this area has often focused on the high-level benefits, but has not shown a full end-to-end implementation [3].

Our key contributions are:

1. **A Practical Hybrid Architecture:** We show a complete, working model of a 3-tier system that solves the "on-chain vs. off-chain" data problem.

2. **A Full-Stack Implementation:** We built all three layers, from the database and smart contract to the backend API and the final user interface.

3. **A Focus on User Experience (UX):** By building a PWA, we show a solution that is designed for the *real user* (the mobile mechanic), which is a step that many academic projects ignore.

1.7 Thesis Outline

The rest of this thesis is organized as follows:

Chapter 2 - Literature Review and State of the Art: This chapter reviews the existing academic literature. We first analyze traditional asset management, then we explain the fundamentals of blockchain, and finally we review other projects that have used blockchain for asset tracking. This chapter ends by identifying the "research gap" that our thesis will fill.

Chapter 3 - Methodology: This is the core technical chapter. It presents the design and implementation of our three-layer system in detail. We will explain the System Architecture, the Smart Contract logic, the Backend API, and the Frontend PWA.

Chapter 4 - Experimental Evaluation: This chapter presents the results of our work. We evaluate the system by measuring its performance, including the smart contract's gas costs, the API response times, and the frontend's usability. We then discuss what these results mean.

Chapter 5 - Conclusion and Future Work: This final chapter concludes the thesis. We summarize our findings, we state how we achieved our goals, and we discuss the limitations of our work and suggest ideas for "future work" that could be built on top of our project.

Chapter 2

Literature Review and State of the Art

2.1 Introduction

In Chapter 1, we introduced the main problem that this thesis will solve. We explained that the railway industry has big challenges with asset management. Their traditional systems often have problems with data integrity, trust, and transparency. We proposed that our new system, which uses blockchain technology, can be a good solution.

Before we can explain our technical contribution (in Chapter 3), we must first do a deep review of the existing academic and technical literature. This chapter is the foundation for our entire research. The main goal is to review all the relevant studies to build a strong base of knowledge. This is a very important step. Without a good literature review, we cannot know if our idea is truly new, or if we are just repeating work that other people have already done.

To build a practical system, our research must understand two main areas at the same time. This is a common challenge when applying a new digital technology (like blockchain) to a traditional industry (like railways) [4].

1. **The Problem Domain:** We must first be experts in the problem we are trying to solve. This means we must do a deep analysis of the railway industry's current challenges. Why are their traditional asset management systems not good enough? What are the specific limitations and data problems they face every day?

2. **The Solution Domain:** We must also be experts in the technology we are using as a solution. This means we must explain the fundamentals of blockchain. What is it? How does it work? What is a smart contract and why is it useful for our project?

Only after we understand both the problem and the technology, we can then look at the "State of the Art". This is where we will review other academic papers where researchers have already tried to combine these two domains. We will look for other projects that used blockchain for supply chain or asset tracking.

This whole review process allows us to find what is *missing* from the existing research. This is called the "research gap". Our thesis is important because our project is designed to fill this gap.

This chapter is organized to build this knowledge step-by-step:

- **Section 2.2** will analyze the challenges of traditional railway asset management and its data systems.

- **Section 2.3** will explain the fundamentals of blockchain, DLT, and smart contracts.

- **Section 2.4** will review the "State of the Art" by looking at other academic projects that use blockchain for asset management.

- **Section 2.5** will conclude the chapter by analyzing what we have found and clearly identifying the "research gap" that our thesis will fill.

2.2 Traditional Railway Asset Management: Challenges and Limitations

In this section, we will do a deep dive into the "problem domain" of our thesis. To justify building a new, complex system using blockchain, we must first prove that the current systems are not good enough. We need to analyze the specific challenges that the railway industry faces in managing its physical assets. This section will show that the problems are not small, but are fundamental issues of safety, cost, and trust.

2.2.1 The Importance of Maintenance in Railway Operations

The railway system is a "safety-critical" industry. This term means that the failure of even a small component can lead to catastrophic events, including loss of life and massive environmental damage. Because of this, asset management is not just an accounting problem or a way to save money; it is the most important part of the industry's safety and operational strategy.

In academia and in the industry, this concept is standardized as **RAMS** (Reliability, Availability, Maintainability, and Safety). This is a engineering framework used to guide the management of railway systems [5]. All of our work is about improving these four points.

We can break down the importance into three main areas:

- **Safety:** This is the first and most important reason. The safe operation of trains, signals, and tracks depends on every component working perfectly. The failure of a single, small component that is not maintained correctly—like a wheel bearing that overheats, a braking system that loses pressure, or a signal that gives the wrong light—can lead to a derailment or collision. Therefore, having a perfect, auditable, and trustworthy record of every part's history and maintenance is a fundamental safety requirement. We cannot have safety without knowing the state of our assets.

- **Service Reliability and Availability:** Railway networks are the backbone of a country's economy, especially here in Europe. They move millions of passengers to their jobs and tons of cargo to factories and ports. The "product" that a railway sells is reliable transportation.

  - **Availability** means the train is ready to use when it is scheduled.
  - **Reliability** means the train does not break down during its journey.

  When a train breaks down (a "service failure"), it causes huge delays. These delays have a big economic cost and make customers and businesses lose trust in the railway. Good asset management and maintenance is the only way to make sure the trains are "available" and "reliable".

- **Regulatory Compliance:** Because it is so important for safety, the railway industry is under very strict rules from governments and international bodies (like the European Union Agency for Railways, ERA). These regulators demand that companies *prove* they are following all safety and maintenance procedures. After any accident, investigators will demand to see the full maintenance history of every part involved. Companies must keep perfect records for auditing. If they fail an audit, or if their records are bad, they can get very large fines or even be shut down.

These three factors—safety, reliability, and compliance—are all linked by one single, fundamental need: **trusted data**. The entire industry runs on data, and if the data is bad, all three of these pillars can fail.

2.2.2 Current Asset Management Models

To manage their assets and ensure safety, railway companies have used different maintenance strategies over the years. We can see an evolution in these strategies, from simple to very complex. Each model has a different need for data, and understanding them shows us *why* our system is needed.

Reactive Maintenance (RM)

This is the oldest and most basic model. It is often called the **"run-to-failure"** or "breakdown" model. In this system, you do not fix a part until it is broken. A part is installed and then ignored until it fails.

This is a very bad model for a safety-critical industry like the railway. It is extremely dangerous because parts can fail at any time, which could cause an accident. It is also very expensive. An emergency repair for a train that is broken down in the middle of the tracks is much, much more costly than a planned repair in a maintenance yard. This model also causes the worst service reliability, because failures are a surprise. Today, this model is only used for non-critical parts, like a lightbulb in a passenger cabin, but it is not used for any serious equipment.

Preventive Maintenance (PM)

This is the most common model used in the railway industry today. It is also called "prophylactic" or **"time-based" maintenance**.

In this model, parts are replaced on a fixed schedule, no matter what their real condition is. The schedule is based on time (e.g., "service all wagons every 12 months") or on usage (e.g., "replace all brake pads every 50,000 km").

- **Pros:** This model is much, much safer than Reactive Maintenance. Because parts are replaced *before* they are expected to fail, the risk of a surprise breakdown is very low. It also allows for planning. The company knows in January that it needs to order 500 brake pads for the maintenance scheduled in March. This makes logistics much easier.

- **Cons:** This model is very **inefficient and wasteful**. A company might replace a brake pad that is still 50% good, just because the schedule said to. This wastes time, money, and valuable parts. This "over-maintenance" is a huge part of the railway's operating budget. Furthermore, it does not stop all failures. It is possible for a part to fail *before* its scheduled maintenance, so the risk is not zero.

The industry uses this model because it is a safe, simple, and low-data solution. You do not need smart sensors; you only need to track the date or the mileage.

Predictive Maintenance (PdM)

This is the modern, data-driven goal that the entire industry is moving towards. This is also called **"Condition-Based Maintenance" (CBM)**.

In this model, you do not use a fixed schedule. Instead, you use sensors to monitor the *actual condition* of the part in real-time. For example, you put a vibration sensor on a wheelset or a temperature sensor on a braking system. This data is then fed into a software model (maybe using Artificial Intelligence, AI) to *predict* when the part will *actually* fail. The system can then alert the crew to "replace the brake pads on Train 102 in the next 5 days, because they are 95% worn out".

- **Pros:** This is the best possible model. It is very safe (because you fix parts *before* they break) and it is extremely efficient (because you use 100% of a part's life and do not waste good parts). This is the main goal of modern railway asset management [6].

- **Cons:** This model has a very high barrier. It requires a huge amount of high-quality, real-time, and *trusted* data. You must have many sensors, and you must be able to trust the data they are sending.

The main argument of this thesis is that the railway industry is "stuck" using inefficient Preventive Maintenance because their traditional data systems make it impossible to get the *trusted data* that is needed for Predictive Maintenance.

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2.2.3   Limitations of Centralized Data Systems

This section is the core of our problem statement. The reason the industry is stuck in PM is because of its *data infrastructure*. The problem is the traditional, centralized database model (like a private SQL server). This model has three main limitations that make it impossible to build a trusted, industry-wide system.

Data Silos and Lack of Interoperability

This is the biggest problem. The railway network is not one single company. It is a large, complex **ecosystem** of different stakeholders. For example:

- The company that builds the train (e.g., Siemens, Alstom).

- The company that owns the train (e.g., a leasing company).

- The company that operates the train (e.g., Trenitalia).

- The many different third-party maintenance crews.

- The government regulators.

Each of these stakeholders has their own private, centralized database. These databases are **"data silos"**. They do not talk to each other, they use different data formats, and they are not "interoperable".

When a maintenance crew services a wagon, they update *their own* database. The train operator might get a PDF or an email, but their main database is not updated. The train manufacturer never knows how their part is performing in the real world. This means it is impossible to get one single, complete life-cycle history of an asset. This lack of interoperability and data sharing is a well-known, major challenge in the industry [1]. You cannot do predictive maintenance if you only have 1/3 of the data.

Data Integrity and Trust

This is the *human* problem. Even if the databases *could* be connected, the stakeholders do not trust each other. This is a rational choice, because a centralized database has no guarantee of data integrity.

- **No Guarantee of Integrity:** A record in a private SQL database can be changed. An administrator can edit a row. A "bad actor" could go into the database and change a maintenance date to pass an audit. A simple employee can make a mistake and type the wrong part number, and this error might be saved forever. There is no way to *prove* that the data in the database is the original, correct, and 'immutable' record.

- **Lack of Trust:** Because the integrity cannot be guaranteed, there is no trust. An operator cannot 100% trust a PDF report from a maintenance crew. They must spend time and money on their own *audits* to verify the work. This lack of trust is

a major barrier to data sharing. Companies will not share their data if they cannot trust the other company's data. This problem of creating trust between partners is a huge topic in all supply chains, and it is a key reason why researchers are interested in blockchain [7].

- **Difficult to Audit:** It is very difficult for a government regulator to audit the system. They have to ask many different companies for their private records (which might be in different formats) and they have no way to prove that the records are the original data and were not changed last week just for the audit.

Inefficiency and Paper-Based Processes

Finally, the current system is very inefficient because it is still based on slow, manual, and paper-based processes. The railway industry has been very slow to adopt new digital technologies [8].

A very common workflow is:

1. A mechanic in the railyard performs maintenance on a wagon.

2. The mechanic writes the details (part numbers, actions taken) on a **paper logbook** or a form on a clipboard.

3. At the end of the day, the mechanic gives this paper to an office administrator.

4. Sometime later (maybe days later), the administrator manually types this information from the paper into a computer, maybe in an Excel file or a local database.

This process is a disaster for a modern data-driven system.

- **It is Slow (High Latency):** The data in the central database is days or even weeks old. This makes real-time predictive maintenance completely impossible. You cannot predict a failure if your data is from last month.

- **It is Error-Prone:** This manual process has many places for errors. The mechanic's handwriting might be bad. The data-entry person might make a typo (e.g., type '100' instead of '1000').

- **It is Fragile:** Paper records can be easily lost in a fire, damaged by water, or just lost in an office.

These three major limitations—data silos, a fundamental lack of trust, and inefficient paper-based processes—show that the traditional, centralized model is broken. It is not safe enough, fast enough, or trustworthy enough for a modern railway system.

This is the foundation for our research. We need a new system that is:

1. **Shared and Interoperable** (to break the silos).

2. **Immutable and Trusted** (to guarantee data integrity).

3. **Digital and Real-Time** (to replace paper).

These three needs are the exact features that blockchain technology (which we will explain in the next section) promises to deliver.

2.3 Fundamentals of Blockchain Technology

In the last section, we showed the big problems with traditional, centralized data systems. We found that they have problems with data silos, a lack of trust, and inefficiency. Because our proposed solution uses blockchain to solve these problems, it is very important to explain what this technology is. This section will explain the "solution domain" for our thesis. We will build the concepts from the ground up, so that the reader can understand our technical design in Chapter 3.

2.3.1 Distributed Ledger Technology (DLT)

The first, and most important, idea is **Distributed Ledger Technology (DLT)**. This is the big category of technology where blockchain belongs.

A "ledger" is a simple idea, it is just a book of records. For thousands of years, banks, governments, and businesses have used ledgers to track value (e.g., "Farid has 100 euro," "Wagon 101 belongs to Company A"). A traditional ledger is **centralized**. This means one single entity (like a bank) owns the ledger. They are the only one who can write in it, and they are the only one who has the "master copy". This is the system we have today. It has a big weakness: you must **trust the central party**. You must trust the bank to not make a mistake, to not get hacked, and to not cheat you. This is the "trusted third-party" problem.

A DLT is a completely new model for a ledger. Instead of one central copy, the ledger is **"distributed"** (copied) to many different computers in a network. These computers are called "nodes" or "peers". When a new record (a "transaction") is added to the ledger, it is sent to all the nodes, and they all update their copy of the book at the same time.

This model has three main features:

1. **It is Decentralized:** There is no single, central boss. No one person or company owns the data or controls the network. All the nodes must agree on the rules.

2. **It is Transparent:** In a public DLT, everyone in the network (all the nodes) can see all the records. This makes it very easy to audit.

3. **It is Resilient:** In a centralized system, if the main server fails, the entire system stops. In a DLT, if one node fails (or 1,000 nodes fail), it does not matter. The other nodes in the network still have the full copy of the ledger, so the system cannot shut down. It has no single point of failure.

A **blockchain** is the most famous and most widely-used *type* of DLT [9]. It is a special DLT that organizes the records in a way that makes them immutable, or unchangeable.

2.3.2 Core Components of a Blockchain

A blockchain is not just a shared database. It has special features that make it "immutable", which means the records cannot be changed or deleted once they are added.

This is the most important feature for our thesis, because it is how we create *trust*. It does this by "chaining" records together in "blocks" using cryptography.

Cryptography and Hashing

The most important tool in a blockchain is a **cryptographic hash function**. Because our thesis is based on the Ethereum platform, we will talk about the main hash function used by Ethereum, which is **KECCAK-256**. This is the function that is used inside the Ethereum Virtual Machine, and it is a modern and secure hash function [10]. This function was also chosen by the U.S. National Institute of Standards and Technology (NIST) to become the official **SHA-3** standard [11].

A hash function is a math algorithm that can take any data (like a name, a whole book, or a list of our maintenance transactions) and turn it into a unique, fixed-length code. For KECCAK-256, this code is 256 bits (64 characters) long. This code is like a **"digital fingerprint"** for the data.

A hash function has three important properties:

1. **It is Deterministic:** The same input will *always* produce the same hash.

2. **It is a One-Way Function:** It is very easy to find the hash from the data, but it is (for all practical purposes) impossible to find the original data if you only have the hash.

3. **It is Highly Sensitive (The Avalanche Effect):** If we change just *one letter* or one small piece of the original data, the hash (the fingerprint) will change completely.

This is how a blockchain makes sure data is not tampered with. If anyone changes even one comma in an old record, the hash of that record will change, and the whole network will know.

This is very relevant to our own project. As we will show in Chapter 3, we use the `keccak256()` function in our Solidity code to create the unique keys for our search indexes (for example, to turn the wagon name "Cargo 101" into a unique `bytes32` key for the mapping).

Blocks and Chains

A blockchain does not just record one transaction at a time. It groups transactions together into a **"block"**. A block is just a list of transactions that happened in a certain time (e.g., the last 10 minutes).

When a new block is created, it also contains two very important pieces of data in its "header":

- The hash of all the transactions inside it.

- The hash of the *previous* block.

This is the "chain" part. Block 5 has the hash of Block 4 in its header. Block 4 has the hash of Block 3 in its header. This creates a "chain" of blocks that are cryptographically linked all the way back to the very first block (the "genesis block").

This is what makes the ledger **immutable**. If an attacker wants to change a transaction in our railway ledger, (for example, to delete a maintenance record from Block 100), they would have to do this:

1. Change the record in Block 100.

2. This change would change the "fingerprint" (hash) of Block 100.

3. Because the hash of Block 100 is *inside* Block 101, this change would "break" Block 101.

4. The attacker would have to re-calculate Block 101 with the new, fake hash.

5. This would then change the hash of Block 101, which would break Block 102.

6. The attacker would have to re-calculate every single block, all the way to the end of the chain, all at the same time, and do it faster than all the other honest nodes in the network.

This is "computationally infeasible", which is a computer science way of saying it is impossible. This is how we get our trust. We do not have to trust a company, we just have to trust the math.

Consensus Mechanisms

This is the last big, complex problem. We have a network of 10,000 nodes. There is no central boss. If two nodes propose a new block at the same time, which one is the correct one?

How does a decentralized network agree on "the" single source of truth? They use a **consensus mechanism**. This is a set of rules for the nodes to agree [12]. There are many types, but the two most famous are Proof-of-Work and Proof-of-Stake.

- **Proof-of-Work (PoW):** This was the first consensus mechanism, and it is used by Bitcoin. It works like a "computational race" or a lottery.

  - Nodes called "miners" use very powerful, special computers (ASICs) to try and solve a very, very hard math puzzle.
  - They are all "racing" to be the first one to find the answer.
  - The first miner to find the answer (the "proof" that they did the "work") gets to add the new block to the chain.
  - As a reward, they get paid in new Bitcoin.
  - **Pros:** It is the most secure and most proven consensus mechanism.

- **Cons:** It is very slow (Bitcoin only handles 7 transactions per second). More important, it uses a huge, huge amount of electricity. This is a very big environmental problem.

- **Proof-of-Stake (PoS):** This is the modern model. Ethereum (the platform we are using) famously "merged" from PoW to PoS in 2022. This is the model that is relevant to our thesis.

  - In PoS, there are no "miners" and there is no "race". Instead, there are "validators".
  - A validator is a node that wants to help create blocks. To do this, they must first "stake" (lock up) their own money (e.g., 32 ETH) as a collateral.
  - The network then randomly chooses one validator and says, "It is your turn to propose the next block."
  - The validator proposes the block, and other validators "attest" (vote) that it is a good block.
  - If the block is good, the validator gets a small reward (like interest on their stake).
  - **Security:** This is how PoS is secure. If a validator tries to cheat (e.g., proposes a fake block with bad transactions), the network will find out, and the validator's stake is **"slashed"** (taken away and destroyed). This is a very strong financial incentive to be honest.
  - **Pros:** It is much faster than PoW and, most important, it is **99.9% more energy-efficient**.
  - **Cons:** It is a more complex system, and some people argue it is less "decentralized" than PoW.

For our thesis, we are building on the Ethereum platform, so we are using the Proof-of-Stake model. This is important because it shows our solution is built on a modern, sustainable, and fast technology.

2.3.3 Ethereum and Smart Contracts

This is the most important part of the "solution domain" for our thesis. Why did we choose Ethereum, and not Bitcoin?

Bitcoin vs. Ethereum

Bitcoin is "Blockchain 1.0". It is a DLT, but its purpose is very simple and limited: it is a "peer-to-peer electronic cash system". The code inside Bitcoin's transactions is very simple. It can only do one thing: move money (bitcoins) from one address to another.

In 2013, a developer named Vitalik Buterin had a new idea. He asked, "What if the blockchain could do more than just move money? What if it could run *any* computer program¿' This idea became **Ethereum**.

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Ethereum is "Blockchain 2.0". It is not just a decentralized ledger; it is a **decentralized "world computer"** (or Ethereum Virtual Machine, EVM). It is a platform that can run *code*.

Smart Contracts

The "code" that runs on the Ethereum platform is called a **Smart Contract**.

This is the key concept of our entire thesis. A smart contract is a "self-enforcing agreement" that is written in code (like Solidity) and deployed to the blockchain [13].

We can think of a smart contract like a "trusted robot" or a digital vending machine. A vending machine is a simple, physical smart contract:

- **The Rule is:** IF you (the user) put in 1.50 euro, THEN the machine (the contract) will give you a coke.

- **It is Automatic:** You do not need to ask a human.

- **It is Trusted:** You know that if you put the money in, you will get the coke. The rules are locked in the machine.

A smart contract is the same, but for digital business logic. Our `RailwayAssetRegistry` contract is an agreement. It has rules, like:

- **IF** a user calls the `addWagon` function,

- **AND** the user proves the parent `trainId` is real,

- **THEN** the contract will run the code to create a new wagon and save it to the ledger.

The most important part is that the smart contract code *also* lives on the blockchain, so it is also **immutable**. Once we deploy our contract, its rules can never be changed. This creates "trustless execution". We do not have to trust a company to follow their own rules; we just have to trust the *code* that is locked on the blockchain. This is how we solve the "trust" problem between the railway stakeholders.

2.3.4 Public vs. Private (Consortium) Blockchains

Finally, it is important to know that there are different *types* of blockchains. This is a very important choice for a business.

1. **Public Blockchains (Permissionless):**

    - **Who can join?** Anyone in the world (e.g., Bitcoin, Ethereum).
    - **Pros:** This is true decentralization. It is highly secure (censorship-resistant) and transparent.
    - **Cons:** It is slow, it is very expensive (you must pay "gas fees" for every transaction, like 'addWagon'), and there is **zero privacy**. All our railway maintenance data would be visible to the public. This is not acceptable for a real business.

2. **Private Blockchains (Permissioned):**

   - **Who can join?** Only one single company (e.g., a company uses Hyperledger to build its own internal blockchain).

   - **Pros:** It is very fast, transactions are free, and it is 100% private.

   - **Cons:** It is not decentralized. It is just a normal database with cryptography. You must trust the one single company that owns it. This does not solve our "trust problem" between different stakeholders.

3. **Consortium Blockchains (Permissioned):**

   - **Who can join?** A pre-selected *group* of trusted organizations. This is the perfect model for our railway problem. The "consortium" would be our stakeholders: the operator, the maintenance crew, the part manufacturer, and the government regulator.

   - **Pros:** It is the "best of both worlds" for business [14]. It is **private** from the public, so our railway data is safe. It is **fast** and has low (or zero) transaction fees. But, it is still **decentralized *among the members***. No single member can cheat the others.

   - **Example Platforms:** Hyperledger Fabric, Corda.

For our thesis, this is our justification: for a real-world, production deployment, a **consortium blockchain** would be the correct and final choice.

However, for this thesis, our goal is to prove the *concept*, the *smart contract logic*, and the *3-tier architecture*. We chose to build on the **Ethereum** platform (using the **Sepolia testnet**). We did this because it is a public network that anyone can audit, and it has the best and most mature tools in the world (like Solidity, Hardhat, and Ethers.js). Our system's logic and our 3-tier architecture can be moved to a consortium chain in the future with very few changes.

2.4 State of the Art: Blockchain in Asset Management

Now that we have established the "problem domain" (the challenges in railway asset management, Section 2.2) and the "solution domain" (the fundamentals of blockchain, Section 2.3), we must review the "State of the Art". This is where we combine the two areas. We must find out what other researchers have already done.

The key question for our thesis is: "Has someone already used blockchain to solve the problems of asset tracking and maintenance¿'

We will review the literature in three parts. First, we will look at the general topic of supply chain management, which is very similar to our problem. Second, we will look at the integration of Internet of Things (IoT) sensors, which is important for our future work. Finally, we will look for research that is *specifically* about the railway industry.

2.4.1 Blockchain for General Supply Chain Management (SCM)

The most common use for blockchain (after cryptocurrency) is in Supply Chain Management (SCM). The problems in SCM are almost the same as our railway problem. A supply chain has many stakeholders (like the farm, the factory, the shipping company, the customer) who all need to share data, but they do not trust each other. They need a single, trusted source of truth for tracking an asset.

A lot of research has been done on this topic. In a major review of this area, [15] analyzed many papers. They found that the main benefits of using blockchain in SCM are: **transparency**, **traceability**, **security**, and **trust**. They argue that blockchain is not just a technical tool, but a tool for "inter-organizational collaboration", which is exactly what our railway stakeholders need.

We can look at some specific examples from different industries.

Food Supply Chains

The food industry is a very popular area for blockchain research. This is because "provenance" (knowing where something came from) is very important for food safety. When there is an *E. coli* outbreak, the government needs to know *immediately* which farm the bad lettuce came from.

A study by [16] proposed a full blockchain-based system for tracking food products. They used smart contracts on Ethereum to track a product from the farm, to the processor, to the distributor, and finally to the retailer. Their system created a "transparent and trusted" record. The main result was that a customer could scan a QR code on a product and see its entire history. This is very similar to our goal of tracking a railway part from its manufacturer to its installation.

Pharmaceutical Supply Chains

The pharmaceutical industry has a very dangerous and expensive problem: counterfeit (fake) drugs. These fake drugs can harm or kill patients. The problem is that it is very easy for a fake product to enter the supply chain.

Researchers like [17] have proposed blockchain systems to solve this. They proposed an "anti-counterfeiting" system using blockchain and smart contracts. In their system, the original manufacturer (like Pfizer) creates a unique digital 'token' for every single bottle of medicine. This token is then tracked on the blockchain as it moves from the factory to the distributor, to the hospital. A pharmacist can scan the bottle and the smart contract will prove if it is the real, official product. This is a very strong comparison to our project, where we need to prove that a railway part is an "official" part and not a cheap, uncertified fake.

Maritime Logistics (Shipping)

The global shipping industry (like Maersk) has the same problems as the railway industry. They have many stakeholders (the factory, the port, the customs office, the ship, the

customer) and they use a huge amount of slow, paper-based documents, like the "Bill of Lading".

A study by [18] reviewed the use of blockchain for "maritime logistics". They found that using a blockchain system (like the real-world TradeLens platform by Maersk and IBM) can solve many of these problems. By putting all the documents on a shared ledger, they can reduce the amount of paper, speed up customs, and reduce fraud. Their findings show that this technology can be used to manage very large, heavy, and complex assets (like shipping containers), which is very similar to our goal of managing wagons.

High-Value Goods (Diamonds)

Another area of research is in tracking high-value goods to prove they are "ethically sourced". The diamond industry has a big problem with "conflict diamonds" (or "blood diamonds") being sold to fund wars.

To solve this, companies like De Beers created a blockchain platform called "Tracr". Academic studies like [19] have analyzed this system. They explain how a unique digital ID is created for a rough diamond when it is mined. This ID is stored on the blockchain. As the diamond is cut, polished, and sold, its certificate is updated on the ledger. This creates a permanent, immutable record of the diamond's "provenance". This proves to the customer that their diamond is not a conflict diamond. This is another example of using blockchain to create trust and a verifiable history for a physical asset.

Limitations and Barriers

It is also important to be realistic. Blockchain is not a perfect solution. A very important review by [20] studied the "barriers to adoption" for blockchain in supply chain. They found that even if the technology is good, there are many challenges. The biggest problems are:

- **Scalability:** Public blockchains (like Ethereum) can be slow and can only handle a small number of transactions per second.

- **High Cost:** The "gas fees" on Ethereum can be very expensive.

- **Interoperability:** It is hard to connect the new blockchain system to the old, "legacy" databases that companies already use.

- **Privacy:** Companies do not want to put all their secret business data (like prices or customer lists) on a public blockchain for their competitors to see.

This is very important for our thesis. This is *why* we chose a **hybrid architecture**. Our system (in Chapter 3) is designed to solve these problems. We keep user data *off-chain* to protect privacy. We use a high-performance backend to manage the system, so the user does not feel the "slowness" of the blockchain. This article helps us justify our hybrid design.

Summary of this section: The literature on SCM is very strong. It proves that the basic concept of using blockchain to track physical assets, prevent fakes, and share

data with partners is a very successful and well-researched idea. This gives us a strong foundation.

2.4.2 Blockchain and Internet of Things (IoT) for Asset Tracking

The next step in the research is to *automate* the data collection. The problem with the SCM systems we just discussed is that a human must still scan the QR code or enter the data. This means a human can still make a mistake or cheat.

The "Internet of Things" (IoT) is the idea of using small sensors to get real-world data, like temperature, vibration, or GPS location. The research in this area tries to connect these IoT sensors *directly* to the blockchain. This is called the "Blockchain of Things" (BCoT). The goal is to create a trusted record of data from the real world, with no human in the middle.

A major review by [21] studied how to combine IoT and blockchain for traceability. They argued that this combination is very powerful. The IoT sensor provides the real-time data, and the blockchain provides the immutable, trusted "backend" to store this data.

Cold Chain Monitoring

A classic example is "cold chain" monitoring. This is for products (like vaccines or fresh food) that must stay at a cold temperature. A study by [21] designed a system for this. They proposed putting an IoT temperature sensor in the shipping container with the food. This sensor would automatically send the temperature to a smart contract every 30 minutes. The smart contract would have a rule, like `if (temperature > 8) { record_violation(); }`. This is a very powerful idea. It creates a *provable, automated* record of the food's quality. This is very relevant to our project. We can (and will) propose in our "Future Work" that our system could be upgraded with IoT sensors to automatically track an asset's condition.

Connected Vehicles and Data Integrity

This area of research is the most similar to our thesis. Some researchers have studied using blockchain for "connected vehicles" or "Vehicular Ad-hoc Networks (VANETs)". A study by [22] proposed a blockchain-based system for vehicles to share data in a trusted way. They were focused on vehicles sharing data about traffic or accidents. Other research has looked at using this for insurance. A sensor in the car could write the car's mileage and speed data to a blockchain. The insurance company could then read this trusted data to give the driver a discount.

This is a direct parallel to our project. One of our biggest "Future Work" ideas is to use an IoT sensor on the train to automatically update the `mileage` field in our smart contract. This literature proves that this idea is a very active and important area of research.

Summary of this section: The literature shows that connecting IoT sensors to the blockchain is a very powerful idea. It allows us to automate data collection and create a

trusted record of real-world data, like temperature or mileage. This strongly supports the "Future Work" section of our thesis.

2.4.3 Specific Research on Blockchain for Railways

This is the most important part of our review. Now that we know blockchain is good for SCM and IoT, we must ask: **has anyone already solved our exact problem?**

We searched for academic papers that specifically mention both "blockchain" and "railway". We found that there is *interest* in this topic, but the research is very new and is not very "mature" (it is not fully developed).

Conceptual Frameworks

Most of the papers we found are **"conceptual frameworks"**. This means they are high-level ideas, not working systems.

A key paper by [23] proposed one of these frameworks. The authors did a very good analysis, very similar to our Section 2.2. They identified the same problems: many stakeholders (operators, manufacturers, maintainers) who do not trust each other, and a need for a "single source of truth" for maintenance data. They *proposed* that a blockchain system (they suggested Hyperledger Fabric) could be a good solution. They drew diagrams of how the system *could* work. This paper is very important for us, because it proves that our "problem statement" (in Section 2.2) is correct and is a real problem that other academics are also trying to solve. But, this paper is only a "framework". They did not *build* the smart contracts, they did not *build* a backend API, and they did not *build* a user interface.

Another paper by [3] also proposed a "blockchain-based system for secure and transparent railway maintenance". This paper is also a very high-level model. It focuses on the data-sharing agreements and proposes a system architecture. It is a very good paper, but again, it does not show a full implementation. It does not include the smart contract code, the API logic, or any user interface.

Research on Different Railway Problems

We also found papers that use blockchain for *different* problems in the railway industry, which are not our problem.

- **Ticketing:** Some researchers, like [24], have proposed using blockchain for railway ticketing. Their idea is to create a decentralized system where users can buy, sell, or trade their train tickets in a peer-to-peer way, without a central company controlling everything.

- **Signaling:** Other researchers, like [25], have looked at using blockchain for railway *signaling systems*. Their goal was to improve the cybersecurity of the signals, so that a hacker cannot cause an accident. They proposed using a blockchain to create a trusted log of all signal commands.

These papers are useful because they show that "blockchain for railways" is an active area of research. But, they are not trying to solve our problem, which is *asset management and maintenance*.

Summary of this section: Our review of the specific railway literature is the most important part of this chapter. We found that while there is a lot of *interest* in this topic, the research is almost all **theoretical**. We found "conceptual frameworks" and "models", but we could not find any academic papers that showed a *complete, end-to-end, working system* with all three layers: a smart contract, a backend API, and a frontend.

2.5   Analysis and Identification of the Research Gap

This is the final and most important section of our literature review. In the previous sections, we have built the foundation for our research. We have analyzed the "problem domain" and shown that traditional railway asset management systems suffer from serious problems of data silos, a lack of trust, and inefficiency (Section 2.2). We have also analyzed the "solution domain" and shown that blockchain technology, with its features of immutability, transparency, and smart contracts, is a powerful tool for building trust (Section 2.3).

Finally, we reviewed the "State of the Art" (Section 2.4), where we saw how other researchers have used blockchain for supply chain management, IoT, and even for the railway industry.

Now, we must do the most important step. We must critically analyze this existing research to find what is *missing*. This analysis will allow us to identify the "research gap" that our thesis will fill.

2.5.1   Summary of Existing Literature

Our review of the State of the Art shows that the idea of using blockchain for asset management is very strong and well-supported by many researchers.

- **The SCM literature** (e.g., [15], [17]) has clearly proven that blockchain is an effective tool for improving **traceability** and **transparency**. It can be used to track everything from food to pharmaceuticals, giving a single, shared source of truth to all stakeholders. This proves our basic idea is correct.

- **The IoT literature** (e.g., [21], [26]) shows that it is possible to connect real-world sensors to the blockchain. This creates a trusted, automated record of an asset's condition (like temperature or location), which is a powerful concept for our future work.

- **The railway-specific literature** (e.g., [23], [3]) is the most relevant. It confirms that the problems we identified in Section 2.2 are real and that other academics agree. These papers specifically propose blockchain as a "conceptual solution" to the problems of data silos and lack of trust in railway maintenance.

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So, the existing research gives us a strong foundation. We know the *problem* is real and we know the *technology* is a good fit. However, a deeper analysis shows that there is a large gap between these high-level proposals and a practical, working, and user-friendly system.

2.5.2 Identified Gaps and Limitations

While the existing literature is a good starting point, we have identified three major gaps. The research tends to be "technology-centric," focusing on high-level ideas, and it often ignores the practical challenges of implementation, user-friendliness, and system architecture.

Gap 1: Lack of Full-Stack Implementation (From Theory to Practice)

The single biggest gap we found, especially in the railway domain, is the gap between *theory* and *practice*.

The vast majority of the papers we found, like [23] and [3], are **"conceptual frameworks"** or **"architectural proposals"**. They do an excellent job of drawing diagrams and explaining how a blockchain system *could* work. They propose "models" and "frameworks" for data sharing.

However, this is a very serious gap. A theoretical model on paper does not have to deal with any real-world engineering problems. The number of academic papers that *propose* a blockchain system is very high, but the number that *actually build and test* a full system is very small [27].

A theoretical framework does not have to solve these hard questions:

- **Smart Contract Complexity:** It is easy to draw a box that says "Smart Contract". It is very difficult to actually write a smart contract that is secure, gas-efficient, and can handle complex, three-level hierarchical relationships (Train → Wagon → Equipment). How do you search this data? How do you update it? The existing literature does not show this.

- **Middleware Development:** A blockchain cannot be used like a normal database. It is slow and hard to talk to. You need a "middleware" (our backend API) to manage this. This backend must handle user requests, manage a queue for slow blockchain transactions, and securely store the private keys for signing. This complex "orchestration" layer is a critical piece of software, and the conceptual papers we found do not design or build it.

- **Gas and Performance Evaluation:** A theoretical paper does not have any "numerical results". It cannot tell us how much the system *costs* to run. How much gas does it cost to add a new wagon? Is it $0.01 or $50? Is the API fast enough for a user, or does it take 30 seconds to load a page?

There is a large gap in the research for a **fully-implemented, full-stack solution**. We could not find any academic papers that present a complete, working, and tested system with all three layers: a smart contract, a backend API, and a frontend.

Gap 2: Ignoring the User Experience (UX) and Mobile Needs

The second major gap we found is that the existing literature is almost 100% **"technology-centric"**. It focuses on the blockchain, the cryptography, and the data. It almost never talks about the **"user-centric"** side of the system.

This is a critical failure. A system, no matter how technically brilliant, is a complete failure if the end-users cannot or will not use it. The success of any new enterprise system depends on **user acceptance** [28].

Our problem domain has a very specific type of user: the **railway mechanic or inspector**. We must ask:

- Where does this user work? They are not at a desk in an office. They are in a railyard, on the tracks, or in a maintenance tunnel.

- What device do they use? They do not have a desktop computer. They have a **mobile phone** or a rugged tablet.

- What is their environment like? It is loud, it is dirty, and they may be wearing gloves. Most importantly, the **internet connection** might be very bad or non-existent (like in a tunnel).

A regular website that requires a perfect, fast internet connection will not work for this user. The existing literature on blockchain for railways does not address this problem at all.

This is a major gap. There is no research on building a **Progressive Web App (PWA)** for this problem. A PWA is a special type of web application that can be "installed" on a phone, and it can be designed with **offline-first capabilities**. This would allow a mechanic to load all the asset data when they have Wi-Fi in the office, then go into the railyard (with no internet), update the maintenance records, and have the app automatically "sync" the new data to the blockchain when they get back to Wi-Fi.

This focus on the real-world **User Experience (UX)** and the need for a **mobile-first, offline-capable PWA** is a practical, user-centric gap that is almost completely ignored by the current academic literature.

Gap 3: Naive Architectures (Privacy, Cost, and the Hybrid Model)

The final gap we identified is that many of the proposed "frameworks" are **"architecturally naive"**. They often make a simple, and very wrong, assumption: that all data can just be put "on the blockchain".

This is a very bad design, and it shows a lack of practical experience. This "all-on-chain" model has three huge, fatal flaws:

1. **Cost:** It is extremely expensive. Storing data on the Ethereum blockchain is the most expensive data storage in the world. Storing every maintenance log, every photo, and every user's name on-chain would cost millions of dollars in gas fees.

2. **Performance (Speed):** A public blockchain is slow. It can take 15 seconds, or even minutes, for a transaction to be confirmed. A user will not wait 2 minutes to log in or to save a simple form.

3. **Privacy and Security:** This is the most serious flaw. You *cannot* put all your data on a public (or even consortium) blockchain. What about user accounts? Employee lists? User email addresses and passwords? It is a terrible, insecure idea to put this private, sensitive data on an immutable ledger. What about business secrets? Does a railway operator want their competitors to see their maintenance schedule or their list of suppliers? No.

These problems of cost and privacy are the main reasons why companies are slow to adopt blockchain. The solution is to use an **"off-chain"** storage strategy [29].

The research gap is the lack of a clear, practical **hybrid architecture** designed for this specific railway problem. We need a system that intelligently separates the data. We need to put:

- **On-Chain:** Only the data that *must* be trusted and immutable (like the asset's ID, its current owner, and a hash of its maintenance report).

- **Off-Chain:** All the private, large, or changeable data (like user accounts, passwords, and the full maintenance report text) in a traditional, fast, and secure database.

While hybrid models are known, their specific application to solve this user-privacy-vs-asset-transparency problem in a full-stack, 3-tier system for railways has not been designed or built in the academic literature.

2.5.3 Thesis Contribution

This thesis is designed to fill these three major gaps. The main contribution of our work is not just the *idea* of using blockchain, but the **design, implementation, and evaluation of a complete, practical, and user-focused solution**.

Our contribution is the answer to the gaps we just identified:

1. **In response to Gap 1 (Lack of Full-Stack Implementation):** We are not just proposing a "framework". The main contribution of this thesis (in Chapter 3) is a **complete, full-stack, and implemented system**. We have built all three layers, from the gas-efficient Solidity smart contract (with hierarchical logic and search indexes), to the secure Python backend, to the final frontend. In Chapter 4, we will *evaluate* this system's real-world performance, providing the "numerical results" (like gas costs and API latency) that the conceptual papers are missing.

2. **In response to Gap 2 (Ignoring the User Experience):** Our project is "user-centric," not "technology-centric". We have designed our solution for the *real user*. Our contribution is the design and implementation of a **mobile-first Progressive Web App (PWA)**. This shows a practical solution for the mobile mechanic in the field, addressing the real-world challenges of a bad internet connection, which is a key part of our "Main Contribution" (Section 3.6).

3. **In response to Gap 3 (Naive Architectures):** Our thesis presents a **practical hybrid architecture** that solves the cost and privacy problems. We show (in Section 3.1) a 3-tier system that intelligently separates data. We use the blockchain for what it is good at (immutable asset integrity) and a traditional, off-chain SQLite database for what it is good at (fast, private, and secure user authentication). This hybrid model is a key part of our contribution.

By filling these gaps, our project is a significant and new contribution to the field of railway asset management. The following chapters will now present the design, implementation, and evaluation of this novel system.

Chapter 3

Methodology

3.1 System Architecture

To build our proposed system, we designed a multi-layer architecture, which is a common and very effective pattern in modern software engineering. This approach is sometimes called a "three-tier architecture" as it logically separates the application's main functions. For our project, this means the user interface (frontend), the business logic (backend), and the data storage (database and blockchain) are all independent components. This separation of concerns is very important because it make the system much easier to develop, test, and maintain.

A general overview of this architecture is shown in Figure 3.1. The following sections will describe each of these layers in more detail.
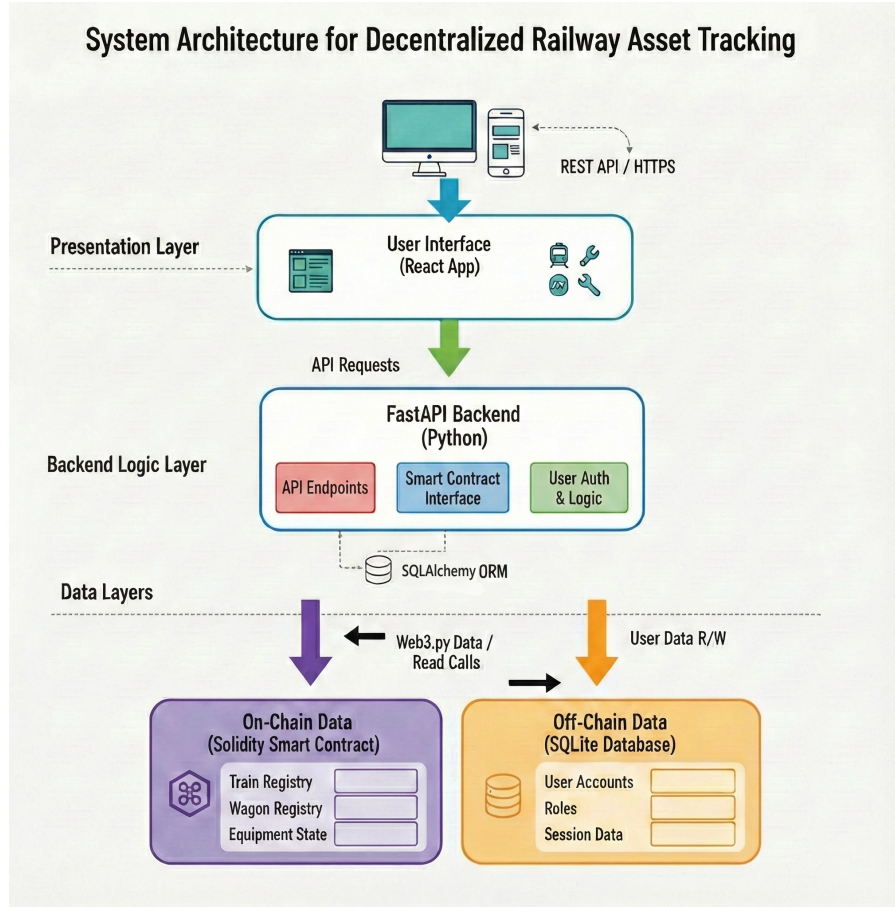
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Figure 3.1. The high-level system architecture, showing the connection between the user, backend, database, and blockchain.

The source code for the implementation is available at:

- **Backend Repository:** https://github.com/amirhossein-shekari/backend-train-inventory

- **Frontend Repository:** https://github.com/amirhossein-shekari/frontend-train-inventory

3.1.1   Architectural Design Rationale

Before building, we had to make a key decision. A "pure" decentralized application (DApp), where all logic and data lives on-chain, has many problems for an enterprise system. It can be very slow, as every action must be a transaction. It is also very expensive, as storing data on the blockchain costs 'gas' (money). This is not practical for a complex system like a railway inventory which might generate thousands of data points.

Therefore, we chose a **hybrid architecture**. This design is the foundation of our contribution. It combines the best parts of a traditional web application (speed, low

cost) with the best parts of blockchain (security, immutability). This hybrid model is a common pattern in enterprise blockchain applications, as it solves the trade-offs between cost, speed, and trust [30].

The core idea is to separate two types of data:

1. **Critical Asset Data:** Information about the trains, wagons, their relationships, and their maintenance history. This data needs to be secure and auditable. This data is perfect for the blockchain.

2. **Application Data:** Information like user accounts, hashed passwords, and session tokens. This data is needed for the application to work, but it does not need tobe immutable or decentralized.

This hybrid design gives us great benefits. We get the speed and low cost of a traditional database for everyday tasks like user login. But we get the high security, immutability, and transparency of the blockchain for the most important data: the asset registry and maintenance logs.

3.1.2 Presentation Layer (Frontend)

This is the user interface (UI) that the railway staff will use. It is the "face" of our application. We developed this as a web-based application built using the React library, a popular and modern choice for building user interfaces.

- **Technology Choice:** We chose React because it allows us to build a **Single-Page Application (SPA)**. This means the user loads the application once, and then all navigation (like moving from the 'Trains' page to the 'Wagons' page) is very fast and smooth, without reloading the whole web page. React's component-based model also allowed us to create reusable UI parts, for example a single 'Asset Form' component could be used for both creating a new train and for editing an existing train.

- **Functionality:** This layer provides all the tools the user interacts with. This includes:

  - A main **Dashboard** to show summary statistics (like how many assets are operational).
  - **Data Grids** and tables for listing all trains, wagons, and equipment.
  - **Interactive Forms** and modal pop-ups for creating new assets or updating existing ones (e.g., changing a wagon's mileage).
  - A secure **Login Page** to handle user authentication.

- **Data Handling:** The frontend does not have any direct business logic. Its main job is to show data from the backend and send the user's input back to the backend. We used a modern data-fetching library, React Query, to manage all API calls. This library is very smart, it handles caching of data (to make the app feel faster) and automatically updates the data in the background.

3.1.3 Backend Logic Layer (API Middleware)

This layer is the central 'bridge' and the 'brain' of our system. It connects the frontend to our data layers. In academic terms, this is a **blockchain middleware** layer [31]. Its role is to abstract the complexity of the blockchain from the end-user. The frontend does not know how to speak to the blockchain; it only speaks to this backend API.

We built this layer as a REST API using the **FastAPI** framework in Python. We choose this technology because it is very high performance, and it automatically creates interactive API documentation (using OpenAPI), which was very helpful for our development and testing process.

The backend is responsible for several critical tasks:

1. **Request Handling and Validation:** It receives all network requests from the frontend. For example, when the user submits a form to create a new train, the frontend sends a request to the `POST /v1/trains` endpoint. The backend validates this data to make sure all required fields (like 'name') are present.

2. **Authentication and Authorization:** This layer handles all user security. When a user tries to login, the API checks their username and password against the data stored in our SQLite database. It creates a secure **JSON Web Token (JWT)** and sends it back to the user. For all other API calls, the frontend must send this token. The backend will validate the token on every request to prove who the user is. This is a key part of our hybrid design: user authentication is handled off-chain, which is faster and more secure, as user passwords should never be stored on a public blockchain [32].

3. **Data Orchestration:** This is the most important job. The backend is the 'orchestrator' that decides where data should go. When a user creates a new user account, the backend hashes the password and saves it to the local SQLite database. When a user creates a new maintenance record, the backend creates and sends a transaction to the blockchain smart contract. The backend is the *only* component that holds the private keys and node connections (e.g., to Alchemy) necessary to write to the blockchain.

3.1.4 Data Layers (A Hybrid Approach)

This is the most critical part of our thesis, the foundation of the whole system. As mentioned in the design rationale, we use a hybrid data model with two distinct storage layers. This approach is recognized in research as a practical solution for balancing the trade-offs of performance, cost, and data integrity [33].

On-Chain Data: The Blockchain Ledger

The smart contract is our decentralized data layer. This is the single source of truth for all *critical asset data*. We decided that any data related to the asset's identity, its hierarchical relationship, and its maintenance status must be on-chain.

This gives us the key benefits of blockchain, which are central to our thesis. For a high-stakes industry like railway transport, an auditable and immutable record of maintenance is essential for safety and regulation. Research has shown that blockchain is an effective tool for this, creating a transparent and verifiable management system [34].

Specifically, we store the following data on-chain:

- The full list of **Trains**, **Wagons**, and **Equipment**.

- The **hierarchical links** between them (e.g., mapping which wagons belong to which train).

- The critical **maintenance status** for each piece of equipment (e.g., `isOperational` and `lastMaintenance`).

- Key metadata like `mileage`, `manufacturer`, and `originCountry`.

This section only describes *what* is stored; the next section (3.2) will describe *how* it is stored and managed inside the contract.

Off-Chain Data: The Local Application Database

At the same time, we use a traditional, centralized database. Our backend uses SQLAlchemy, an 'Object Relational Mapper' (ORM), to connect to a simple **SQLite** database file.

We use this database for storing *non-critical and centralized application data.* This includes:

- User accounts (username, hashed passwords).

- User roles (e.g., 'admin', 'mechanic'), which we can use to control permissions.

- Authentication tokens for managing user sessions.

This information must not be on the blockchain. It is a very bad and insecure practice to store user passwords or other personally identifiable information (PII) on a public ledger. This data is also not part of the 'asset history' which we want to make immutable. This choice makes our application more secure, faster (logging in is a simple database check, not a slow blockchain transaction), and much cheaper.

3.1.5 Example Workflow: The Maintenance Process

To make the full architecture clear, let's follow the data flow for one complete action: "A mechanic performs maintenance on a piece of equipment."

1. **Login:** The mechanic opens the web application and enters their username and password. The **Frontend** sends this to the **Backend**. The Backend hashes the password and compares it to the hash in the **SQLite Database**. The check is successful. The Backend creates a JWT token and sends it back to the Frontend.

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2. **View Data:** The mechanic navigates to the 'Equipment' page. The **Frontend** sends a request to the Backend (with the JWT token) to get all equipment. The **Backend** checks the token (using SQLite) to see if the user is authenticated. The token is valid.

3. **Read from Blockchain:** The **Backend** then calls a 'view' (read-only) function on the **Blockchain Smart Contract** to get the list of all active equipment. This read operation is free and does not cost gas.

4. **Display Data:** The **Blockchain** returns the data to the **Backend**, which then formats it as JSON and sends it to the **Frontend**. The mechanic sees the full list of equipment.

5. **Perform Maintenance:** The mechanic finds a broken part (its status is `isOperational: false`). They fix it, and then go to the application to update its status. They fill out the form and click "Submit".

6. **Write to Blockchain:** The **Frontend** sends this new data to the **Backend**. The Backend validates the JWT token and the new data.

7. **Backend Orchestration:** This is the key step. The **Backend** creates and signs a new *transaction* to call the `updateEquipment` function on the **Blockchain Smart Contract**. This is a 'write' operation, so it will cost a small amount of gas to execute.

8. **Confirmation:** The blockchain network confirms the transaction. The new data (the updated status and maintenance date) is now permanently recorded in the ledger.

9. **Update UI:** The **Backend** receives the confirmation and sends a "Success" message to the **Frontend**. The mechanic's screen updates to show the new, 'operational' status for the part.

This flow shows how all the layers work together perfectly. We use the fast off-chain database for centralized tasks like login, and the secure, immutable on-chain ledger for the important maintenance record.

3.2 The Blockchain Core: Railway Asset Registry

This section details the technical implementation of the on-chain component, which is the heart of our decentralized system. As we discussed in the system architecture, this component is a smart contract that acts as a secure, immutable, and auditable ledger for all railway assets. It is designed to be the single source of truth for asset identity, relationships, and maintenance status.

Our design goals for this smart contract were:

- **Data Integrity:** Ensuring that data is correct and that relationships (like a wagon belonging to a train) are always valid.

- **Auditable History:** Making it impossible to delete or modify maintenance records, while still allowing for assets to be 'retired' from active service.

- **Query Efficiency:** Allowing the backend to retrieve data for the application (like "all wagons on train 5") quickly and efficiently.

- **Gas Optimization:** Making all operations, especially writing data, as cheap as possible to ensure the system is economically viable to use.

To achieve these goals, we used the Solidity programming language, compiling with version 0̂.8.0. This version is important, as it includes built-in arithmetic safety checks, which protects our contract from overflow and underflow bugs without needing external libraries.

3.2.1   Development, and Deployment Lifecycle

A complex smart contract is not a simple script. It requires a professional development lifecycle, which includes a local development environment, a strong testing framework, and a clear deployment pipeline. This is critical because smart contracts are immutable, meaning a bug deployed to the main network can be impossible to fix and can lead to major problems.

Development Environment

For building this complex contract, we need a professional development environment. We chose **Hardhat**, which is a very popular and powerful framework for Ethereum development [35]. Hardhat is important for our project because it provides many tools that make development easier and more reliable.

The most important feature for us was the **Hardhat Network**. This is a local Ethereum network that runs on our own computer. It starts up instantly and gives us 'fake' ETH to pay for transactions. This allowed us to compile and test our contract hundreds of times very quickly, without needing to connect to a real, slow, and expensive public network. We also wrote scripts to deploy our contract to this local network, so we could connect our backend and frontend to it for full-stack testing.

Deployment to a Test Network

After all local tests passed, we deployed our contract to a public **test network (testnet)**. We chose the **Sepolia testnet**. Sepolia is the modern, recommended testnet for Ethereum application development, as it is maintained by the core developers.

To deploy to Sepolia, we cannot connect directly. We must use a **node provider** service. For this project, we used **Alchemy** [36]. Alchemy runs a high-availability Ethereum node for us, and gives us a special URL (an RPC endpoint) that our deployment scripts can use. We used Hardhat's scripting tools to write a deployment script that reads our compiled contract, connects to Alchemy, and securely sends the 'create contract' transaction to the Sepolia network using our private key. This process gave us a real contract

address on a public network, which our backend could then be configured to use. This is the same process that would be used for a final 'mainnet' (production) deployment.

3.2.2 On-Chain Data Structures

The first step in designing the contract was to define the data models. We used Solidity's `struct` type to create custom data templates for our three main asset types.

- **Train struct:** This is the highest-level asset. It contains basic identity fields like `name`, `manufacturer`, and `originCountry`. Critically, it also includes a `mileage` field. This is a `uint32` (32-bit unsigned integer) that the backend must update. This field is the foundation for any future predictive maintenance logic, as the system can check this value to schedule service.

- **Wagon struct:** This is the intermediate asset, representing a single car. It contains its own metadata, like `wagonType` (e.g., "Passenger" or "Cargo") and `purchaseDate`. Its most important field is `trainId`. This is the 'foreign key' that creates the hierarchical link, proving which train this wagon is part of.

- **Equipment struct:** This is the most granular asset, representing a component inside a wagon (e.g., a braking system, HVAC unit, or door assembly). This struct is the linchpin of our thesis's "maintenance" goal. It contains two vital fields:

  1. `isOperational`: A boolean (`true/false`) value that gives an immediate, real-time status of the part.
  2. `lastMaintenance`: A timestamp (stored as a `uint32`) that is updated by a mechanic. The combination of these two fields provides a complete, auditable maintenance log.

  This struct also contains a `wagonId` to link it to its parent wagon.

A key part of our optimization strategy was the choice of data types. For all identifiers (`id`) and timestamps, we chose `uint32` instead of the default `uint256`. This is a significant **gas optimization**. A `uint32` uses 8 times less storage on the blockchain than a `uint256`. Because writing to storage is the most expensive operation in Ethereum, this choice makes every transaction that creates or updates an asset cheaper. This is a common best practice in gas optimization [37]. A 32-bit integer can store a number up to 4.29 billion, which is more than enough for the number of assets in a railway system, and it can represent Unix timestamps until the year 2106.

3.2.3 Storage, Relationships, and Indexing

After defining our data *shape* (the structs), we needed to design the data *storage*. In Solidity, the primary way to store data is with `mapping` variables. A mapping is like a giant hash map or dictionary, where you can store a value at a specific key. This is the only way to efficiently retrieve a single piece of data without looping through an entire array.

We designed three different types of mappings to manage our data, relationships, and search indexes.

Data Storage Mappings

These are our primary "database tables". They link a unique ID to the full struct data for that asset.

```
mapping(uint32 => Train) private trains;
mapping(uint32 => Wagon) private wagons;
mapping(uint32 => Equipment) private equipment;
```

This allows us to instantly find any asset (e.g., `wagons[101]`) just by knowing its ID. We marked these as `private` so that other contracts cannot access them directly; they must use our designated functions.

Hierarchical Relationship Mappings

This is how we solved the problem of linking assets together. We created mappings that link a parent's ID to a *list* of its children's IDs.

```
mapping(uint32 => EnumerableSet.UintSet) private _wagonsByTrain;
mapping(uint32 => EnumerableSet.UintSet) private _equipmentByWagon;
```

Here, we made another key design choice. We did not use a simple array (`uint32[]`) for the list. Instead, we imported the **EnumerableSet** library from OpenZeppelin [38]. OpenZeppelin is a trusted provider of secure smart contracts. An `EnumerableSet` is a special data structure that acts like a list, but has several advantages:

- **Add/Remove:** Adding or removing an ID is very fast and has a constant gas cost. In a large array, removing an item can be very expensive.

- **Contains:** The set can instantly check if an ID is already in the list (`contains(id)`). This is impossible in an array without an expensive loop.

This set is the key to our tracking logic. When we add a new wagon, we also add its ID to the `_wagonsByTrain` set of its parent train.

Search Index Mappings

A major challenge in Solidity is that mappings are not searchable by their *value*. For example, we cannot ask the `wagons` mapping to "find all wagons where `wagonType` is 'Cargo'".

To solve this, we implemented our own **inverted indexes**. This is a common software engineering design pattern that we applied to Solidity [39]. We created special mappings where the *key* is the value we want to search for, and the *value* is a set of IDs.

```
mapping(bytes32 => EnumerableSet.UintSet) private _wagonsByName;
mapping(bytes32 => EnumerableSet.UintSet) private _wagonsByType;
```

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The key is `bytes32`, not a `string`. This is because strings are complex and expensive to use as mapping keys. When a new wagon is added, we take its name (e.g., "Wagon 12A"), convert it to bytes, and then compute its `keccak256` hash. This hash is a unique 32-byte key. We then add the wagon's ID to the `EnumerableSet` stored at that hash in the `_wagonsByName` mapping.

This is a powerful technique. Now, if the user wants to search for all wagons named "Wagon 12A", the backend just computes the same hash and queries our mapping. It instantly gets the set of all IDs for wagons with that name.

3.2.4 Asset Lifecycle Management Functions

These are the state-changing functions that our backend API calls to create, update, and delete assets. These functions are the core of the business logic and are directly related to the goals of using blockchain for asset management. Studies have shown that blockchain can significantly improve the security and reliability of maintenance data [40], and these functions are how we implement that promise.

Asset Creation

We created `addTrain`, `addWagon`, and `addEquipment` functions. The logic for adding a child asset (like a wagon) is more complex than adding a parent (like a train). When `addWagon` is called:

1. **Parent Check:** The function first checks if the parent `trainId` exists and is an active train. If not, it reverts the transaction. This is a critical data integrity check to prevent "orphan" assets.

2. **ID Generation:** It increments a private counter (`_wagonCount`) to get a new, unique ID.

3. **Data Storage:** It creates the new `Wagon` struct and saves it in the main `wagons` mapping.

4. **Index Update:** This is the crucial part. The function updates all our other mappings. It adds the new ID to the `_activeWagons` set, the `_wagonsByTrain` set of its parent, and the search indexes.

5. **Event Emission:** Finally, it emits an event to notify the backend that a new wagon was created.

Asset Updating

The update functions are the most complex in the entire contract, as they must carefully manage all the indexes. The `updateWagon` function is the best example. When a user changes a wagon's name and moves it to a new train:

1. **Existence Check:** It checks if the wagon ID exists and is active.

2. **Parent Check:** It checks if the *new* parent train ID is also active.

3. **Relationship Update:** It removes the wagon ID from the `_wagonsByTrain` set of the *old* train and adds it to the set of the *new* train.

4. **Search Index Update:** This is the most complex step. It must:

   - Get the *old* name, hash it, and *remove* the wagon ID from the `_wagonsByName` index.

   - Get the *new* name, hash it, and *add* the wagon ID to the `_wagonsByName` index.

   - It does the same for the `wagonType` if it was changed.

5. **Data Update:** Only after all indexes are updated, it updates the data in the main `wagons` struct.

Asset Deletion Strategy (Soft vs. Hard)

This is a core part of our "auditable history" goal. One of the main benefits of using blockchain for asset tracking is to create an immutable log [41]. Deleting data from a blockchain is permanent and generally a bad idea for an audit trail.

   Soft Deletion: We implemented a 'soft delete' pattern. We maintain an `EnumerableSet` for all active assets (`_activeTrains`, `_activeWagons`, `_activeEquipment`). When the `deleteWagon` function is called, it does *not* use the `delete` keyword. Instead, it simply removes the wagon's ID from the `_activeWagons` set and from all search/relationship indexes. The original `Wagon` struct is still in the blockchain storage, forever. It is now "inactive". Our query functions are designed to only return "active" assets, so this wagon disappears from the application, but its history is preserved for any auditor.

   This soft delete is also **cascading**. When `deleteTrain` is called, it loops through all wagon IDs in its `_wagonsByTrain` set and calls `_deleteWagon` on each one. This, in turn, cascades down and soft-deletes all equipment. This prevents "orphan" child assets. We also implemented `undeleteTrain` functions that can restore an asset by re-adding it to the active sets and indexes.

   Hard Deletion: We also included `hardDeleteTrain` functions. These functions use the `delete` keyword, which completely removes the struct data from storage and provides a small gas refund. These are dangerous functions and should only be exposed to a high-level admin. They are not for normal operation, but are useful for purging data that was created by mistake.

3.2.5   Query and Data Retrieval Functions

These are the `view` (read-only) functions that our backend calls to get data for the frontend. These functions do not cost any gas to call.

   - **Relational Queries:** Functions like `wagonsOfTrain(trainId)` are simple. They just look up the `trainId` in the `_wagonsByTrain` mapping and return the list of wagon IDs from the `EnumerableSet`.

- **Search Queries:** Functions like `searchWagonsByName(string calldata name)` are more complex. They first hash the input name to get the `bytes32` key. Then they query the `_wagonsByName` index to get the set of matching IDs.

- **The Active Filter:** A key detail is that search queries do not return the set directly. They pass the results to an internal helper function, `_filterActive`. This function loops through the IDs from the search index and, for each ID, checks `_activeWagons.contains(id)`. It builds a new array containing *only* the IDs that are in the active set. This is the other half of our soft-delete logic. It guarantees that our search results never contain "deleted" assets.

- **Detail Queries:** We created helper functions like `getWagonDetail(wagonId)`. This is an aggregation function for the backend. In one call, it returns the `Wagon` struct itself, the parent `Train` struct, and the array of all child `Equipment` IDs. This is very efficient for the backend, as it prevents it from having to make three separate calls to the contract to get all the data for one page.

3.2.6 Gas, Security, and Opcode Optimization

Finally, a smart contract must be efficient. High gas costs can make a system unusable. Academic research has shown that inefficient smart contracts are a major problem, and that many optimizations are possible [42]. We focused on several key optimizations.

Compiler Opcode Optimization

A smart contract must be compiled from Solidity into 'opcodes' (operation codes) for the Ethereum Virtual Machine (EVM). We can 'optimize' this process. We enabled the Solidity optimizer with a **'runs' value of 200**.

This `runs` value is a setting we give to the compiler. It tells the compiler how many times we expect to *call* each function during the contract's lifetime. A value of 200 is a standard default that finds a good balance between two different costs [43]:

1. **Deployment Cost:** The one-time cost to put the contract on the blockchain.

2. **Runtime Cost:** The cost to call a function, like `addWagon`, every time.

A low `runs` value (like 1) makes the deployment cheap but the functions more expensive. A high `runs` value (like 10,000) makes the deployment very expensive but optimizes the functions to be very cheap. We chose **200** as a sensible trade-off for our system.

Custom Errors

This is a modern Solidity feature for gas optimization. Instead of reverting a transaction with a string, like `revert("Parent train is not active");`, which is very expensive, we define custom errors at the top of the contract.

```
error NotActive(uint8 kind);
error NotFound(uint8 kind);
error ParentNotActive(uint8 parent);
```

When a check fails, we use `revert ParentNotActive(K_TRAIN);`. This seems like a small change, but it has a huge impact. Using custom errors instead of strings saves a large amount of gas when we first *deploy* the contract, and also saves gas every time a transaction *fails.* This is a modern best practice [37].

Asynchronous Events

The blockchain is asynchronous. When the backend sends a transaction (like `addWagon`), it only knows that the transaction was *sent*, not when it was *confirmed*. To solve this, we use an `event`.

```
event AssetChanged(uint32 indexed id, AssetType indexed assetType);
```

We emit this event every time an asset is created, updated, or deleted. The `indexed` keyword allows our backend to easily filter for events (e.g., "only tell me about changes to `AssetType.Wagon`"). Our backend server can subscribe to this event. This is much more efficient than "polling" (asking the contract "any changes¿' every 5 seconds). The blockchain *tells* our server immediately when a change happens.

3.3 Application Backend (API Layer)

If the smart contract is the 'decentralized ledger', then the backend is the 'central brain' of our application. This layer is a **middleware**, it works as the bridge between the simple frontend application and the very complex blockchain. This layer is responsible for three main jobs: 1) handling user authentication, 2) managing off-chain data (like user accounts), and 3) orchestrating all communication with the smart contract (like sending transactions).

Our choice of a middleware-based architecture is a very important design decision. A 'pure' decentralized application (DApp) would require the user's web browser to talk directly to the blockchain. This has many problems, it is not secure (users must manage their own private keys), it is complex, and it cannot handle centralized logic like user roles. Our backend API solves this. Research on blockchain systems calls this an 'API-centric' or 'middleware' pattern, which is a practical way to build hybrid applications [44].

3.3.1 Technology Choice: Python and FastAPI

For our backend technology, we choice to use Python with the **FastAPI** framework. This was not a random choice. We needed a framework that was very high-performance and modern.

- **Performance:** FastAPI is an 'asynchronous' framework (ASGI). This means it can handle many user requests at the same time without getting stuck. This is important

for us, because some requests might be very slow (like waiting for a blockchain transaction to be confirmed). The async design means the server can handle other user requests while it waits.

- **Data Validation:** FastAPI is built on a library called **Pydantic**. This is maybe the most important feature for our project. We used Pydantic to create 'schemas' for all of our API endpoints. This means the API automatically checks, validates, and cleans all data that comes from the user. If a user tries to create a train and sends "abc" for the `mileage`, Pydantic stops the request before it ever gets to our logic. This is a critical security layer. It protects our smart contract from bad data, and it saves us money by preventing transactions that would fail and still cost gas.

- **Developer Tools:** FastAPI automatically generates interactive API documentation (using OpenAPI and Swagger UI). This was very important for our development, as it allowed us to test our API endpoints very easily, without needing the frontend to be finished.

3.3.2   API Structure and Request Flow

Our backend application is not one single file. We structured our code in a modular way to make it easy to understand. We used FastAPI's `APIRouter` to separate the three main parts of our system:

- **Authentication Router:** This handles everything for user login, like `/token`.

- **Users Router:** This handles creating new user accounts, for example `POST /users`.

- **Assets Router:** This is the biggest and most important part. It handles all requests for `/trains`, `/wagons`, and `/equipment`.

The main application file just includes these routers. This makes our code very clean. When a new request comes from the user, the backend follows a clear process, which is shown in Figure 3.2.
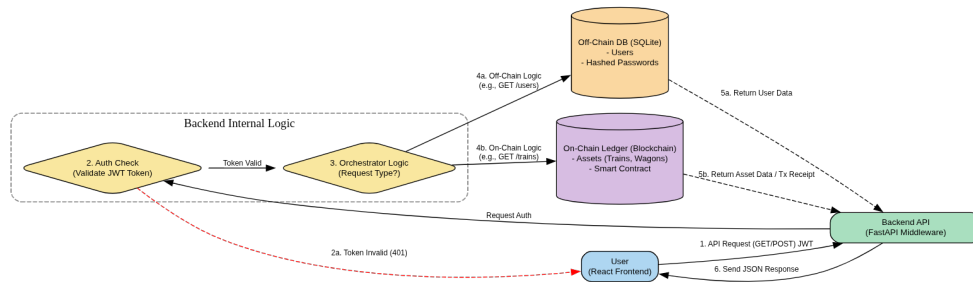

Figure 3.2.   The flow of a user request through the backend API. The API acts as an orchestrator, first checking authentication and then deciding to use off-chain (SQLite) or on-chain (Blockchain) logic.

3.3.3 Off-Chain User and Authentication Service

A core part of our hybrid design is the separation of user data from asset data. It is a very bad and insecure idea to store user information, especially passwords, on a public blockchain. Therefore, we built a traditional, off-chain authentication service. This is a common and secure pattern for decentralized applications [32].

Off-Chain Database

For this service, we used a simple **SQLite** database. This database is managed by our backend using the **SQLAlchemy** library, which is an 'Object Relational Mapper' (ORM). The ORM lets us write our database models using Python classes. Our `User` model is very simple:

```
class User(Base):
    id = Column(Integer, primary_key=True, index=True)
    email = Column(String, unique=True, index=True, nullable=False)
    hashed_password = Column(String, nullable=False)
    role = Column(String, default=''user'')
```

This database only stores the user's email, a role (like 'admin' or 'user'), and a *hashed* password. We use the **Passlib** library to ensure we never store the real password, only a secure hash.

Authentication with JWT

Our security is based on **OAuth2** and **JSON Web Tokens (JWT)**. The flow is simple:

1. The user sends their email and password to the `/token` endpoint.

2. The backend gets the user's data from the SQLite database.

3. It uses `Passlib` to check if the password is correct.

4. If it is correct, the backend creates a JWT. This token is a small piece of text that is "signed" by the backend with a secret key. It contains the user's ID.

5. The backend sends this token back to the frontend.

From this point, for every other request (like "get all trains"), the frontend must include this token in the header. FastAPI automatically checks the signature of the token to make sure the user is who they say they are. This is how we "protect" our endpoints and make sure that only logged-in users can manage assets.

3.3.4 Blockchain Orchestration Service

This is the most important job of the backend. The backend is the **orchestrator** that decides how and when to talk to the blockchain. The frontend application has no idea

that a blockchain exists; it just knows how to talk to our API. This is a very good design because it makes our system simple.

All of this complex logic is in our 'asset controller' file. This controller is the only part of our system that has the blockchain's address, its ABI (Application Binary Interface), and the server's private key.

We have two different flows for blockchain communication: reading data and writing data.

Reading Data (Read-Only Calls)

Reading data from the blockchain is free and fast. When the user opens the 'Trains' page, the frontend calls our `GET /v1/trains` endpoint. The backend then performs these steps:

1. It checks the user's JWT token to make sure they are logged in.

2. It uses the **Web3.py** library to connect to our blockchain node (the Alchemy RPC endpoint).

3. It loads the smart contract using its address and ABI.

4. It makes a **'call()'** to the contract's `getAllTrains()` function. This is a 'view' function, so it is a read-only operation.

5. The blockchain node runs the function and instantly returns the list of all trains.

6. The backend formats this list as JSON and sends it to the frontend.

This process is fast and costs no gas. The same logic is used for `getWagonDetail` and all other 'get' requests.

Writing Data (Signed Transactions)

This is the most complex and most important flow. Writing data (like adding a new train) costs gas and must be done very securely. When a user fills the form to add a new train, this is the flow:

1. The frontend sends a `POST /v1/trains` request to our backend. The request body has the new train's data (name, manufacturer, etc.).

2. **Validation:** First, Pydantic validates the data. It checks that `mileage` is a number and that `name` is a string. If not, the request is rejected.

3. **Authentication:** Second, FastAPI checks the user's JWT token to make sure they are logged in and have permission (we could check for an 'admin' role here).

4. **Transaction Building:** The backend's controller function now builds the transaction. It uses `web3.py` to call our contract's `addTrain` function.

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5. **Signing:** This is the key step. The backend server has a **private key** stored securely in an environment variable. It uses this key to *sign* the new transaction. This signature proves to the blockchain that the backend (which we trust) is the one sending this request.

6. **Sending:** The backend sends this *signed transaction* to the blockchain via our Alchemy node.

7. **Waiting:** The backend then 'waits' for the transaction to be mined and confirmed.

8. When the blockchain confirms the transaction, it sends back a 'receipt'. The backend then sends a "Success" message to the frontend.

This flow is very secure. The user's private key is never exposed. In fact, the user does not even have a key. The only key is the server's key, which is hidden. This makes the system much easier to use for non-technical railway staff.

3.3.5 Data Validation Schemas

As we mentioned, we use Pydantic to define 'schemas' for our data. This is a critical part of our backend. These schemas are Python classes that define what the data should look like.

For example, our `WagonCreate` schema looks like this:

```
class WagonCreate(BaseModel):
    name: str
    wagon_type: str
    purchase_date: int
    origin_country: str
    manufacturer_address: str
    mileage: int
```

When the frontend sends a request to create a new wagon, FastAPI automatically checks the data against this model. If the `mileage` is missing, or if the `name` is a number, Pydantic will automatically reject the request and send a helpful error message back to the frontend.

This is very important for two reasons. First, it is a key part of API security, as it stops 'bad' data from entering our system [45]. Second, it saves us money. If we let 'bad' data get to the smart contract, the transaction would fail, but it would *still* cost us gas. By validating the data first, we ensure that we only send valid transactions to the blockchain. This makes our whole system more robust and more efficient.

3.4 Frontend Application (User Interface)

The Frontend Application is the final layer of our three-tier architecture. It is the 'face' of our system and the only part that the end-users, like railway staff or maintenance crews, will ever interact with. The main goal of this layer is to provide a simple, fast, and secure

user interface (UI) that hides all the complexity of the backend and the blockchain. The user does not need to know what a 'smart contract' is, they only need to know how to add a wagon or update a maintenance record.

We developed this application as a **Single-Page Application (SPA)**. This is a modern approach for web applications, where the user loads the application only one time. After that, when the user navigates between pages (like from '/trains' to '/wagons'), the application does not reload. It just changes the content on the page. This makes the application feel very fast and responsive, almost like a desktop application.

3.4.1 Core Technologies and Rationale

We choice our technologies very carefully to build a modern and maintainable system.

- **React and TypeScript:** The main library for our UI is **React**. We chose React because it is based on a **component architecture**. This means we can build small, reusable pieces of code. For example, we built one `WagonForm` component, and we can use this same component for both 'creating a new wagon' and 'editing an old wagon'. This saves a lot of time and reduces bugs. We also used **TypeScript** instead of plain JavaScript. TypeScript adds 'types' to our code, which helps us catch many errors before we even run the application. For a big project like this, type safety is very important [46].

- **Styling with TailwindCSS:** For the visual design, we used **TailwindCSS**. This is a 'utility-first' CSS framework. Instead of writing separate CSS files, we build the design directly in our components. This made our development much faster and it let us create a custom, responsive design that looks good on both desktop and mobile, without being stuck with a heavy library like Bootstrap.

- **Routing:** To manage the different pages of our SPA, we used the **React Router** library. This library connects a URL (like `/dashboard`) to the correct React component (like our `Dashboard` page component).

3.4.2 State Management Strategy

A complex application needs to manage a lot of 'state'. State is all the data that can change, like the list of trains, or if a user is logged in. We divided our state into two types: Server State and Client State.

Server State with React Query

This was one of our most important design decisions. For all data that comes from our backend API, we used **React Query** (also known as TanStack Query). In older applications, developers would use 'Redux' or 'useState' to store this data, which is very complex and needs a lot of manual code.

React Query is a modern data-fetching library that is much simpler. It treats data from the API as 'server state' and it handles everything for us [47].

- **Caching:** When we fetch the list of trains, React Query saves it in a cache. If the user moves to another page and comes back, the list loads instantly from the cache, it doesn't need to ask the server again.

- **Automatic Updates:** The best feature is 'stale-while-revalidate'. This means it shows the old, cached data first (so the page is fast), but it still fetches new data in the background. When the new data arrives, it updates the page.

- **Mutations:** When we need to change data (like creating a new train with our `TrainForm`), we use a 'mutation'. We tell React Query to send the `POST` request to our API. After the mutation is successful, we can tell it to automatically 'invalidate' the cache for "all trains". This makes React Query fetch the list of trains again, so the user's new train appears in the list right away.

Using React Query made our component code much cleaner and simpler, and it made the application feel much faster to the user.

Client State with React Context

For the state that is not from the server, like "is the user currently logged in¿', we used React's built-in **Context API**. We created an `AuthContext`. This context wraps our entire application. When a user logs in, the `Login` page calls the API, gets the JWT token, and saves this token in the `AuthContext`. Now, any other component in the application can ask this context, "is the user authenticated¿'. This is how we manage security on the frontend.

3.4.3 Application Structure and User Workflow

The structure of our application is defined by its pages and components. The main application file defines all the available routes.

Security with Protected Routes

Security is the first step. We created a special component called `ProtectedRoute`. This component wraps all our main pages, like `/trains` and `/dashboard`. Before it shows the page, it checks our `AuthContext`. If the user is not authenticated, this component will immediately redirect the user to the `/login` page. This makes it impossible for an unauthorized person to see any of the asset data.

Main Pages and Functionality

Our application provides several key pages for the railway staff:

- **Login Page:** A simple form to send a username and password to our backend's `/token` endpoint to get a JWT.

- **Dashboard Page:** This is the main landing page. It shows a high-level overview of the entire system. We built several data visualization components here, like `PieChartByCountry`, which shows the distribution of asset manufacturers. We also have map components that can show the location of suppliers, which is useful for supply chain tracking.

- A screenshot of the main "Equipment" page is shown in Figure 3.3. This shows the main user interface for managing assets, including the list of equipment and the interactive map.

Figure 3.3. A screenshot of the main Equipment Management page in our system.

- **Asset Management Pages (`/trains, /wagons, /equipment`):** These are the main "work" pages. Each page shows a table or list of all the assets, fetched from our API using React Query. From here, a user can click a button to open a form (like `TrainForm` or `WagonForm`) to create a new asset or edit an existing one.

- **Detail Pages (`/equipment/:id`):** We also have detail pages for when a user needs more information. This page shows all the details for one single piece of equipment, and it might also fetch and show the parent wagon and train that it belongs to.

As shown in Figure 3.4, the detail page provides a full summary of the component. A key feature we implemented is the QR code. A mechanic can scan this label to find the exact location of a broken part inside the wagon, using our schematic addressing format. This page is also designed to be printable, so it can act as a physical maintenance paper or "work order" for a mechanic who is going to fix the part.
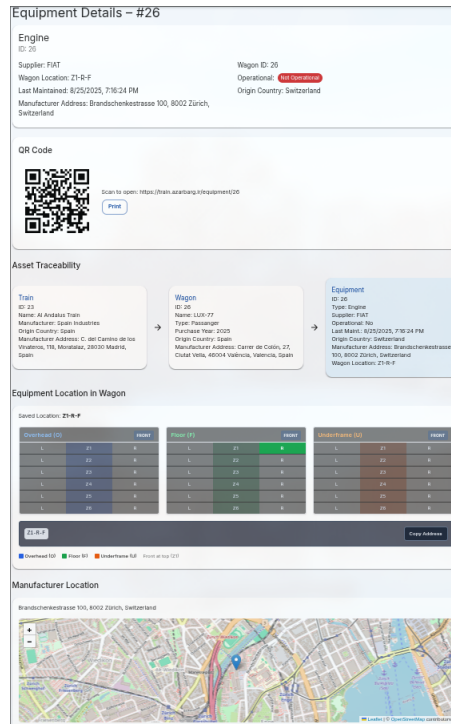
Figure 3.4.   A screenshot of the Equipment Detail page. This page shows all asset data, the parent train and wagon, and a QR code for location tracking and printing.

Example Maintenance Workflow

We can describe a full workflow for a user:

1. A maintenance mechanic logs in on the **Login Page**. The app saves their token in the `AuthContext`.

2. They are sent to the **Dashboard**. They see a chart that shows "5 pieces of equipment are not operational".

3. They click on the **Equipment Page**. The page uses React Query to call our backend `GET /v1/equipment` and shows a list of all equipment. The mechanic filters this list to see the broken parts.

4. They find the broken part (e.g., 'Brake Unit 105') and go to the train to fix it.

5. After fixing it, they come back to the app and click 'Edit' on that part.

6. The app opens the `EquipmentForm` component, filled with the data for 'Brake Unit 105'.

7. The mechanic changes the `isOperational` status from 'false' to 'true' and clicks 'Save'.

8. The app uses a React Query 'mutation' to send a `PUT /v1/equipment/105` request to our backend.

9. The backend validates the request, sends the transaction to the blockchain, and when it is confirmed, it sends "Success" back to the frontend.

10. The mutation is successful, so React Query automatically refetches the equipment list. The list updates, and 'Brake Unit 105' now shows its status as 'Operational'.

For example, as seen in the screenshot, a location code of `Z3-L-F` means the part is in "Zone 3, on the Left side, at Floor level". This simple, standardized code makes it very efficient for a mechanic to find a specific component inside a complex train wagon. A screenshot of this edit form is shown in Figure 3.5. This form allows the user to update all the key information for the asset, including its maintenance status and its specific physical location inside the wagon.

We designed a special schematic addressing format for the `locationCode` to help mechanics find parts much faster. This code is stored in the smart contract and is a key part of our system. The format is `Z{zone}-(L|R)-(O|F|U)`.

- `Z` stands for the Zone (e.g., Z1, Z2, Z3...).

- `L|R` stands for the side (Left or Right).

- `O|F|U` stands for the vertical level (Overhead, Floor, or Underframe).

Figure 3.5. A screenshot of the "Edit Equipment" form in our application. This shows the fields for updating maintenance status and the schematic location code.

3.4.4 Progressive Web App (PWA) for Mobile Access

A very important part of our project is supporting mobile users. A railway mechanic or inspector is not always at a desk. They are in the field, in a maintenance yard, or even in a tunnel where the internet connection is bad. They cannot depend on a normal website.

To solve this, we built our frontend as a **Progressive Web App (PWA)**. A PWA is a website that can be "installed" on a user's phone (Android or iOS) or desktop, just like a native app from the App Store. This gives us the best of both worlds: we have one codebase (our React app) that works on all platforms. This is a very common strategy in modern enterprise applications [48].

We implemented this using two key files:

- **manifest.json:** This is a simple JSON file that tells the phone's operating system about our application. It defines the app's name ("Train Inventory"), and its theme colors. This is what allows the "Add to Home Screen" prompt to appear.

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- **service-worker.js:** This is the "brain" of the PWA. A service worker is a special script that the browser runs in the background, separate from the web page. We configured our service worker to do **offline caching**. When the user first loads the app, the service worker saves all the main application files (the HTML, CSS, and JavaScript) to the device.

This provides a huge benefit: **Offline Access**. If a mechanic opens the app on their phone in an area with no internet, the service worker will still load the application "shell" from the cache. The user can still open the app, see the layout, and maybe even see the data that was cached the last time they were online. This makes the application much more reliable for real-world use [49]. This offline capability is a key feature that makes our solution much more practical than a standard website.

Chapter 4

Experimental Evaluation

In the previous chapters, we presented the design and implementation of our hybrid blockchain system for railway asset tracking. However, a theoretical design is not sufficient to prove the viability of a system in an industrial context. To validate that our solution is practical, cost-effective, and performant, we conducted a rigorous series of experimental evaluations.

The goal of this chapter is to measure the concrete trade-offs of our architecture. We specifically aim to answer three research questions:

1. **Economic Viability:** Does our optimized smart contract actually save money compared to a standard implementation?

2. **System Performance:** Does the hybrid architecture provide a fast enough response time for a real-world user, despite the latency of the blockchain?

3. **Usability:** Does the Progressive Web App (PWA) perform well on mobile devices with limited resources?

4.1 Methodology and Experimental Setup

To ensure that our results are reliable and reproducible, we established a controlled testing environment that mirrors a real-world production scenario. This section details the hardware, software, and procedural methodologies used in our experiments.

4.1.1 Hardware and Cloud Infrastructure

We separated our environment into two distinct contexts: the **Production Simulation Environment** (hosting the backend and frontend) and the **Development Environment** (executing tests and compiling contracts).

Server Environment (Production Simulation)

For the server-side deployment, we utilized a cloud-based Virtual Private Server (VPS) provided by Hetzner Cloud (Model CX22). This choice was deliberate; it represents a

cost-effective, scalable cloud node that a mid-sized railway operator might use to host the middleware. We avoided using a high-end, expensive server to demonstrate that our middleware is efficient and lightweight.

The specific hardware configuration, verified via the Linux `/proc/cpuinfo` and `/proc/meminfo` system files, is detailed in Table 4.1.

Table 4.1.   Production Server Specifications (Hetzner CX22)

Parameter	Specification
Processor Model	Intel Xeon Processor (Skylake, IBRS)
Clock Speed	2.10 GHz
CPU Architecture	x86_64 (64-bit)
vCPUs	2 Physical Cores (Siblings: 2)
L3 Cache	16384 KB
Total Memory (RAM)	4 GB (3.91 GB Available)
Storage	40 GB NVMe SSD
Operating System	Ubuntu Linux (Dockerized)

All application components on this server (FastAPI backend, React frontend, Nginx reverse proxy, and SQLite database) were orchestrated using **Docker**. This containerization ensures that the performance metrics we captured are isolated from external system noise.

Local Development Environment

The "heavy lifting" of compiling the smart contracts and running the automated Hardhat test suites was performed on a high-performance local workstation.

- **Machine:** ASUS Zenbook 14 OLED (Q425MA)

- **Processor:** Intel Core Ultra 7 155H (High-performance mobile processor)

- **Role:** Execution of the gas comparison scripts and local simulation of blockchain transactions.

4.1.2   Blockchain Network Configuration

For the decentralized component, we utilized the **Sepolia Testnet**. Sepolia is currently the primary recommended test network for Ethereum application development. It operates using the same **Proof-of-Stake (PoS)** consensus mechanism and the same Ethereum Virtual Machine (EVM) rules as the Ethereum Mainnet.

This choice is critical for our methodology:

1. **Realistic Execution:** Because Sepolia is a public, distributed network, the latency we measure for transaction confirmation (block mining times) is realistic and comparable to the Mainnet.

2. **Accurate Gas Measurement:** The gas units consumed by a function on Sepolia are identical to the gas units that would be consumed on Mainnet, allowing us to project real-world costs accurately.

To connect our middleware to this network, we used **Alchemy** as our Remote Procedure Call (RPC) provider. Alchemy acts as our gateway to the blockchain, allowing our backend to submit signed transactions without needing to run a full Ethereum node, which would require terabytes of storage.

4.1.3   Procedure for Gas Cost Comparison

One of the core contributions of this thesis is the optimization of the smart contract for gas efficiency. To scientifically prove that our optimization strategies worked, we devised a **comparative experiment**.

It is not sufficient to simply measure our contract's cost. We need a baseline to compare it against. Therefore, we developed a secondary contract specifically for this experiment, which we named the **"Naive Contract"**.

The "Naive" Baseline vs. The "Optimized" Solution

We created the "Naive" contract by taking our final system and systematically removing the optimizations we discussed in Chapter 3. This represents how an inexperienced developer might write the system using standard defaults.

The differences are detailed below:

1. **Data Types (Storage):**

   - *Naive:* Used `uint256` for all IDs and timestamps. This is the default type in Solidity but takes up a full 32-byte storage slot for every variable.
   - *Optimized:* Used `uint32` for IDs and timestamps. This allows Solidity to "pack" multiple variables (e.g., an ID, a timestamp, and a boolean) into a single storage slot. Since writing to storage is the most expensive operation in Ethereum, this should theoretically reduce costs.

2. **Error Handling:**

   - *Naive:* Used `require()` statements with long string messages (e.g., `require(x, "Train not found")`). Storing and processing these strings costs gas.
   - *Optimized:* Used `custom errors` (e.g., `error NotFound()`). This feature, introduced in Solidity 0.8.4, is much cheaper as it only returns a 4-byte selector code.

Execution Script

We wrote an automated script using the **Hardhat** framework. This script performs the following steps automatically to ensure a fair test:

1. Deploy the `RailwayAssetRegistryNaive` contract.

2. Deploy the `RailwayAssetRegistry` (Optimized) contract.

3. Execute the **exact same sequence** of four transactions on both contracts:

   - `addTrain`: Creating a parent asset.
   - `addWagon`: Creating a child asset (triggers index updates).
   - `addEquipment`: Creating a grandchild asset (triggers heavy storage writing).
   - `updateEquipment`: Modifying the status (the most common maintenance task).

4. Capture the `gasUsed` field from the transaction receipt for every call.

This methodology gives us a precise, side-by-side comparison of the "Gas Units" consumed by each approach.

4.2 Numerical Results: Smart Contract Evaluation

This section presents the quantitative results of our gas efficiency experiments. We first present the raw gas usage data and then perform an economic analysis to project these costs into real-world currency (USD/EUR).

4.2.1 Gas Consumption Comparison

Table 4.2 presents the direct output of our Hardhat comparison script. The values represent "Gas Units," which is the measure of computational work required by the Ethereum network.

Table 4.2.   Experimental Gas Comparison: Naive vs. Optimized Contract

Function	Naive (Gas Units)	Optimized (Gas Units)	Savings
`addTrain`	272,502	273,072	0.00%
`addWagon`	499,453	**460,450**	**7.00%**
`addEquipment`	387,053	**326,530**	**15.00%**
`updateEquipment`	55,070	55,745	-1.00%

Technical Analysis of Gas Results

The results provide a fascinating insight into the behavior of the Ethereum Virtual Machine (EVM):

- **Significant Savings in Asset Creation:** The most successful result is for `addEquipment`, where we achieved a **15% reduction** in gas costs. `addWagon` also showed a strong **7% reduction**. This confirms that our "struct packing" strategy is highly effective. When creating a new asset, we are writing many fields to storage. By packing

`uint32` variables together, we reduced the number of storage slots (SSTORE operations) required. Since SSTORE is the most expensive opcode (20,000 gas), this leads to massive savings.

- **The "Unpacking" Overhead:** Interestingly, for `addTrain` and `updateEquipment`, the costs are almost identical, or slightly higher (by 1%) in the optimized version. This is a known trade-off. While `uint32` saves storage space, the CPU must do extra work to "unpack" and "mask" these bits when reading them or performing math on them. For simple operations where we are not saving a whole storage slot, this CPU overhead cancels out the storage savings.

- **Conclusion:** The optimization is a success because **scale matters**. A railway system has few Trains, but thousands of Wagons and tens of thousands of Equipment parts. Achieving 15% savings on the most numerous asset (Equipment) is far more valuable than losing 1% on the rarest asset (Trains).

4.2.2 Economic Feasibility and Cost Projection

Gas units are abstract. To prove to a railway stakeholder that this system is economically viable, we must convert these units into money.

The price of a transaction depends on the "Gas Price" of the network, measured in Gwei (10^{-9} ETH). This price fluctuates wildly based on network demand. To give a fair evaluation, we projected the costs in two scenarios:

1. **Ethereum Mainnet Scenario:** Assuming a standard gas price of **20 Gwei**. This represents the "premium" option of using the most secure public blockchain in the world.

2. **Layer 2 (L2) Scenario:** Assuming a deployment on an L2 network like Optimism or Base, or a private consortium chain. Gas prices here are typically **0.1 Gwei** or less.

Assumption: 1 ETH = $3,000 USD.

Table 4.3. Projected Operational Costs in USD (Optimized Contract)

Function	Gas Used	Mainnet Cost ($) @ 20 Gwei	Layer 2 Cost ($) @ 0.1 Gwei
`addTrain`	273,072	$16.38	$0.08
`addWagon`	460,450	$27.62	$0.14
`addEquipment`	326,530	$19.59	$0.10
`updateEquipment`	**55,745**	**$3.34**	**$0.016**

Discussion of Economic Viability

Table 4.3 reveals the critical importance of our hybrid architecture and optimization.

- **The "Setup" Cost:** Adding a new Train or Wagon is relatively expensive on Mainnet (\$16 - \$27). However, this is a **one-time event** in the asset's life. For a railway wagon that costs \$100,000+ and lasts 30 years, paying \$27 to register its immutable "birth certificate" is a negligible capital expense.

- **The "Maintenance" Cost:** The `updateEquipment` function is the one that will be called most often (e.g., every few months).

  - On **Mainnet**, it costs **\$3.34**. This might be acceptable for major safety checks, but perhaps too expensive for daily logs.
  - On **Layer 2**, it costs **\$0.016** (1.6 cents). This is extremely cheap. At this price, a company could record thousands of maintenance events per day for the price of a cup of coffee.

- **The Value of Optimization:** Let's look at the savings for `addEquipment` on Mainnet.

  - *Naive Cost:* 387,053 gas × 20 Gwei ≈ \$23.22
  - *Optimized Cost:* 326,530 gas × 20 Gwei ≈ \$19.59
  - **Savings per Unit:** \$3.63.

If a train has 2,000 pieces of equipment, our code optimization saves the operator **\$7,260 per train** during the registration phase. This proves that our technical decisions in Chapter 3 have a direct, measurable financial impact.

4.3 System Performance: API Latency

To evaluate the user experience and the effectiveness of our hybrid middleware, we measured the "Round Trip Time" (RTT) for key API operations. This metric measures the total time from the moment the user clicks a button in the frontend until the operation is complete and the data is visible.

We categorized operations into two types:

- **Off-Chain / Read Operations:** These interact only with the backend database or read from the blockchain cache. We expect these to be responsive (< 1 second).

- **On-Chain / Write Operations:** These involve sending a signed transaction to the Sepolia network. We expect these to be slower, dictated by the blockchain's block time (12-15 seconds).

4.3.1 Latency Measurements

The following measurements were captured using the Google Chrome Developer Tools (Network Tab) connected to our production VPS.

Authentication (Off-Chain Write)

Figure 4.1 shows the response time for the user login process (`POST /token`). This operation involves receiving the credentials, securely hashing the password (which is computationally intensive by design), verifying it against the SQLite database, and issuing a JWT token.

Figure 4.1.   Network analysis of the Login request. The operation completed in **727 ms**, which is a standard acceptable time for a secure authentication handshake.

Data Retrieval (On-Chain Read)

Figure 4.2 displays the time required to fetch the full list of assets (`GET /trains`). Although this data originates from the smart contract, our middleware efficiently queries the node.

Figure 4.2.   Network analysis of a Read operation. The system retrieved the asset list in **255 ms**, confirming high performance for data retrieval.

Asset Creation (On-Chain Write)

Figure 4.3 illustrates the cost of immutability. This request (`POST /wagons`) triggers a blockchain transaction. The backend waits for the transaction to be mined before responding.

Name	Status	Type	Initiator	Size	Time
<> update-train	200	xhr	api.ts:104	0.4 kB	13.72 s
<> trains/	200	xhr	api.ts:74	(ServiceWorker)	307 ms
<> ⊕ trains/	200	fetch	service-worker.js:51	0.6 kB	305 ms
data:image/gif;base...	200	gif	TileLayer.js:269	(memory cache)	0 ms
<> search?format=json&q=23%20Bd%20de%20Cimiez%2C%2006000%20Nice%2C%20France	200	fetch	geocode.ts:14	(ServiceWorker)	400 ms

Figure 4.3. Network analysis of a Write operation. The request took **13.72 s**, which corresponds to the block confirmation time of the Sepolia network.

4.3.2 Discussion of Latency Results

The results confirm the validity of our hybrid architecture.

- **Fast Reads:** The data retrieval operation (Figure 4.2) is extremely fast (255 ms). This proves that for the majority of user interactions (viewing dashboards, listing assets), the system performs with the speed of a standard web application.

- **Secure Writes:** The write operation (Figure 4.3) shows a latency of 13.72 seconds. This is the expected trade-off. While slower than a standard database, this delay represents the time required to gain **global, immutable consensus** on the asset's state. In a maintenance context, waiting roughly 14 seconds to permanently secure a safety-critical record is an acceptable operational cost.

4.4 Frontend Evaluation: PWA and Usability

The final pillar of our evaluation focuses on the "User Experience" gap. To verify that our application serves the needs of mobile railway mechanics, we evaluated its **Progressive Web App (PWA)** capabilities.

A successful PWA must satisfy two technical requirements:

1. **Offline Capability:** It must register a "Service Worker" to cache assets and load without a network connection.

2. **Installability:** It must provide a valid "Web App Manifest" so the operating system recognizes it as a native-like application.

4.4.1 PWA Technical Verification

We verified the PWA implementation using the Google Chrome Developer Tools "Application" audit.

Service Worker Registration

Figure 4.4 shows the active status of our Service Worker. The status "Activated and is running" confirms that the browser has successfully installed the script 'service-worker.js'. This script intercepts network requests and serves the cached "Application Shell" (HTML,

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CSS, JS) when the device is offline, satisfying our requirement for remote access in tunnels or dead zones.
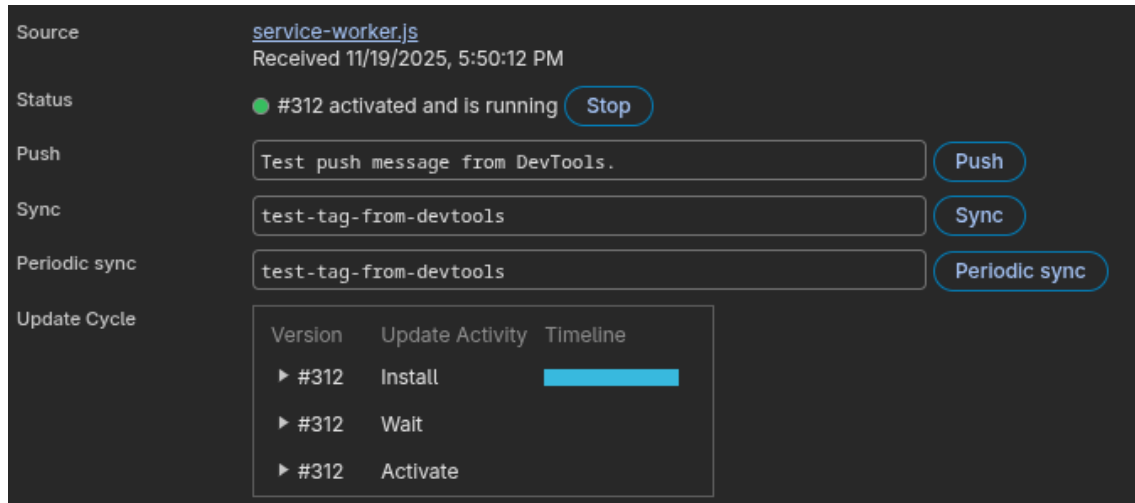

Figure 4.4. Verification of the Service Worker in Chrome DevTools. The "Activated" status proves that the offline caching logic is running in the background.

Manifest and Installability

Figure 4.5 displays the parsed Web App Manifest. The browser successfully detects the application name ("Train Inventory"), the theme colors, and the icon set. This valid manifest triggers the "Add to Home Screen" prompt on Android and iOS devices, allowing mechanics to install the tool alongside their native apps.
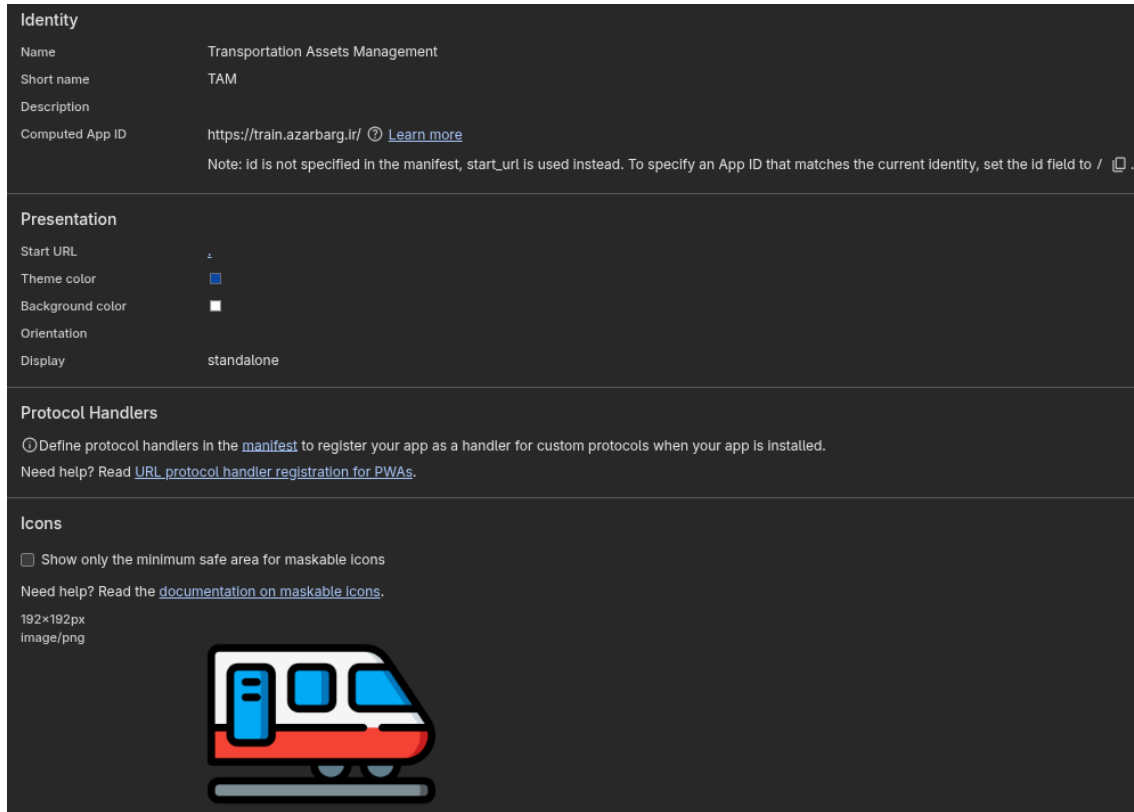
Figure 4.5. The Web App Manifest configuration detected by the browser. This ensures the application provides a native-like experience with proper icons and full-screen display modes.

4.4.2 Lighthouse Quality Audit

In addition to the manual verification, we performed an automated audit using Google Lighthouse to ensure general code quality and accessibility.

The system achieved the following scores:

- **Accessibility: 98/100**. This near-perfect score ensures that the application is usable by staff with varying needs, including high-contrast visibility for outdoor work.

- **Best Practices: 96/100**. This indicates the code follows modern security and performance standards (e.g., using HTTPS, avoiding deprecated APIs).

- **Performance: 76/100**. While the First Contentful Paint (FCP) was fast (1.3s), the overall score reflects the heavy nature of a full Single Page Application loaded on a mobile simulation. This is an acceptable trade-off for the rich functionality provided.

4.4.3   Conclusion of Evaluation

The combined results from the API latency tests and the PWA verification confirm that our system is:

1. **Technically Sound:** It correctly handles the "Offline" constraints of a railway environment.

2. **User Ready:** It provides a fast, installable interface that abstracts away the complexity of the underlying blockchain interactions.

Chapter 5

Conclusion

5.1 Summary of the Thesis

This thesis project started with a clear and serious problem. As we discussed in our Introduction in Chapter 1, the railway industry is a safety-critical part of our economy. It depends on managing a huge inventory of complex assets. The traditional systems used for this asset management are often old, centralized, and not connected to each other. This creates "data silos," where different stakeholders (like operators, maintenance crews, and part suppliers) cannot share information. This leads to a fundamental lack of trust, transparency, and data integrity. These problems are not just about inefficiency; they create serious risks for safety and cost the industry a lot of money.

Our goal was to design and build a modern system to solve this. We wanted to create a single, shared, and trusted source of truth for all asset data and maintenance records.

To understand how to build this, we first did a deep review of the academic literature in Chapter 2. This review showed two main things. First, we confirmed that the problems in the railway industry are real and well-known, and many researchers are trying to find better, data-driven solutions. Second, we saw that blockchain technology is a very powerful tool for creating trust, transparency, and immutability, and it is used in many other industries (like food, pharma, and shipping) for asset tracking.

However, our literature review found three major "gaps" in the existing research for the railway industry:

1. **A Gap Between Theory and Practice:** Most of the existing papers are only "conceptual frameworks". They propose high-level models but do not show a full, working, end-to-end implementation.

2. **A Lack of Focus on the User:** The research was "technology-centric" and ignored the real-world user. We found no research that designed a system for the *mobile mechanic*, who needs a simple, fast application that can work in a railyard with a bad internet connection.

3. **A Naive Architecture:** Many papers did not have a good solution for the high cost, slow speed, and big privacy problems of storing *all* data on a public blockchain.

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The main goal of this thesis, therefore, was to fill these specific gaps. We did not want to write another theoretical paper. We wanted to design, build, and evaluate a **complete, full-stack, and practical prototype** that solves all three of these problems at the same time.

5.2   Analysis of the Contribution

In Chapter 3, we presented the main contribution of this thesis: our **3-tier hybrid architecture**. This system is a complete, working solution that intelligently balances the trade-offs between decentralization and practicality. Our contribution is the design and implementation of all three layers, which work together to create a single, cohesive application.

First, we built the Data Layer. This is our `RailwayAssetRegistry` smart contract. We wrote it in Solidity and deployed it on the Sepolia testnet. This is the "on-chain" heart of our system. It solves the problem of "trust" and "data integrity".

- We designed a clear, hierarchical data structure (`Train` → `Wagon` → `Equipment`) that models the real-world relationships.

- We implemented a strong "soft-delete" and "undelete" logic, which is very important for an auditable system where you should never permanently destroy a record.

- We built efficient storage and search indexes. We used `keccak256` hashing for our inverted indexes (`_wagonsByName`, `_wagonsByType`) and used the OpenZeppelin `EnumerableSet` library to manage our relational mappings (`_wagonsByTrain`).

- We made it gas-efficient by using `uint32` for IDs and modern features like `custom errors` instead of long string messages.

This smart contract is our "immutable ledger" and acts as the single source of truth for all asset data.

Second, we built the Logic Layer. This is our **backend API**, which we wrote in Python using the FastAPI framework. This backend is the "middleware" or "orchestrator" of our system. This layer is our answer to the "naive architecture" gap.

- It creates our **hybrid model**. It manages all "off-chain" data, like user accounts, emails, and hashed passwords, in a private and fast SQLite database. This solves the privacy and security problem.

- It is the only part of the system that talks to the blockchain. It holds the server's private key and manages all the complex `web3.py` calls. This makes the system very secure and very simple for the user.

- It provides a fast, modern REST API for the frontend, and it handles all user authentication using **JWT tokens**.

This backend layer is the "bridge" that connects a normal, user-friendly web application to the complex, decentralized blockchain world.

Third, we built the Presentation Layer. This is our **frontend application**, which we built with React and TypeScript. This layer is our answer to the "User Experience (UX)" gap.

- We focused on a clean, component-based design using `TailwindCSS`.

- We used modern state management with **React Query**. This makes the app feel very fast by caching data and updating it in the background ("stale-while-revalidate").

- Most important, we built it as a **Progressive Web App (PWA)**. This is a critical feature for our target user. A mechanic can "install" our application on their mobile phone, and the PWA's `service-worker` provides offline caching. This means the app will still load in a railyard or a tunnel with no internet.

This PWA, with its maps, charts, and simple forms (as shown in our screenshots in Chapter 3), proves that a complex blockchain system can be made simple and practical for a non-technical user.

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