AI-Driven Generative Design & Blockchain-Enabled Collaboration for Sustainable Smart Cities

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Abstract

This report introduces an innovative AI-powered smart city platform that combines generative AI, machine learning (ML), and Blockchain technologies to transform the urban planning process. The platform is designed to automate and optimize the development of sustainable urban layouts, supporting eco-friendly, energy efficient, and regulatory compliant urban plans. Through the combination of real-time data simulation, intelligent design generation, and blockchain enabled transparency, the system provides a complete tool set for architects, city planners, and stakeholders to collaboratively create smart cities. This platform is a generative AI model that can produce urban layouts that respect zoning regulations, topographic constraints, and climate considerations. These initial designs are evaluated using ML algorithms to ensure they meet energy efficiency goals.

In addition to its technical foundation, the platform highlights inclusive and user-friendly participation. The interface, powered by natural language processing, enables technical and non-technical users, such as citizens and government officials, to engage with the system meaningfully. Real-time feedback mechanisms allow users to explore options, ask questions, and contribute to the decision-making process. Finally, this project delivers a scalable, data-driven solution that improves the sustainability, efficiency, and transparency of urban development.

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List of Abbreviations

- ML – Machine Learning
- GAN – Generative Adversarial Network
- RL – Reinforcement Learning
- FEA – Finite Element Analysis
- LEED – Leadership in Energy and Environmental Design
- BIM – Building Information Modeling
- IPFS – InterPlanetary File System
- GIS – Geographic Information System
- SUS – System Usability Score
- API – Application Programming Interface
- OOP – Object-Oriented Programming
- SVM – Support Vector Machine
- RMSE – Root Mean Square Error
- MAPE – Mean Absolute Percentage Error
- NLP – Natural Language Processing
- SHP – Shape File Format (GIS)
- SRTM – Shuttle Radar Topography Mission
- ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer
- IDE – Integrated Development Environment
- UML – Unified Modeling Language

Chapter 1

Problem

1.1 Chapter Overview

Traditional urban design processes are often time consuming, fragmented and lack transparency for stakeholders. This project proposes an innovative solution combining with Generative AI, Machine Learning and Blockchain to automate the process for a sustainable smart city design. In this project, mainly focus to creating AI generate sustainable city designs for Sri Lankan cities. This chapter introduce the background of problems, motivations, challenges and existing gaps within the domain of sustainable smart city design.

1.2 Problem Background/ Problem Domain

As a result of rapid urbanization and the growing threat of climate changes, sustainable city development has become a major priority in the world. Traditional urban planning is manual, time consuming and has limited access to real time data or analytical feedback. These traditional methods aren't suitable for the complexity and scale of modern urban designs. Modern cities must be sustainable and efficient in Sri Lanka. Moreover, the problem domain intersects with architecture, engineering, environmental science and governance. However, current tools and processes fail to facilitate modern sustainable city designs leading to miscommunication, lack of accountability and poor decision making. Modern urban planning requires technologically advanced, automated, transparent systems and long-term valid designs. This requires AI-Driven generative design and blockchain-enabled collaboration innovations.

1.3 Problem Definition

The challenges of modern sustainable city development are increasing due to the rapid urbanization, increasing regulatory requirements and environmental sustainability. Current city planning processes are typically manual and iterative, most of the time there are project delays and inconsistent compliance with sustainability standards. Collaboration tends to occur between key stakeholders such as architects, engineers, urban planners and government authorities, leading to a lack of transparency and accountability in decision-making. Because of those limitations, the ability to design and implement smart, sustainable and environmentally friendly cities through traditional city planning methods is limited. There is a clear need for AI-Driven generative system that can automate planning and enable secure and transparent collaboration with all stakeholders that involved in the sustainable urban development process.

1.3.1 Problem Statement

Current traditional urban planning is manual, inefficient, lack transparency, not consider about climate and environmental changes and do not effectively balance creativity and sustainability in Sri Lanka.

1.4 Motivation

The urban development is an urgent global need to develop with sustainable, intelligent urban environments. When cities continuously grow, traditional urban planning approaches fall short in addressing the environmental, social and infrastructural challenges of modern urbanization. Manual city planning processes are not only time wasting but also lack the integration of data-driven insights, innovative technologies, and collaborative decision-making mechanisms. Those are motivated to innovate a solution combines with Generative AI, Machine Learning (ML), and Blockchain to automate sustainable architectural design.

1.4.1 Benefits

By combining those technologies into a single platform, this project aims to contribute toward building smarter cities. There are some key benefits of this project:

- Faster and More Efficient Urban Design Generation

  The integration of Generative AI enables automated urban layout generation, greatly reducing design time compared to traditional manual methods. This leads to faster project initiation, planning, and implementation, ultimately accelerating smart city development.

- Sustainable and Compliant Urban Layouts

  AI models create eco-friendly urban layouts that adhere to sustainability goals such as energy efficiency, green space optimization, and climate resilience. These plans ensure compliance with local zoning laws, LEED, and BREEAM standards, promoting eco-friendly infrastructure.

- Improved Stakeholder Engagement and Transparency

  By integrating blockchain technology, the system ensures secure and transparent records of all design interactions, approvals, and modifications. This fosters trust and collaboration among stakeholders, ensuring fair decision-making and accountability throughout the urban planning process.

- Risk Mitigation with Structural and Energy Validation

  Machine learning models, coupled with Finite Element Analysis (FEA), assess the structural integrity of urban layouts, ensuring designs are safe. At the same time, energy consumption is validated to optimize sustainability, reducing the risk of inefficient or unsafe designs that could cause future problems.

- Scalable and Adaptable Framework for Future Needs

  Modular design of the platform and use of cutting-edge technologies (AI, ML, and Blockchain) ensure scalability. New features, such as real-time data feeds or smart city integrations, can be added seamlessly, making the platform future-proof and adaptable according to urban planning needs.

- Cost-Effective and Reducing Manual Effort

  By automating design generation and validation processes, the platform reduces the need for manual interaction, reduces labor costs and minimizes errors. The use of AI and ML eliminates repetitive tasks that typically occur in urban planning, allowing resources to be reallocated to higher-value activities.

- Data-Driven Decision-Making Based on AI and Real-Time Simulations

  The platform enables real-time feedback and data-driven decision-making, powered by AI simulations. Planners can instantly visualize and test different design scenarios, ensuring that decisions are informed by accurate, data-driven insights instead of assumptions or guesswork.

- Environmental Impact Reduction

  Through the use of sustainable urban design, green spaces, and energy-efficient building models, this project helps cities reduce carbon emissions and energy consumption, contribute to a greener, more environmentally friendly urban landscape, and achieve global sustainability goals.

1.5 Existing Work

Several research efforts to explore uses of emerging technologies such as Artificial Intelligence, Machine Learning, and Blockchain in the context of sustainable urban planning process in the world. However, most studies focus on isolated components of generative modeling, validation, or compliance tracking rather than a fully integrated framework. The table below summarizes the main tasks, contributions, and limitations currently being implemented for smart city planning.

Table 1.1: Summary of Existing Work in Smart City Planning

Citation	**Summary**	**Limitation**	**Contribution**
Zhao et al., 2021	Proposed a GAN-based model to generate green urban layouts using spatial and environmental constraints.	Lacks integration with regulatory codes and multi-stakeholder collaboration.	Demonstrated potential of generative models for sustainable city design.
Li et al., 2020	Developed an ML-based validation system for smart building compliance with energy efficiency standards.	Focused only on buildings, not broader urban infrastructure or collaborative planning.	Provided insight into real-time validation using historical energy datasets.
Nawari & Kuenstle, 2019	Explored blockchain for digital building permits and compliance tracking.	Did not integrate with design or AI systems; limited scalability.	Highlighted blockchain's potential in accountability and transparency in construction workflows.
Shin et al., 2022	Presented a 3D urban simulation platform using Unity for citizen participation.	Lacked backend AI or blockchain integration; only focused on visualization.	Enhanced urban visualization for stakeholder engagement.
Zhou et al., 2021	Proposed a decentralized BIM system using IPFS and blockchain.	Focused on construction phase, not conceptual urban design.	Showed feasibility of decentralized storage and smart contracts for managing design documents.

1.6 Research Gap

Despite significant development in artificial intelligence (AI), machine learning (ML), and Blockchain technologies, there is a clear gap in integrating these technologies into a unified platform for sustainable smart city planning, especially in Sri Lanka. Most existing research focuses on isolated, specific components such as layout generation, conformance validation, or stakeholder coordination. However, only a few studies present a comprehensive framework that integrates all three elements in a functional real-world application.

- Lack of Integrated Platforms for Generative Design, Validation, and Collaboration

  Current tools usually specialize for only one of these areas in the urban plan workflow. So, can justify the urban planners need strong platforms that validate performances and integrate and coordinate stakeholders in real time.

- Limited AI Use Beyond Visualization and Simulation

  Second gap discuss about limitation of the AI usage. Weather, some research has demonstrated the ability to generate urban plans using AI, these technologies often ignore the legal and sustainable constraints required for practical implementation. Traditional construction planners rarely incorporate zoning laws, energy efficiency guidelines, or local climate conditions into the design generation process.

- Lack of AI-Assisted, Real-Time Regulatory Compliance.

  Another gap is about lack of real-time AI- Assisted Regulatory Compliance. In most models performed as offline or after the design phase, which leads to delays. Delivering ML-driven validation directly into design systems could reduce compliance errors and accelerate decision making.

- Insufficient Use of Blockchain in Conceptual Planning Phases

  Blockchain technology is often used only in post-design or construction phases, such as tracking permits or keeping records. Stakeholder input, design approval, and version control are required, not just during implementation, but also from the start, with secure logging.

- Limited Stakeholder Accessibility for Non-Technical Users

  Many current systems assume that users have technical expertise, but important decision-makers, such as government officials or community leaders, are excluded. A natural language interface and accessible frontend can enable wider participation and trust.

1.7 Contribution to Body of Knowledge

1.7.1 Contribution to Problem Domain

Contribution 1: Development of an Integrated Platform This project proposes the creation of a platform that uses AI to automate sustainable urban planning, compliance validation and stakeholder governance. The combination of generative AI with regulatory datasets and validation mechanisms addresses inefficiencies in current urban planning processes.

Contribution 2: Transparent and Accountable Stakeholder Collaboration
The project introduces a mechanism to record stakeholder's actions in real time, transparently with trust and evidence, through the implementation of the permission blockchain technology. It ensures accountability and improves transparency in decision making with key stakeholders in urban planning projects.

1.7.2 Contribution to Research Domain

Contribution 1: Interdisciplinary integration of AI, ML and Blockchain
This research contributes to the smart city planning project by integrating generative AI, machine learning validation models, and blockchain mechanisms. This combination has not been thoroughly explored in Sri Lanka before. Also, it can serve this as a blueprint for future smart city planning projects, offering high performance and enhanced security.

Contribution 2: Application of Generative AI in Urban Design
This research involves advanced generative models for developing sustainable smart city layouts using inputs such as climate data, zoning laws and energy goals. AI has been explored in several platforms, which is a new experience for urban environments and city planning projects in Sri Lanka. This contribution of developing an application (flutter) can solve most of the issues in smart city planning projects. Moreover, it becomes a guide for the future smart city planning platform in Sri Lanka.

1.8 Research Challenge

• Difficulty in Integrating Multi modal Datasets for AI generated Urban Design

One of the major challenges is collecting divers, location specific and high-quality datasets needed for training AI models in urban design. To develop a model that can generate smart city plans, essential datasets include climate data, geographical maps, zoning regulations, building footprints and structural data.

• Validation of AI-Generated Designs Against Engineering and Environmental Standards

Measurable engineering terms are needed to validate AI-generated urban plans with legal standards. Machine learning validation models must be trained on different types of urban scenarios with engineering and environmental standards.

• Blockchain-Backed Collaborative Governance in Urban Planning

In urban design models, integrating blockchain technology for stakeholder collaboration presents challenges related to scalability, data storage and legal validation. Storing and verifying large architectural files and as well as tracking complex multi-stakeholder approvals within a blockchain environment remains a significant challenge.

1.8.1 Research Questions

1. How can generative AI models be designed to produce sustainable urban layouts using datasets?
2. What machine learning validation methods can be employed to access the environmental and structural compliance of AI-generated urban plans?
3. Using blockchain technology, how can integrated into the urban design to ensure transparent, trust, and accountable stakeholder collaboration?

1.9 Research Aim

The aim of this research is to design and develop an integrated platform that leverages generative AI, machine learning, and blockchain technology to automate sustainable smart city planning in Sri Lanka. The research seeks to validate AI-generated designs against engineering and environmental standards while enabling secure and transparent collaboration among key stakeholders involved in urban planning. Addresses limitations in traditional city planning by proposing AI-driven automated designs, reinforced with validation models and blockchain-based governance. The ultimate goal is to create a secure, trustworthy, transparent, and high-performance platform to develop sustainable urban plans in Sri Lanka.

1.10 Research Objectives

1. **Develop a generative AI model for sustainable urban layout generation**

   The main objective of the project is to develop a generative AI model for the generation of sustainable urban layouts. This project focuses on creating urban designs optimize space utilization, carbon footprint, and energy efficiency. The system wants to produce at least ten unique designs based on input datasets such as, zoning laws, topographical data, and climate patterns. The model will develop advanced generative methods, and diffusion models, combined with available AI development frameworks such as PyTorch. The final outcome aims to support planners in developing sustainable and creative urban plans. This task is expected to be completed within two months of the project timeline.

2. **Train ML models for validating generated designs against structural, environmental, and legal constraints.**

   The second project objective involves training Machine Learning models to validate AI generated designs. These models will assess the layouts for structural, environmental, and legal constraints. The validation includes predictions related to energy efficiency, zoning compliance and structural safety. The model will be trained using datasets like, climate conditions, geographical mappings, historical records. The models are predicted to achieve at least 85% accuracy in validation tasks. Also, model training will be ensured safety and practicality of the AI-generated designs. This objective also expected to be completed within two months.

3. **Implementation of a Permissioned Blockchain Network**

   The next objective is to implement a permissioned blockchain network to log design iterations and stakeholder interactions securely. This objective use blockchain technology to secure and enable transparent collaboration among urban planners, architects, and government. Smart contracts will be configured to automate approvals and ensure validations. The system focuses to track at least five types of stakeholder's actions such as, approvals, rejections, design comments, revision requests, and versioning. The blockchain network increases traceability of the models in planning decisions. This objective is scheduled for development over a one-month period.

4. **Design and deploy a user-friendly web interface**

   The fourth objective is to create a web interface that enables interaction with the system for technical and non-technical users. The interface will allow users to interact with AI-generated layouts, validation processes, and blockchain-logged design records. The frontend will build with React.js and integrated with AI and blockchain backend for seamless user experience. Usability testing will be conducted to enhance accessibility, applicability responsiveness and functionality. This Web interface promotes stakeholder participation in city planning projects. It will be developed within one month of the project timeline.

5. **Developing the Application**

   The last objective of the project is to develop a fully integrated application that applies all components about sustainable city planning. The project mainly focused on building a unified platform for design generation using AI layout generation, ML validation, blockchain logging, and user interaction. The application will provide an end-to-end solution for automate sustainable smart city planning and collaborative governance. The platform will be built using a modular architecture, with backend services likely to be implemented in Flask or a similar Python framework. Front-end elements, AI components, and blockchain services will be organized to work collaboratively. The integration and testing of the full system will span the three months of the project.

1.11 Chapter Summary

This chapter provides an overview of the proposed AI-powered platform for sustainable urban planning in Sri Lanka, integrating Generative AI, Machine Learning (ML), and Blockchain technologies. It discusses the key features, including eco-friendly urban layouts, improved stakeholder engagement, risk mitigation with structural and energy validation. The chapter also highlights the research gaps in current urban planning systems, explain the lack of integrated platforms, real-time regulatory compliance, and inclusive stakeholder participation. this project combines with AI, ML, and Blockchain to create a transparent, secure, and collaborative urban planning process.

Chapter 2

Literature Review

2.1 Chapter Overview

This chapter presents a deep analysis of the academic and technological foundation that supports the sustainable city development project. It explains deeply about generative AI, machine learning validations, and blockchain technologies to address key challenges in modern urban planning, mainly in the context of Sri Lanka.

Furthermore, in this chapter explains concept maps, existing works and mainly about technological reviews. This chapter analyzes the limitations of traditional urban planning methods and highlights the need for intelligent, transparent, and collaborative planning solutions. A review of similar existing works is conducted to assess their contributions and identify gaps, that the proposed system aims to address.

The chapter concludes with an evaluation framework and benchmark criteria to measure the accuracy, performance, and usability of the system. This literature review sets the foundation for designing an integrated and future-ready urban planning platform.

2.2 Concept Map

Figure 2.1: Concept Map

2.3 Sustainable Urban Design through AI-Blockchain Integration

With a growing population, limited resources and the urgent needs to address climate changes, the evolution of urban environment is undergoing significant changes. As city density increases and infrastructure demands increase, urban planning faces the dual challenge of sustainability and efficiency.

The traditional urban planning method is often manual, static, and highly dependent on human expertise. Traditional approaches are no longer sufficient to manage the complexity of modern smart cities. There is a clear need for a digital transformation in urban planning, especially in Sri Lanka, not only to automate the generation of city layouts, but also to ensure stakeholder trust, real-time data integration, and regulatory compliance.

This problem domain explores how to face to those challenges and develop a model for sustainable urban design in the smart city era in Sri Lanka by utilizing artificial intelligence (AI) in collaboration with Machine Learning and Blockchain technology and it's enable to create more transparent adaptive and efficient planning systems for the cities of the future.

- **Limitations of traditional urban design models**

Traditional urban design typically follows a top-down approach and involves key stakeholders such as architects, engineers, policymakers, and regulators. While all of those roles are important for security, compliance, and meeting community needs, their efforts often occur in isolation. This workflow leads to several common issues such as process delays and delayed approvals. Furthermore, traditional design methods often lack the flexibility needed to adapt to real-time factors such as weather conditions, population dynamics, or changing energy demand. Due to those issues, sustainability is integrated into urban planning from the beginning of the planning process.

- **Urban Design Complexity in Smart Cities**

In modern smart cities, urban design must consider sustainability goals such as LEED certifications or national energy efficiency programs. In addition, dynamic systems including automated traffic management and responsive building envelopes.Such complexity requires tools that can automatically generate, validate, and track design decisions, with the ability to incorporate diverse data sources and stakeholder input.

- **Key problem in this domain**

A key challenge in sustainable urban design is ensuring performance and compliance. Traditionally, once a design is proposed, it involves multiple layers of manual review to ensure it meets environmental standards, structural safety and regulatory requirements. As a result, delays and inconsistencies often occur. This issue is further complicated by issues of collaborative governance and accountability, as an urban planning project typically involves a variety of stakeholders, from architects to government regulators and local communities. Without an integrated system for tracking decisions, approvals, and changes, there can be a risk of miscommunication, unauthorized changes, and increased risk.

Another important issue is data fragmentation. Information related to design layouts, environmental simulations, zoning laws, stakeholder feedback, legal documents and all of other details about projects are often scattered across disconnected systems. This fragmentation prevents efficient collaboration, version control and real-time decision making. Finally, the design generation process became a difficult task and traditional methods lacked the computational capability to quickly produce multiple sustainable designs under complex constraints such as sunlight, airflow, and zoning regulations. These issues collectively highlight the need for an urgent, integrated, intelligent and transparent solution to support sustainable urban design.

2.4 Existing Work

Similar Study 1: Green Urban Layout Generation Using GANs (Zhao et al., 2021)

This study proposed a Generative Adversarial Network (GAN)-based model to generate sustainable city designs by optimizing input data like environmental factors.
The project demonstrated how generative models can support eco-friendly city design using data-driven spatial rules. However, the system did not recognize legal constraints such as zoning laws or regulatory codes and did not support the key limitations of multi-stakeholder collaboration in this approach.
Integrating real-world zoning and environmental regulations directly into the generative model and using blockchain technologies for collaborative design validation and stakeholder review tracking could further improve the project.

Similar Study 2: Machine Learning for Building Energy Compliance (Li et al., 2020)

This work developed a machine learning model to check building designs for compliance with energy efficiency standards using historical performance datasets.
It allowed real-time validation of building performance to ensure regulatory compliance. However, it focused solely on individual buildings and did not address broader urban planning or collaborative design processes.
Expanding ML validation to generative design workflows and integrating it into an interconnected planning environment could enhance the utility of this approach.

Similar Study 3: Blockchain for Building Permits and Compliance (Nawari & Kuenstle, 2019)

This study explored the application of blockchain in digital permitting and compliance tracking for architectural projects, aiming to make regulatory approvals more transparent.
It used blockchain to increase trust and traceability in architectural compliance workflows. However, it did not integrate blockchain at the AI-driven design level and had limited scalability across complex urban systems.
Incorporating blockchain early in the planning workflow to record iterative approvals, stakeholder decisions, and generative AI outputs can support a traceable, collaborative urban planning process.

Similar Study 4: 3D Urban Simulation Platform for Citizen Engagement (Shin et al., 2022)

This study introduced a Unity-based 3D urban simulation platform designed to support citizen feedback and improve participatory urban design.
The platform improved visualization and stakeholder engagement through interactive models, which is a key advantage. However, it lacked AI-driven design tools and did not integrate blockchain for decision tracking or revision history.
The proposed urban planning project should integrate generative AI, real-time feedback systems, and blockchain-based audit trails to visually and functionally complete the design and approval loop.

Similar Study 5: AI-Powered Architecture Design Platform (Architechtures.com)

Architechtures.com is a commercial platform that leverages artificial intelligence to automate building design, focusing on efficient space usage and regulatory compliance within predefined parameters.
The system enables users, often architects and real estate developers, to enter design requirements such as building area, shape, and typology, and then generate optimal layouts in real time. The platform emphasizes user interaction and supports rapid prototyping. However, it mainly focuses on individual buildings and lacks integration with broader urban sustainability goals or mechanisms for collaborative governance.
The ability to support sustainable smart city planning at scale can be expanded by incorporating generative urban scale planning, environmental validation through machine learning, and blockchain-based collaboration.

2.5 Technological review

This section focuses on the key technological components that underpin the proposed AI-driven, machine learning-validated, and blockchain-enabled system for sustainable smart city design. The architecture combines four main pillars: a Generative AI pipeline, a Machine Learning (ML) validation layer, a Blockchain-based audit and storage mechanism, and a stakeholder facing interactive interface. Together, these technologies enable the generation of city layouts, validation of their environmental performance, collaboration among stakeholders, and user-friendly visualization and interaction. Each technological flow is described in detail below:

1. Generative AI Pipeline

The Generative AI pipeline acts as the creative core of the system, producing innovative, and sustainable urban layouts by incorporating diverse inputs and applying advanced generative techniques.

• **Input Encoding:** Critical urban planning data including, zoning regulations, topography details, climate profiles (e.g., temperature and rainfall patterns), and sustainability goals (e.g., LEED standards) are preprocessed as structured input vectors. This ensures that the model understands design constraints from the beginning, generating outputs within feasible boundaries.

• **Model Type:** Generative Diffusion Models and Generative Adversarial Networks (GANs) are used to produce high-quality urban layouts. These models are chosen over traditional Variational Autoencoders (VAEs) because they more effectively maintain spatial relationships, adhere to embedded planning constraints, and generate designs that are both visually coherent and aligned with policy requirements.

• **Post-processing:** Once raw layouts are generated, they are put through a post-processing stage using CAD tools like Rhino to refine feasibility like, ensuring walkability, green space ratios, and structural integrity. This layer integrates scripting in Python using libraries like PyTorch or TensorFlow to automate and filter layouts based on performance scores or stakeholder preferences

• **Challenges and Solutions:** Ensuring design viability beyond AI generation requires tight integration with CAD tools and domain-specific scripting for performance validation

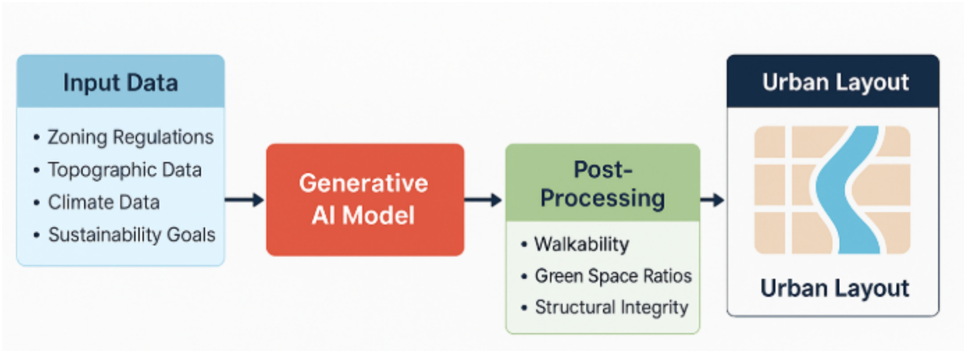

Figure 2.2: Workflow of the Generative AI pipeline

2. Machine Learning Validation

After generating urban layouts, it is important to validate their structural, energy, and environmental efficiency using data-driven Machine Learning techniques.

• **Preprocessing:** Historical and simulated energy datasets (often time series in nature) are normalized in preparation for model training. This step ensures consistency of input features used for prediction and simulation tasks.

• **Model Selection:** The system uses Random Forests to predict energy efficiency due to the robustness, interpretability, and relatively low training complexity of the generated designs. For more complex simulations involving structural analysis, Finite Element Analysis (FEA) outputs are used along with Reinforcement Learning (RL) techniques.

• **Evaluation Metrics:** To quantify performance, the Mean Absolute Percentage Error (MAPE) is used to predict energy consumption. For simulation environments using reinforcement learning (RL), benefit scores are calculated to determine the long-term sustainability, comfort levels, or economic viability of proposed designs.

• **Challenges and Solutions:** Balancing model complexity with interpretability and integrating multi-domain data for validation are key challenges addressed through hybrid ML techniques.

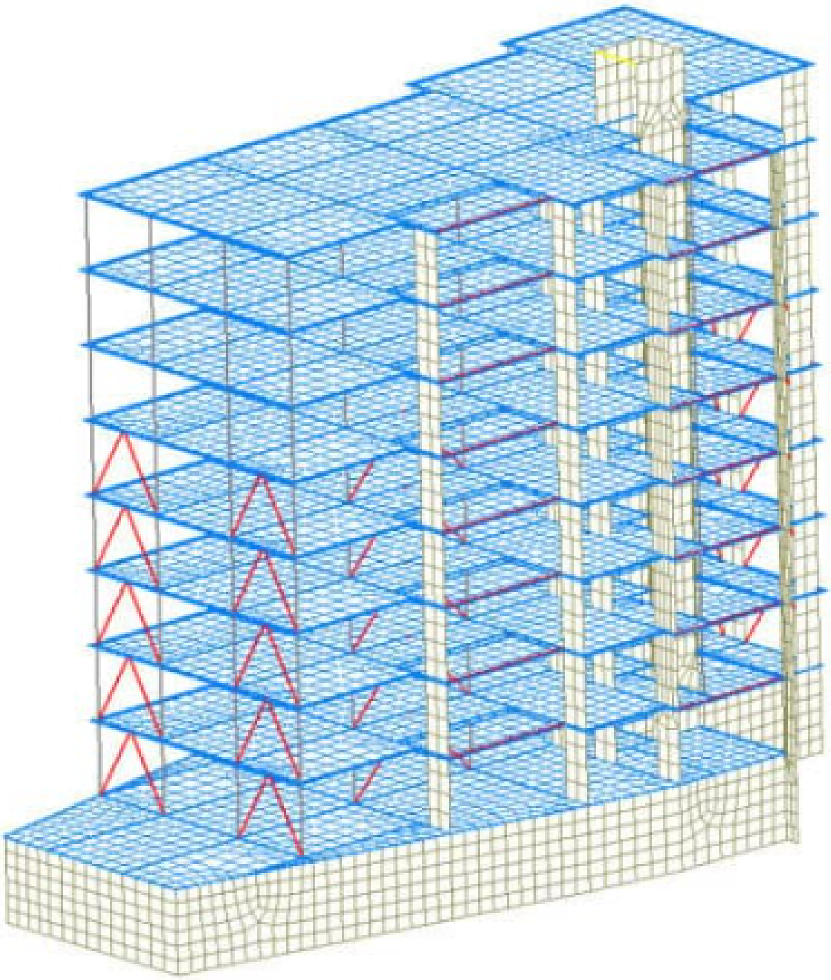

Figure 2.3: FEA structural analysis

3. Blockchain Architecture

A dedicated blockchain layer is integrated into the system, to ensure traceability, transparency, and trust among stakeholders, especially in collaborative urban planning environments.

• **Network:** This solution uses Hyperledger Fabric, a permissioned blockchain network secured for enterprise use cases. It provides identity-based access control, ensuring that only authorized users such as architects, city planners, environmental officers can contribute or modify design records.

• **Smart Contracts:** The logic for checking rules and enforcing policies is implemented using smart contracts written in Solidity. For example, these contracts can enforce compliance with zoning restrictions, record approval actions, or trigger alerts about potential violations.

• **Storage Mechanism:** Since 3D city design files are large and not suitable for direct chain storage, a hybrid storage strategy is adopted. Design files are stored off-chain using IPFS (InterPlanetary File System), and metadata (e.g. timestamps, author, version history) are anchored on-chain for immutable tracking and accountability.

• **Challenges and Solutions:** Storing large files on-chain is not practical; therefore, the hybrid approach balances decentralization and scalability.

4. Stakeholder Interface Layer

User interaction and collaborative feedback are critical for participatory urban design. Therefore, the system includes an advanced interface layer designed to bridge technical complexity with intuitive usability.

• **LLM Integration:** Integration with Large Language Models (LLMs) such as GPT-4-style queries allows users to ask natural language queries (e.g. "How does this design handle flood risk?") and receive contextual, data-informed responses. This significantly lowers the barrier for non-technical users like community leaders or local residents to engage with design results.

• **Rendering:** Real-time 3D visualization is enabled using the Unity engine, allowing users to explore city layouts interactively. This immersive environment supports better decision-making and fosters a co-creation interface during stakeholder consultations.

• **Challenges and Solutions:** Bridging the gap between complex data and accessible insights is achieved through conversational AI and immersive graphics.

Figure 2.4: 3D city model visualization

5. Technological Tools and Frameworks

Table 2.1: Tools and Technologies Used

Component	**Tools/Technologies**
Generative AI	PyTorch, Stable Diffusion, Autodesk Forge API
ML Validation	Scikit-learn, MATLAB, ANSYS (for FEA simulations)
Blockchain	Hyperledger Fabric, Solidity, IPFS
Frontend	React.js, Three.js (for 3D rendering), Streamlit (for rapid prototype UI deployment), Mapbox/Leaflet
Database	MongoDB (for ML datasets), Blockchain ledger (for metadata and records), PostGIS, S3/MinIO

This versatile tool set allows for robust development, modular integration, and future scalability. For example, Autodesk Forge API allows dynamic interaction with 3D building models, while Streamlit offers a fast and effective UI framework for testing and stakeholder features.

2.6 Evaluation and Benchmarking

1. Evaluation

- **Generative Accuracy:**
In sustainable urban planning, generative accuracy reflects how well the planning system produces urban layouts that meet critical zoning regulations such as land use, building heights, and green space allocation while complying with energy efficiency standards aimed at minimizing environmental impact. This accuracy is reflects as the percentage of generated urban plans that successfully comply with these multiple constraints. Achieving high generative accuracy means the system can reliably propose sustainable and regulatory compliant urban designs, which helps planners make informed decisions and reduces costly revisions.

- **ML Validation Performance:**
Machine learning models play a key role in predicting environmental outcomes and optimizing urban characteristics, such as energy consumption, traffic flow, or pollution levels. Validation through measures such as, RMSE and F1-Score ensures that these models produce reliable and accurate predictions. RMSE measures how closely the model's predicted energy or environmental values match the actual benchmark data, while the F1-Score evaluates the accuracy of classification tasks, such as identifying sustainable land uses or mobility zones. Together, these metrics confirm that AI components strongly support sustainability goals.

- **Blockchain Efficiency:**
Blockchain technology in urban planning provides transparent records of design proposals, approvals, and modifications. Efficiency is measured by the speed of processing transactions, such as submitting or updating urban plan versions, and the speed of retrieving data stored on decentralized networks such as IPFS. To ensure smooth collaboration between various stakeholders, including planners, developers, and community members, fast transaction throughput and turnaround times are crucial to building trust while maintaining responsiveness.

- **User Experience:**
Sustainable urban planning requires the participation of active stakeholders, from city officials to residents and environmental groups. The System Usability Score (SUS) captures how user-friendly and accessible the planning system is for these various stakeholders. High usability promotes inclusive participation, allowing users to easily review, critique, and contribute to urban plans, ultimately supporting more democratic and sustainable planning outcomes.

2. Benchmarks

- **Public BIM and Zoning Datasets:**

These datasets provide detailed information on existing urban infrastructure, land use patterns, and zoning laws, and serve as essential references for evaluating new urban plans. By benchmarking generated layouts against such authoritative data, planners can ensure proposed developments respect local regulations, protect cultural heritage, and conserve natural resources, all key principles of sustainable urbanism.

- **Green Building Studio for Energy Benchmarks:**

This simulation platform provides valid data on energy consumption on the building and neighborhood scale, allowing the project to assess how well its urban designs perform in reducing energy use and greenhouse gas emissions. Using Green Building Studio benchmarks helps ensure that designs contribute to climate-resilient, energy-efficient urban environments.

- **OpenAI Gym for RL Validation of Mobility Layouts:**

Mobility and transportation are key challenges in sustainable urban planning. Using OpenAI Gym to test reinforcement learning models, it confirms how well-generated layouts optimize pedestrian transportation, public transport accessibility, and traffic reduction. Benchmarking in this way ensures that urban planning fosters sustainable mobility solutions, reduces congestion and pollution, and improves the quality of life.

2.7 Chapter summary

This chapter explains foundational research in the field AI, ML, and blockchain to identify essential technologies for developing an integrated smart city design platform. Generative models or blockchain approval mechanisms have been experimented with, and their combined potential for addressing stakeholder collaboration.The aim of the proposed project is to develop a real-time platform for future-ready urban planning in Sri Lanka.

Chapter 3

Methodology

3.1 Chapter Overview

This chapter outlines the broad methodology adopted for the design, development, validation, and project management of the proposed AI-driven and blockchain-enabled system for sustainable smart city planning. The research methodology is based on Saunders's research onion framework, employing a practical philosophy with a deductive, mixed methods approach. It describes a multi-layered methodology that covers the integration of generative AI, machine learning, and blockchain technologies from requirements elicitation to solution implementation. Furthermore, this chapter explains on the Agile Prince2-based technical development approach, design principles, programming paradigms, testing methods, and structured project management plan. The goal is to ensure transparency, and adaptability in developing an innovative urban planning system.

3.2 Research Methodology

Table 3.1: Research Methodology

Layer	**What is being used**	**Why it is being used**
Philosophy	Pragmatism	The project integrates both quantitative techniques (ML models, performance metrics) and qualitative elements (stakeholder inputs).
Approach	Deductive	Based on existing theories in ML, AI architecture, and smart city frameworks, which are tested in a new urban design plan.
Methodological Choice	Mixed Method	Combined numerical outputs from AI/ML models with qualitative feedback and interviews with stakeholders.
Strategy	Interviews, Experiments, Surveys, Observation, Self-evaluation, Brainstorming	Interviews: Stakeholder input Experiments: AI/ML validation Surveys: Collect non-technical - user feedback on design outputs
Time Horizon	Longitudinal	Long-term evaluation is needed for ML training, iterative stakeholder validation.
Data Collection and Analysis	Urban data samples, zoning rules, simulation outputs	Data collected from urban - planning datasets, BIM files and simulations. Analysis is continued through stakeholder reviews.

3.3 Development Methodology

3.3.1 Development Approach

This project follows a flexible development methodology that combines Prototyping and the Agile-inspired One-Person Scrum framework. The prototyping approach facilitates early experimentation and iterative refinements, which is especially important when integrating complex technologies such as generative AI, machine learning, Blockchain, and stakeholder interfaces. Prototyping allows quick validation of concepts and helps identify challenges early. Complementing this, the Agile One-Person Scrum methodology supports adaptability by incorporating continuous feedback and encouraging rapid iteration, even when development is led by a single developer. This mix ensures both innovation and responsiveness to evolving project needs.

3.3.2 Requirement Elicitation Methodology

Requirements for this project were gathered through a combination of collaborative and analytical methods. Brainstorming sessions were held with consultants and technical experts to generate a broad understanding of project goals and technical limitations. Semi-structured interviews with urban planners and architects provided valuable insights into real-world planning practices, challenges, and user expectations. Additionally, an in-depth document analysis was conducted on relevant zoning laws and sustainability frameworks such as LEED, ensuring that regulatory compliance and sustainability standards were firmly incorporated into the project requirements.

3.3.3 Design Methodology

The design methodology revolves around upgrading cutting-edge technologies to achieve project goals. Generative AI is used to create innovative, sustainable city designs that balance urban functionality and environmental impact. Machine Learning validation models assess the structural strength, environmental sustainability, and transportation efficiency of the generated designs. Blockchain technology ensures data integrity and transparency, maintains tamper-proof creation records, and enables secure collaboration. Finally, a stakeholder interaction layer is designed to provide an user-friendly interface, including real-time 3D visualizations, that enables planners and community members to easily explore and engage with urban plans.

3.3.4 Programming Paradigm

The development uses a hybrid programming paradigm to maximize modularity and efficiency. Object-oriented programming (OOP) principles facilitate the encapsulation of clear system components, promoting clean, maintainable code and well-defined module interactions. At the same time, functional programming techniques are used for mathematically intensive operations and data transformations, allowing for clear, concise, and error-resistant code that is particularly suitable for processing complex data sets and implementing ML algorithms.

3.3.5 Testing Methodology

The inspection includes both quantitative and qualitative methods to ensure comprehensive system evaluation. Quantitative evaluation focuses on objective model accuracy assessed through specific metrics such as RMSE and F1-Score, as well as system efficiency in terms of computational and blockchain transaction performance. Qualitative evaluation involves stakeholder usability testing, gathering feedback on system intuitiveness, functionality, and overall user satisfaction through interviews and hands-on sessions. This balanced approach ensures that both technical robustness and user experience are valid.

3.3.6 Solution Methodology

- **Feature selection and engineering**
  Feature selection and engineering focuses on identifying and creating meaningful variables that improve model performance and overall system accuracy. The process begins by extracting features such as proximity to infrastructure like roads, transportation, and elevation. Urban layout characteristics include population density, zoning classifications, and land use restrictions that affect planning feasibility. Environmental characteristics, including solar energy potential, proportion of green spaces, and flood-prone areas, are also key.

- **Data Preprocessing**
  Data preprocessing is the preparation of raw data sets to ensure compatibility with AI/ML models and blockchain integration. The process begins with data cleaning, addressing missing values, and errors to improve reliability. Next, data transformation is performed, this includes normalizing and scaling values for machine learning and converting to geographic formats (such as GeoJSON or SHP) for spatial analysis. Finally, feature extraction transforms complex inputs, such as satellite imagery, into structured variables, such as land use categories, building density, and elevation, enabling meaningful analysis.

- **Data Collection and Preparation**

The project uses various datasets, including climate data (temperature, rainfall), zoning laws, topographical maps, and sustainability benchmarks. Collect and preprocess relevant data to train AI models, validate urban planning, and integrate into the system.

Table 3.2: Standard Datasets Used for AI-Driven Urban Design

Dataset Type	**Sources**
Topographical Data	SRTM, ASTER, or LiDAR data (elevation models, terrain features)
Satellite Imagery	Google Earth Engine, Sentinel-2, Landsat
Building Footprints & Infrastructure	OpenStreetMap (OSM), Microsoft Building Footprints
Zoning & Land Use	Local zoning maps, official government datasets
Climate & Environmental	WorldClim, OpenWeatherMap API, national meteorological data
Socio-Economic & Demographic	Census data, UN statistical databases

- **Model selection**

Select appropriate models for generative city layout, compliance validation, and stakeholder feedback.

1.Generative AI Models:

- GANs (Generative Adversarial Networks) for city layout generation
- Diffusion models to simulate realistic urban growth based on real-world constraints

2.ML Models:

- Random Forests or Gradient Boosting for energy consumption prediction
- Support Vector Machines (SVMs) for classification tasks

3.Reinforcement Learning (RL): Could be used for dynamic optimization

4.Training AI Models:

- Generative models - Use PyTorch or TensorFlow
- ML models - Random Forest, Gradient Boosting

Testing
Validate model accuracy and performance against real-world test scenarios, ensuring that the system can produce functional, compliant urban layouts.

- Real-world test cases: Evaluate AI models in unseen areas and see if they generate realistic and legally compliant city layouts.
- Scenario testing: Test specific scenarios, such as flood-prone areas or energy usage scenarios, to ensure accuracy.
- Stakeholder Validation: Use stakeholder feedback to assess whether the generated city layouts meet expectations and compliance.

3.4 Project Management Methodology

For this project, a hybrid Agile Prince2 methodology is used as the project management approach. This combines the structured governance and control aspects of Prince2, with the flexibility and iterative delivery characteristics of Agile. The hybrid model ensures that the project maintains clear oversight while also responding to evolving stakeholder feedback and changing requirements throughout the development cycle.

3.4.1 Project Scope

The project scope defines what is included and excluded in this initiative to keep the focus clear. In scope this project includes development of a Generative AI system to produce sustainable smart city designs, Machine learning modeling for design validation, blockchain integration to enable collaborative auditing of designs, and a user interface that facilitates stakeholder interaction and feedback. The project also includes integration with third-party datasets and tools to enrich the design and validation process.Real-world deployment of the system with real-time data feeds and legal approvals related to zoning or building plans, which exceeds the current objectives of the project, is out of scope.

In Scope

- Development of a Generative AI system to produce sustainable smart city designs
- Creation of machine learning models for design validation
- Blockchain integration to enable collaborative auditing of designs
- User interface that facilitates stakeholder interaction and feedback

- Integration with third-party datasets and tools to enrich the design and validation process

Out of Scope

- Real-world deployment of the system with real-time data feeds
- Legal approvals related to zoning or building designs

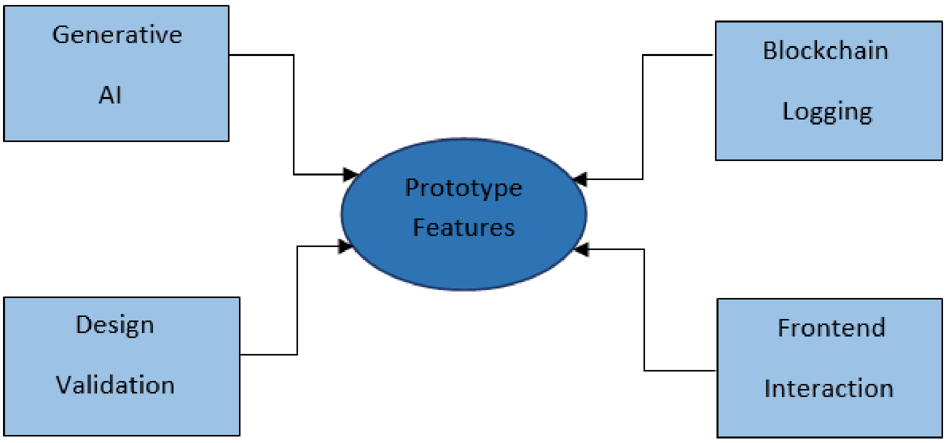

Figure 3.1: Prototype features

3.4.2 Resource Requirements

Resource requirements range from hardware, software, data, and skills needed to complete projects.

1. Hardware Requirements

- Standard development laptops or PCs

2. Software Requirements

- Python (PyTorch, Scikit-learn)
- React.js (frontend development)
- Streamlit (UI prototyping)
- Hyperledger Fabric (blockchain network)
- Figma (API testing and UI design)
- GitHub (version control)

3. Data Requirements

- Sustainability certification rules like LEED, WELL
- Topographical and zoning datasets from government sources
- Public datasets on energy consumption
- Synthetic datasets for simulation

4. Skill Requirements

- AI/ML development – model evaluation
- Blockchain development – permissioned networks
- Web development – JavaScript, React
- App development – Flutter
- System integration – API design and module coordination
- UI/UX design – stakeholder interaction model and usability tests

3.4.3 Risk and Mitigation

Several risks and strategies to mitigate them have been identified. Risks of data unavailability are addressed by using academic datasets and formally requesting data from government agencies. By adopting a modular system design with clearly defined APIs, the complexity of integration across AI, ML, blockchain, and UI components is minimized. Technical skills gaps, especially in integrating blockchain and AI, are addressed by allocating time for tutorials and training sessions. Blockchain scaling issues for large design files are managed using a hybrid storage solution that combines on-chain and off-chain storage.Finally, the challenge of limited training data for engineering validation models is mitigated by using transfer learning techniques and collaborating with civil engineering experts to supplement the data.

Table 3.3: Risk and Mitigation Strategies

Risk	Description	Mitigation Strategy
Data unavailability	Key datasets not available in public domain	Use academic datasets and file formal requests to government bodies
Integration complexity	Coordinating AI, ML, blockchain, and UI components may be challenging	Adopt modular design with clearly defined APIs
Technical skill gaps	Blockchain and AI integration may require learning curves	Allocate time for tutorials, training sessions, and expert guidance
Blockchain scalability for large design files	Large design files may be inefficient to store on blockchain	Use hybrid storage combining on-chain and off-chain solutions
Limited training data	Engineering validation models may lack sufficient data	Employ transfer learning and collaborate with civil engineering experts

3.4.4 Schedule

The project schedule is organized into phases, each with specific timelines and deliverables, typically depicted on a Gantt chart to visualize overlapping activities and dependencies. This scheduling ensures that every milestone is tracked and managed effectively, ensuring deadlines are met. **GANTT Chart**

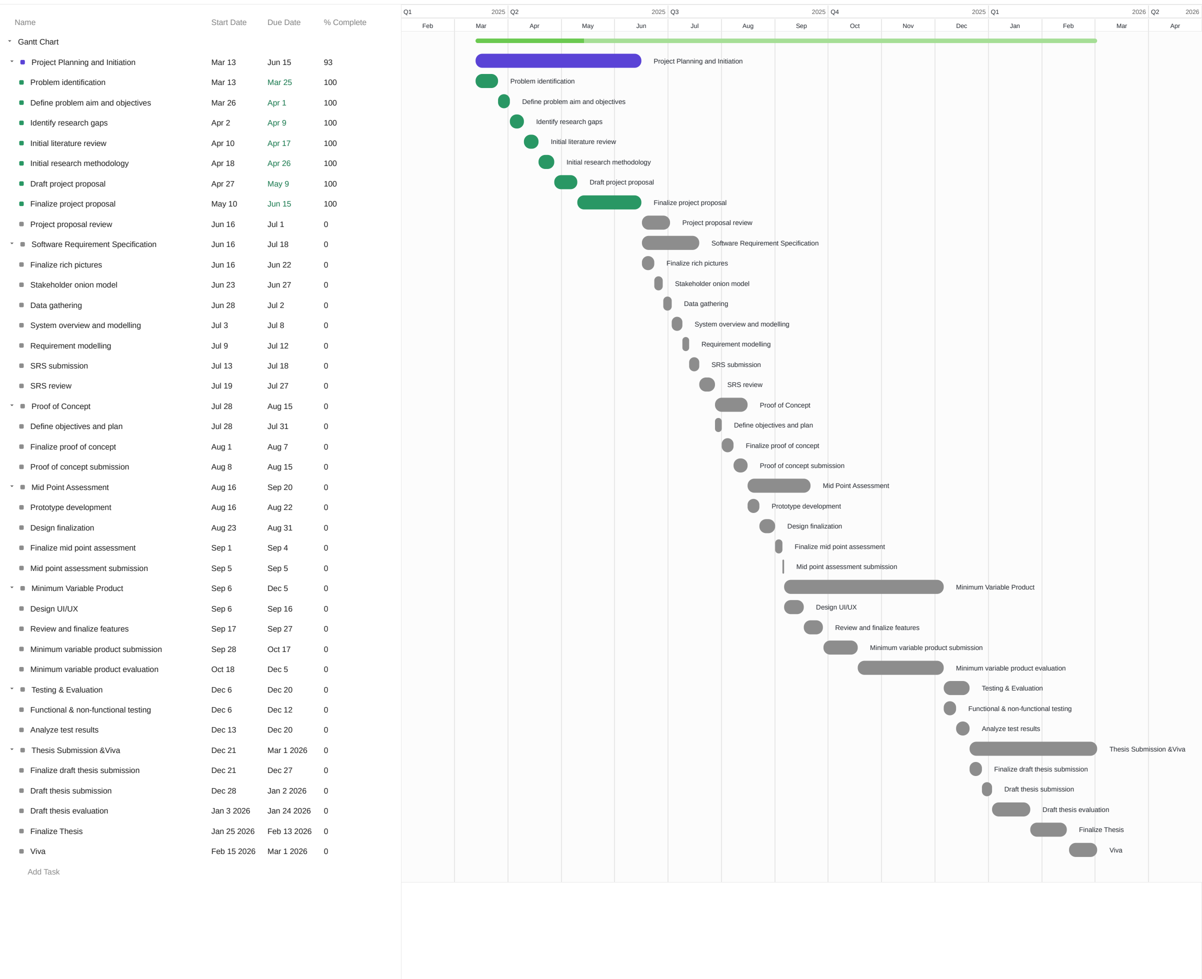

Figure 3.2: Project Gantt Chart

3.4.5 Success Criteria

Success criteria define measurable outcomes used to evaluate whether the project has met its stated objectives and delivered the intended value. For this AI-powered sustainable smart city planning system, success is assessed through a combination of functional validation, performance testing, and stakeholder feedback.

1. Functional Completeness

- Objective: The system should allow users to create a project, select a real-world location using a map interface, and generate an editable 3D city layout.
- Measurement: Manual testing and demonstration against use cases.

2. Accuracy of AI-Generated Urban Layout

- Objective: The AI model should produce city layouts that comply with real-world zoning and sustainability constraints.
- Measurement: Comparison with actual design regulations; goal is $\geq$85% compliance accuracy on test cases.

3. Usability and Interactivity

- Objective: The 3D layout should be editable in real time with intuitive controls and visual feedback.
- Measurement: Usability test with 5–10 users; success if average System Usability Score (SUS) ≥ 75.

4. Blockchain Audit Functionality

- Objective: All key user interactions such as, edits, approvals, submissions should be recorded immutably using blockchain.
- Measurement: Check for at least 95% accuracy in logging actions with time stamps and user ID.

5. Performance and Responsiveness

- Objective: The application should respond to user actions like generate layout, edit design with minimal delay.

- Measurement: The average response time for key features is ≤ 2 seconds that measured via browser developer tools or performance logging.

6. Deployment and Demonstration

- Objective:The system should be deployed locally or on a test server with a working UI, AI backend, and blockchain components.
- Measurement: Successful end-to-end system demonstration for a selected case study area.

7. Evaluation Against Research Objectives

- Objective: All research objectives outlined in 1st chapter must be achieved.
- Measurement: A checklist that matches the implemented modules and documented outputs.

8. Academic Contribution

- Objective: This project should contribute to both the problem area (urban planning) and the research area (integrating AI/ML + Blockchain).
- Measurement: The project report will be evaluated through literature review and supervisor feedback.

3.5 Chapter Summary

In summary, this chapter presents the layered methodology used to implement a new, data-driven smart city planning system. The research approach combines quantitative techniques (such as ML models and validation measurements) with qualitative inputs (stakeholder interviews and feedback). The development followed a hybrid methodology that combines prototyping and Agile One-Person Scrum for flexibility and adaptability. The solution combines Generative AI for layout design, ML for performance validation, and Blockchain for transparent collaboration. Testing included both model-based accuracy checks and user-centered quality assessments. Project management was handled using Agile Prince2, ensuring iterative development with structured control. The chapter concludes with resource planning and risk mitigation strategies, ensuring the viability and resilience of the project.

Conclusion

This project offers an innovative approach to smart city planning by combining generative AI, machine learning, and blockchain technologies into a unified, user-friendly platform. It addresses key challenges in traditional urban development by automating layout generation, enabling real-time compliance validation, and fostering transparent stakeholder collaboration through blockchain.

By using various datasets and advanced technologies, the system ensures that urban planning is sustainable, regulatory-compliant, and adaptable to real-world needs. This solution not only improves the efficiency and accuracy of city planning in Sri Lanka, but also establishes a scalable foundation for future smart city initiatives around the world.

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