Implementation Framework for Hyperloop Decision-Making Ecosystem

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Abstract

The Hyperloop technology is an ultra-high-speed transportation mode proposed and envisioned by Elon Musk in 2012 by reimagining vactrains. It leverages pods moving un supersonic speed in 3-m vacuum tubes using magnetic levitation for propulsion. Technology Readiness Level is TRL 5 according to HORIZON 2020 standards. At the end of 2023, the shutdown of Hyperloop ONE, one of the largest companies in the Hyperloop industry, emphasized significant challenges in the implementation of Hyperloop technology and revealed dynamic nature of Hyperloop project. This study identifies a research gap: the absence of digital decision-making systems specifically designed for Hyperloop projects. To address this gap, the research presents a six-stage implementation framework for an Hyperloop decision-making ecosystem. The study involves the creation of a functional block diagram, the design of a technical solution blueprint, and the proposal and validation of the implementation framework using a unit testing method on an Hyperloop project case. The proposed technical solution integrates several advanced technologies, including the Snowflake data warehouse, Streamlit, Vensim, Microsoft PowerBI, GPT-4, PostgreSQL, and custom Python applications. The framework's validation process involved iterative testing and refinement, resulting in an increase in the project maturity model from the level 'Defined' to the 'Capable'.

Keywords

Hyperloop, software ecosystem, data engineering, dataops, decision-making, digital transformation

1. Introduction

Hyperloop marked revolution in transportation since its complex and innovative concept was introduced by Elon Musk back in 2012 that was later documented in Hyperloop Alpha Paper publication by Tesla (SpaceX) [1]. Technology initially is envisioned as ultra-high speed transportation mode which is able to transfer passengers and cargo on supersonic speed overcoming Kantrowitz limit [2]. According to Hyperloop Alpha Paper, a new mobility solution proposed to use vacuum tubes of 3.3 m diameter and capsules with

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frontal area up to 4 m2. These capsules are propelled and guided along a track, it was designed with distributed acceleration points to minimize the infrastructure, only requiring energy over a small fraction of the track. The Hyperloop transportation system (HTS) is considered a promising alternative to short-haul flights, offering reduced travel times and lower fuel consumption per passenger revenue kilometer [3].

The technology is currently at a low maturity level from engineering, operational, and cost perspectives [4]. Significant technological, regulatory, planning, financial, and environmental issues must be resolved before HTS can achieve commercial viability. The successful deployment of Hyperloop systems requires an integrated approach that leverages advanced digital tools and technologies to stream-line decision-making processes.

Research aims to propose a structured approach for integrating various digital tools and technologies to support decision-making processes in Hyperloop projects. **The goal** is to design a framework for implementing Hyperloop decision-making ecosystem.

Research questions.

Q1. What are the key components necessary for developing and deploying a digital decision-making ecosystem specifically designed for Hyperloop technology projects?

Q2. What strategy(s) can be adopted to implement decision-making ecosystem?

Q3. How does the proposed Hyperloop decision-making ecosystem improve project maturity levels?

Research tasks and objectives.

O1. Review existing literature on Hyperloop projects, frameworks and best practices in digital systems, particularly in the context of complex techno-logical projects and define decision-making ecosystem.

O2. Identify and define key components, technologies, and methodologies that are relevant to the implementation of digital ecosystems.

O3. Establish the relationships and interactions between Hyperloop decision-making ecosystem components within the framework.

O4. Develop an implementation framework.

O5. Conduct framework approbation.

2. Research Methodology

The research methodology for the development of implementation framework for Hyperloop decision-making ecosystem is shown in Figure 1. The state-of-the-art contains a problem definition, literature analysis to define research gap, ecosystem definition.

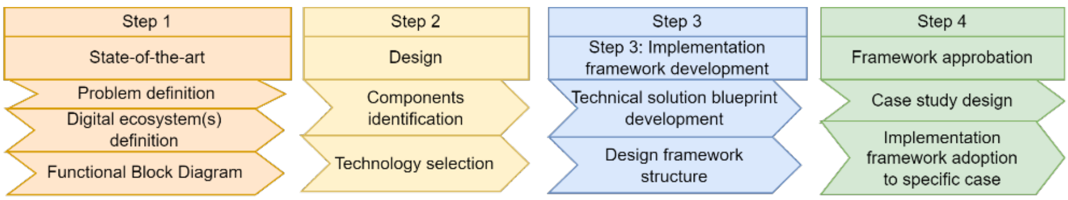

Figure 1: Research methodology overview.

The Functional Block Diagram (FBD) method is selected to map underlying ecosystem's processes in structured approach. It serves as a basis for the technical solution blueprint. The design step involves identifying the key components and technologies necessary for development and deployment of a digital decision-making ecosystem. Step 3 is the development of implementation framework based on the conceptual model. It contains framework design, integration and deployment strategy, and discussion on potential challenges. Step 4 is framework approbation and conceptional adoption using Python programming language unit testing method. The proposed research methodology is aimed to achieve research goals, addressing the complex and multidisciplinary nature of implementing digital decision-making ecosystems for Hyperloop projects.

3. State-of-the-Art

In this Section, research state-of-the-art is presented. Hyperloop decision-making ecosystem is described, concept is discussed, and Functional Block diagram is de-signed. It contributes to completing Research Objective 1 (O1).

3.1. Problem Definition

Due to technology complexity [3], dynamic nature of Hyperloop project [5], challenged decisions [6], the Hyperloop is still in TRL 5 according to Horizon 2020 standards [7]. The implementation of Hyperloop systems present complex decision-making challenges that underlines necessitate a robust ecosystem for effective management that answers the following success factors: namely reliability, scalability, technical feasibility, quantum factor, safety, regulatory approval, social acceptance, environmental sustainability, infrastructure integration and usability factors [8]. Study has filtered out and analysed **95 papers in Scopus DB** (*keywords – hyperloop, hyperloop system(s), hyperloop project(s), hyperloop decision-making, hyperloop challenges, et al*) and **identified research gap, that currently there is no hyperloop decision-making ecosystem software** that can improve decision-making process for Hyperloop project, by assessing success factors of Hyperloop implementation for specific case.

3.2. Hyperloop Decision-Making Ecosystem

To address the research gap, the study proposes the concept of the Hyperloop Decision-Making Ecosystem and implementation framework for future product deployment. The Hyperloop Decision-Making Ecosystem is a technology platform that applies the enhanced ETL process with use of Generative AI. Research proposed refined ecosystem definition for ecosystem specific for Hyperloop project based on literature analysis: *a networked community of actors (organisations, software products, individuals) supported by an underpinning technological platform in the same environment that enables actors to process multivariate data, produce knowledge, extract insights, foster innovation, create value, and support decision-making*.

Ecosystem's functional block diagram (FBD) is shown on Figure 2. Initial INPUT 1-7 correlates to multivariate input sources (1 – Generative AI model, 2 – external database(s), 3 – internal database(s), 4 - sensors, 5 – satellite data, 6 – industry reports, 7 – user input).

The Hyperloop decision-making ecosystem is a software framework designed to leverage big data for the efficient planning and implementation of Hyperloop project. As a big data product, this ecosystem integrates diverse datasets, employing advanced analytics, machine learning, and predictive modeling to facilitate informed decision-making. The ecosystem is structured to handle the complexity and scale of data generated by various actors (see INPUTS 1-7 above). By transforming raw data into actionable insights, the ecosystem enables stakeholders to make data-driven decisions that enhance safety, efficiency, and cost-effectiveness. Advanced analytics tools process data to identify patterns, predict potential issues, and optimize performance. Ecosystem finite state is data visualization and system modelling which accessed by end users of the system.

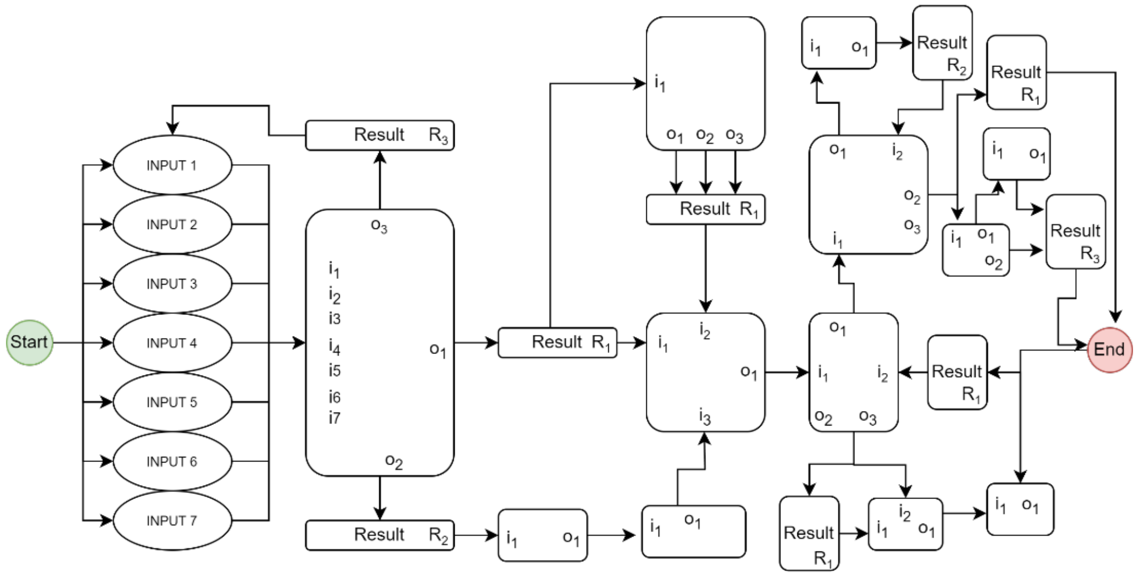

Figure 2: Hyperloop decision-making ecosystem functional block diagram.

4. Design

In this Section Hyperloop decision-making ecosystem technical solution blueprint is prosed, and components are identified and defined. It contributes to the completion of Research Objectives 2 and 3 (O2 and O3).

As a big data product, Hyperloop decision-making ecosystem utilizes Extract-Transform-Load approach [9], enhanced with Generative AI (GenAI), namely Extract-Generate-Transform-Load. The ecosystem's adaptive structure promotes scalability, flexibility, enabling continuous improvement and development in response to the evolving needs of the Hyperloop industry.

The technical solution presented in Figure 3 is a sophisticated system designed to streamline the collection, processing, analysis, and visualisation of data pertinent to decision-making in Hyperloop technology according to FBD (Figure 2).

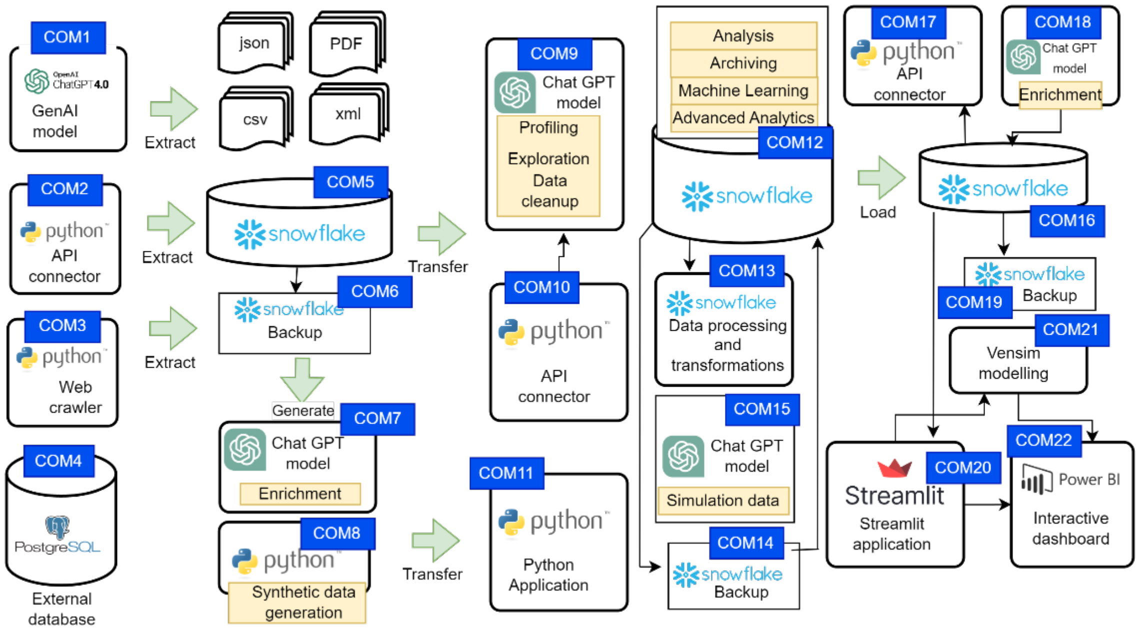

Figure 3: Hyperloop decision-making ecosystem technical solution blueprint. Data load stages are presented in green colour and component codes are highlighted in blue colour.

Detailed ecosystem's components are presented in Table 1. The framework starts with the ingestion of diverse datasets through external databases, web crawlers, and API connectors. Once data is collected, a dedicated component utilising AI technology interprets and extracts relevant information from various. This data is transferred to a centralised data warehouse managed in Snowflake. In the next phase, data is cleaned and enriched to improve its quality with the help of AI. To supplement decision-making in cases when data is missing, synthetic data is generated based on existing statistical patterns using Generative AI. The architecture emphasises data resilience through multiple backups within Snowflake.

System dynamics models used to simulate various scenarios, thereby aiding in the prediction of outcomes based on different Hyperloop design and operational strategies. The final stage is data visualization using PowerBI interactive dashboards, built on top of Streamlit applications.

5. Implementation Framework

In this Section Implementation framework is proposed, implementation challenges are discussed, and framework approbation is conducted. It contributes to the completion of Research Objectives 3, 4 and 5 (O3, O4, O5).

Table 1
Hyperloop decision-making ecosystem components

Component	Name	Technology	Description
COM1	Data extraction	ChatGPT 4	Extracts from GenAI knowledge base.
COM2	API connector	Python	Connects to external APIs to fetch data directly into the system from various Internet of Things devices.
COM3	Web crawler	Python	Gathers data from various online sources to be processed and analysed.
COM4	External data source	PostgreSQL	External data collected from various sources for processing.
COM5	Data transfer	Snowflake	Transfers extracted data into Snowflake for centralized data handling.
COM6	Database backup	Snowflake	Provides backup services for data.
COM7	Data enrichment	ChatGPT 4	Enhances data quality by adding missing information or correcting errors.
COM8	Synthetic data generation	Python	Generates artificial data based on patterns learned from real data.
COM9	Data cleanup	ChatGPT 4	Cleans and prepares data for analysis, removing errors and inconsistencies.
COM10	Python application	Python	Application built in Python to process and handle data operations.
COM11	Data transfer	Python	Facilitates the movement of processed data to different parts of the system.
COM12	Data analytics	Snowflake	Component that analyses big data, applies machine learning and advanced analytics
COM13	Data processing, transformations	Snowflake	Processes and further transforms data applying business logic.
COM14	Database backup	Snowflake	Provides backup services for data.
COM15	Simulation data	ChatGPT 4	Uses advanced models to simulate data scenarios for further analysis.
COM16	Database backup	Snowflake	Snowflake database containing production data gathered in all previous steps.
COM17	API enrichment	ChatGPT 4	Uses APIs to enrich data with additional external insights.
COM18	Data enrichment	ChatGPT 4	Further enriches data post-transfer with additional context and information.
COM19	Database backup	Snowflake	Provides backup services for data.
COM20	Application	Streamlit	A bridge between data and visualizations.
COM21	System modelling	Vensim	System modelling core that will be used for visualization in COM22.
COM22	Dashboard visualization	Power BI	Creates interactive dashboards for data analysis and reporting.

5.1. Framework Overview

Existing software development frameworks, methods, and paradigms are analysed. Agile and Waterfall do not exactly fit given ecosystem, because they are mainly aimed at the team's approach to managing project tasks, rather specific digital system implementation framework. They can be adopted to develop specific components of ecosystem as different teams can be involved for their development. For example, COM6 and COM16 can be done by one team using Waterfall method and COM1-COM4 can be implemented by another team which adopted Agile. Proposed framework utilizes hybrid methodology adopting selected methods features (Table 2).

Table 2
Software development methods adopted in the framework

Method	Features selected for framework	Source
DevOps	Continuous integration/deployment, automated testing, collaboration.	[10]
Lean	Value stream mapping, continuous improvement.	[11]
DataOps	Collaboration, rapid data delivery, integration, automation.	[12]
RAD	Prototyping, user feedback, iterative.	[13]
PRINCE2	Roles-responsibility model, control, stage-based process.	[14]
Data mesh	Data as a product, decentralized data ownership, federal computational governance.	[15]
Six Sigma	Data-driven approach, control, quality improvement.	[16]

The framework is presented in Figure 4. It is purposed for evaluating and guiding the deployment of Hyperloop decision-making ecosystem. At the end of each cycle project maturity model is reevaluated according to Capability Maturity Model Integration (CMMI) [17].

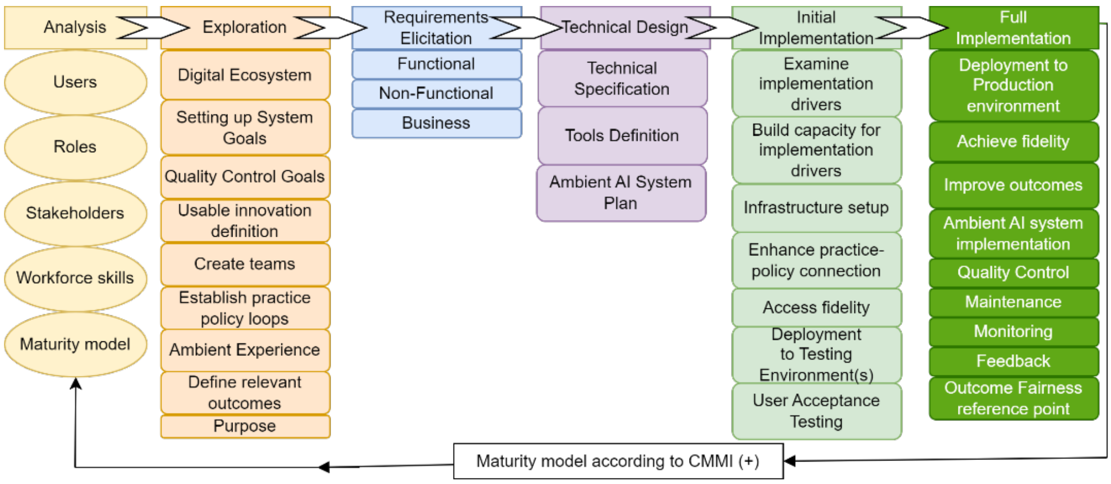

Figure 4: Hyperloop decision-making ecosystem implementation framework.

Implementing a digital ecosystem for Hyperloop projects presents several challenges. Integration of diverse and vast data sources can pose a challenge as Hyperloop systems generate large amounts of data from various sensors, operational logs, and maintenance records. Ensuring data quality and consistency across these different sources is crucial for accurate analysis and decision-making, involving data cleaning, transformation, and enrichment processes that can be resource-intensive and complex to manage, however integrated in the ecosystem by design (Figure 3, COM7-9).

Ecosystem and implementation framework can be considered as part of digital transformation processes of the society and introduces shift to digital business system from monolithic by its design. It incorporates such technologies as AI, Big Data, Data Analytics, Internet of Things, Cloud Computing, Data Warehousing, and others (Table 1) which are essential drivers of digital transformation. Digital transformation has an influence on human lives, industrial processes, circular economy, various systems, and their Key Performance Indicators. Data privacy and cybersecurity of ecosystem affect all mentioned above impacts [18]. Therefore, each component of ecosystem must answer regional data protection policies, such as General Data Protection Regulation (GDPR) [19] in EU and incorporate best software development practices in mitigating cybersecurity risks. Further, pursuit to comply with European strategy for data [20] principles must be considered as summarized in Figure 5.

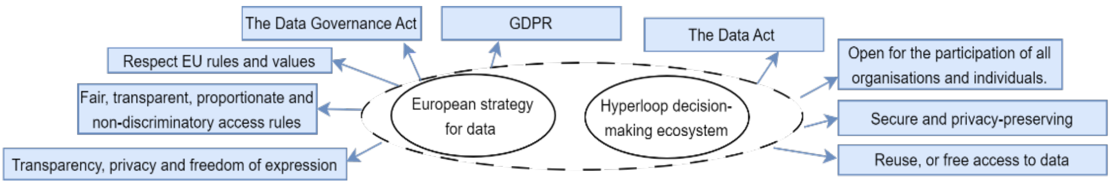

Figure 5: European strategy of data for Hyperloop decision-making ecosystem [20].

Another challenge is the need for seamless collaboration among a wide range of stakeholders, including engineers, regulatory bodies, investors, and business users. The project leadership must provide transparent and accessible means for stakeholders to monitor system performance, simulate scenarios, and make informed decisions. The implementation process must address the scalability and flexibility of the ecosystem to accommodate the evolving needs of the Hyperloop industry. To conclude, the success of the Hyperloop decision-making ecosystem depends on effectively managing these challenges to create a scalable, efficient, and reliable framework for data-driven decision-making.

5.2. Framework Approbation

Framework approbation is conducted on hypothetical case of Hyperloop Baltics implementation, for which synthetic data was generated and included in Python script (Appendices A, files *tests/unit/synthetic_data.py* and *tests/unit/synthetic_maturity_data.py*).

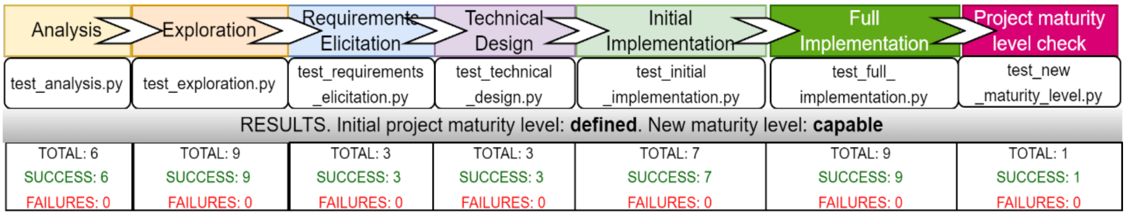

Figure 6: Implementation framework validation using unit testing strategy and results.

Implementation framework approbation is conducted using unittest method in Python programming language pytest library on synthetic data generated for Hyperloop Baltics project. Unit testing strategy and results are presented in Figure 6, source code is publicly available on GitHub, see Appendices A. In scope of tests, 43 unit tests were executed with SUCCESS status. Project maturity level check indicates an increase of maturity model CMMI metrics which include Hyperloop project success factors (Section 3.1). As a result, project maturity model increased from defined to capable and each of underlying contributing factors increased as well.

6. Conclusions

The research goal is completed by proposing a framework (Figure 4) for implementing a digital decision-making ecosystem designed specifically for Hyperloop projects (Figure 3). The framework integrates ETL process enhanced with Generative AI envisioned in solution components (COM1-COM22, Table 1). Structured technical solution blueprint is based on FBD (Figure 2) correlating to system inputs, outputs, and desired result which contributes to completion of research aim. By unifying diverse data sources into a centralized platform, the ecosystem facilitates informed decision-making, predictive maintenance, and process optimization, providing knowledge and insights to end users. Implementation framework guides ecosystem development and integration. It is scalable and flexible as it incorporates selected features from seven software development methods (Table 2) and can be adopted to other digital systems with similar parameters. The approbation is conducted using unit tests on synthetic data (Figure 6), contributing to implementation strategy adoption to given use case. The output of each implementation cycle is revised project maturity model according to CMMI.

Contribution. Research contributes to the field of telematics and logistics, data engineering and project management, within the context of Hyperloop technology. It supports EU digital targets 2030 [21] by enabling digital transformation of businesses and European strategy for data [20]. Framework is designed for use by Hyperloop project stakeholders as guiding steps for digital system deployment and integration. It is committed to increasing the Hyperloop technology project's chances of success given the dynamic and innovative nature of HTS and ability to adapt to scope changes.

Limitations. Synthetic data is used for implementation framework approbation.

Future steps. The next step involves further tests and framework approbation using real world data for various real Hyperloop projects from different regions and using different methods. It is planned to apply the given framework to the Hyperloop Baltics startup project, aiming to implement Hyperloop technology for passenger and freight transport in the Baltic and Nordic regions. This development will contribute to the green and digital transformation aligned with the EU Mobility Strategy [22].

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A. Online Resources

The code for framework approbation can be accessed via public GitHub repository at https://github.com/pirrencode/tsi_hl_framework_implementation/tree/main.