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EVALUATION OF HYPERLOOP TECHNOLOGY PROJECT MATURITY THROUGH SYSTEM DYNAMICS: MODELLING AND SIMULATION

Aleksejs VESJOLIJS*[1,2]

[1]*Engineering Faculty, Transport and Telecommunication Institute, Lauvas iela 2, Riga, LV-1019, Latvia*
[2] *Accenture, 1 Grand Canal Square, Dublin, Ireland*

**Corresponding author's e-mail: vesjolijs.a@tsi.lv*

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Abstract. This paper introduces eight stock-and-flow models to assess project maturity in the Hyperloop technology domain, based on multivariate technical, social, and financial criteria. Four scenarios are simulated: rapid decline, gradual decline, rapid growth, and sustainable growth. An interactive dashboard has been developed to visualise the simulation results and provide public access to the models. The primary users of these models are project decision-makers and industry analysts. The core research methodology utilised is system dynamics modelling, which captures the challenging dynamics of multi-loop systems inherent in Hyperloop transportation projects. The results demonstrate the models' effectiveness in providing real-time insights into how various factors interact and affect project performance. The proposed models facilitate real-time evaluation of project maturity and offer a conceptual framework for analysing context-specific factors critical to successful project implementation. This research supports the European Green Deal and Digital Transformation 2030 strategies by contributing to the development of strategies for Hyperloop technology advancement – an EU Commission priority for Tourism and Sustainable Transportation, as set by the European Commission President on 18 September 2024.

Keywords*: Decision-making, system dynamics, Hyperloop, project maturity, business process modelling, multiple-loop systems.*

JEL Classification: **C61** – Optimization Techniques; Programming Models; Dynamic Analysis. **C69** – Mathematical Methods; Programming Models; Mathematical and Simulation Modeling: Other. **R40** – Transportation Economics: General. **O32** – Management of Technological Innovation and R&D

INTRODUCTION

Hyperloop technology was suggested by SpaceX back in 2012 as a revision of transportation in vacuum tube, while technology specification is presented in Hyperloop Alpha paper (Tesla, 2012). Currently, Hyperloop is at the technology readiness level (TRL) 6, which corresponds to technology validated in a relevant environment (Horizon, 2023). Hyperloop is a zero-emission, sustainable, ultra-high-speed transportation mode compared to air, rail, car and naval. However, there is debate in the industry and scientific society (Doppelbauer, 2022). Despite the positive anticipated outcomes of this technology, its implementation faced technical, financial and socio-economic challenges due to the complexity of the technology itself and its subsystems, for example, magnetic levitation, vacuum tubes, unmanned pods, etc. (Hansen, 2019). Problems in technology implementation alongside financial issues and negative public opinion, led to the closure of one of the largest Hyperloop projects in the world – Hyperloop ONE. It was discontinued in 2023, and overall losses of the Hyperloop technology industry in 2023 reached almost 1 billion EUR (Bloomberg, 2023).

The successful implementation of the Hyperloop project requires a rigorous and multifaceted decision-making approach that can address the complex interplay of technical, economic, environmental, and social factors according to its concept definition by Barbosa, 2020. System dynamics serves as the foundation for evaluating project maturity over time, offering a powerful tool to model and simulate dynamic interactions between the various criteria impacting the Hyperloop project. Maturity models are considered to be an effective way to evaluate various processes in projects (Wendler, 2012). Further, system dynamics allows for a holistic analysis that reveals how changes in one aspect of the project can influence outcomes across the entire system, reflecting the maturity level of development, management, monitoring, and implementation factors (DMMI) (Miller et al., 2002).

The aim of the research is to propose a conceptual system dynamics framework to evaluate the maturity of Hyperloop technology projects by modelling key technical, social, economic, and environmental dynamics, providing actionable insights to support decision-making in project management.

Research answers the following question: How can system dynamics modelling effectively evaluate the maturity of Hyperloop technology projects by integrating technical, social, economic, and environmental factors to support informed decision-making in project management?

The following research objectives are defined to solve the research question and fulfil the research aim:

1. To propose system dynamics models to measure the Hyperloop project's DMMI factors.
2. To propose a conceptual system dynamics framework for the evaluation of Hyperloop project maturity.
3. To validate system dynamics models using simulation scenarios.

Purpose. Potential users of the proposed conceptual framework and system dynamic models are decision-makers – to support choices and decisions increasing the project's chance of success, minimize project risks, prepare the workforce, policies development, support digital and green transformation of projects; researchers – to explore different development scenarios and evaluate impacts; industry analysts – to improve planning of Hyperloop project, develop business strategies, launch businesses and business transformation, and provide industry insights.

1. SYSTEM DYNAMICS MODELS DEVELOPMENT

Chapter 1 covers the development of system dynamics models that allow to measure the Hyperloop project's DMMI factors. It contributes to the completion of Objective 1. System dynamics is a methodology designed to understand the behaviour of complex systems over time, particularly focusing on the interactions between various components within these systems (Sterman, 2000). In the context of the Hyperloop project, system dynamics offers a powerful tool to model, simulate, and analyse the intricate interdependencies that influence the project's success.

1.1. Application of System Dynamics to Hyperloop Project

Given the multifaceted nature of the Hyperloop – encompassing technological, economic, environmental, and social dimensions — the application of system dynamics is both appropriate and necessary. These principles are employed to model critical success criteria (CR).

Figure 1 provides an overview of the key inputs required to evaluate the CR within the Hyperloop project and their calculation according to inputs. These criteria are environmental sustainability (CR_ENV), social acceptance (CR_SAC), technical feasibility (CR_TFE), safety (CR_SFY), regulatory approval (CR_REG), quantum factor (CR_QMF), economic viability (CR_ECV), usability (CR_USB), reliability (CR_RLB), infrastructure integration (CR_INF), and scalability (CR_SCL) (Vesjolijs, 2024a). Each criterion is a quantitative number in range (0…1). Inputs are associated with specific parameters, such as energy consumption (kWh), CO_2 emissions (kg), public opinion metrics, risk scores, and financial metrics. In business processes modelling, each CR is represented by stocks, flows, and feedback loops, which together define the dynamics of the system derived from the behaviour of systems theory (Forrester, 1990).

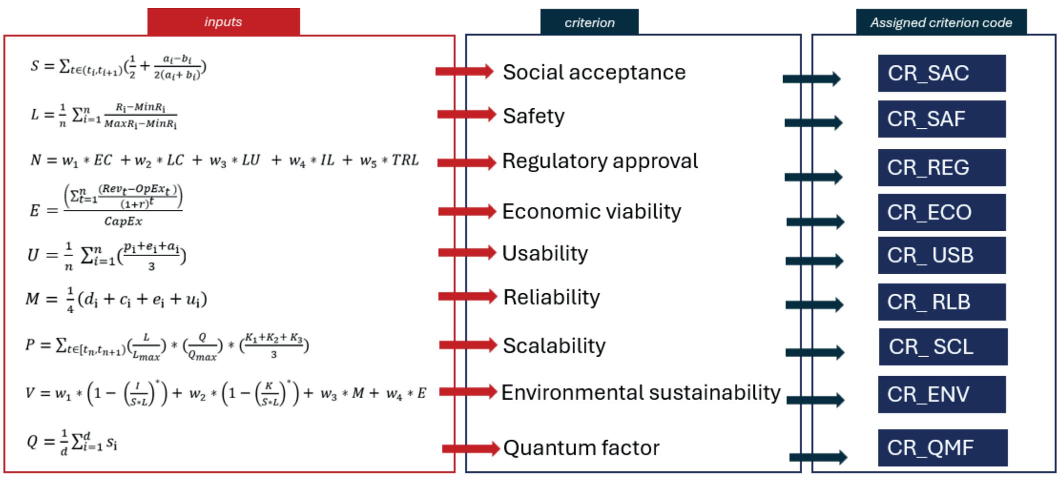

Fig. 1. Critical factors for the analysis of the Hyperloop project, mapping of formulae with criteria. Red lines indicate input mapping with criteria. Blue lines show the mapping between criteria and assigned codes (Vesjolijs, 2024a).

Table 1 shows the influence of the CR on the DMMI factors within the Hyperloop project. The table provides a mapping of how specific CR affect key aspects of project governance, strategic planning, technological integration, process optimisation, and performance evaluation.

Table 1. Overview of High-Level Inputs for Hyperloop Project Maturity

DMMI Factor	Input CR
Governance and management	CR_REG, CR_TFE, CR_SFY
Strategy and planning	CR_TFE, CR_ENV, CR_ECV
Technology and infrastructure	CR_TFE, CR_INF, CR_RLB
Processes and methodologies	CR_SFY, CR_TFE
People and culture	CR_SAC, CR_USB
Data and information management	CR_QMF, CR_RLB
Performance measurement	CR_ECV, CR_USB

1.2. Hyperloop System Dynamics Models

Research defined a set of conceptual system dynamics models to visualise feedback loops (Figs. 2–9). Based on conceptual models of feedback loops, the study provided a conceptual framework of Hyperloop project system dynamics (Fig. 9) that is the basis assessment methodology for Hyperloop technology implementation.

The conceptual model for governance and management (Fig. 2) serves as a strategic blueprint that aligns project execution with regulatory, technical, and safety standards. This model emphasises the critical role of regulatory approval (CR_REG), technical feasibility (CR_TFE), and safety (CR_SFY) in establishing a robust governance structure.

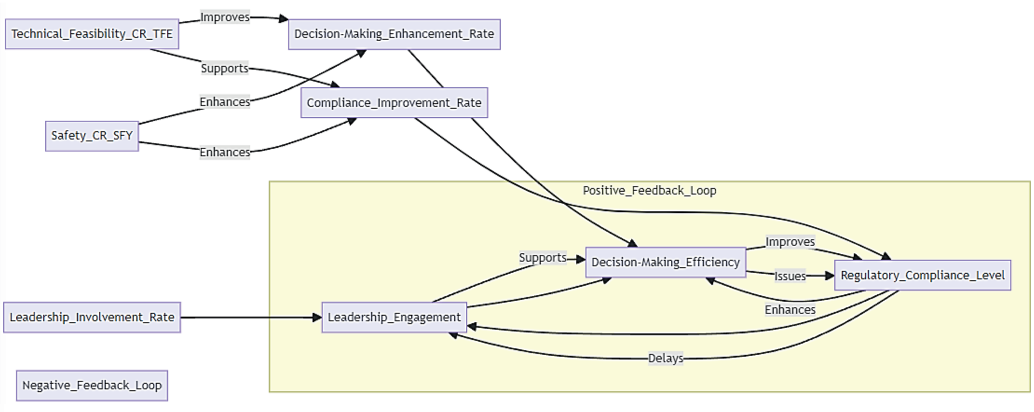

Fig. 2. Conceptual model for governance and management.

The conceptual model for strategy and planning (Fig. 3) is designed to evaluate the impacts of the project's long-term objectives against its operational capabilities and external environmental factors. This model integrates technical feasibility

(CR_TFE), environmental sustainability (CR_ENV), and economic viability (CR_ECV) to create a comprehensive planning approach that addresses current project needs.

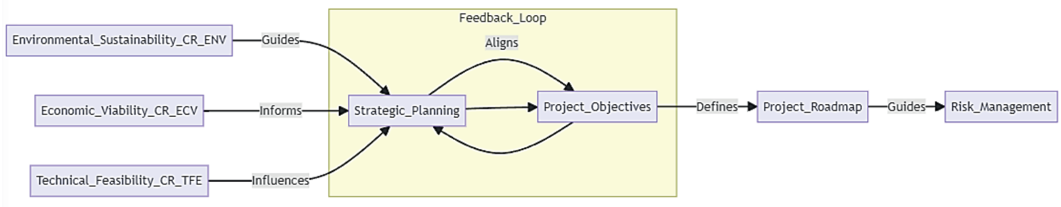

Fig. 3. Conceptual model for strategy and planning.

However, the conceptual model for technology and infrastructure (Fig. 4) is focused on supporting the system's long-term operational goals by ensuring that the technological and infrastructural components of the project are fully integrated and reliable. This model incorporates technical feasibility (CR_TFE), infrastructure integration (CR_INF), and reliability (CR_RLB) to create a cohesive and robust infrastructure plan.

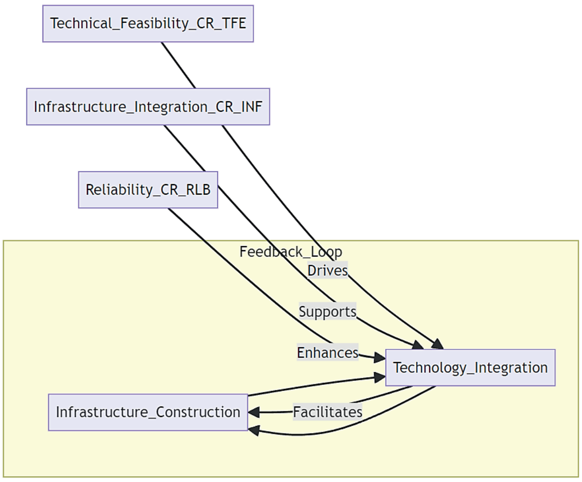

Fig. 4. Conceptual model for technology and infrastructure.

The conceptual model for processes and methodologies (Fig. 5) is designed to standardise and optimise the operational procedures that drive the project's execution. This model integrates safety (CR_SFY) and technical feasibility (CR_TFE) to establish efficient and reliable processes. The project must adhere to high standards of performance and risk management to be able to operate in the rapidly changing Hyperloop industry.

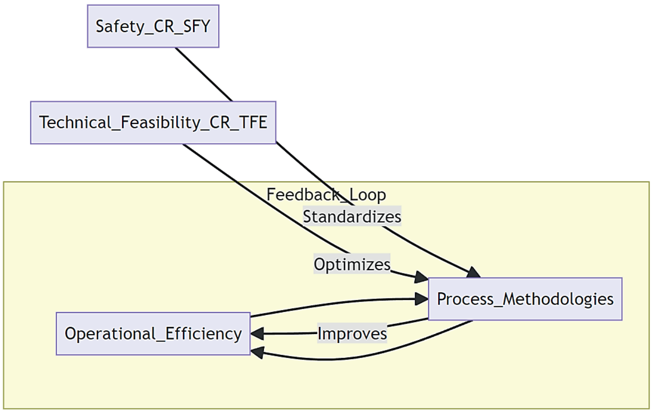

Fig. 5. Conceptual model for processes and methodologies.

The conceptual model for people and culture (Fig. 6) emphasises the importance of aligning the project's objectives with the needs, values, and expectations of both the workforce and the wider community. This model incorporates social acceptance (CR_SAC) and usability (CR_USB) to foster a supportive and inclusive environment that enhances both employee engagement and public perception.

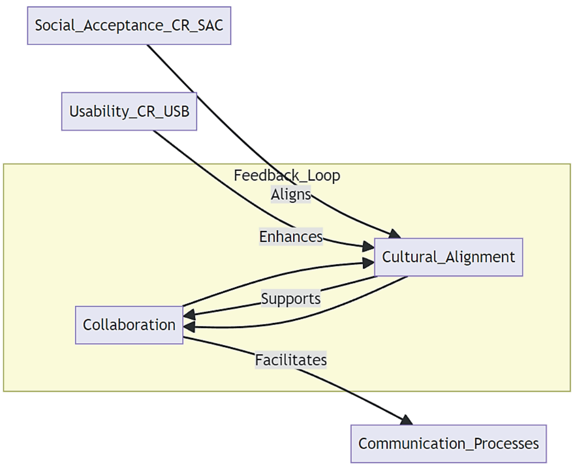

Fig. 6. Conceptual model for people and culture.

The conceptual model for data and information management (Fig. 7) is designed to ensure the effective handling, analysis, and utilisation of data throughout the project's lifecycle. This model integrates quantum factor (CR_QMF) and reliability (CR_RLB) to establish a comprehensive approach to managing both digital and technological data streams. CR_QMF reflects the cumulative impact of all disruptive technologies employed in the project, including but not limited to maglev levitation, ambient intelligence, generative AI, AI and machine learning, digital twins, 5G, quantum computing, augmented reality, virtual reality, large-scale 3D printing, blockchain, and self-driving autonomous vehicles.

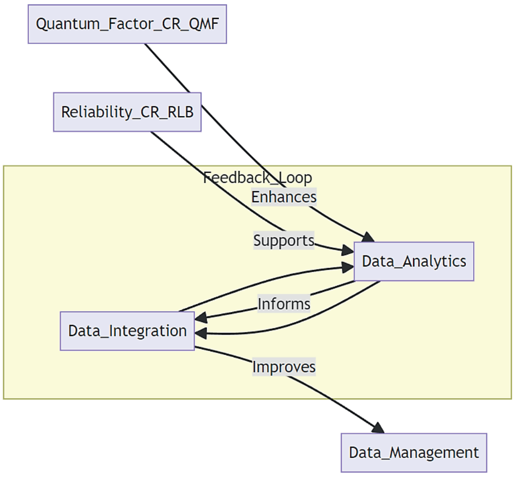

Fig. 7. Conceptual model for data and information management.

The conceptual model for performance measurement (Fig. 8) focuses on assessing the project's overall success through various key performance indicators that reflect its economic, operational, and user-centric outcomes. This model incorporates economic viability (CR_ECV) and usability (CR_USB) to establish a framework for evaluating the project's performance across multiple dimensions.

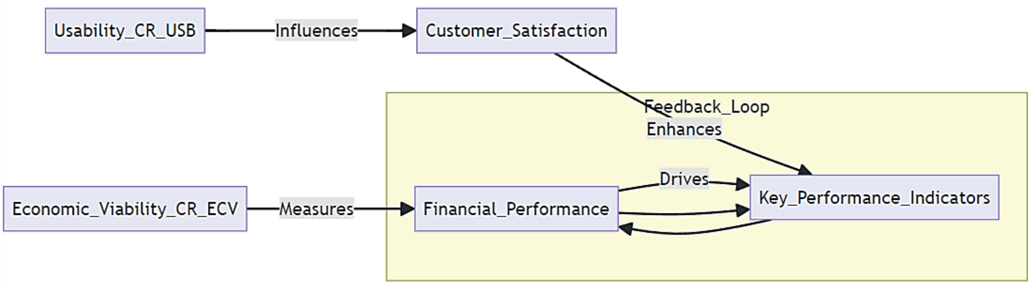

Fig. 8. Conceptual model for performance measurement.

2. CONCEPTUAL FRAMEWORK FOR HYPERLOOP PROJECT MATURITY EVALUATION

Chapter 2 covers the proposal of a conceptual framework for the Hyperloop project maturity evaluation. It contributes to the completion of Objective 2. The conceptual framework for the Hyperloop project's successful implementation (Fig. 9) represents the impact of Hyperloop system dynamics models on the project maturity level according to DMMI. It is a model designed to map out the intricate interactions between various factors that contribute to the successful implementation and progression of the Hyperloop project. The framework integrates key domains such as governance and management, strategy and planning, technology and infrastructure, processes and methodologies, people and culture, data and information management, and performance measurement. These domains do not operate in isolation; instead, they are interconnected through dynamic feedback loops that influence the project's overall maturity level.

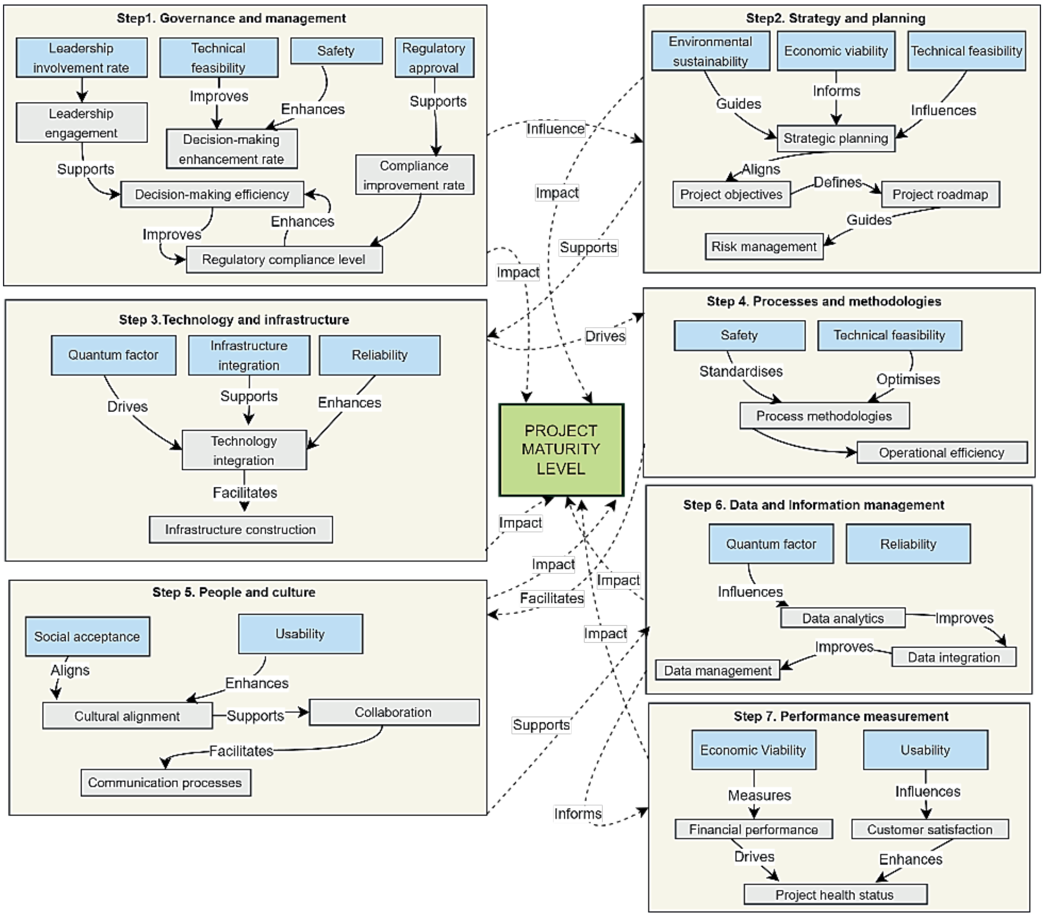

Fig. 9. Conceptual system dynamics framework for Hyperloop project maturity. Relations between conceptual models are represented with dotted lines. Processes in the maturity model are represented with hard lines. Input criteria are represented with blue blocks. Outputs are represented in grey blocks. Final project maturity is shown as a green block.

At the heart of this framework is the understanding that each domain supports and reinforces other domains, creating a robust structure that guides the project through its various stages of development. Governance and management set the foundation for decision-making and compliance, which in turn shapes strategic planning. The step-by-step framework breakdown with outcomes is shown in Table 2.

Table 2. Conceptual Framework's Step-by-Step Breakdown

Step	Component	Key processes and influences	Outcome
1	Governance and management	P1: Leadership involvement enhances technical feasibility and safety. P2: Regulatory approval improves compliance.	O1: Enhanced decision-making efficiency. O2: Increased regulatory compliance level.
2	Strategy and planning	P3: Strategic planning informed by environmental sustainability, economic viability, and technical feasibility.	O3: Aligned project objectives. O4: Defined project roadmap and guided risk management.
3	Technology and infrastructure	P4: Technology integration driven by technical feasibility, infrastructure integration, and reliability.	O5: Facilitated infrastructure construction. O6: Robust and operational technological foundation.
4	Processes and methodologies	P5: Standardisation and optimisation of processes based on safety and technical feasibility.	O7: Improved operational efficiency. O8: Alignment with safety and technical standards.
5	People and culture	P6: Social acceptance and usability drive cultural alignment.	O9: Enhanced collaboration. O10: Strong public and workforce support.
6	Data and information management	P7: Data analytics enhanced by the quantum factor and reliability. P8: Advanced data integration and management.	O11: Accurate and timely data for decision-making. O12: Continuous project improvement.
7	Performance measurement	P9: Evaluation through KPIs based on economic viability and usability.	O13: Informed project maturity level. O14: Assessment of financial performance and customer satisfaction.

2.1. Practical Implementation of System Dynamics Model

Simulations modelling inputs and outputs are schematically presented in Fig. 10. Inputs ($x_1 ... x_n$) are input parameters for each criterion calculation (Fig. 1, Table 1), where $t_1 ... t_n$ is dynamics over time represented in time periods.

System dynamics models are implemented as a software application, the prototype package name is HDME, corresponding to Hyperloop decision-making ecosystem according to the implementation framework (Vesjolijs, 2024b). The version released for deployment is v0.1.33. The application was developed using Python programming language and Streamlit library (Streamlit, 2024), with underlying data storage on Snowflake Data warehouse (Snowflake, 2024) featuring EGTL model (Vesjolijs, 2024c). Input data for simulations is synthetically generated and randomised based on analysis of the following Hyperloop projects: Hardt (Hardt, 2023), ePICenter (ePICenter, 2024), Swiftube (Swiftube, 2024) / (Wsimg, 2024), Zeleros (Zeleros, 2024), also dynamics of safety and technical feasibility factors for Hyperloop project are based on secondary research by evaluating IHT Hyperloop testing facility at Emden/Leer in Germany (IHT, 2024).

The HDME's GitHub repository (Digital.gov, 2024) (GitHub, 2024), contains developed application code. Technical implementation is tested using the Python unit test framework.

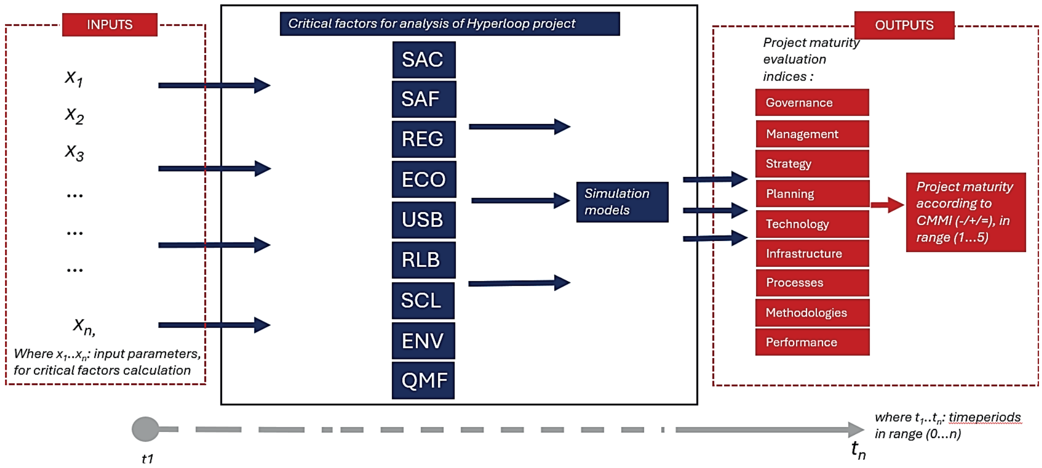

Fig. 10. Overview of simulation modelling inputs and outputs.

In evaluating the potential outcomes and risks associated with the implementation of the Hyperloop project, four distinct simulation scenarios were developed: rapid decline, decline over time, sustainable growth, and rapid growth. Each scenario models the project's performance under varying conditions, offering insights into project maturity evaluation. Scenarios are crafted corresponding to the simulation modelling theory proposed by Jay W. Forrester in Industrial Dynamics (Forrester, 2013).

3. RESULTS AND DISCUSSION

Chapter 3 covers the execution of simulation model scenarios, contributing to the completion of Objective 3. The results contain an analysis of simulation modelling results for rapid decline, decline over time, sustainable growth, and rapid growth scenarios obtained during the research. All simulations are conducted on time periods n = 100, where n represents the relative time measurement unit. The objective of running simulation scenarios was to validate the conceptual framework for evaluation of Hyperloop project maturity so that they are able to properly reflect project maturity level over time.

3.1. Hyperloop Project's Rapid Decline Simulation Modelling

The rapid decline simulation scenario was conducted to assess the resilience of the system under conditions of accelerated negative impact on various critical success factors.

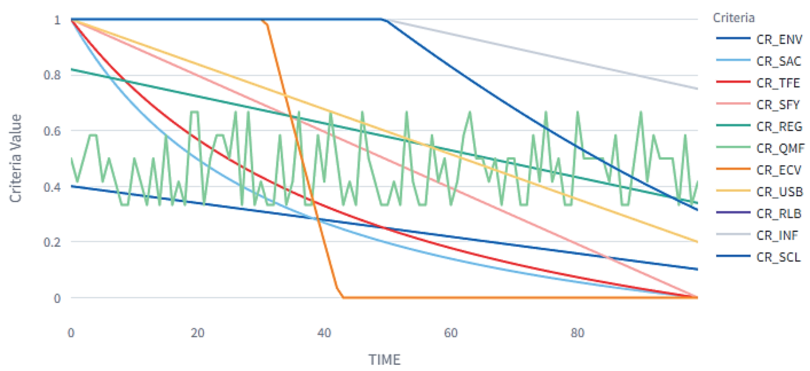

Fig. 11. Hyperloop project's rapid decline simulation – comparison of all criteria.

The comparison of simulation modelling results, as visualised in Fig. 11, demonstrated a steep decline across several critical criteria over time. For instance, the CR_ENV shows a marked decrease from an initial value of 0.4 to nearly 0.1 by the end of the simulation period. This trend indicates that the project's environmental viability is highly sensitive to adverse conditions, which could undermine its long-term sustainability and acceptance by stakeholders.

CR_SAC also plummets sharply, reflecting the project's vulnerability to public opinion and media influence. The rapid decline in this criterion suggests that negative perceptions or controversies surrounding the project could rapidly erode public support, posing a significant risk to its continuation. Similarly, CR_TFE exhibits a substantial downward trend, highlighting potential challenges in maintaining technological robustness under stress.

3.2. Hyperloop Project's Decline Over Time Simulation Modelling

Hyperloop project's decline over time scenario simulation was conducted to evaluate how various critical success factors degrade gradually under adverse conditions. It provided insights into the long-term sustainability and resilience of the Hyperloop system when exposed to persistent negative influences.

Figure 12 illustrates the decline of several critical criteria over time. CR_ENV criterion, which starts at 0.4, decreases steadily throughout the simulation, reaching approximately 0.35 by the end. This trend suggests that the project's environmental performance will deteriorate gradually if not actively managed. CR_SAC and CR_TFE also follow a similar declining trajectory, indicating that without continuous public engagement and technological innovation, the project's viability may be compromised over time.

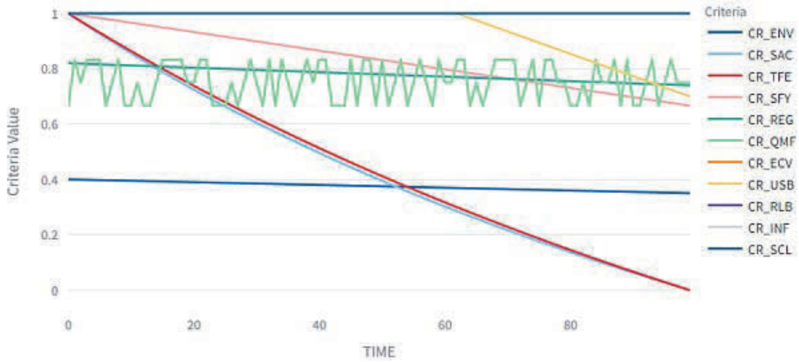

Fig. 12. Hyperloop project's decline over time simulation – comparison of all criteria.

3.3. Hyperloop Project's Sustainable Growth Simulation Modelling

The sustainable growth scenario for the Hyperloop project was simulated to evaluate the system's performance under favourable conditions where all critical success factors improve steadily over time. This scenario provides insights into the potential long-term success and scalability of the Hyperloop project if it receives consistent support, innovation, and regulatory approval.

Figure 13 illustrates the upward trends in key criteria such as CR_ENV, CR_SAC, and CR_TFE. Notably, CR_ENV shows a steady increase from an initial value of 0.4 to approximately 0.45 by the end of the simulation, indicating a continuous improvement in the project's environmental impact, likely due to advancements in green technologies and efficient resource use. CR_SAC and CR_TFE also exhibit significant growth, reaching their maximum values by the end of the period. This suggests that ongoing public engagement and technological development can lead to widespread acceptance and operational success.

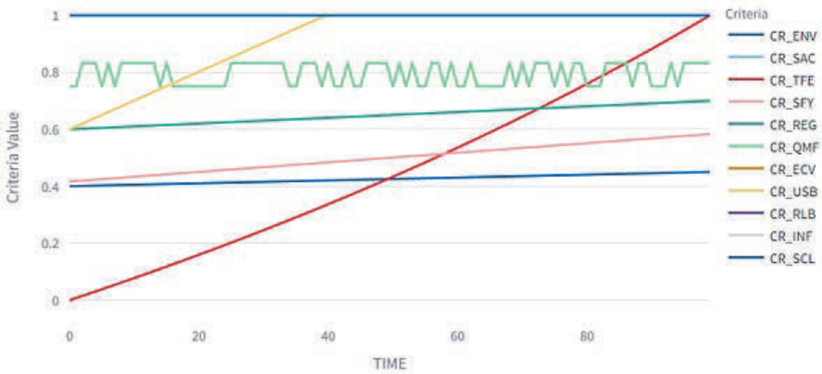

Fig. 13. Hyperloop project sustainable growth simulation – comparison of all criteria.

3.4. Hyperloop Project's Rapid Growth Simulation Modelling

The rapid growth scenario for the Hyperloop project was simulated to assess how the system would perform under conditions of accelerated positive development across critical success factors. This scenario explores the potential for the Hyperloop project to quickly achieve high levels of maturity and operational excellence.

Figure 14 highlights the upward trends in CR_ENV, CR_SAC, and CR_TFE. CR_ENV begins at 0.4 and rises steadily to approximately 0.46, reflecting the rapid integration of environmentally friendly practices and technologies. CR_SAC and CR_TFE both exhibit strong growth, with CR_SAC reaching its peak by the end of the simulation. This suggests that rapid public endorsement and technological advancements are achievable with the right strategies and innovations in place.

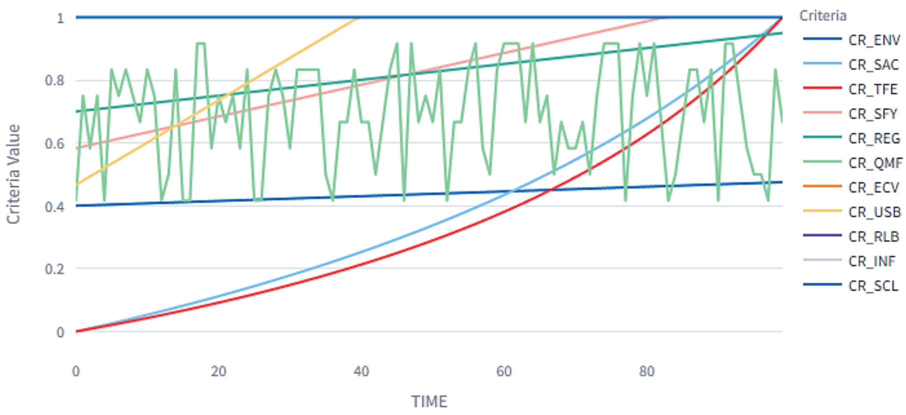

Fig. 14. Hyperloop project rapid growth simulation – comparison of all criteria.

3.5. Comparison of Simulation Modelling Analysis

The simulation of the given scenarios for the Hyperloop project provided insights into the potential trajectories and risks associated with each. A comparison of simulation maturity model changes is shown in Fig. 15.

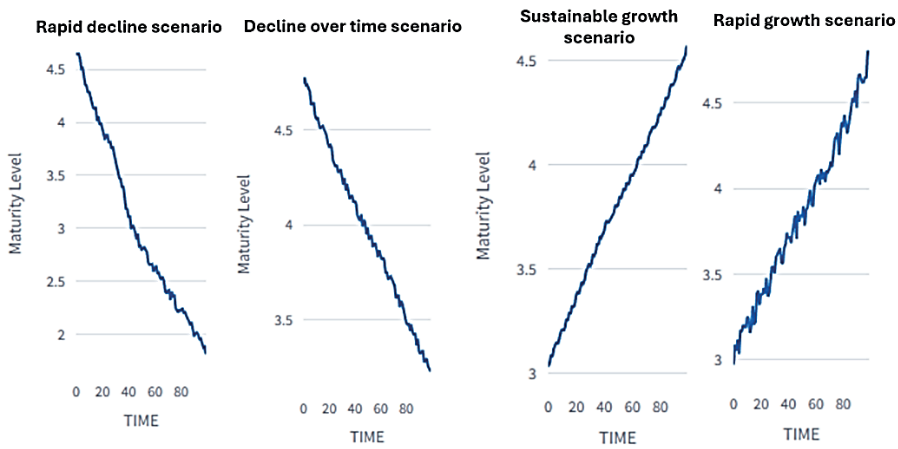

Fig. 15. Comparison of project maturity level based on simulation results.

The decline over time scenario poses the highest risk to the project. Unlike the rapid decline scenario, where quick, noticeable failures trigger immediate action, the gradual erosion of crucial factors like sustainability, social acceptance, and feasibility in decline over time scenario is subtle and often overlooked. This slow degradation fosters unseen vulnerabilities, leading to prolonged failures that may become irreversible if left unaddressed.

In contrast, the sustainable growth scenario is the most advantageous, demonstrating consistent, balanced progress across key success factors. This approach enhances long-term resilience by progressively improving environmental sustainability, social acceptance, and technical viability while maintaining economic stability.

Though promising, the rapid growth scenario introduces risks by accelerating development, which may strain existing protocols and infrastructure, heightening the likelihood of unforeseen setbacks. While it holds high potential, careful management is essential to mitigate these risks.

The findings underscore the framework's utility in assessing project maturity over time, addressing the research question effectively.

CONCLUSIONS

Implemented system dynamics models provide a multi-dimensional and real-time quantitative assessment tool for Hyperloop project maturity evaluation. It equips decision-makers with the insights needed to navigate the complexities of Hyperloop implementation, ultimately enhancing the likelihood of the project's success. The proposed framework demonstrated the ability to detect both negative and positive dynamics of changes in maturity and how each of the criteria with underlying parameters affect it.

By proposing a conceptual framework for Hyperloop project maturity evaluation, conducting simulation scenarios and comparing them, the research goal is achieved, objectives OBJ1, OBJ2, and OBJ3 are successfully completed, and the research question is answered.

The following Hyperloop project system dynamic models were developed and implemented: governance and management, strategy and planning, technology and infrastructure, processes and methodologies, people and culture, data and information management, and performance measurement, which are represented in the conceptual framework.

Developed system dynamics models enabled traceability of Hyperloop project processes, showed interrelations between different factors for its implementation, and evaluated maturity over time, ultimately providing insights for project managers, decision-makers, researchers and industry analysts. The research contributes to supporting European Green and Digital transformation, the EU Commission's mission for sustainable transportation (European Commission, 2024), and the United Nations Sustainable Development Goals 9, 10, and 13.

The next steps for the research are as follows:

1. Policy recommendation for Sustainable Transport and Tourism Committee (European Commission)
2. Propose a strategy for Hyperloop technology development and promotion in the EU.
3. Adopt system dynamics framework for Hyperloop project evaluation to EU Hyperloop industry: TUM, Institute for Hyperloop Technology, HARDT, Zeleros, Swissloop, and others.

Limitations. The simulation models may simplify complex realities of the mathematical framework. Simulation model dynamics over time is limited to system resources allocated to simulation.

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AUTHORS' SHORT BIOGRAPHY

Aleksejs Vesjolijs, PhD candidate, is a Senior Data Engineer at Accenture with more than 10 years of experience in building Big Data applications and is a certified AWS developer. Aleksejs holds a Master's degree in Engineering and successfully defended his Master's Thesis, "Evaluation of the importance of ethical requirements in AI solutions using an empirical approach". He is the Winner of the AI Global Hackathon 2020/Q3 as part of the Accenture Latvia team. Currently, he is a lecturer in STEM disciplines at the Transport and Telecommunication Institute in Riga.
E-mail: vesjolijs.a@tsi.lv; aleksejs.vesjolijs@accenture.com
ORCID iD: https://orcid.org/0009-0008-2845-7498