Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical & Industrial Engineering

Enhancing Railway Infrastructure Protection through System Dynamics Modeling and Analysis: A Case of the Ethio-Djibouti Railway

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University in partial fulfillment for the Degree of Master of Science in Industrial Engineering

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Declaration

I hereby declare that the work which is being presented in this thesis entitled “Enhancing Railway Infrastructure Protection through System Dynamics Modeling and Analysis: A Case of the Ethio-Djibouti Railway” is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of my Knowledge.

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ABSTRACT

The railway infrastructure in Ethiopia faces significant threats from natural disasters, human-made destruction, and technical failures. Reports indicate a concerning trend of frequent theft and vandalism incidents targeting critical railway components, which disrupt service, compromise safety, and incur substantial financial losses. This study aims to develop a comprehensive system dynamics model to identify the risks and challenges associated with protecting the Ethio-Djibouti Railway (EDR) infrastructure and propose effective mitigation strategies.

The research employs a mixed-methods approach, combining qualitative and quantitative data gathered through expert interviews, questioners and literature review. A system dynamics model is constructed to capture the key variables and their interrelationships affecting railway infrastructure protection. The model is used to simulate different scenarios and test the effectiveness of interventions.

The findings reveal that the selected Exogenous variables "community empowerment and awareness creation, accidents on domestic animals, and population density" have a great impact on the entire infrastructure security. Those variables are found to be effective in minimizing accidents, train delay time and blockages, and overall infrastructure damage. The study also highlights the impact of population density, where highly populated areas tend to experience increased theft and vandalism, leading to more train delays. In Addition to that this research also recommended and showed in the system dynamics model, Implementing various surveillance mechanisms, such as technology-enabled monitoring, can significantly reduce the incidents of theft and vandalism.

By integrating Crime Prevention Through Environmental Design (CPTED) principles with system dynamics modeling, this research provides a holistic framework for improving the overall safety and security of the EDR infrastructure. The study's recommendations serve as a valuable resource for future studies, policymakers and railway operators to develop and implement targeted interventions to safeguard railway infrastructure.

Keywords: System Dynamics; Railway Infrastructure; CPTED; Critical Infrastructure

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EDR- Ethio-Djibouti Railway

CPTED- Crime Prevention Through Environmental Design

SD- System Dynamics

CIs- Critical Infrastructures

RIS- Railway Infrastructure Systems

EU-European Union

US-United States

ECIs- European Critical Infrastructures

ITS- Intelligent Transportation Systems

IoT- Internet of Things

AI- Artificial Intelligence

DL- Deep Learning

ML- Machine Learning

UAV- Unmanned Autonomous Vehicle

CCTV- Closed Circuit Television

HSR- High Speed Railway

CLD- Causal Loop Diagram

SFD- Stock Flow Diagram

OCS- Overhead Contact Systems

OCC- Operation Control Centers

HMI- Human Machine Interfaces

NA-Not Available

CHAPTER ONE

1. INTRODUCTION

1.1. Background and Justification of the study

The most industrialized countries are equipped with increasingly extensive and sophisticated infrastructure systems, so-called critical infrastructures (CIs) such as energy distribution networks and transport infrastructures (De Felice et al., 2022). Critical infrastructures are crucial components of modern society, encompassing vital systems like electricity generation, transmission, and distribution, transportation networks, and water supply systems. These infrastructures are indispensable for the smooth operation of various sectors and the provision of essential services to the public. However, their importance also renders them susceptible to malicious attacks, natural disasters, and other disruptive events, making their security and resilience of utmost importance (Šarūnienė et al., 2024). Railway transport infrastructure is one of the most important and critical modes of transport on land for people and freight. Studies indicated that due to its criticality and significant influence on social, economic, psychological, and political aspects it is frequently prime targets for attacks (Rehak & Slivkova, 2020).

The Ethio-Djibouti Railway (EDR) was established as a joint-ventured commercial enterprise following an agreement between the governments of Ethiopia and Djibouti. It operates under the Ethiopian Commerce Code and falls under the jurisdiction of the FDRE Ministry of Transport and Logistics, as stated in Proclamation No. 1097/2018 (Logistics, 2022). The company was founded in April 2017 with an initial capital investment of $500 million USD, based on a Bilateral Agreement between the two states, the Federal Democratic Republic of Ethiopia and the Republic of Djibouti. Starting from January 1, 2018, the EDR has been providing passenger and freight transport services. The railway infrastructure of the EDR spans a total of 756 km, with the majority (656 km) located in Ethiopia and the remaining portion (approximately 100 km) in Djibouti (Railway, 2023).

According to the company's the last four years reports, a number of theft and vandalism occurrences prevented the railway from operating at maximum efficiency. Over time, the company has encountered more and more theft and vandalism incidents. Due to this, most frequently, the company canceled its several-day train operation. For this reason, it lost its expected income and is exposed to unnecessary additional maintenance costs. Therefore, in order to mitigate the problem this study aims to develop a system dynamics model to analyze the impact of the threats and to provide a protection strategy. The study also try to analyze the vulnerability of EDR infrastructure to various risks, including terrorism, theft and vandalism, which can cause significant damage and disruption. Furthermore, since the infrastructure is a critical transportation link between Ethiopia and Djibouti and is vital to both countries' economies, the study demonstrates the situation by using a system dynamics approach to model and analyze the complex interdependencies between the various factors that affect the railway infrastructure's protection. The overall goal is to provide decision-makers with insights into the most effective strategies for mitigating risks and protecting railway infrastructure.

In the years following independence, the railway was an essential part of African logistics and transportation. However, a variety of issues limit the progress of the infrastructure. Today, railway transportation has recently gained attention for its potential for considerable social, economic, and environmental benefits (Bouraima et al., 2023). Studies don't deny that in the past years African railways are far behind those of most other parts of the world. The main causes of these situations in Africa are the unfavorable institutional, technological, and economic circumstances (Transport & Department, 2015). Railway Infrastructure Systems (RIS) in urban areas are attractive targets for attackers due to their inherent value, vulnerability, and challenges associated with ensuring proper protection. Factors contributing to this vulnerability include open infrastructure design, presence of hazardous materials, extensive infrastructure coverage, and the significant economic and social importance of railway transportation services. Consequently, effective prevention and preparedness measures are crucial to mitigate risks associated with RIS (Sforza et al., 2013).

Beside this, there exist hazards to the railway system and its individual components in terms of politics, economy, society, technology, and the environment. Additionally, the location of particular parts of the railways in relation to their surrounds, connections, and other transportation networks can create risks (Kotalovaa et al., 2021). While it may not be possible to entirely eliminate certain risks, it is essential to accurately and promptly identify them in order to develop a mitigation plan. Effective risk management enhances management's understanding, increases the likelihood of achieving goals, promotes internal communication within the organization, minimizes unexpected occurrences, boosts confidence in making challenging decisions, enhances the quality of services, and safeguards the organization's reputation (Macura et al., 2022).

The Ethio-Djibouti Railway is a major railway infrastructure connecting Ethiopia and Djibouti. The railway was inaugurated in 2017 and has since become a vital transportation route for both countries. However, the railway was not performing to its potential due mainly to theft and vandalism. The past reports of the company for 2020 indicated that the railway had lost 114 million ETB in the first quarter of the fiscal year (Mekonnen, 2020). Due to this, the speed limit of the trains has been reduced from 80 km per hour to 50 km per hour. Many damages to the railway infrastructure are the major obstacle to the entire train operation. At the beginning of the railway operation, the trip from Addis Abeba to Djibouti took 12 hours; now it takes 18 hours, lagging by 6 hours from its previous arrival time (Mekonnen, 2020). Therefore, it is essential to study in this area in order to mitigate the problem. This study will try to identify the potential threats that affect the EDR infrastructure, and evaluate their impacts using a system dynamics approach, then finally try to provide and recommend different mitigation strategies.

1.2.Problem Statement

The EDR infrastructure is vulnerable to various hazards, including natural disasters, human made destruction and technical failures. Reports indicated that there is a frequent theft and vandalism record on the EDR infrastructure (Israel, 2023). This frequent theft and vandalism on the railway infrastructure poses a significant threat to the sustainability and safety of the line. The theft of critical components, such as signaling equipment, power cables rail fasteners can cause disruptions to train services and compromise transportation safety. Similarly, vandalism of the railway infrastructure, such as damage to tracks, concrete masts, culverts and bridges, can lead to accidents and derailments (Burroughs, 2020). According to the company’s safety and security first biannual 2023 report 311 thefts and vandalisms are recorded on the first half of 2022. Similar reports indicated that 212 thefts and vandalism records on the first half of 2023.

Table 1.1:Theft and vandalism incident comparison of first biannual 2022 report with 2023

Period	Theft and Vandalism	Train Blocking	Total Incidents
First half of 2023	311	41	352
First half of 2022	212	50	262
Comparison	+ 99	- 9	+ 90

The increasing thefts and vandalism can disrupt the normal functioning of the company and lead to delays in production or service delivery (George et al., 2018). The company incurs extra expenses for repairing damages and replacing stolen items, which can have a negative impact on its profitability and competitive position in the market. According to the Railway Safety, Environment, and Quality Department report, the estimated damage for the first eleven months of the fiscal year (2023) was above 115 million birr (Israel, 2023). Additionally, if these incidents are not promptly addressed, it could erode customer trust and loyalty. Moreover, since the railway line is the primary transportation link connecting the sea port of Djibouti to Ethiopia, such incidents have a significant impact on the country's overall economy.

Therefore, to ensure the protection and sustainability of the railway infrastructure, this study tried to model a comprehensive system dynamics model and by analyzing it tried to identify potential risks, evaluate their impacts, and recommend and suggest effective mitigation strategies.

1.3.Research Questions

Specifically, the following research questions need to be addressed:

1. What are the existing practices and recent research advancements in the global railway industry regarding the modeling and resolution of issues related to railway infrastructure protection?
2. What are critical factors and decision points that significantly influence the safety and security of the EDR infrastructure?

3. How can we categorize and describe the factors in a manner that facilitates understanding through the development of a system dynamics model?
4. What potential recommendations can be offered to the Ethio-Djibouti Railway (EDR) regarding strategies to effectively mitigate the impact of theft and vandalism, to enhancing the overall safety of the railway infrastructure?

1.4.Objectives of the Study

1.4.1. General Objective

The main objective of this research is to identify the risks and challenges of the EDR infrastructure protection and to recommend strategies to mitigate these risks.

1.4.2. Specific Objectives

1. To examine scenarios within the global railway industry practices, it allows for a comparative assessment of international practices, with the aim of identifying strategies to enhance safety and security measures.
2. To provide a comprehensive review of sources to identify and analyze critical factors and decision points to safety and security risks associated with railway infrastructure protection.
3. To categorize and describe factors by providing a system dynamics model to easier understanding of the characteristics of factors affecting railway infrastructure protection.
4. To recommend strategies to effectively mitigate the impact of theft and vandalism, thereby enhancing the overall safety of the railway infrastructure.

1.5.Significance of the Study

As mentioned in the above subtopics, this study aims to develop a system dynamics model that can help identify potential threats to railway infrastructure and assess their impact. By doing so, the study can help EDR to recommend effective strategies to mitigate the impact of these threats and enhance the safety of railway infrastructure. Moreover, it is significant to improve the resilience of railway infrastructure in the face of potential threats. also help to ensure that railway infrastructure can withstand potential threats and continue to operate smoothly. Furthermore, the study will contribute to the body of knowledge on system dynamics modeling and analysis for the protection of railway infrastructure. This can help inform future research in the field and lead to further improvements in the safety and resilience of railway infrastructure. Overall, the study is significant as it has the potential to improve the safety and resilience of railway infrastructure, inform policy decisions, and contribute to knowledge in the field.

1.6.Scope of the Research

The scope of this study is to provide valuable insights into the impact of human-made threats, specifically vandalism, theft and sabotage, on the Ethio-Djibouti Railway (EDR) infrastructure. The study focusses on identifying the various physical threats that can affect the railway infrastructure, with particular emphasis in Ethiopia section of the line starting from SEBETA to DAWANLE. While the study may not encompass a full-scale implementation of system dynamics modeling for the railway infrastructure, it utilized this modeling approach to analyze the consequences of identified threats and propose mitigation strategies.

The sample of interviewees selected for this study focus primarily on employees from the Addis Ababa (INDODE) and DIRE DAWA infrastructure maintenance centers in Ethiopia. Because the workers have deep understanding of the operations and challenges within the railway infrastructure along the EDR line. These individuals had specifically chosen to provide valuable insights and perspectives regarding the research questions.

Similarly, the data collection process and site visits primarily take place within the infrastructure located in Ethiopia, ensuring a comprehensive understanding of the specific context and challenges faced by the EDR in this region. By concentrating on these specific areas, the study aims to gather in-depth information and firsthand experiences related to the impact of human-made threats on the EDR infrastructure in Ethiopia.

1.7.Limitations of the Study

The study tried to gather the last three to four years of recorded data that encompasses various incidents and accidents on the Ethio-Djibouti Railway (EDR) infrastructure facilities. This data is used in this study as a secondary data source, but some of the data is not complete; therefore, it is used as representative data, which makes it difficult to address all the vulnerabilities of the company's infrastructure to threats. Despite these limitations, the study tried to provide valuable insights within the available data constraints, drawing on literature and targeted research to shed light on the impact of human-made threats on the EDR infrastructure.

1.8.Organization of the Paper

The study has six major chapters. The first chapter includes the problem statement, research questions, and objective of the study. The second chapter discusses related literature reviews on railway infrastructure protection, emerging technologies and innovations for the protection of railway infrastructure, stakeholder engagement and collaboration, and the best practices of selected countries. In the third chapter, the research design and methodological approach are discussed. The collected data from primary and secondary sources is analyzed, and the core problems of the Ethio Djibouti Railway (EDR) are identified in the fourth chapter. The next chapter is Chapter five this chapter shows the system dynamics model development. The results and testing of the models are included in the sixth chapter. The last part included conclusions, recommendations, references used, and appendices.

CHAPTER TWO

2. LITERATURE REVIEW

2.1.Introduction

The development and maintenance of transportation infrastructure are crucial for the social and economic advancement of a country. Investments in infrastructure expansion play a vital role in promoting faster economic growth for a nation (Macura et al., 2022). Rail transportation offers a high level of comfort, safety, and environmental friendliness. However, it requires substantial capital investment and faces limitations in terms of accessibility. To remain competitive, rail systems need to be well-maintained, and their performance should be regularly evaluated (Stenström et al., 2015). The railway is a cost-effective transportation mode that fosters social development, environmental sustainability, economic expansion, and interregional cooperation. It plays a significant role in public transit and provides extensive transportation services on a global scale. With its large capacity, high safety standards, relative comfort, speed, fair fares, and environmental consciousness, the railway stands out as a unique form of mass transit (Roy et al., 2023). Railway systems are extensive and encompass a wide range of interconnected systems, subsystems, and components. Considering features of a railway station and its interconnections, it is important to recognize that various threats can jeopardize the integrity of railway infrastructure. These threats may arise from political, economic, social, technological, legislative, or environmental factors. To address these risks, proactive or reactive measures can be implemented to prevent or reduce their impact (Kotalovaa et al., 2021).

The interconnections among critical infrastructure sectors establish distinct interdependence relationships, indicating that each infrastructure relies on the products and services of others. In the event of a disruption, damage, or destruction in any one infrastructure, it can trigger a chain reaction, causing cascading effects across multiple critical infrastructures (Alcaraza & Zeadally, 2015). In an era of ongoing globalization, safeguarding critical infrastructure presents a transnational challenge. Among various targets, transport networks often become prime targets for terrorist attacks due to their substantial impact on social, economic, psychological, and political domains (Hedel, 2018). Rail transportation was included as one of the European Critical Infrastructure sectors in 2008. Subsequently, EU member states began to acknowledge and identify the various components of critical railway infrastructure at both the European and national levels (Rehak & Slivkova, 2020)

2.2.Railway Infrastructure Protection

2.2.1. Railway Infrastructure Assets

According to Urbancová and Sventeková (2019) the railway network is composed of tracks, terminals, and permanent equipment that ensure safe and uninterrupted train operations. Railway infrastructures can be categorized into three types: point elements, linear elements, and surface elements. Linear elements facilitate transportation between two points and connect individual components like tracks, track sections, and interstate segments. Point elements are concentrated units serving specific line elements, such as security devices, switches, and electrical equipment. Surface elements are complex units involving multiple point and linear elements, such as railway nodes, crossings with security equipment, and stations with security equipment. They also include certain traffic management systems.

Furthermore, a railway-based transportation system encompasses a multitude of significant assets, known as Main Areas of Interest, which differ in type and purpose. As highlighted by D'Amore and Tedesco (2015), these assets include public areas (entrance, waiting rooms, platforms), technical and operative rooms (command center, interlocking room), restricted areas (tracks, tunnels, depot), and open areas (bridges, viaducts, level crossing) within the train station.

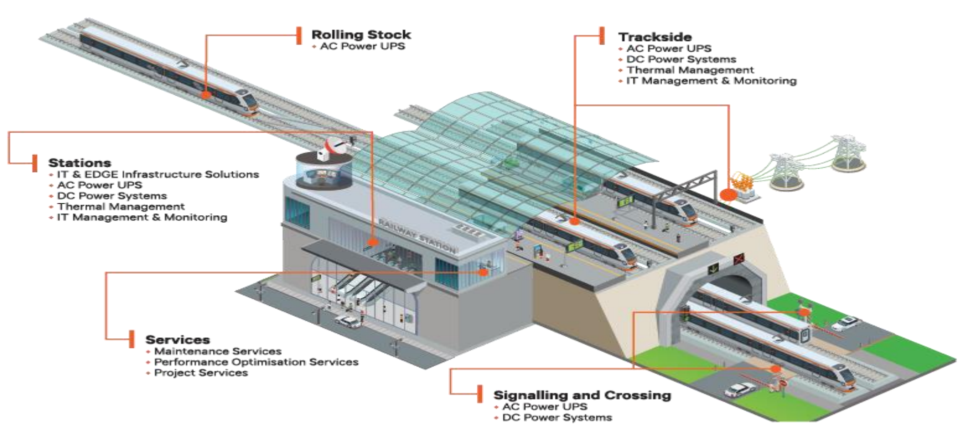

Figure 2.1: Railway Infrastructure Assets(https://www.vertiv.com)

Every asset in the system plays a distinct role, and each asset's proper operation might have an impact on other assets' ongoing operability and functionality. An electrical substation's continuous operation, for instance, is essential to the line's overall operability. Therefore, the electrical substation needs to be properly protected and should be viewed as a potential target of a hostile attack (D’Amore & Tedesco, 2015).

2.2.2. Railway Infrastructure Safety & Security

Railways have always been based on the idea that transportation should be as safe as feasible. Rail transportation is still one of the safest forms of transportation, despite the fact that accidents happen frequently in the railway industry because of the volume of cargo transported, the density of traffic, and the range of services provided. Also there are more dangers threatening the railway industry, like criminality and terrorism (Colliard, 2015). The identification, mitigation, and protection of peoples as well as railway infrastructure against physical threats are the core of transportation system security (Hedel, 2018). With this point of view Bullock et al. (2018) stated that “Transportation security, namely the identification, assessment, and reduction of vulnerabilities within and threats to the vast transportation network, has expanded greatly, experiencing great change and challenge along the way”.

Regardless of their size or industry, businesses require security measures to ensure the safety and integrity of their data, assets, and key operations. These days, modern security organizations prioritize protecting any relevant information about technology, organization, marketing, or production that could give the business a competitive advantage. To put it another way, they have expanded their previous surveillance and protection efforts to include business intelligence, competitive intelligence, crisis management, risk management, and information communication security technology (Fiumara, 2015). The most significant difficulty facing railways worldwide is improving their security standards while maintaining their accessibility, openness, extensiveness and affordability. Security for railway systems can be summed up as keeping an eye on and safeguarding the infrastructure such as stations, tunnels, rolling stock, bridges, viaducts, depots, yards, etc. against antisocial behavior, theft, vandalism, terrorism, sabotage, and unauthorized access to restricted areas (D’Amore & Tedesco, 2015). For further understanding Jankura (2021) stated that numerous internal and external risks have the potential to compromise the safety of rail stations. Stations in general, including train stations, might be categorized as soft targets. It is reasonable to anticipate that it could be the target of several attacks. The term "Soft target" has multiple definitions that might be applied. They are generally recognized as areas with a high population density and inadequate security against assaults, making them appealing targets, particularly for terrorists (Jankura, 2021).

In light of these safety and security concerns, as well as the fact that the railway system is susceptible to numerous security-related vulnerabilities and that railway traffic safety is a major concern, as well as the fact that the railway system provides mass transportation for remote areas, it is essential to develop security activities in addition to industrial and service ones in order to ensure the railway system's continued existence as the largest national network infrastructure (Fiumara, 2015). Implementing a security system is highly valuable as it helps prevent incidents and instills confidence, even though achieving absolute security is challenging. A heightened level of security enhances the perception of a railway system's resilience against potential attacks, making it a trusted and reliable mode of mass transportation. The standard methodology for designing security systems in rail-based transportation consists of four fundamental components: developing subsystems for sensing and monitoring, conducting risk assessment and analysis, and constructing an integrated management system for security (D'Amore & Tedesco, 2015).

These rail infrastructures have a basic economic role for the country, and they are a means of mass transportation systems for people as well as fright. So they could be in a unique position as potential targets for attacks (Hedel, 2018). Furthermore, these infrastructures for mass transit networks are considerably more vulnerable in industrialized nations, especially to dangers related to cyber and physical security (Hedel, 2018).

2.2.3. Vulnerability of Railway Infrastructure for Potential Threats

Research showed that governments in various nations have enumerated the sectors based on how important they are to society. For example, the US government identified 16 critical sectors that are so important to the country that their failure or impairment would seriously compromise national security, national economic security, national public health or safety, or any combination of these (Agency, 2023). Furthermore, the European Commission in the early time identified 11 industries based on their criticality in its COM (2006)787. The transportation sector is one of the mentioned things among these sectors in every instance. The 2008/114/EC, which calls on Member

States to identify European Critical Infrastructures (ECIs) as a first step towards their protection, demonstrates the significance of this industry. This protocol was only requested in the transportation and energy sectors, as well as their subsectors (Maggio & Setola, 2013).

Critical infrastructures are vulnerable to attacks because to their particular features and symbolic significance, as demonstrated by the high number of targeted incidents that have taken place. The Railway Infrastructure System is a prominent entity in this regard. The sheer volume of events globally indicates how appealing the Railway Infrastructure System is as a target for terrorists and criminals (Cillis et al., 2015). On the other hand, from the standpoint of risks, railway infrastructure is especially exposed to and susceptible to hydrometeorological or weather-related disasters. Examples of atmospheric, hydrological, and oceanic phenomena that have the potential to significantly affect infrastructure and human life include storm surges, flooding, droughts, and extremely high or low temperatures. Unaccounted for in its original design, the exposure of railway infrastructure to severe temperatures may reduce its lifespan, physically endanger the safe running of rail services, and raise maintenance and operating expenses (Blackwood et al., 2022)

Researches exemplify different possible threats to the entire railway infrastructure. For instance, Possible threats of railway stations and railway trucks are classified as caused by natural impacts and human activity. Under the natural impact studies categories flood, fire, earthquake, landslides and external weather fluctuations such as storms, hailstorms and windstorms can mention. Threats like fire and bomb attack categorized under threats caused by human activity (Urbancová & Sventeková, 2019). Furthermore, section breakdowns and unpredictable train operations are mostly caused by theft and vandalism of rail infrastructure equipment, especially along general freight lines (George et al., 2018). The threats to railway infrastructure include vandalism, theft and aggression, sabotage, and terrorism. Vandalism involves the intentional destruction, defacement, and harm to infrastructure. Theft and aggression encompass physical attacks on staff and passengers and property theft. Sabotage refers to acts aimed at interfering with or damaging the physical infrastructure. Terrorism involves threats and premeditated acts of violence, such as gas attacks, bombings, and other forms of harm and disruption (De Cillis et al., 2013). Other risks that should be mentioned are the risk of organized crime, extremism, the risk of noise externalities, the risks employees of the railways exposed and consequences of the extreme negative social impact on the population (Dvořáka et al., 2017).

2.3. Emerging Technologies and Innovations for Protection of Railway Infrastructure

Emerging technologies are science-based innovations that have the potential to create new industries or transform existing ones. They can benefit the entire railway system, the economy, and social integration. These technologies encompass radical and evolutionary advancements, including the convergence of research streams (platform, 2019). These technologies explore various aspects like characteristics and effects, including shifting value chains, digitization of goods, and shifting locus of innovation. While they show high potential, their value and consensus are yet to be established. Common threads in the definitions of emerging technologies include rapid growth, transitional nature, untapped market potential, and reliance on scientific foundations (Rotolo et al., 2015). In the coming years, the railway industry and its associated sectors will increasingly depend on the Intelligent Transportation Systems (ITS) paradigm. This shift will bring forth a range of innovative integrated security services. Additionally, it will lead to enhanced fleet management and the application of Industry 4.0 concepts, such as predictive maintenance for railway vehicles and infrastructure. These advancements aim to minimize operational costs and improve traffic capacity in the rail network (Kljaic et al., 2023).

2.3.1. Advanced analytics and System Thinking

In the context of railway infrastructure, vandalism and theft are the most prevalent risk scenarios. To mitigate these vulnerabilities and implement appropriate countermeasures, it is crucial to select the right technologies for the security system's design. Studies emphasize the importance of utilizing CCTV and video analytics, access control and anti-intrusion measures, abnormal sound detection, and subsystems for detecting chemical, biological, radiological, nuclear, and explosive threats. These technological subsystems are commonly employed by designers to safeguard rail transport assets (D’Amore & Tedesco, 2015). Digital technologies offer the rail sector a chance to achieve social, economic, and environmental sustainability, provided they are implemented correctly. However, realizing the full potential of technology will necessitate more than just technological changes. It will require integrating physical assets with digital assets and effectively utilizing data, simulation, and modeling. To bring about this transformation, visionary leadership informed by systems engineering will be essential, enabling innovation across the entire railway life cycle (Steele & Roberts, 2022).

Furthermore, since critical infrastructure in the modern day, such as railways, is evolving into a more intelligent and adaptive system, Scholars agree that system thinking is necessary to ensure the resilience of critical infrastructure. They proposed a number of essential features that public policies should take into account when shifting from a protection-centric strategy to one that stresses resilience from a system-thinking perspective, extending the idea of system approach as it relates to critical infrastructure resilience (OECDilibrary, 2023). According to OECDilibrary (2023) Infrastructure resilience requires an all-hazards and threats approach that considers the entire system, interdependencies between sectors, and public-private cooperation. Resilience measures should be implemented throughout the infrastructure life-cycle and the entire risk management cycle. A risk-based and layered approach is necessary to prioritize measures and account for complex interdependencies. Fostering international cooperation is also important in addressing transboundary risks.

2.4.Stakeholder Engagement and Community Collaboration

Stakeholders are vital players who contribute significantly to transportation networks. Stakeholders can directly influence the factors that promote sustainable development, infrastructure development, and technological innovation. Researching stakeholder interactions, behaviors, and perceptions is essential because technology-driven projects frequently fail. According to research, the stakeholders include the media, law firms, commuters, neighborhoods, company owners, and government agencies including City and Reginal administrations. (Rangarajan et al., 2013).

2.5. Countries Best Practices in railway infrastructure protection.

This portion of the literature review focuses on the third aspect of the research specific objective. In today's world, rail transport plays a vital role in a country's economy and it is imperative to understand global practices within the railway industry. By examining international practices in the railway sector, valuable insights can be gained to identify strategies for improving safety and security measures.

2.5.1. China

At present, railway is developing rapidly in China, where the length of High Speed Railway (HSR) is more than 30,000 km and it is about two-third of the world's high speed railways (Yu et al., 2023). Also, China has one of the world's most extensive railway networks, spanning thousands of miles and connecting numerous cities and regions. With the increasing importance of railway transportation, ensuring the safety and security of passengers, infrastructure, and operations has become a top priority. China Railways are the primary railway operators under the supervision and management of government departments and is also the safety goals setter. It is responsible for the scheduling and commanding of the railway, monitoring, early warning, risk management, etc., which is a power conferred by law and regulation (Liu et al., 2023).

China Railways has successfully deployed cutting-edge surveillance systems throughout its extensive railway network. Currently, fixed-line video equipment plays a pivotal role in monitoring the environment of high-speed railways. The camera equipment remains stationary, providing continuous monitoring of crucial locations along the railway tracks (Jiang & Wang, 2021). These systems utilize a combination of high-definition CCTV cameras, thermal imaging technology, and video analytics to monitor critical areas such as platforms, stations, and tracks. The surveillance systems are integrated with a centralized control center, enabling real-time monitoring, incident detection, and proactive response to security threats (Yu et al., 2023).

To regulate access to restricted areas and ensure the safety of railway facilities, China Railways has implemented robust access control measures. Authorized personnel are issued smart cards or biometric credentials, allowing them to enter sensitive areas. This ensures that only authorized individuals have access to critical infrastructure, reducing the risk of unauthorized entry and potential security breaches (Martha Lawrence et al., 2019).

Public awareness initiatives that teach the public and passengers about safety procedures and emergency protocols are highly valued by China Railways. Most Chinese railway operators are socially responsible companies that use digital displays and announcements to efficiently spread important safety information throughout the whole railway network. Moreover, cooperative efforts have been undertaken to investigate various methods in specific sectors of poverty alleviation, including infrastructure development, consumption, industrial expansion, and e-commerce initiatives. Intellectual progress has the power to foster community trust and ownership in the system. Such activities help to prevent malicious attackers (CRRC, 2020).

2.5.2. India

India stands as one of Asia's swiftly urbanizing and economically thriving nations. The development of transportation infrastructure, particularly railroads, is closely linked with rapid economic growth. Indian Railways continues to hold a crucial role in the nation's economy and the integration of markets (Chakraborty & Dutta, 2022). It serves as a means of political unification by connecting vast territories. Over the years, rail passenger travel in India has witnessed a remarkable surge of approximately 200%, while freight traffic has grown by 150%. These figures highlight the social and economic achievements of the country. As urbanization continues to increase, the reliance on rail transportation is bound to escalate. This presents opportunities for investments in metro systems, high-speed railways, freight corridors, technological advancements, and the pressing need to replace outdated assets in the existing rail infrastructure. However, it is important to admit that this widespread rail network is exposed to various hazards, which pose risks in the event of disasters (Joshi et al., 2024).

Prior to the 2014-15 fiscal year, the safety record of the Indian Railways was suboptimal. During the 5-year period from 2009-10 to 2013-14, an average of 135 major train accidents occurred each year. Derailments accounted for around 47% of these consequential train accidents. Additionally, an average of 39% of the annual consequential train accidents took place at unmanned level crossings, which were responsible for approximately 56% of the total fatalities. However, the Indian Railways has since placed a strong emphasis on safety-critical areas such as level crossings, track maintenance, passenger coaches, and signaling systems. This concerted focus has led to a significant improvement in the overall safety performance of the rail network (Railways, 2021).

2.6.System Dynamics and Modeling with Vensim Professional Software

System Dynamics (SD), originally known as industrial dynamics, was introduced by Jay Forrester in the 1960s. Its primary objective was to comprehend and manage complex system behaviors. SD modeling enables a deeper understanding of the relationship between a system's behavior over time and its underlying structure, strategy, and policies (Lu et al., 2019).

The world is very complicated, and sometimes it's hard for us to understand everything. Our ideas about how things work is limited, inconsistent, and not always reliable. This means we often don't fully understand the long-term effects of the choices we make. We tend to focus on short-term and narrow views, which can end up causing problems for us in the future. To understand why policies sometimes don't work, we need to understand how complex systems and our ideas about them affect our decisions. Complexity can mean having a lot of different parts or connections in a system, but the most common issues come from dynamic complexity. This means that complex systems can behave in unexpected ways over time because of how different parts interact (Sterman, 2003). Infrastructure theft, vandalism, and sabotage are complicated problems because they involve many different factors, like different people being involved, many things that can be targeted, systems that are connected to each other, and environments that are always changing. System dynamics approaches can help us understand this complexity better and make smarter choices to solve these problems (Gonçalves & Serfontein, 2022).

SD offers a framework for modeling the intricate and ever-changing dynamics of organizational safety. It enables the modeling of complex cause-and-effect relationships that may not be immediately apparent and draws on various fields such as cognitive and social psychology, organization theory, and technical engineering processes (Lu et al., 2019). One of the system Dynamics Modeling software is Vensim Professional it is a popular software package for developing and analyzing System Dynamics models. Using System Dynamics Modeling, it is possible to simulate different scenarios and evaluate the effectiveness of various protection strategies. For example, the model helps to analyze the impact of physical security measures, emergency response plans, and maintenance and upgrades on the safety and security of railway infrastructure (Maggio & Setola, 2013). The software can also be used to identify potential vulnerabilities in railway infrastructure and evaluate the effectiveness of different risk mitigation strategies. By simulating different scenarios, it is possible to identify potential weaknesses in the infrastructure and develop strategies to address these vulnerabilities (Zeng et al., 2022).

In the model conceptualization stage, a causal loop diagram is the main simplified representation of a social-technical system that identifies important cause-and-effect relationships related to a problem. Feedback loops, which can be reinforcing or balancing, are the driving forces behind the system's behavior over time. Positive and negative links denote the causal relationship between two variables, indicating whether the effect and cause change in the same or opposite directions (Lu et al., 2019).

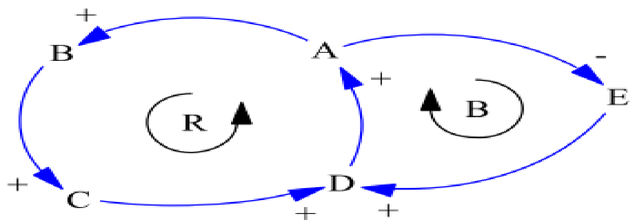

Figure 2.1: A causal loop diagram.

Furthermore, the stock and flow model structure will be designed to capture the accumulation and delay effects that are present in real-world systems. Stock variables serve as a representation of the system's current state, and they are influenced exclusively by flow variables. These stocks provide a foundation for taking action and influencing the flow variables to achieve desired outcomes. However, it's important to note that stocks cannot be changed instantaneously, and they will gradually rise or fall over time, resulting in a delay effect within the system (Lu et al., 2019).

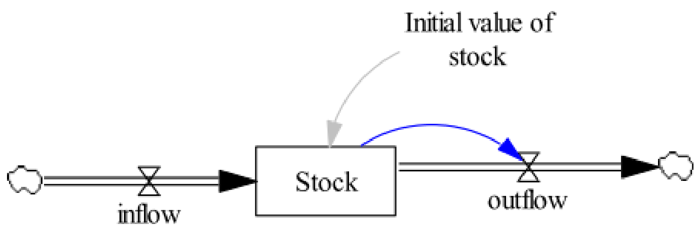

Figure 2.2:A stock flow diagram.

Through experimentation with the system, we can learn about its dynamic behavior. It could sometimes cost a lot of money and take time. Making several physical model prototypes and testing them out is an alternative to this approach. Occasionally, constructing a physical model for experimentation or conducting experiments with the current system may not be feasible. Using a mathematical or computer model is therefore the least expensive and time-consuming approach. Vensim Professional Software provides a user-friendly interface for building complex System Dynamics models. The software allows users to create models using a variety of modeling techniques, including stock and flow diagrams, causal loop diagrams, and influence diagrams (Bala et al., 2017). Vensim Professional Software also allows us to simulate models, observe how different variables change over time, manage different scenarios, and test the impact of different assumptions on system behavior. The software includes a range of scenario analysis tools, including sensitivity analysis, optimization, and goal-seeking (Zeng et al., 2022).

2.7.System Dynamics and Railway Infrastructure Protection

The System Dynamics (SD) approach is widely recognized as an effective method for addressing security and defense challenges. It stands out for its capacity to simulate interdependencies and randomness, which are common in real-world business environments. Additionally, the SD approach takes into consideration the influence of soft variables associated with interconnected social networks that are often overlooked in linear modeling approaches. In this approach, a system's behavior is shaped by its underlying structure (Armenia et al., 2014). According to studies, the system dynamics approach can be used to build protective strategies and obtain insight into the causes of significant incidents (Goh et al., 2012). SD is an approach that can readily handle the non-linearity, time delay, and multi-loop structures of complex and dynamic systems. It is based on feedback systems, which are taken from control theory (Bala et al., 2017).

The focus of most organizational discussions is on safeguarding infrastructure assets, which often overlooks the viewpoints, mindsets, anticipations, and conduct of individuals and groups impacted by the crisis or involved in its handling. This approach is problematic since every infrastructure, regardless of its tangible nature, is always interconnected with the social environment, and neglecting its social and psychological aspects can lead to complications (Cavallini et al., 2014).

While a railway infrastructure is primarily made up of physical components such as stations, railroads, tunnels, bridges, and crossings, it is essential to recognize that these elements are interconnected with the social environment they serve. Therefore, it is crucial to safeguard not only the physical components but also the people who rely on them. Adequate protection against attacks is necessary to ensure the safety and security of both the infrastructure and its users (Maggio & Setola, 2013).

By adopting a systemic approach that aligns with the principles of Systems Thinking & System Dynamics Methodology, it becomes possible to create a straightforward yet highly efficient representation of the complex context in which railway infrastructure operates. This method involves identifying the various parameters that interconnect and influence the behavior of the entire system, much like a chain reaction. By understanding these factors and their relationships, it is possible to gain insights into how changes in one area can affect other areas of the system.

This approach allows for a more comprehensive understanding of the railway infrastructure and its social environment, enabling stakeholders to make informed decisions that support the safety and security of both the physical components and the people who use them (Armenia et al., 2014).

The System Dynamics approach is used to understand the behavior of complex systems based on their circular, interlocking, and time-delayed relationships. It is suitable for systems with varying quantities, causal dependencies, and feedback loops. This approach is particularly useful in contexts where standard analysis is challenging due to the wide range of available data and where soft variables play a significant role. It has been increasingly applied to security and defense issues due to its ability to simulate randomness and interdependency. The approach suggests that accurately analyzing the interrelationships among system components produces an accurate understanding of the system's dynamics (Cavallini et al., 2014).

2.8.Crime Prevention Through Environmental Design (CPTED)

The primary issue addressed in this research is the frequent incidents of theft and vandalism of EDR infrastructure, which are largely attributed to criminal activity. In order to effectively tackle this problem, adopting a system thinking approach could prove to be beneficial. One such approach is Crime Prevention Through Environmental Design (CPTED), which emphasizes that proper design and utilization of the built environment can lead to a reduction in crime rates and fear, and an overall improvement in the quality of life (Cozens et al., 2005). The fundamental strategies of CPTED are based on three overlapping principles: "controlling access, rising opportunities for casual surveillance, and promoting a sense of ownership" These environmental strategies to be implement in various settings, such as communities, industrial areas, public transportation, and businesses, to combat crime and enhance the overall quality of life (Arabi et al., 2020).

The CPTED approach and System Dynamics combined results in the development of a dynamic model that enable analysis of the possible impact of implementing security systems to a defined asset or changing other aspects of the asset. This will ultimately help determine the overall effects on the risk level as well as the realistic probability and impact of an attack on the asset itself (Maggio & Setola, 2013).

2.8.1. The first-generation of CPTED principles

According to Cozens et al. (2005) the first-generation CPTED principles include six essential elements (territoriality, formal and informal surveillance, access control, image/maintenance, support for activity programs, and target hardening). By taking this as direct affecting variables systems dynamic model can be developed and Stakeholders can make the railway infrastructure and its users safer and more secure by putting the principles into practice.

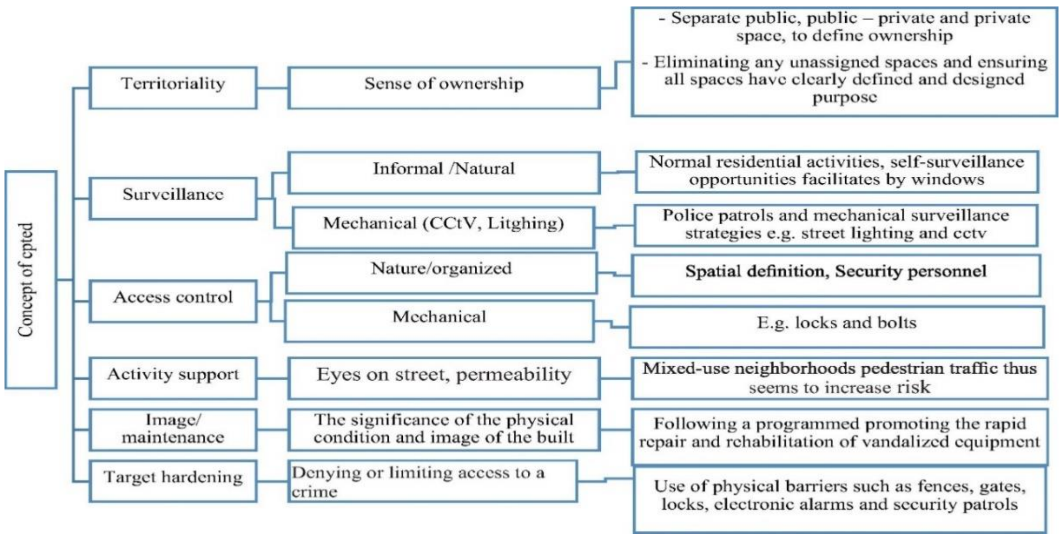

Figure 2.3: The first-generation of CPTED principles (Arabi et al., 2020)

2.8.2. The second generation of CPTED principles

The second generation of CPTED focuses on human factors such as social cohesion, connection, community culture, and capacity threshold. This approach aims to promote participation in local events, provide transportation facilities, promote equality strategies, and maintain a balance in social stabilizers. It is associated with advances in urbanization, ecology, sustainability, transportation, and socio-political movements (Arabi et al., 2020).

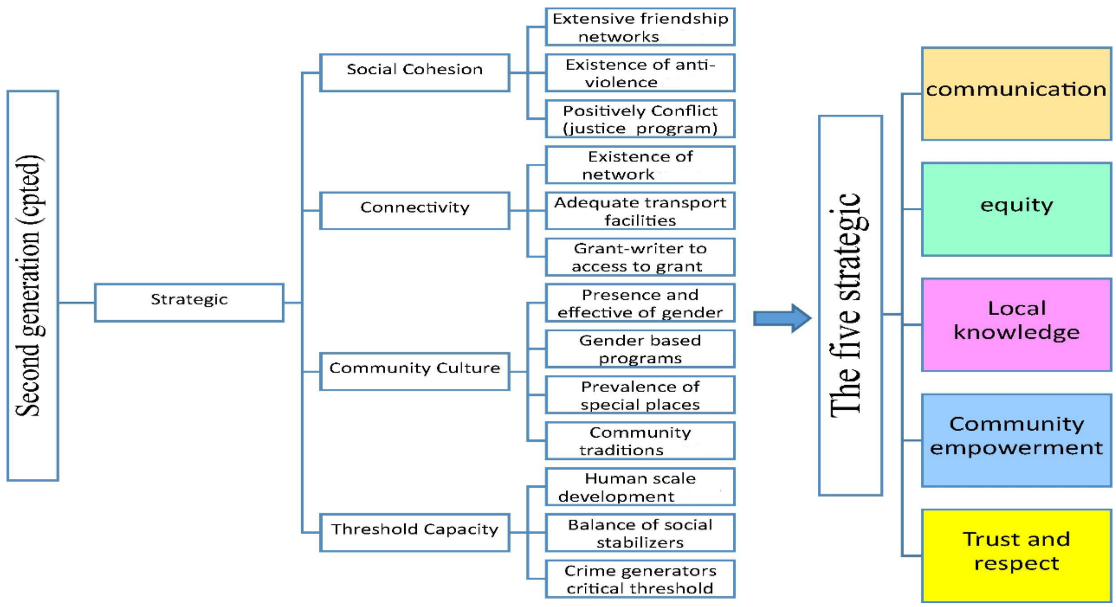

Figure 2.4: The second generation of CPTED principles (Arabi et al., 2020)

By using the above principles, it is possible to develop a system dynamics model for railway infrastructure protection. The primary objective of the model is to identify the main dependencies that impact the evolution of an event. Territorial features, the socio-economic environment, event timing (e.g., time and duration) and actor preparedness (Cavallini et al., 2014). According to Cavallini et al. (2014) In the system dynamics approach the first thing is the system characteristics must be defined and key reference points should have to be established. This is done by creating a theoretical model that identifies variables and parameters that represent the infrastructure being studied. Social system variables, which are difficult to quantify, will be given special attention and represented in a way that is compatible with system dynamics, based on a thorough analysis of existing literature. The main aim of the theoretical model is to pinpoint the key factors that influence the progression of an occurrence. This entails examining territorial characteristics, the socio-economic context, event timing (such as duration and time), and the readiness of actors involved in the event.

The theoretical model identifies four domains that influence the progression of an occurrence: Territory, Environment, Apparatus, and Events. Territory includes geographic features, while Environment includes human activities in the area. Apparatus refers to the professionals and organizations managing the event, and Events describe the evolution of normal situations over time. Specific variables and parameters for each domain include surface area, population by age, the federal and reginal police activity, and operating time (Cavallini et al., 2014).

In order to comprehend the framework and the system design behavior and to help develop a formal quantitative dynamic model, it is necessary to create a casual loop diagram (CLD) and a stock-flow diagram (SFD). The system's important causal variables can be linked to impact variables to form the CLD (Sterman, 2000). The development of the System Dynamics Model involves defining causal relationships between parameters in the theoretical model, which can be used to construct reinforcing and balancing causal loops. These loops form the basis of the simulation model structure, which is validated through real case studies. As a result, a Decision Support System prototype can be created to allow for simulation runs and comparison of the effects on the territory. This will enable both territory analysts and first responders to analyze the impacts of various situations, such as the nature and size of the event, timing and extent of direct damages, and different possible evolutions with alternative mitigation policies and resource deployment. This prototype will provide valuable insights for decision-making and help operators better understand the consequences of their actions (Armenia et al., 2014).

2.9.Gaps in the Literature

Referring to specific literature on the study area helps identify gaps in the literature related to the study on protecting railway infrastructure. While there may be research on the general threats facing railway infrastructure, there is a lack of research specifically focused on the threats facing the EDR system. There is a lack of discussion or research on the limitations of existing methods used in railway infrastructure protection.

Furthermore, there is limited research on the use of system dynamics modeling for railway infrastructure protection. There are many different systems dynamics models that have been used in other fields, such as healthcare and environmental management, but there is limited research on their application to railway infrastructure. This research will try to contribute to filling these gaps.

CHAPTER THREE

3. RESEARCH DESIGN AND METHODOLOGY

3.1. Research Design

This study used a mixed research method, each component of the mixed research method includes both qualitative and quantitative components. In a single study, both qualitative and quantitative data had gathered and analyzed. Incorporating qualitative and quantitative approaches regarding a topic leads to a better understanding than using only one of the pure methods, which is the obvious assumption driving the usage of mixed methods.

In this research, both qualitative and quantitative data is gathered on the various factors that affect the railway infrastructure's protection, including theft, vandalism and maintenance issues. The data is used to develop a conceptual model that captures the key variables and their interrelationships.

The Qualitative data that this research gathered is such as different experts and railway professionals' interviews, different case studies throughout the world experience, and literature review. So, these methods help this research to gather insights from experts in the field in order to analyze real-life scenarios, and review existing literature on the topic. In addition to that the Quantitative data also will be used in the research this data is statistical data that had recorded before which helps for statistical analysis, and other sample data from the literature that will be used for system dynamics modeling. Such Statistical analysis can help to identify trends and patterns in data, while system dynamics modeling can be used to simulate different scenarios and test the effectiveness of different interventions.

The data collection with a mixed approach helped the study to develop a conceptual model that captures the key variables and their interrelationships. This model helps to understand how different factors interact with each other and affect the protection of railway infrastructure. It can also be used to identify areas where interventions may be required to improve the protection of railway infrastructure.

3.2. Data collection procedure

3.2.1. Literature Review

The literature review conducted in this study represents a comprehensive investigation into the topic of railway infrastructure protection. The primary focus was on peer-reviewed academic journals written in English. The review specifically examined papers published within the last two decades that addressed railway infrastructure protection. In order to gather relevant research papers, various online databases were searched using specific keywords. These keywords included terms such as "Critical infrastructure protection," "Railway infrastructure protection," "Safety and security of rail infrastructure," and "System dynamics modeling for critical infrastructure protection." Multiple combinations of these keywords were employed to ensure the thoroughness and validity of the search results. By employing this rigorous methodology, the literature review yielded valuable insights and findings on the subject of railway infrastructure protection.

3.2.2. Primary Data

The primary Data collection for this study involved the utilization of questionnaires and interviews with experts in the Ethio-Djibouti railway (EDR). The primary objectives were to evaluate the existing safety and security measures implemented in the EDR and to determine the factors that impact the safety and security of its infrastructure. To achieve these goals, a comprehensive questionnaire was developed, encompassing inquiries regarding the respondents' general knowledge about infrastructure protection and their perception of the company's preparedness in ensuring infrastructure security.

The questionnaire was shared to various experts working in maintenance workshops located throughout the railway line. These experts were chosen as key informants due to their firsthand experience and expertise in the field. The collected data from the questionnaire and interviews provided valuable insights into the current state of safety measures within the EDR. Additionally, it shed light on the utilization of technology for rail asset protection and the level of social collaboration involved in safeguarding these assets.

By employing this approach, combining questionnaires and interviews, a comprehensive understanding of the safety practices, technological advancements, and collaborative efforts relating to the protection of the rail infrastructure in the EDR was obtained. This data will serve as a foundation for further analysis and recommendations aimed at enhancing the safety and security of the railway system.

3.2.3. Secondary Data

In addition to conducting a comprehensive literature review, a wide range of secondary data relevant to the study were gathered from the company. These secondary data encompassed crucial information about the company's primary infrastructure assets, the occurrence of theft and vandalism incidents over a period of five years, the number of accidents involving domestic animals, and the duration of train blocking delays. To ensure a thorough understanding of the subject matter, an extensive literature review was conducted. Furthermore, the study collected a diverse set of secondary data directly from the company, thereby broadening the scope of information available for analysis. The collected secondary data encompassed vital details regarding the company's main infrastructure assets, offering valuable insights into their composition, condition, and overall significance. This information served as a foundation for evaluating the company's operational capabilities and assessing potential vulnerabilities.

3.3.Target Population

The survey aims to target a specific group of Experts who are actively engaged in various workshops located along the railway line in the Ethiopia section. These Experts possess specialized knowledge and experience related to their respective fields within the railway industry. By focusing on this particular population, the survey aims to gather valuable insights and perspectives from those who possess a deep understanding of the operations and challenges within the railway infrastructure along the EDR line.

3.4.System Dynamics Modeling and Simulation

The focus of this study is to identify the risks and challenges of the EDR infrastructure protection by using system dynamics modeling approach. To achieve this goal, it is essential to establish a clear understanding of the modeling process from the outset. While there is no universally agreed-upon definition, there are a few widely accepted opinions that have emerged from years of research and practical application.

Sterman (2000) suggests that the modeler typically collaborates with the client team to develop an initial understanding of the problem, using a range of methods such as archival research, data collection, interviews, and direct observation or participation. The system dynamics modeling process, as described by the author, involves five steps. These steps include problem articulation, where the issues, time horizon, and model boundaries are clearly stated, and reference modes are identified. The formulation of a dynamic hypothesis follows, utilizing tools like diagrams to illustrate it. Next, a simulation model is created by defining parameters and equations based on further information. Testing is then conducted, including extreme condition tests and sensitivity tests, to compare the simulation's performance with reference modes. Finally, policy design and evaluation are carried out by formulating and assessing policies using the simulation model (Sterman, 2000).

The general process of model development steps flowchart is provided as follows by taking into account Sterman (2000)'s steps:

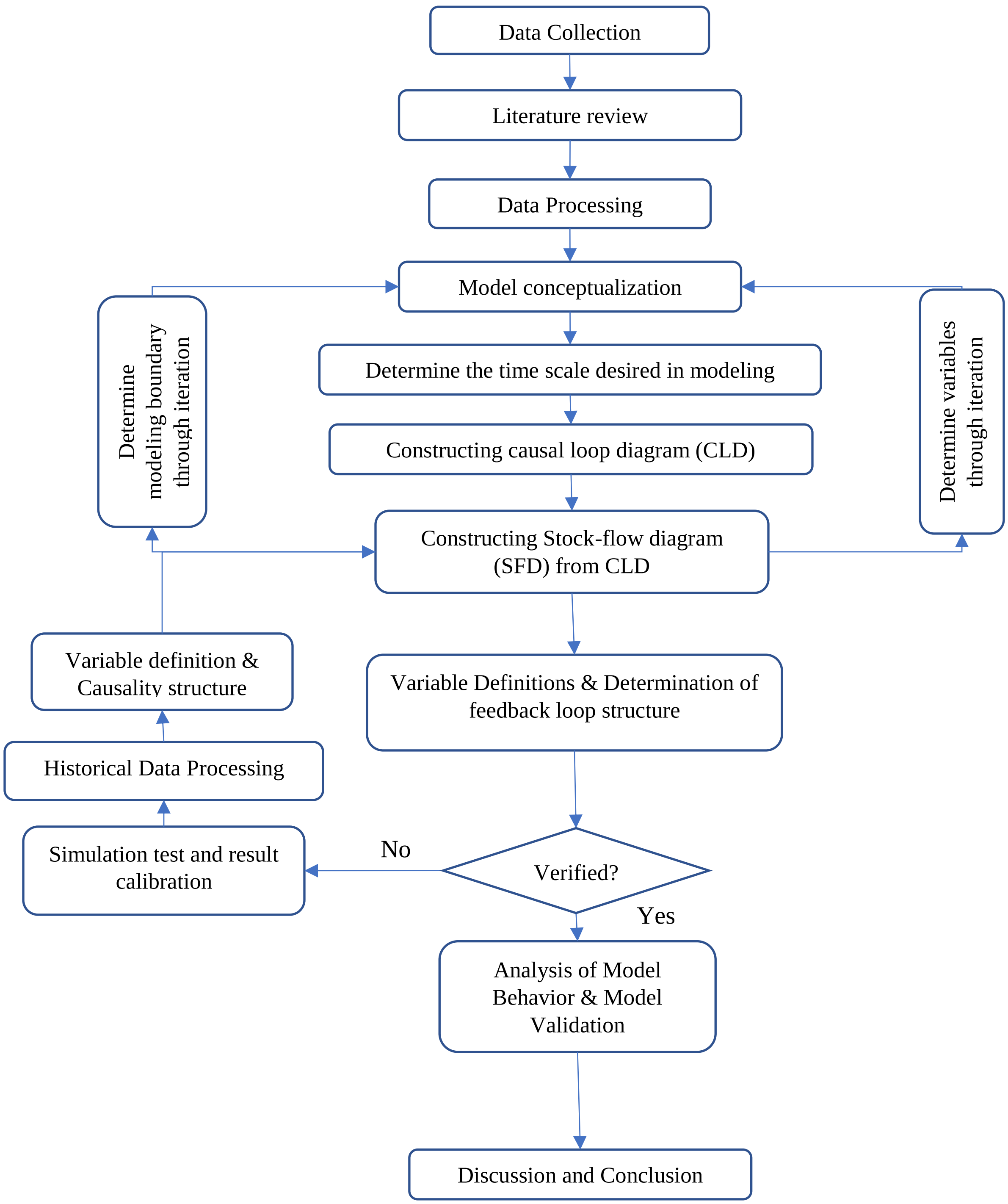

Figure 3.1 System Dynamics Modeling and Simulation flowchart

3.4.1. Model Verification

During the model verification stage of this study, various variables and their corresponding equations are thoroughly examined to ensure that the model successfully achieves its objective without any errors. Additionally, this stage involves testing different scenarios through iterative processes to ascertain the accuracy and correctness of the developed model. The purpose of these tests is to verify whether the model fulfills the anticipated requirements to achieve the enhancement of railway infrastructure protection as intended. By conducting these comprehensive verifications, the study assessed the reliability and effectiveness of the developed model.

3.4.2. Model Validation

Procedurally during this stage of model development, the study focuses on evaluating whether the developed model is indeed the correct model for the purpose of enhancing railway infrastructure protection. This evaluation involves assessing whether the model meets the necessary criteria, or, in other words, if it fulfills the high-level requirements. The purpose of this examination is to ensure that the model is aligned with the desired expectations. By conducting this assessment, the study discussed determining whether the developed model is suitable for its intended purpose and possesses the necessary qualities to meet the requirements.

3.4.3. Ethical consideration

The data utilized for this research originated from publicly available documents and reports. The responses from individuals were anonymized when presented. Consent was obtained from the company's managers and team leaders to conduct data collection, with due consideration given to ethical concerns such as confidentiality and potential impact on the company and communities involved in gathering information related to railway infrastructure protection. The individual's participation in this research is entirely voluntary.

3.5.Research Framework

The overall research framework is visually represented in the figure provided below. This figure serves to show the primary steps undertaken throughout the study, starting from the initial point and progressing towards its ultimate destination. By presenting the research framework in this manner, it becomes easier to comprehend the sequential flow of activities and milestones involved in the study. This visual representation offers a concise overview of the study's entire trajectory, providing a clear roadmap for understanding the progression from the beginning to the final outcome.

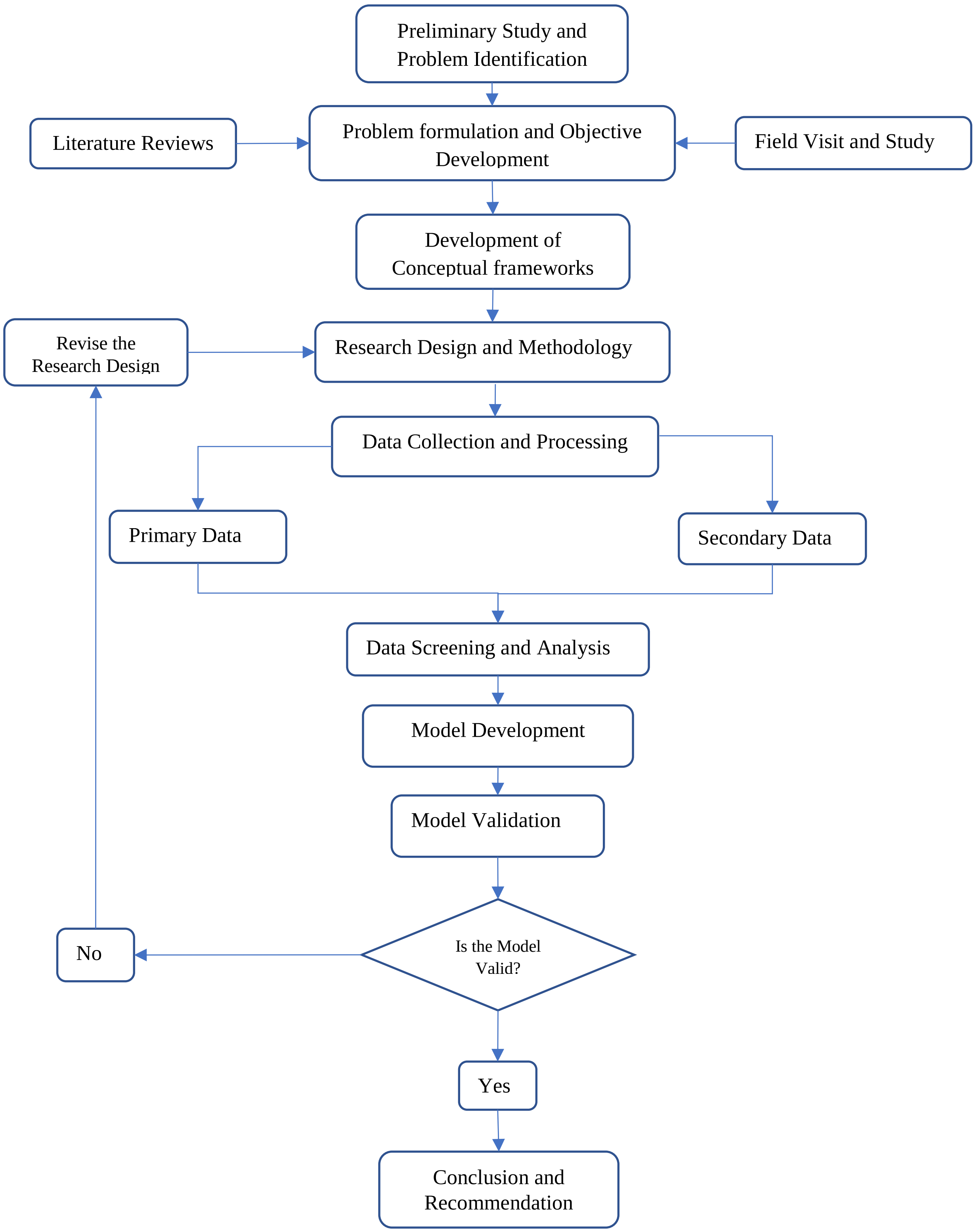

Figure 3.2: Research Framework

CHAPTER FOUR

4. DATA PRESENTATION AND ANALYSIS

4.1.Overview of the Ethio-Djibouti Railway Infrastructure Facilities

Railway infrastructure facilities are physical components and structures necessary for operating and maintaining a railway system. They ensure the safe and efficient movement of trains and passengers. Key facilities include tracks, stations, signaling systems, bridges, Culvert, depots, overhead contact systems (OCS), level crossings, freight terminals, maintenance equipment, and control centers. Tracks provide a stable path for trains, stations serve as passenger points, signaling systems maintain safe operations, bridges and tunnels overcome obstacles, depots facilitate uses for train inspection and maintenance, overhead contact system (OCS) are uses for power electric trains , level crossings ensure safety at road intersections, freight terminals handle goods, maintenance workshops supports infrastructure upkeep, and operation control centers (OCC) monitor and manage railway operations.

The infrastructure of EDR encompasses a comprehensive range of facilities that support its operations. One of the prominent features is the main truck line, which extends over a significant distance of 667 kilometers within the Ethiopian section of the railway infrastructure. This extensive track provides the backbone for the transportation of goods and passengers across the country. Along the main truck line, there are numerous buildings and structures strategically located to facilitate the smooth functioning of the railway system. These structures serve various purposes such as stations, maintenance depots, signaling installations, bridges, and tunnels. They are designed to ensure the safety, efficiency, and convenience of railway operations and the passengers and freight being transported.

To provide a comprehensive overview, the following table presents information regarding the total length coverage of both the main truck line and the station line, as well as the total number of buildings and structures associated with EDR:

Table 4.1: The total length coverage of both the main truck line and the station line

No.	Infrastructure Facility in Ethiopia	Unit	Quantity
1.	Main Line	km	667
2.	Station Line	km	63
3.	Main Building and Structures	Number	189

In order to guarantee safe train movement, bridges, culverts, and level crossings are essential components of railroad operations that need to be carefully protected and maintained. In order to reduce safety hazards, bridges that allow trains to pass obstacles must be examined and maintained on a regular basis. In order to prevent erosion and instability, culverts control the water flow beneath the railway. Train safety may be compromised by damaged culverts. To prevent accidents, level crossings at intersections need to be equipped with barriers and signaling systems. Safety aspects that are neglected may cause serious problems with safety as well as accidents. The entire quantity in relation to its section mileage is presented in the following table.

Table 4.2: Bridge, Culvert and Level Crossing Structural Facilities.

No.	Responsible Center	Structure Facility	Total Quantity	Section Mileage
1.	Adiss Ababa (Indode) Maintenance Center	Bridge	98	K000+000-K329+082
		Culvert	443	
		Level Crossings	97	
2.	Dire Dawa Maintenance Center	Bridge	94	K329+082-K666+994
		Culvert	677	
		Level Crossings	46	

To provide a more comprehensive illustration of the buildings and structures along the EDR line, the following table highlights some of the main infrastructures, along with their corresponding mileage, coordinates, and the region where they are located. Additionally, to gain insights into the societal impact, the table also includes the total population density of the areas where the infrastructure exists.

Table 4.3: Main infrastructure of EDR

No.	Infrastructure Facility	Mileage	Coordinate	Region	Population (www.citypopulation.de)
1.	Sebeta Station	K1+970	8°53'57.8"N 38°34'35.6"E	Oromia, Sebeta	102,300 Population-13,812/km²
2.	Electric Control room	K2+400	8°53'56.4"N 38°34'48.9"E	Oromia, Sebeta	102,300 Population-13,812/km²
3.	Labu Station	K15+521	8°55'56.1"N 38°41'16.1"E	Oromia, Sebeta	102,300 Population-13,812/km²
4.	Indode Traction substation	K33+196	8°51'44.0"N 38°45'21.4"E	Oromia. Indode	113,316 Population-194.5/km²
5.	Indode Maintenance Workshop		8°51'41.0"N 38°45'28.7"E	Oromia. Indode	113,316 Population-194.5/km²
6.	Indode fright yard	K33+688	8°51'17.9"N 38°45'42.5"E	Oromia. Indode	113,316 Population-194.5/km²
7.	Indode Station	K34+229	8°51'26.3"N 38°45'46.1"E	Oromia. Indode	113,316 Population-194.5/km²
8.	Indode Rolling stock		8°50'28.3"N 38°46'15.2"E	Oromia. Indode	113,316 Population-194.5/km²
9.	Electric Control room	K64+130	8°47'23.3"N 39°00'24.5"E	Oromia, Bishoftu	207,383 Population-5,182/km²
10.	Bishoftu Station	K67+281	8°45'52.3"N 39°01'08.9"E	Oromia, Bishoftu	207,383 Population-5,182/km²
11.	Modjo Station	K91+310	8°35'16.7"N 39°08'15.4"E	Oromia, Modjo	61,300 Population
12.	Mojo Traction Sub station	K94+410	8°34'22.6"N 39°08'29.3"E	Oromia, Modjo	61,300 Population
13.	Adama Station	K113+687	8°30'20.7"N 39°15'52.2"E	Oromia, Adama	456,900 Population
14.	Welenchiti Traction substation	K141+900	8°38'15.2"N 39°23'43.9"E	Oromia, Welenchiti	31,500 Population
15.	Feto passing loop Station		8°40'38.58"N 39°31'58.67"E	Oromia, Feto	31,500 Population
16.	Melka JiloTraction Sub station	K175+900	8°50'36.4"N 39°35'42.7"E	Amhara, Melka Jilo	31,500 Population
17.	Metehara passing loop Station	K217+645	8°54'47.8"N 39°55'14.3"E	Oromia, Metehara	23,000 Population
18.	Metehara Traction substation	K218+162	8°54'50.7"N 39°55'31.1"E	Oromia, Metehara	23,000 Population

19.	Metehara Maintenance Workshop		8°54'49.9"N 39°55'36.5"E	Oromia, Metehara	23,000 Population
20.	Awash Traction substation	K258+760	9°00'14.9"N 40°09'19.5"E	Afar, Awash	36,500 Population
21.	Sirba Kunkur Traction substation	K279+965	9°02'56.9"N 40°25'30.2"E	Oromia, Boardoode	36,500 Population
22.	Sirba Kunkur Passing loop Station	K280+223	9°03'05.2"N 40°25'32.4"E	Oromia, Boardoode	36,500 Population
23.	Mieso Traction Substation	K322+950	9°12'47.4"N 40°43'34.9"E	Oromia, Mieso	27,700 Population
24.	Mieso Passenger Station	K323+682	9°12'53.4"N 40°43'58.7"E	Oromia, Mieso	27,700 Population
25.	Mieso Maintenance Workshop		9°12'56.9"N 40°44'25.2"E	Oromia, Mieso	27,700 Population
26.	Afdem Traction Substation	K368+173	9°28'33.3"N 41°00'32.0"E	Somali, Afdem	95,640 Population-29.67/km²
27.	Bike Passenger Station	K391+093	9°33'04.4"N 41°11'33.7"E	Somali, Bike	113,929 Population-11.12/km²
28.	Bike Maintenance Workshop		9°33'02.0"N 41°11'55.7"E	Somali, Bike	113,929 Population-11.12/km²
29.	Gota Traction Substation	K405+653	9°30'38.3"N 41°18'07.9"E	Somali, Gota	113,929 Population-11.12/km²
30.	Hurso Traction Substation	K445+627	9°37'05.0"N 41°37'47.3"E	Somali, Hurso	150,900 Population-12.90/km²
31.	Dire Dawa Passenger Station	K461+465	9°37'42.1"N 41°46'21.9"E	Dire Dawa, Melka Jebdu	535,000 Population-343.2/km²
32.	Lonnis Traction Substation	K486+483	9°47'40.2"N 41°51'07.0"E	Somali, Shinile lonnis	150,900 Population - 12.90/km²
33.	Arawa Passing loop Station	K509+531	9°58'41.3"N 41°56'33.9"E	Somali, Harewa	14.43/km²
34.	Mile Traction Substation	K528+431	10°08'06.9"N 42°00'35.2"E	Somali, Mile	150,900 Population - 12.90/km²

35.	Adigala Traction Substation	K570+670	10°28'37.2"N 42°10'34.0"E	Somali, Adigala	150,900 Population - 12.90/km²
36.	Adigala Passing Loop Station	K571+544	10°29'03.8"N 42°10'44.7"E	Somali, Adigala	150,900 Population - 12.90/km²
37.	Adigala Maintenance Workshop		10°29'28.5"N 42°10'54.6"E	Somali, Adigala	150,900 Population - 12.90/km²
38.	Aysha Traction Substation	K618+143	10°43'12.1"N 42°31'11.6"E	Somali, Aysha	85,155 Population- 9.136/km²
39.	Aysha Passing Loop Station	K622+144	10°44'35.5"N 42°32'52.9"E	Somali, Aysha	85,155 Population- 9.136/km²
40.	Dawanle Passenger Station	K663+094	11°03'22.1"N 42°37'56.8"E	Somali, Dawanle	85,155 Population- 9.136/km²
41.	Dawanle Traction Substation	K663+803	11°03'43.3"N 42°38'06.1"E	Somali, Dawanle	85,155 Population- 9.136/km²
42.	Dawanle Maintenance Workshop		11°03'50.1"N 42°38'07.6"E	Somali, Dawanle	85,155 Population- 9.136/km²
43.	Dawanle Border Inspection Yard	K664+594	11°04'07.6"N 42°38'14.9"E	Somali, Dawanle	85,155 Population- 9.136/km²
44.	Ethiopia and Djibouti Separation	K667+135	11°05'32.0"N 42°38'36.4"E	Border	-

4.2.City and Regional Administration offices along the EDR Infrastructure Facilities

City and regional administration offices play a crucial role in ensuring the protection and maintenance of the EDR infrastructure. These administrative bodies are responsible for coordinating efforts to safeguard the railway facilities and address any issues that may arise. Their involvement is vital in ensuring the smooth operation and longevity of the railway system. Additionally, law enforcement bodies within the respective localities also share the responsibility of protecting the EDR infrastructure. They play a significant role in monitoring and preventing vandalism, theft, or any malicious activities that could cause damage to the infrastructure.

Collaborating with law enforcement agencies ensures a secure environment for the railway network, reducing the risk of disruptions and safety hazards.

To provide a comprehensive overview of the EDR infrastructure and its corresponding locations, the following table showcases the localities in relation to the mileage range:

Table 4.4: The EDR infrastructure and its corresponding region

S.N	Region	Mileage	
		Starting	Ending
1	Sebeta City	k1+000	k17+000
2	Nifas Silk Lafto	k17+000	k20+000
3	Sebeta Awash	k20+000	k27+000
4	Akaki Wereda	k27+000	k35+000
5	Gelan City	k35+000	k42+000
6	Dukem City	k42+000	k50+000
7	Adea	k50+000	k58+000
8	Bishoftu	k58+000	k68+000
9	Adea	k68+000	k74+000
10	Lome	k74+000	k90+000
11	Mojo	k90+000	k92+000
12	Lome	k92+000	k105+000
13	Adama City	k105+000	k130+000
14	Adama Woreda	k130+000	k150+000
15	Boset	k150+000	k174+000
16	Minjar	k174+000	k208+000
17	Fentale	k208+000	k251+000
18	Awash Fentale	k251+000	k259+000
19	Amibara	k259+000	k270+000
20	Bordede	k270+000	k300+000
21	Meiso	k300+000	k340+000
22	Mele	k340+000	k355+000
23	Afdem	k355+000	k396+000
24	Gota Bike	k396+000	k424+000
25	Erer	k424+000	k470+000
26	Shinele	k470+000	k524+000
27	Adigala	k524+000	k600+000
28	Aysha	k600+000	k654+000

4.3.Accidents, Theft and Vandalism Incidents

The following section of the study focuses on the first research question. As highlighted in the problem statement, EDR has experienced several instances of theft and vandalism over the last six years. These events have sat significant challenges for the company, Furthermore, the geographical trajectory of the EDR line traverses an array of several urban and rural living areas, which has resulted in a recurring occurrence of accidents on domestic animals. The consequences of these incidents have not been limited only to the welfare of the affected animals. The occurrence of these accidents has led to the disruption of train operations, leading to substantial delays lasting several minutes and it is the cause of vandalism and theft. Such interruptions impose additional costs and operational complexities on EDR.

The following table indicates the past five years of recorded data on the number of facilities stolen and vandalized, accident occurrences on domestic animals, and train delays due to different incidents that happened along the line. This study did not get any data for the second half of 2020. NA (not available) refers to the unavailability of any recorded data for those specific months.

Table 4.5: Number of facilities stolen and vandalized, accident occurrences on domestic animals, and train delays.

Year	Month	Number of Facilities Stolen and Damaged	Accident on Domestic Animals	Train Blocking & Delay time (minutes)
2019	January	155	67	1457
	February	141	80	2523
	March	86	56	1928
	April	237	25	1606
	May	594	26	332
	June	130	24	1371
	July	379	38	320
	August	1327	35	222
	September	331	31	303
	October	188	36	900
	November	182	21	1031
	December	214	30	233
2020	January	136	16	3352
	February	79	12	1983
	March	225	51	987

	April	157	2	714
	May	62	5	611
	June	49	11	24
	July	N/A	N/A	N/A
	August	N/A	N/A	N/A
	September	N/A	N/A	N/A
	October	N/A	N/A	N/A
	November	N/A	N/A	N/A
	December	N/A	N/A	N/A
2021	January	538	22	328
	February	284	13	548
	March	629	3	26
	April	911	6	199
	May	2240	11	17
	June	194	20	298
	July	2282	13	459
	August	2466	3	405
	September	3120	5	288
	October	1407	8	69
	November	1274	7	0
	December	474	21	0
2022	January	1225	18	384
	February	1468	11	377
	March	788	22	783
	April	935	9	162
	May	3107	28	477
	June	3812	11	178
	July	1918	20	315
	August	3919	13	425
	September	8857	12	244
	October	7718	13	642
	November	7754	16	613
	December	6256	25	299
2023	January	4566	11	295
	February	2962	34	239
	March	3857	7	3033
	April	3765	4	114
	May	1911	13	213
	June	1057	13	130
	July	1445	12	206
	August	1341	15	322

	September	647	32	240
	October	1229	5	88
	November	387	25	3128
	December	309	19	912

The majority of the stolen items primarily consist of essential rail fasteners, including fish plates, bolts, nuts, rail clips, and elastic washers. These specific components play a critical role in the railway infrastructure as they are utilized to secure and reinforce the joints between rails. Additionally, they are responsible for tightly fastening and clamping the rail with the slipper, ensuring the stability and integrity of the track system.

The theft of these rail fasteners poses significant concerns for EDR's operations and safety. Without these essential components in place, the structural integrity of the railway track is compromised, leading to potential hazards and risks for train operations. The absence or improper installation of these fasteners can result in track misalignment, increased wear and tear, and even derailments, endangering the lives of passengers and freight transport.

Figure 4.1: Fish plates, bolts, nuts and rail clips

Figure 4.2: Exhibited rail fasteners

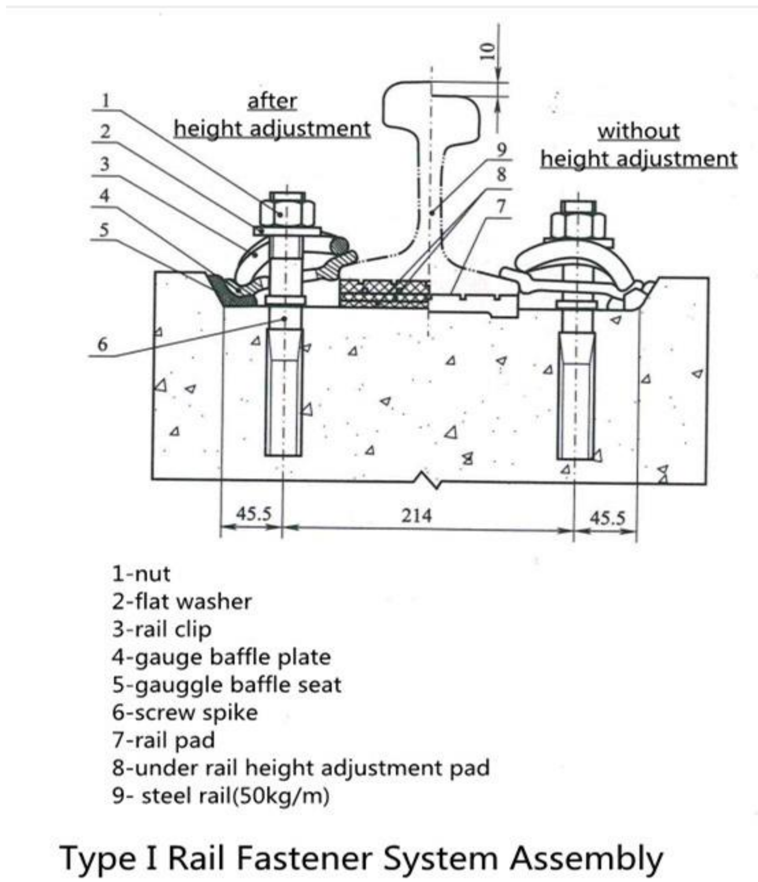

Figure 4.3: Type I Rail Fastener

Concrete masts, Track circuit boxes, signaling equipment, switch machine terminal boxes and optical fiber cables are the other frequently targeted assets when it comes to vandalism. These components play vital roles in ensuring the safe and efficient operation of railway systems.

Track circuit boxes have a crucial function in supervising train occupancy and verifying the integrity of the track circuit. By monitoring train movement and occupancy, track circuits enable the detection of potential obstructions or faults on the line. They serve as a fundamental basis for displaying clear signals, establishing routes, and forming track blocks. Damage or tampering with track circuit boxes can disrupt the accurate monitoring of train presence, compromising the overall safety and functionality of the railway network.

Figure 4.4:Vandalized Track circuit and signaling boxes

Signaling equipment, including switch machine terminal boxes, enables the remote guidance of trains from one track to another. These systems rely on human-machine interfaces (HMIs) to facilitate communication and control. Through signaling and switch machine terminal boxes, railway operators can ensure the smooth flow of train traffic, coordinate train movements, and maintain appropriate spacing between trains. Vandalism targeting these components can disrupt the signaling system's integrity, leading to potential confusion, delays, and safety hazards.

The other targeted assets are concrete masts, also known as concrete poles or posts, are essential components of railway infrastructure. These sturdy structures play a crucial role in supporting and maintaining the overhead contact system (OCS) that supplies electrical power to trains. Concrete masts are strategically positioned along railway tracks to provide support for the overhead wires that carry the electrical current. These wires, commonly referred to as contact wires or catenary wires, are responsible for transmitting power to the pantographs on the trains, enabling them to operate efficiently and smoothly. Concrete masts are vulnerable to acts of vandalism for various reasons, often stemming from political or social circumstances. These acts of vandalism can be driven by individuals or groups expressing their discontent or frustration with the prevailing situation.

In some cases, political motives may be behind the targeting of concrete masts. Political unrest or disagreement with the government's policies can lead to acts of sabotage or destruction of critical infrastructure, including railway assets. Vandalism against these masts may be seen as a symbolic gesture or a means to disrupt transportation networks, thereby drawing attention to political grievances.

Social circumstances can also contribute to the vandalism of concrete masts. One such circumstance involves incidents of uncompensated domestic animal accidents. When accidents involving domestic animals occur on the railway tracks, causing harm or financial loss to individuals in the community, some members of the society may resort to acts of violence or revenge. These acts of vandalism, aimed at damaging the infrastructure, are often misguided attempts to seek retribution or vent frustration.

Figure 4.5:Vandalized concrete mast.

4.4.Secondary data analysis

In order to make the data suitable for model development, the company's last three years essential gathered data has been summarized and thoroughly analyzed. Visualizations were created to better understand the data and communicate the findings to the reader. This comprehensive data preparation and analysis phase is helpful for proper model development.

The following bar graph provides a comparison of the number of facilities stolen and damaged over the past three years:

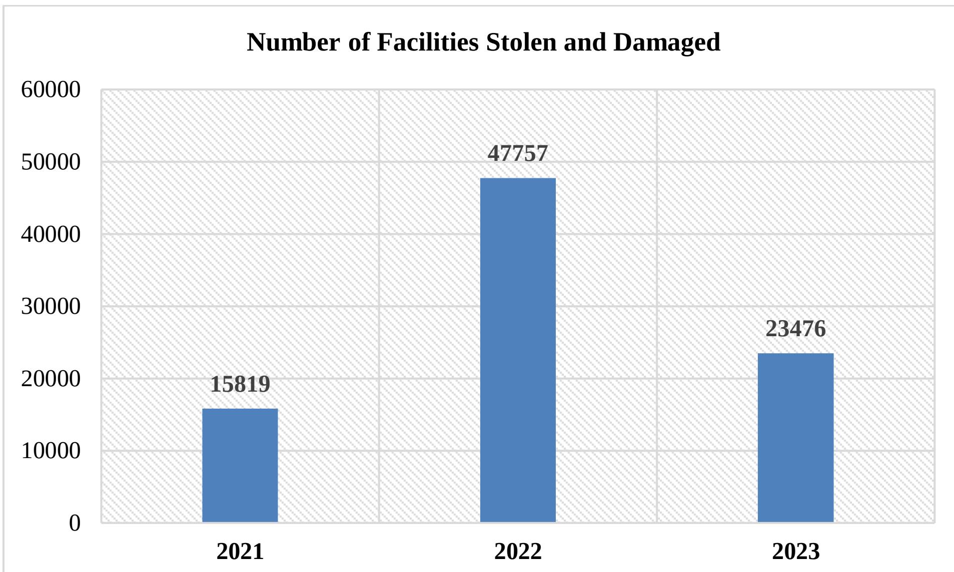

Figure 4.6: Number of facilities stolen and damaged

The bar graph reveals the concerning trend of an increase in both stolen and damaged facilities over the analyzed period. In 2021, there were 15819 recorded cases of stolen facilities, which rose to 47757 in 2022, and decline to 23476 in 2023.

As mentioned earlier, accidents involving domestic animals have had a detrimental impact on the destruction of railway infrastructure. To further illustrate the severity of this issue, the following bar graph presents a comparison of accidents involving on domestic animals over the past three years:

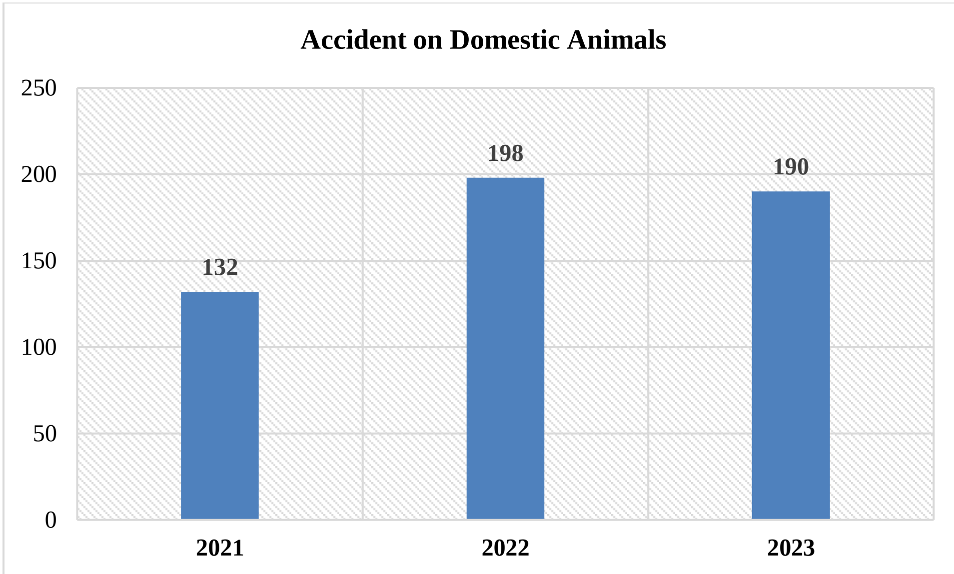

Figure 4.7:Accidents on Domestic Animals

The bar graph reveals a concerning upward trend in the number of accidents involving domestic animals over the analyzed period. In 2021, there were 132 incidents recorded, which increased to 198 in 2022. The most recent data from 2023 shows some decline to 190 accidents. These figures indicate a persistent and growing challenge that must be addressed to protect both the welfare of the animals and the integrity of the railway infrastructure.

The effect of the aforementioned situations, such as accidents involving domestic animals and the theft or damage of facilities, often results in lengthy delays for trains as various checks and assessments need to be conducted. These incidents have a significant impact on the overall train operations along the railway line. Since the majority of the railway line is single-track lines, when a train comes to a stop in the middle of a track section due to these incidents, it disrupts not only the immediate train but also the entire upward as well as downward train operation.

The following bar graph provides a comparison of the time delays caused by train blockages over the past three years:

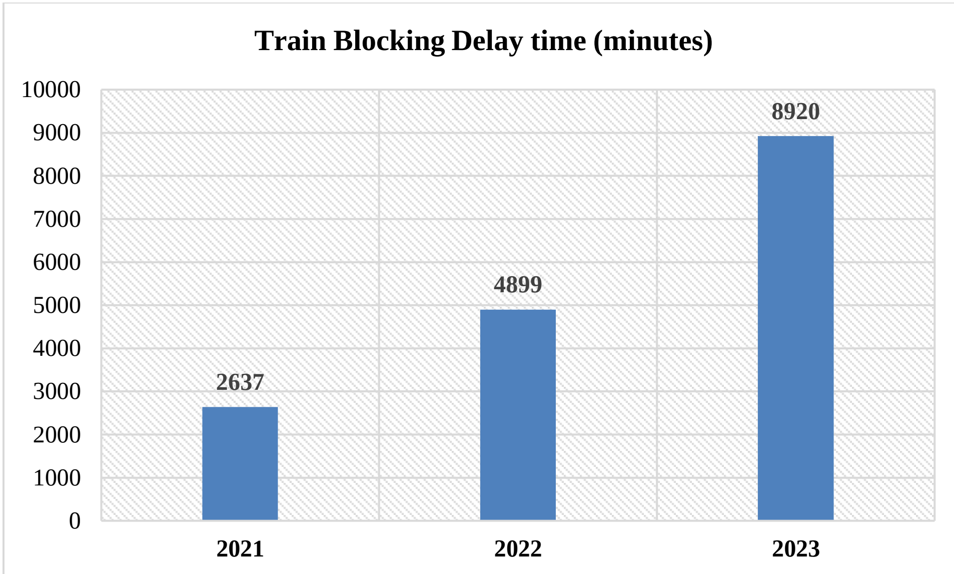

Figure 4.8:Train Blocking Delay time

The bar graph illustrates a noticeable increase in the duration of train blockages over the analyzed period. In 2021, train blockages caused a total delay of 2637 minutes. This figure rose to 4899 minutes in 2022, and further increased to 8920 minutes in 2023. These escalating delays not only inconvenience passengers and freights but also have broader implications for the inefficient functioning of the railway system.

4.5.Primary Data Analysis

The primary data collection for this study was conducted through the use of questionnaire. The questionnaire was structured to gather information about the current status of the company's societal engagement for railway infrastructure protection, technology usage, and the existing security measures in place. To obtain a representative sample, the questionnaires were randomly distributed to employees stationed along the railway line. The distribution was facilitated through an online form to make the data collection process more efficient and accessible. Out of the total number of questionnaires distributed, only 23 respondents provided feedback and completed the survey. The data collected from these respondents' forms is the basis for the subsequent data analysis.

Figure 4.9 shows the percentage level of respondent's workplaces by location. The largest number of respondents about 44% are based in Dire Dawa. The next largest segment is from Addis Ababa

(Indode) representing about 18% of the total. The remaining respondents are distributed across other workplace, including smaller percentages from Adama, Metehara, Bike and Adigala.

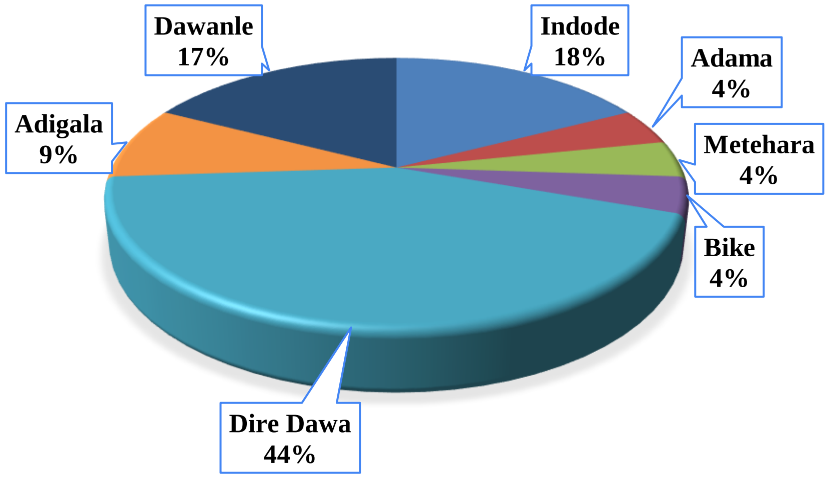

Figure 4.9:Percentage level of respondent's working place

The data shows that the majority of respondents have more than two years of working experience in the company. Figure 4.10 provides a visual representation of the respondents' work experience.

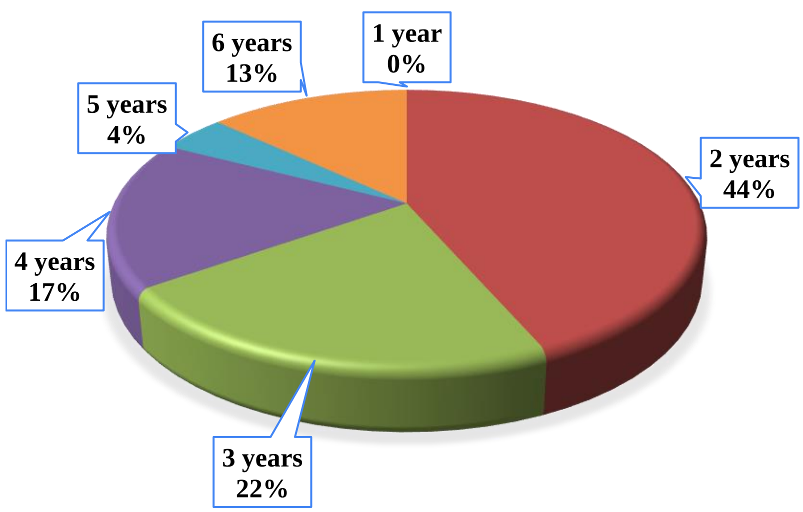

Figure 4.10:Percentage level of respondent's experience

The data additionally tells that the majority of respondents, approximately 70%, hold a bachelor's degree. Furthermore, 26% of the respondents have attained a master's degree.

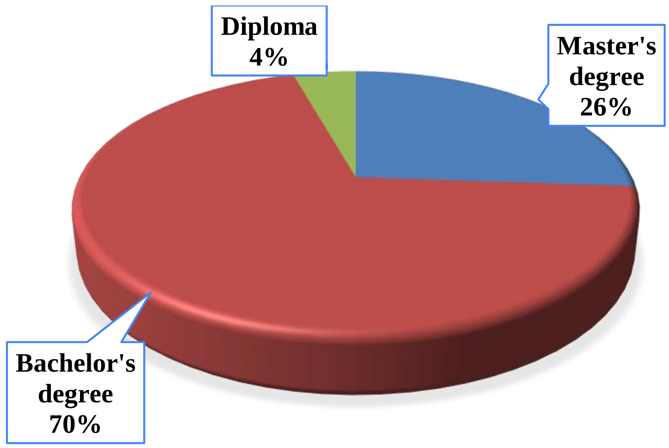

Figure 4.11:Percentage level of highest educational level of respondents

Furthermore, the respondents' positions within the company shows that 44% hold the role of Team Leader, while 30% are employed as Experts, the rests are working as a manager and other different positions.

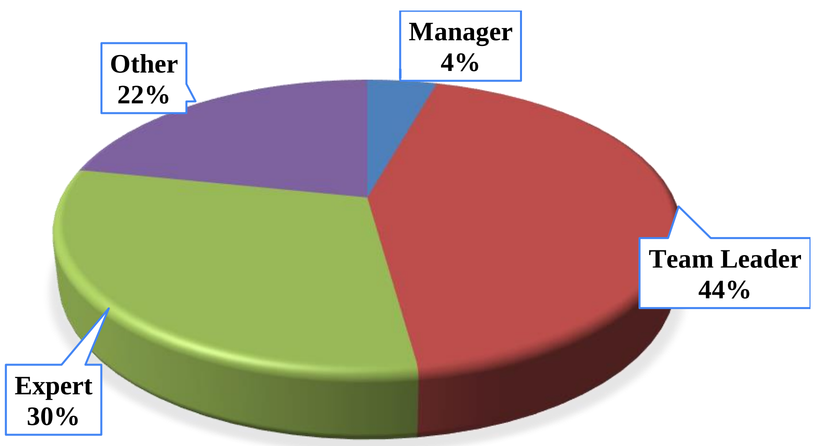

Figure 4.12:Percentage level of respondent's position

Table 4.6:A survey result on railway infrastructure safety and security

	Survey on railway infrastructure safety and security	1.00 SDA	2.00	3.00	4.00	5.00 SA	Total	Mean	STD
Existing Security Measures									
1	Implementation of security measures to protect railway infrastructure.	4.35%	30.43%	34.78%	17.39%	13.04%	100.00%	3.04	2.72
2	Security protocols or guidelines in place within the company to protect railway infrastructure.	4.35%	39.13%	21.74%	21.74%	13.04%	100.00%	3.00	2.70
3	A frequent security assessment to evaluate the vulnerabilities and risks associated with railway infrastructures.	17.39%	21.74%	21.74%	34.78%	4.35%	100.00%	2.87	2.60
4	Security teams responsible for monitoring and safeguarding railway infrastructures.	8.70%	26.09%	21.74%	30.43%	13.04%	100.00%	3.13	2.84
5	Dedication of security teams, training and equipment to handle security incidents and emergencies related to railway infrastructures.	8.70%	17.39%	26.09%	34.78%	8.70%	95.65%	3.18	2.86
6	Security incidents related to railway infrastructures in the past years	0.00%	17.39%	21.74%	26.09%	34.78%	100.00%	3.78	3.43
7	Surveillance systems (CCTV cameras) in workshop/station to monitor railway infrastructures.	47.83%	17.39%	17.39%	8.70%	8.70%	100.00%	2.13	2.04
8	The surveillance systems coverage and effectiveness.	52.17%	26.09%	13.04%	4.35%	4.35%	100.00%	1.83	1.64
9	Access control measures (Fences, Gates, Barriers, Guards... Etc.) Implementation.	26.09%	34.78%	21.74%	13.04%	4.35%	100.00%	2.35	2.11
10	The security measures integration with other safety systems (e.g., signaling, emergency response)	21.74%	30.43%	13.04%	26.09%	8.70%	100.00%	2.70	2.50
11	Regular exercises to test the effectiveness of the security measures and response protocols.	8.70%	47.83%	26.09%	17.39%	0.00%	100.00%	2.52	2.15
12	Cooperation and collaboration with external stakeholders (e.g., government agencies, law enforcement).	8.70%	8.70%	17.39%	43.48%	21.74%	100.00%	3.61	3.28

13	Mechanisms in place for reporting and investigating security incidents or suspicious activities.	4.35%	21.74%	39.13%	26.09%	8.70%	100.00%	3.13	2.77
	Technological Improvement								
14	Investment on advanced technologies	30.43%	30.43%	21.74%	13.04%	4.35%	100.00%	2.30	2.09
15	Level of integration between security systems and technologies	30.43%	30.43%	21.74%	8.70%	8.70%	100.00%	2.35	2.17
16	Projects or initiatives to improve railway infrastructure protection through technological advancements.	30.43%	30.43%	21.74%	4.35%	8.70%	95.65%	2.27	2.09
17	Cost-effectiveness of Implementing technological solutions	8.70%	13.04%	26.09%	26.09%	17.39%	91.30%	3.33	3.04
18	Assessments of the existing security measures and technological systems	13.04%	21.74%	34.78%	17.39%	8.70%	95.65%	2.86	2.58
19	Commitment to investing in technological advancements.	17.39%	30.43%	26.09%	17.39%	8.70%	100.00%	2.70	2.45
20	Collaboration with technology providers or research institutions to explore and implement innovative solutions.	26.09%	39.13%	21.74%	8.70%	4.35%	100.00%	2.26	2.00
21	Technological advancements for the improvement of the overall security of railway infrastructure.	21.74%	34.78%	30.43%	8.70%	4.35%	100.00%	2.39	2.11
	Societal Engagement								
22	Collaborative initiatives with the community	21.74%	17.39%	34.78%	26.09%	0.00%	100.00%	2.65	2.36
23	Effectiveness of collaboration with the society.	13.04%	21.74%	47.83%	13.04%	4.35%	100.00%	2.74	2.40
24	Information sharing with the community on security threats and incidents, strategy development, and advocacy.	8.70%	17.39%	34.78%	34.78%	4.35%	100.00%	3.09	2.73
25	Consistency and frequency of Collaboration with the society.	13.04%	17.39%	43.48%	21.74%	4.35%	100.00%	2.87	2.54
26	Level of engagement and participation on the activities of providing support for the community along the line.	13.04%	8.70%	39.13%	21.74%	17.39%	100.00%	3.22	2.93

Regarding the existing security measure the survey results show that the respondents generally agreed that in the last years, EDR has experienced security incidents related to railway infrastructures. The mean response value for this variable is 3.78 on the Likert scale, and the standard deviation is 3.43. This indicates that the respondents largely agreed that frequent security incidents have occurred on the line. Likewise, the survey respondents agreed that the EDR cooperates and collaborates with external stakeholders in order to secure the infrastructure. The mean response value for this variable is 3.61 on the Likert scale, with a standard deviation of 3.28. This indicates a general agreement among the respondents that EDR engages in cooperative efforts with outside parties to enhance infrastructure security.

On the other hand, the respondents likely neutral on the Implementation of security measures to protect railway infrastructure; Security protocols or guidelines in place within the company to protect railway infrastructure and Dedication of security teams training and equipment to handle security incidents and emergencies related to railway infrastructures. The respondents did not feel strongly one way or the other about the pointes.

The survey result shows that 47.83% of the respondents strongly disagree with the implementation of surveillance systems (CCTV cameras) in workshops or stations to monitor railway infrastructure. The mean value for this is 2.13, with a standard deviation of 2.04, which shows the highest diffusion of the respondent's disagreement. Similarly, respondents disagree with the surveillance system's coverage and effectiveness. It's mean value is 1.83, with a standard deviation of 1.64.

Similarly, the survey results showed that respondents mostly disagreed with the current state of technological advancement and usage related to the protection of railway infrastructure. This indicates that EDR needs to focus more on improving the technological capabilities of its solutions in order to better protection of infrastructure and systems. 26.09% of the respondents agreed that implementing technological solutions is cost-effective in the context of EDR, even though the mean value is 3.33 with a standard deviation of 3.04.

Lastly, for most of the societal engagement variables, the respondents gave a neutral response; they did not feel strongly one way or another. For instance, the mean value of collaborative initiatives with the community is 2.65, with a standard deviation of 2.36. This shows that most respondents give a neutral response to this variable.

In general, the survey indicates that in order to improve the safety and security of the railway infrastructure, it is important to focus on those variables that indicated in the survey results, which are the basics for safety and security measures. For further understanding and to elaborate the factors more system dynamics modeling is helpful for demonstration of such complex problems. This study will discuss more about SD modeling in the next sections.

CHAPTER FIVE

5. SYSTEM DYNAMICS MODEL DEVELOPMENT

5.1. Introduction

Infrastructure theft, vandalism, and sabotage are complicated problems because they involve many different factors, like different people being involved, many things that can be targeted, systems that are connected to each other, and environments that are always changing. System dynamics (SD) approaches can help us understand this complexity better and make smarter choices to solve these problems (Gonçalves & Serfontein, 2022).

SD offers a framework for modeling the intricate and ever-changing dynamics of organizational safety. It enables the modeling of complex cause-and-effect relationships that may not be immediately apparent and draws on various fields such as cognitive and social psychology, organization theory, and technical engineering processes (Lu et al., 2019). One of the system Dynamics Modeling software is Vensim Professional it is a popular software package for developing and analyzing System Dynamics models. Using System Dynamics Modeling, it is possible to simulate different scenarios and evaluate the effectiveness of various protection strategies. For example, the model helps to analyze the impact of physical security measures, emergency response plans, and maintenance and upgrades on the safety and security of railway infrastructure (Maggio & Setola, 2013). The software can also be used to identify potential vulnerabilities in railway infrastructure and evaluate the effectiveness of different risk mitigation strategies. By simulating different scenarios, it is possible to identify potential weaknesses in the infrastructure and develop strategies to address these vulnerabilities (Zeng et al., 2022).

The focus of this study is to identify the risks and challenges of the EDR infrastructure protection by using system dynamics modeling approach. To achieve this goal, it is essential to establish a clear understanding of the modeling process from the outset. While there is no universally agreed-upon definition, there are a few widely accepted opinions that have emerged from years of research and practical application.

Sterman (2000) suggests that the modeler typically collaborates with the client team to develop an initial understanding of the problem, using a range of methods such as archival research, data collection, interviews, and direct observation or participation. The system dynamics modeling process, as described by the author, involves five steps. These steps include **Problem Articulation**, where the issues, time horizon, and model boundaries are clearly stated, and reference modes are identified. The **Formulation of a Dynamic Hypothesis** follows, utilizing tools like diagrams to illustrate it. Next, **Formulating A Simulation Model** by defining parameters and equations based on further information. **Testing** is then conducted, including extreme condition tests and sensitivity tests, to compare the simulation's performance with reference modes. Finally, **Policy Design and Evaluation** are carried out by formulating and assessing policies using the simulation model (Sterman, 2000).

5.2. Problem Articulation

As the Chapter four of this study it presents a comprehensive data set comprising various graphs and descriptive information, illustrating the evolution of the problem over time. The issue at hand relates to the increasing occurrences of thefts and vandalisms on the EDR infrastructure, which have become a significant concern for the company. To effectively address this problem, a system dynamics model has been employed to capture the various factors that impact the safety and security of the rail infrastructure. This model not only provides valuable insights into the relationship and interdependencies among different variables influencing rail infrastructure safety and security but also provides the necessary information for analysis.

The time horizon of the model spans a period of 10 years, commencing from 2021 and extending up to 2031. This timeframe has been carefully chosen to encompass a significant duration, allowing for a comprehensive understanding of the problem's emergence and its associated symptoms. By extending the time horizon far back into history, the model illuminates the gradual development of the issue, shedding light on its root causes and early indicators. Moreover, the chosen time horizon extends far into the future, enabling the model to capture the delayed and indirect effects of potential strategies (Sterman, 2000). This ensures a holistic and forward-looking approach to addressing the problem of thefts and vandalisms on the EDR infrastructure, facilitating the formulation of effective strategies and policies.

5.2.1. Key Variables

To address the second research question in this study, a comprehensive range of variables were selected, which are factors linked to the protection of railway infrastructure. These variables classified into two generations of Crime Prevention Through Environmental Design (CPTED). An expanded table that outlines the crucial variables identified along with their corresponding descriptions presented below as follows:

Table 5.1: Key Variables

NO.	Variables	Description
1.	Target Hardening	It is directed at denying or limiting access to a crime target through the use of physical barriers such as fences, gates, locks, electronic alarms, and security patrols.
2.	Gate Locks	Proper and functional locks on the gates of passenger stations, power substations, freight yards, and workshops.
3.	Fences	The states of fences on passenger stations, power substations, freight yards, and workshops.
4.	Interior door	Using interior doors for protection of electrical and communication equipment.
5.	Access control	Focused on reducing opportunities for crime by denying access to potential targets and creating a heightened perception of risk among offenders.
6.	Locks and unique bolts	Using unique locks and bolts to prevent rail fastener theft and electrical equipment vandalism.
7.	Barriers	Construct additional protective barriers in order to protect the facility from damage.
8.	Guards	Guards need to be there to prevent critical signaling, communication equipment theft, and vandalism.
9.	Gates	Proper protective gates are needed to prevent unauthorized access.
10.	Surveillance	The monitoring of behavior, many activities, or information for the purpose of information gathering, influencing, managing or directing.
11.	CCTV	Installing a camera system in a critical place.
12.	Lighting	Make sure that there is proper lighting at passenger stations, power substations, freight yards, and workshops during the night.
13.	Entry Control Stations	Security check by using device or manually
14.	Alarms	Using sound signals during unsuspected activity.
15.	Biometric Surveillance	Using biometric surveillance technology to detect unauthorized persons.
16.	Drones	Drones are helpful in patrolling infrastructure.
17.	Police Patrol	Police are needed to patrol the infrastructure regularly.
18.	Social Network Analysis	Analysis of the integrity of society to the infrastructure.
19.	Activity program support	Encourage intended patterns of usage of public space. Activities serve as magnets for ordinary citizens, who may then act to discourage the presence of criminals.

20.	Sport Activities	Different sport activities around the infrastructure help to protect the infrastructure.
21.	Land Users	Increase the number of land users along the line for farming or other.
22.	Urban Features	Increase urbanization along the line.
23.	Territoriality	A design concept intended to discourage unauthorized users in order to decrease potential for offense by promoting ideas of property concern and a "sense of ownership" in genuine users of space.
24.	Pavements	Using access roads as a territory.
25.	Signs	Putting different regulatory signs on the infrastructure.
26.	Landscaping	Increase the visibility of the infrastructure area.
27.	Defensible Space	The buffer between railway infrastructure and the surrounding area.
28.	Low Decorative Fences	Using cost-effective fences in critical areas of the infrastructure.
29.	Greenery	Presence of green plants and vegetation in the main infrastructure area.
30.	Rule and Boundary Setting	Establishing guidelines, regulations, and limitations to govern behavior and define acceptable actions within the railway facilities.
31.	Induce Shame of Guilty	Working on the society to induce self-blaming for the damaged railway assets.
32.	Potential Criminal Attack	Possibility of an unlawful or harmful act being carried out by an individual or group of individuals on railway assets.
33.	Criminal Attack Rate	The frequency of the attack in different infrastructure locations.
34.	Coverage of the Infrastructure	How wide is the infrastructure in that specific location?
35.	Motives to Engage in Theft and Vandalism	A reason that makes somebody want to vandalize or steal.
36.	Personal Factors	Like unemployment and Economical problem.
37.	Compensation Issue	Revenge for an uncompensated accident occurrence.
38.	Accidents on Domestic Animal	Number of Accidents on Domestic Animal
39.	Vulnerability of The Infrastructure	Exposure of the infrastructure to damage.
40.	Political Factor	Violence arises from political issues.
41.	Absence of Awareness	If there is a lack of awareness in the community about the infrastructure facility.
42.	Maintenance	Following a program promoting the rapid repair and rehabilitation of vandalized equipment.
43.	Rapid Civil Infrastructure Maintenance	Active response to maintenance for vandalized civil infrastructure.

44.	Rapid Electricity Infrastructure Maintenance	Active response to maintenance for vandalized electrical infrastructure.
45.	Social Cohesion	Participation in local and social events, local networks, solve community issues and conflicts, and promote positive awareness-raising and anti-violence education.
46.	Sense of Ownership	The feeling of responsibility and pride associated with being an owner of the infrastructure.
47.	Social Satisfaction	a society's categorization of its people into rankings based on factors like wealth, income, education etc
48.	Social Unity	Communities informally in agreement to the company and decide to act jointly for protection of the infrastructure.
49.	Social Security	Provide a safety net and a source of income for eligible individuals along the railway line.
50.	Community Problem-Solving	Solving the problem of the community by providing different projects like water hole drilling.
51.	Connectivity	Develop a good connection with different stakeholders for information exchange.
52.	Existence of Networks with Federal Police	Making a strong network with federal police for the infrastructure safety and security.
53.	Existence of Networks with Reginal Police	Making a strong network with reginal police for the infrastructure safety and security.
54.	Existence of Networks with Zonal and Wereda Administration	Making a strong network with the Zonal and Wereda administrations for infrastructure safety and security.
55.	Community Culture	Understanding the community culture and improving positive attitudes about the railway infrastructure facilities.
56.	Minority Equality Strategies	Strategic priorities for addressing inequality about using the infrastructure.
57.	Unique Sense of Pride	Making the community feel proud of what they have done about the security of the infrastructure.
58.	Extent of Community Traditions and Cultural Activities	Cooperating with the community in their traditions and cultural activities by integrating the infrastructure service with them.
59.	Threshold Capacity	Human scale, land use density, maximum diversity, and balance in social stabilizers such as street cafes and exhibitions; criminal offenders under the threshold of criticism, such as deprived homes and crime places.
60.	Land Use Density	The density of using land along the line for agriculture, residence, and so on.
61.	Plentiful Access to Social and Economic Resources	Creating a chain within a society to use social and economic resources.
62.	Population Density	Number of populations in the main infrastructure facility.

63.	Communication	Encouragement of bilateral communication and free dialogue.
64.	Equity	Making sure that the community gets fair access to the rail infrastructure.
65.	Local Knowledge	Knowledge of the community that lives around the facilities and awareness of how the infrastructure is used for the country's development.
66.	Community Empowerment and Awareness Creation	Enabling the community to participate in decision-making, access the infrastructure, and create awareness.
67.	Trust and Respect	Developing trust and respect between the community and the company.
68.	Growth rate in 1st generation of CPTED	The development of facilities related to the 1^{st} generation of CPTED helps to protect the infrastructure.
69.	Infrastructure Security	The level of security of the entire infrastructure.
70.	Growth rate in 2nd generation of CPTED	The development of social aspects related to the 2nd generation of CPTED helps to protect the infrastructure.
71.	The Societal Engagement	The communities along the infrastructure need to be engaged and take responsibility for the infrastructure.
72.	Number of Facilities Stolen and Damaged	Periodic increment and decrement of the number of stolen and damaged facilities.
73.	Train Blocking	Stopping the train forcefully by the community.
74.	Incidents and Accidents rate	Increment and Decrement on Incidents and Accidents.
75.	Train delay time	The delay of train operation due to several reason.

These identified key variables play a crucial role in comprehensively modeling and addressing the factors associated with the protection of railway infrastructure.

5.3. Formulating a Dynamic Hypothesis

To provide a comprehensive summary of the model, it is crucial to identify and delineate its boundaries by categorizing the variables into two groups: endogenous variables and exogenous variables. The term "endogenous" refers to variables that originate from within the system, while "exogenous" variables are those that originate from outside the system. In the context of this study, the system under consideration is the railway infrastructure system.

Within this model, there are two distinct subsystems: the 1st generation of CPTED related subsystem and the 2nd generation of CPTED related subsystem. Consequently, each of these subsystems possesses its own unique model boundary, which can be visualized as depicted in the table below:

Table 5.2:1st generation of CPTED related subsystem

Endogenous variables	Exogenous variables
Target Hardening	Social Network Analysis
Gate Locks	Activity program support
Fences	Sport Activities
Interior door	Land Users
Access control	Urban Features
Locks and unique bolts	Rule and Boundary Setting
Barriers	Induce Shame of Guilty
Guards	Potential Criminal Attack
Gates	Criminal Attack Rate
Surveillance	Coverage of the Infrastructure
CCTV	Motives to Engage in Theft and Vandalism
Lighting	Personal Factors
Entry Control Stations	Compensation Issue
Alarms	Accidents on Domestic Animal
Biometric Surveillance	Vulnerability of The Infrastructure
Drones	Political Factor
Police Patrol	Absence of Awareness
Territoriality	
Pavements	
Signs	
Landscaping	
Defensible Space	
Low Decorative Fences	
Greenery	
Maintenance	
Rapid Civil Infrastructure Maintenance	
Rapid Electricity Infrastructure Maintenance	
Growth rate in 1st gen of CPTED	

Infrastructure Security	

Table 5.3:2nd generation of CPTED related subsystem

Endogenous variables	**Exogenous variables**
Connectivity	Social Cohesion
Existence of Networks with Federal Police	Sense of Ownership
Existence of Networks with Reginal Police	Social Satisfaction
Existence of Networks with Zonal and Wereda Administration	Social Unity
Communication	Social Security
Equity	Community Problem-Solving
Local Knowledge	Community Culture
Trust and Respect	Minority Equality Strategies
Growth rate in 2nd gen of CPTED	Community Empowerment and Awareness Creation
Number of Facilities Stolen and Damaged	Unique Sense of Pride
Train Blocking	Extent of Community Traditions and Cultural Activities
Incidents and Accidents rate	Threshold Capacity
Train delay time	The Societal Engagement
	Land Use Density
	Plentiful Access to Social and Economic Resources
	Population Density

5.4. Formulating a Simulation Model

5.4.1. Causal loop diagrams

Based on the first and second generations of CPTED the causal loop diagrams are developed. These diagrams provide insights into the complex relationships and influences among variables within the system. the study has been tried to develop the diagrams by incorporating data obtained from extensive literature reviews, comprehensive interviews, and considerately conducted surveys. The diagrams are divided into two sections, specifically addressing the factors relating to the 1st and 2nd generations of CPTED respectively. By examining these diagrams, one can gain a comprehensive understanding of how these factors interact and impact one another within the CPTED framework.

The table below depicts the feedback loops associated with the first generation of CPTED in this subsystem, there are four feedback loops, consisting of three reinforcing loops and one balancing loop.

Table 5.4: Causal loops associated with the first generation of CPTED

Loop No. (Balancing and Reinforcing)	**Variable Within the Loop**
R1	Infrastructure Security
	Growth rate in 1st gen of CPTED
R2	Surveillance
	Growth rate in 1st gen of CPTED
	Infrastructure Security
	Induce Shame of Guilty
	Defensible Space
	Target Hardening
	Access control
	Vulnerability of The Infrastructure
R3	Motives to Engage in Theft and Vandalism
	Growth rate in 1st gen of CPTED
	Infrastructure Security
	Induce Shame of Guilty
	Defensible Space
	Target Hardening
	Access control
	Vulnerability of The Infrastructure
	Maintenance

B1	Growth rate in 1st gen of CPTED
	Infrastructure Security
	Induce Shame of Guilty
	Defensible Space
	Target Hardening
	Access control
	Vulnerability of The Infrastructure
	Criminal Attack Rate
	Potential Criminal Attack

These feedback loops play a crucial role in shaping the effectiveness of 1st generations of CPTED strategies. Reinforcing loops amplify the impact of positive changes, while the balancing loop ensures a harmonious equilibrium is maintained.

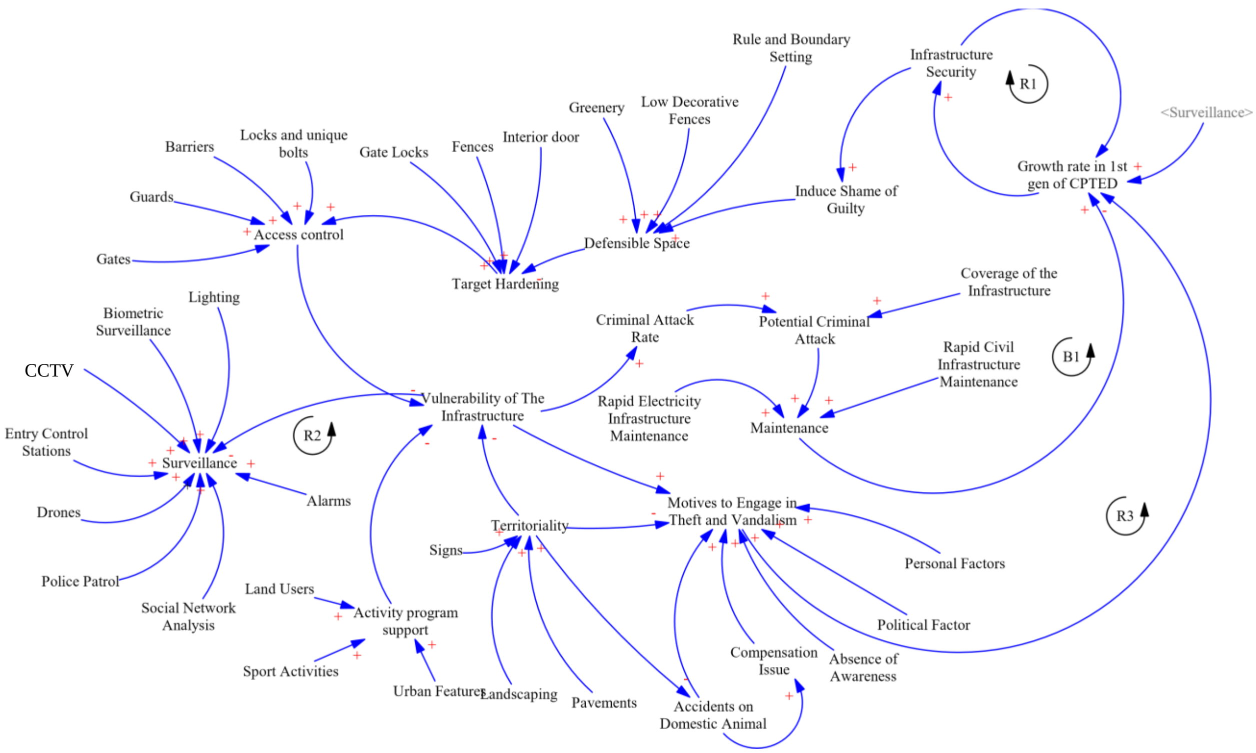

Figure 5.1:Causal Loop diagram for 1st generation of CPTED related factors

The second subsystem of the model is demonstrating the impact of the second generation of CPTED on railway infrastructure protection. In a similar manner, the table presented below illustrates the feedback loops identified within this sub model. Specifically, there are two reinforcing loops and one balancing loop observed within these feedback mechanisms.

Table 5.5:Causal loops associated with the second generation of CPTED

Loop No. (Balancing and Reinforcing)	Variable Within the Loop
R4	Increase the Social Engagement
	Growth rate in 2nd gen of CPTED
R5	Growth rate in 2nd gen of CPTED
	The Societal Engagement
	Sense of Ownership
	Social Cohesion
	Threshold Capacity
	Community Culture
B2	Train delay time
	Plentiful Access to Social and Economic Resources
	Train Blocking
	Incidents and Accidents rate

These feedback loops have a significant role in understanding the dynamics and impact of the second generation of CPTED. The reinforcing loops contribute to the amplification of positive effects and outcomes, while the balancing loop ensures a harmonizing steadiness a system in the model.

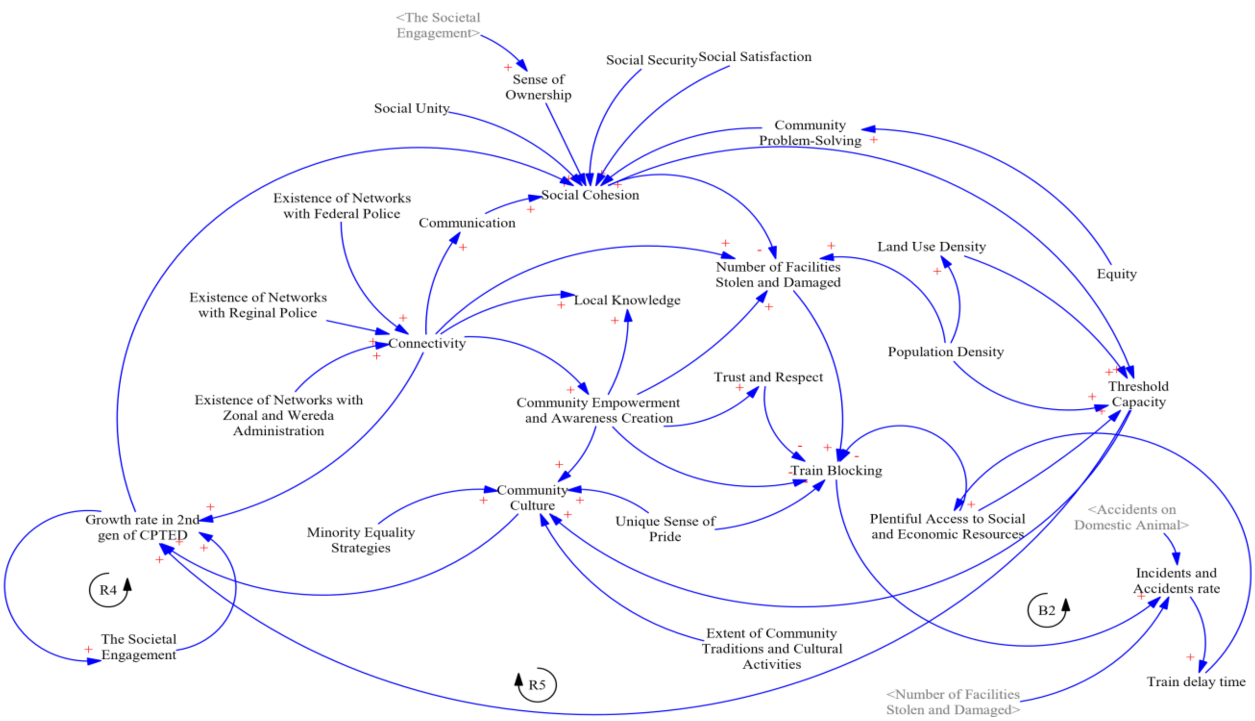

Figure 5.2:Causal Loop diagram for 2nd generation of CPTED related factors

5.5.Mathematical Formulation

Table 5.6: Mathematical formulae for each variable used for SD Model

NO.	Variables	Mathematical Relation	Unit
1.	Target Hardening	(Fences + Defensible Space + Gate Locks + Interior door)/4	km
2.	Gate Locks	Constant	km
3.	Fences	Constant	km
4.	Interior door	Constant	km
5.	Access control	(Barriers + Gates + Guards + Locks and unique bolts)/4 + Target Hardening	km
6.	Locks and unique bolts	Constant	km
7.	Barriers	Constant	km
8.	Guards	Constant	km
9.	Gates	Constant	km
10.	Surveillance	((Alarms + Biometric Surveillance + CCTV + Drones + Entry Control Stations + Lighting + Police Patrol + Social Network Analysis - Vulnerability of The Infrastructure)/9) * 667	km
11.	CCTV	Constant	km
12.	Lighting	Constant	km
13.	Entry Control Stations	Constant	km
14.	Alarms	Constant	km
15.	Biometric Surveillance	Constant	km
16.	Drones	Constant	km
17.	Police Patrol	Constant	km
18.	Social Network Analysis	Constant	Dmnl
19.	Activity program support	(Land Users + Sport Activities + Urban Features)/3	Dmnl
20.	Sport Activities	Constant	km
21.	Land Users	Constant	km
22.	Urban Features	Constant	km
23.	Territoriality	(Landscaping + Pavements + Signs)/3	km
24.	Pavements	Constant	km
25.	Signs	Constant	km
26.	Landscaping	Constant	km
27.	Defensible Space	Constant	km

28.	Low Decorative Fences	Constant	km
29.	Greenery	Constant	km
30.	Rule and Boundary Setting	Constant	Dmnl
31.	Induce Shame of Guilty	Infrastructure Security + Community Culture	Dmnl
32.	Potential Criminal Attack	(Criminal Attack Rate * Coverage of the Infrastructure)	Dmnl
33.	Criminal Attack Rate	(Vulnerability of The Infrastructure/667)*100	Dmnl
34.	Coverage of the Infrastructure	667	km
35.	Motives to Engage in Theft and Vandalism	((Absence of Awareness *Accidents on Domestic Animal + Compensation Issue + Personal Factors + Political Factor + Vulnerability of The Infrastructure)/ (Territoriality + Connectivity + The Social Engagement))	Dmnl
36.	Personal Factors	Constant	Dmnl
37.	Compensation Issue	Constant	Dmnl
38.	Accidents on Domestic Animal	Constant	Dmnl
39.	Vulnerability of The Infrastructure	667 - ((Access control + Activity program support + Territoriality)/3)	km
40.	Political Factor	Constant	Dmnl
41.	Absence of Awareness	Constant	Dmnl
42.	Maintenance	Potential Criminal Attack/(Rapid Civil Infrastructure Maintenance + Rapid Electricity Infrastructure Maintenance)	Dmnl
43.	Rapid Civil Infrastructure Maintenance	Constant	Dmnl
44.	Rapid Electricity Infrastructure Maintenance	Constant	Dmnl
45.	Social Cohesion	Constant	Dmnl
46.	Sense of Ownership	Constant	Dmnl
47.	Social Satisfaction	Constant	Dmnl
48.	Social Unity	Constant	Dmnl
49.	Social Security	Constant	Dmnl

50.	Community Problem-Solving	1*Equity	Dmnl
51.	Connectivity	(Existence of Networks with Federal Police + Existence of Networks with Reginal Police + Existence of Networks with Zonal and Wereda Administration)/3	Dmnl
52.	Existence of Networks with Federal Police	Constant	Dmnl
53.	Existence of Networks with Reginal Police	Constant	Dmnl
54.	Existence of Networks with Zonal and Wereda Administration	Constant	Dmnl
55.	Community Culture	Community Empowerment and Awareness Creation + Extent of Community Traditions and Cultural Activities + Minority Equality Strategies + Threshold Capacity + Unique Sense of Pride	Dmnl
56.	Minority Equality Strategies	Constant	Dmnl
57.	Unique Sense of Pride	Constant	Dmnl
58.	Extent of Community Traditions and Cultural Activities	Constant	Dmnl
59.	Threshold Capacity	(Land Use Density + Population Density + Social Cohesion)/3	Dmnl
60.	Land Use Density	1*Population Density	Km^2
61.	Plentiful Access to Social and Economic Resources	Threshold Capacity + (1/Train delay time)	
62.	Population Density	Constant	Per km^2
63.	Communication	1*Connectivity	Dmnl
64.	Equity	Constant	Dmnl
65.	Local Knowledge	Constant	Dmnl
66.	Community Empowerment and Awareness Creation	Constant	Peoples

67.	Trust and Respect	Constant	Dmnl
68.	Growth rate in 1st gen of CPTED	((((Surveillance + Maintenance)/(Vulnerability of The Infrastructure*Motives to Engage in Theft and Vandalism)) + Infrastructure Security)/667)*100	Dmnl
69.	Infrastructure Security	INTEG(Growth rate in 1st gen of CPTED)	Dmnl
70.	Growth rate in 2nd gen of CPTED	(((Community Culture + Connectivity + Social Cohesion + Threshold Capacity) + The Societal Engagement)/667)*100	Dmnl
71.	The Societal Engagement	INTEG(Growth rate in 2nd gen of CPTED)	Peoples
72.	Number of Facilities Stolen and Damaged	(29017.3*Population Density)/(Community Empowerment and Awareness Creation + Connectivity + Social Cohesion + Infrastructure Security)-(Infrastructure Security*9)	Dmnl
73.	Train Blocking	(Number of Facilities Stolen and Damaged + Accidents on Domestic Animal) / (Community Empowerment and Awareness Creation + Trust and Respect + Unique Sense of Pride + Plentiful Access to Social and Economic Resources)	Dmnl
74.	Incidents and Accidents rate	(Accidents on Domestic Animal*667+Number of Facilities Stolen and Damaged+Train Blocking)/667	Dmnl
75.	Train delay time	INTEG(Incidents and Accidents rate)	Minutes

5.5.1. Stocks and Flows diagram

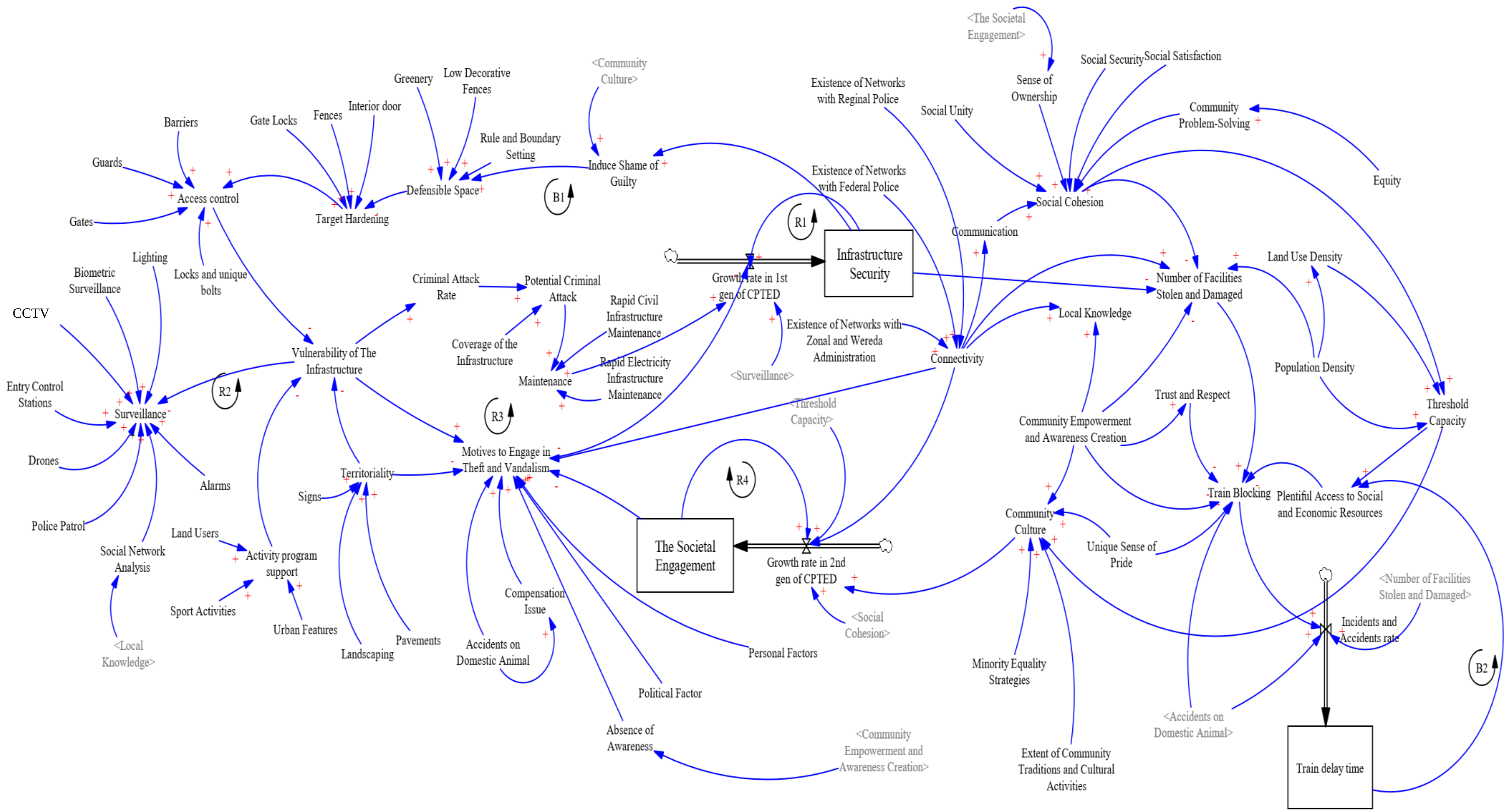

Figure 5.3:Stocks and Flows diagram

CHAPTER SIX

6. RESULTS AND TESTING OF MODELS

6.1.Introduction

In the previous chapter, the study discusses into the general steps and techniques involved in the development of the SD model. In order to justification for the existing conditions of the railway infrastructure, real data was utilized for some of the variables. But a significant portion of the 2nd generation of Crime Prevention Through Environmental Design (CPTED) variables are qualitative in nature and lacking of real data, the study made use of assumptions based on the situations.

In this chapter, the study focusses on examining the simulation results of the SD model. By iterating the testing of model and by altering the magnitude of critical variables the study observed various scenarios. By doing so, the study tried to provide valuable insights into the dynamic behavior of the model and its responses to different inputs. Altering all the exogenous variables are made a change on the behavior of endogenous variables however for this case only three exogenous variables are selected to examine their impact on *Train Delay time*, *number of facilities stolen and damaged, train blocking, Societal engagement as well as Infrastructure Security.* The selected three Exogenous variables are *Community Empowerment and Awareness Creation*, *Accidents on domestic Animal* and *Population Density*.

Furthermore, the study also presented a casualty of the variables by increasing the input value. This involves systematically assessing the impact of changes in the model's inputs of the selected exogenous variables on the outputs of the endogenous variables. By conducting such an analysis, it is possible to identify the variables that have the most significant influence on the overall system behavior. This knowledge is crucial for understanding the underlying dynamics and making informed decisions to improve the railway infrastructure's safety and security.

6.1.1. Effects of Community Empowerment and Awareness Creation on Infrastructure Security

Although exogenous variables are constant and exist outside the system boundary, changes to their values can still affect the behavior of the endogenous variables within the system. An important scenario to observe in the model simulation is the examination of how community empowerment and awareness creation impact railway infrastructure protection. These factors play a crucial role in fostering a sense of collective responsibility and proactive engagement among the community members.

One of significant security concern that arises in the context of train operations is the delay time experienced by trains. Addressing this issue requires a focus on community empowerment and awareness creation, working on the people's awareness and their empowerment as a factors can contribute to minimizing train delays and improving overall efficiency. As the initial value for this specific variable was set at 100 people, increasing the number to 500 and then 1,000 peoples, we can observe a change in selected endogenous variables.

The following figure illustrates the impact of community empowerment and awareness creation on train delay time. As mentioned in chapter four on figure 4.8 the train delay time has an increasing trend due to several incidents and its initial value on 2021 is 2,637 minutes. Therefore, it is important to observe the behavior how to minimize this delay time by demonstrating in the SD model. The simulation reveals results, indicating that community empowerment and awareness creation play a crucial role in reducing delays. Specifically, when community empowerment and awareness creation variables were increased by 500 people, the train delay time decreased significantly from 2,028 minutes to 1,841 minutes. Furthermore, a 1000 people increment in community empowerment and awareness creation led to an even more substantial reduction, with the delay time reaching 1,745 minutes at the end of the simulation period which is 2031.

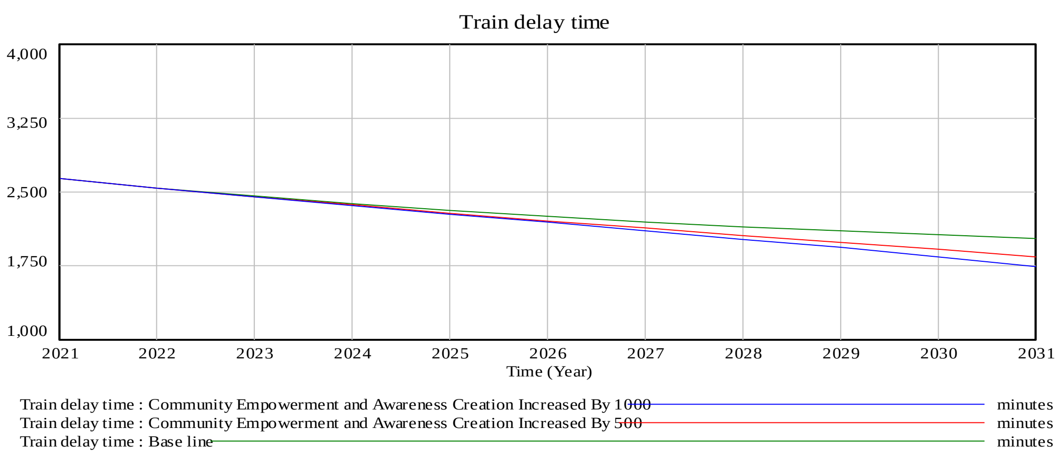

Figure 6.1: Simulation result of Train delay time by varying community empowerment and awareness creation with 500 and 1000 people

Similarly, as highlighted in earlier sections, the issue of facilities being stolen and damaged results a significant challenge to the effectiveness of the EDR train operations. Resolving this problem requires a focused approach, particularly in terms of community empowerment and awareness creation.

The simulation results present encouraging findings, indicating that these factors play a pivotal role in mitigating the occurrence of such incidents. As indicated on the data presentation section by the year of 2021 the number of facilities stolen and damaged was 15,819. According to the simulation, the initial number of facilities stolen and damaged experienced a notable decrease when community empowerment and awareness creation variables were increased by 500 people, the figure dropped from 54,591 to 25,338. Furthermore, a 1000 people increment in community empowerment and awareness creation resulted in a substantial reduction, with the number declining to 5,380. Importantly, the simulation predicts that the occurrence of stolen and damaged facilities becomes declined by the 10th year of the simulation period.

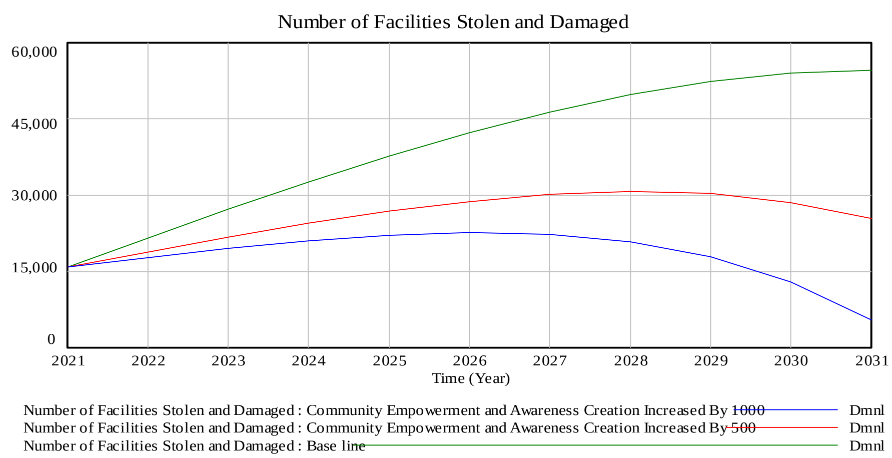

Figure 6.2:Simulation result of number of facilities stolen and damaged by varying community empowerment and awareness creation with 500 and 1000 people

Community empowerment and awareness creation also play a crucial role in addressing the issue of train blocking. The simulation results indicate that these factors have a significant impact on reducing train blocking incidents.

According to the simulation, an increase of 500 people in community empowerment and awareness creation variables leads to a decrease in the initial train blocking. The value drops from 196 to 23. Furthermore, a 1000 change in community empowerment and awareness creation results in a further reduction, with the train blocking decreasing to 2. Notably, the simulation predicts that the train blocking incidents continue to diminish over time, reaching zero by the 10th year of the simulation period.

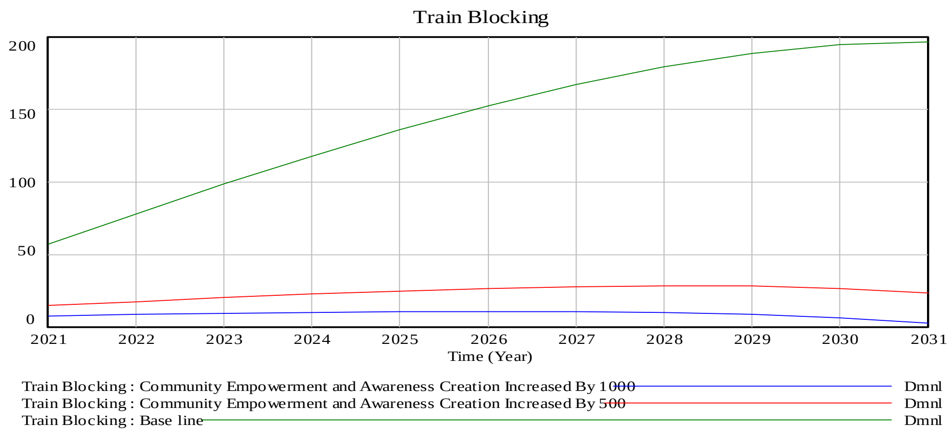

Figure 6.3:Simulation result of train blocking by varying community empowerment and awareness creation with 500 and 1000 people

As community awareness about the railway infrastructure increases over time, society becomes more engaged in protecting this infrastructure with a sense of ownership. The following simulation results demonstrate that when community empowerment and awareness creation increased by 500, societal engagement rose from 3,371 people to 4589 people. A further increment in community empowerment and awareness creation by 1000 leads to an increase the variable to 6,111 people.

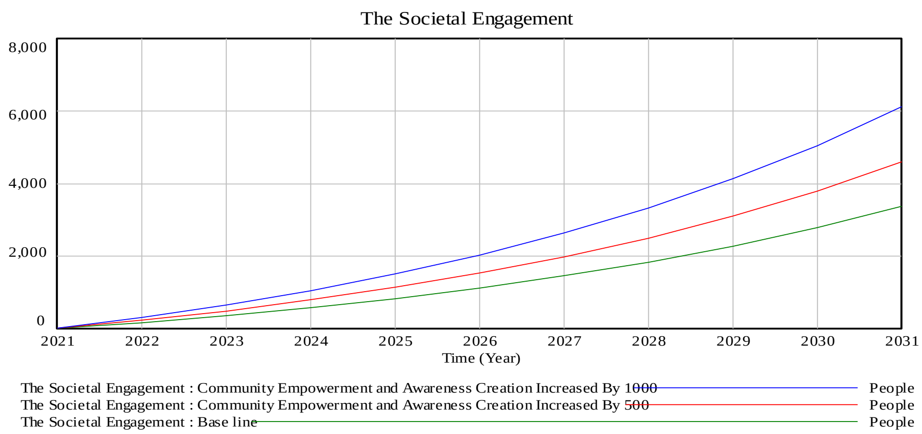

Figure 6.4: Simulation result of the Societal Engagement by varying community empowerment and awareness creation with 500 and 1000 people

Overall the impact of community empowerment and awareness creation on societal engagement is highly significant. These factors play a pivotal role in developing active participation and involvement within the community.

6.1.2. Effects of "Accidents on domestic Animal" on Infrastructure Security

As this study discussed earlier one of the reasons for Infrastructure damage is accidents involving on domestic animals. As shown earlier in chapter four on figure 4.7 accidents on domestic animal in three consecutive years shows an increasing trend. In this SD model simulation, the impact of such accidents is further demonstrated. The initial value for the 2021 of accidents involving domestic animals over the year is set to 132 in the model. To demonstrate the changes on selected endogenous variables caused by animal-related accidents, the number increased to 200 and then 250 accidents.

Increasing the number of accidents involving domestic animals by 200 leads to a significant rise in the initial value of facilities stolen and damaged. Specifically, the initial number of facilities stolen and damaged increases from 54,591 to 55,515.

Furthermore, a change of 250 in accidents involving domestic animals results in an even more substantial increase, with the initial number of facilities stolen and damaged reaching 56,138.

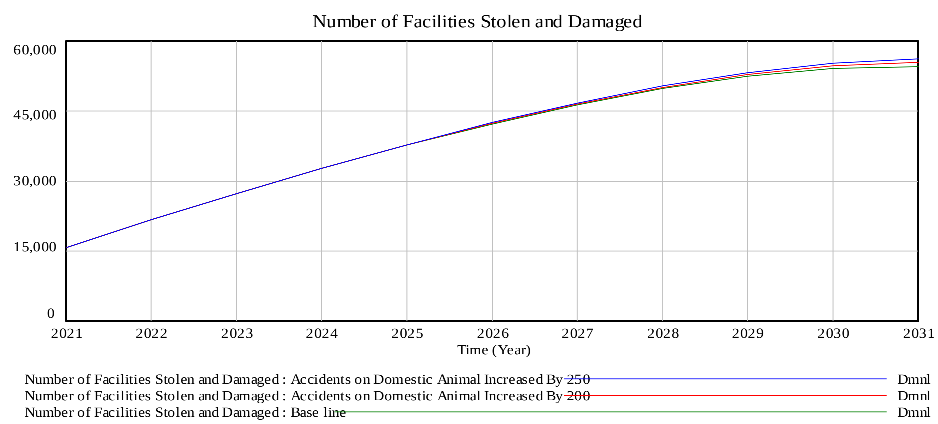

Figure 6.5:Simulation result of number of facilities stolen and damaged by increasing Accidents on Domestic Animals with 200 and 250

According to the simulation, an increase of 200 in accidents involving domestic animals leads to a significant rise in train delay time. Specifically, the delay time increases from 2,028 minutes to

2,711 minutes. Moreover, a 250 change in accidents involving domestic animals results in a further substantial increase, with the delay time reaching 3,213 minutes.

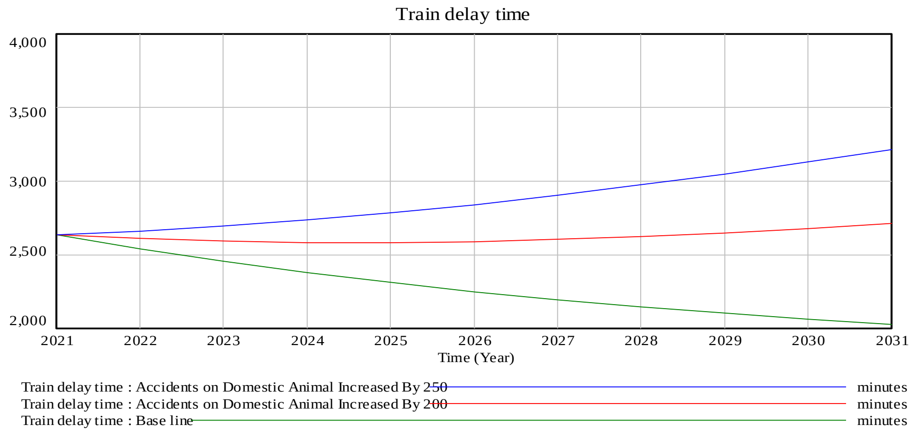

Figure 6.6:Simulation result of Train delay time by increasing Accidents on Domestic Animals with 200 and 250

Similarly, an increase of 200 in accidents involving domestic animals leads to a rise in train blocking. Specifically, the train blocking value shifts from 197 to 200. Furthermore, a 250 change in accidents involving domestic animals results in an even greater increase, with the train blocking reaching 203 by the end of the simulation year. Additionally, when accidents occur involving domestic animals, the affected community tends to frequently block the railway line in order to demand compensation for the injured cattle and other animals.

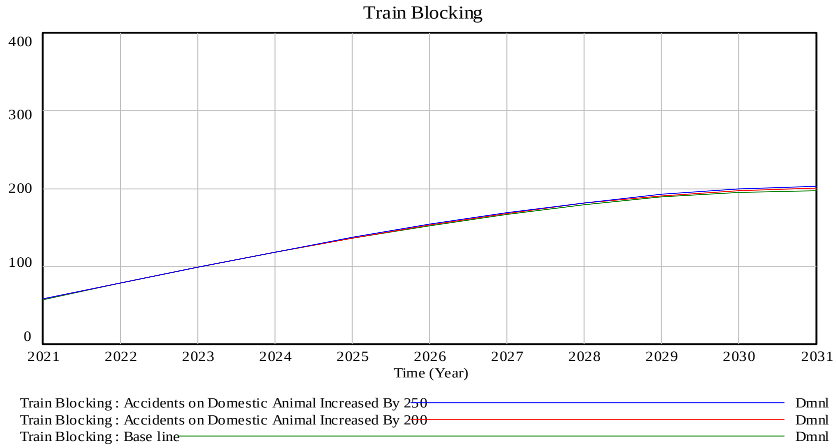

Figure 6.7:Simulation result of Train Blocking by increasing Accidents on Domestic Animals with 200 and 250

In general, infrastructure security is affected by accidents involving domestic animals. The following figure shows a decreasing shift in the graph due to the increasing number of accidents occurred on domestic animals. The graph shifts from 418 to 394 when the number of accidents reaches 200. Moreover, it decreased to 378 when the number of accidents increased by 250.

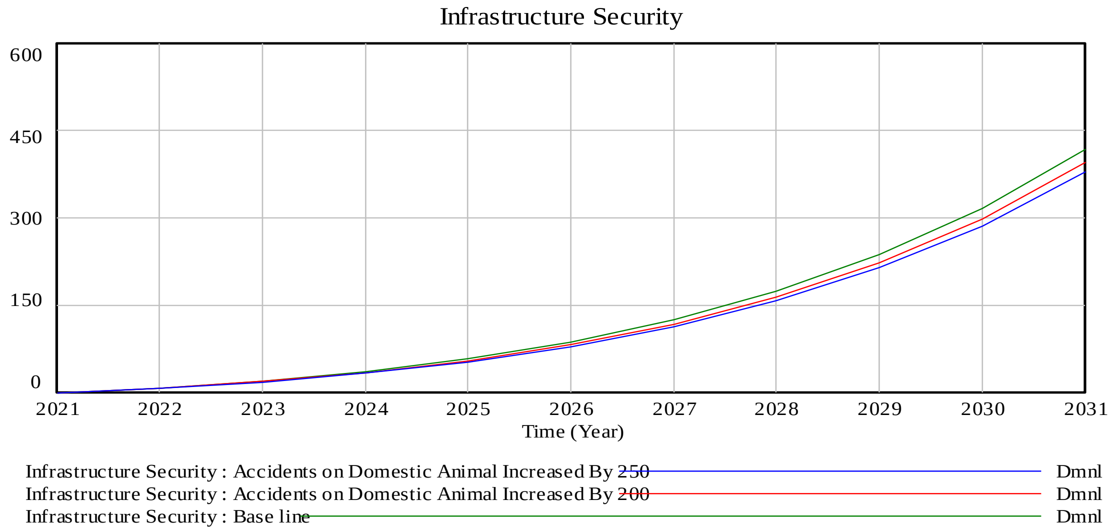

Figure 6.8: Simulation result of Infrastructure Security by increasing Accidents on Domestic Animals with 200 and 250

6.1.3. Effects of Population Density on Infrastructure Security

The infrastructure in highly populated areas demands significant attention due to the increased accessibility and exposure to various incidents caused by the density of the population. This model simulation analysis focuses on examining the effect of population density on selected endogenous variables. Figures 6.9, 6.10 and 6.11 illustrate the impact of population density on the number of facilities stolen and damaged, train delay time, and train blockings respectively.

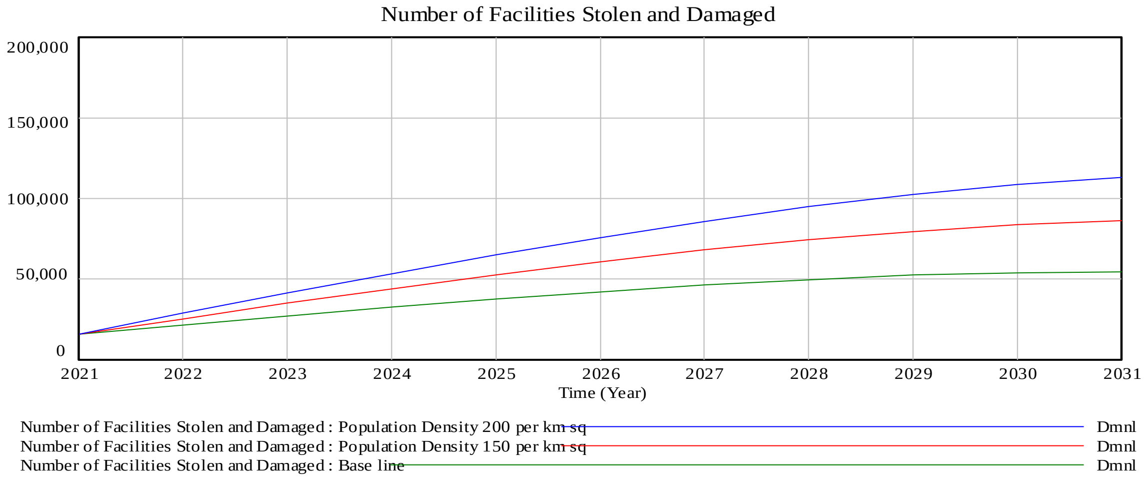

Figure 6.9:Simulation result of number of facilities stolen and damaged by varying population density with 150 /km^2 and 200 /km^2

According to the simulation results, the initial number of facilities stolen and damaged shows a notable increase as population density rises. The initial value of population density was taken by assuming a minimum of 90 per square kilometer in average for the model. Specifically, for a change in population density to 150 per square kilometer the number of facilities stolen and damaged rises from 54,591 to 86,447, and further increases to 112,881 for a population density of 200 per square kilometer. However, it is important to note that the simulation predicts a rises over time with the number of facilities stolen due to the increased population density and it has a great impact on the infrastructure safety and security.

Similarly, the simulation demonstrates that train delay time is significantly affected by population density. An increase in population density to 150 per square kilometer leads to a rise in train delay time from 2,028 to 2,267 minutes. Furthermore, for a population density of 200 per square kilometer, the delay time further increases to 2,466 minutes by the 10th year of the simulation.

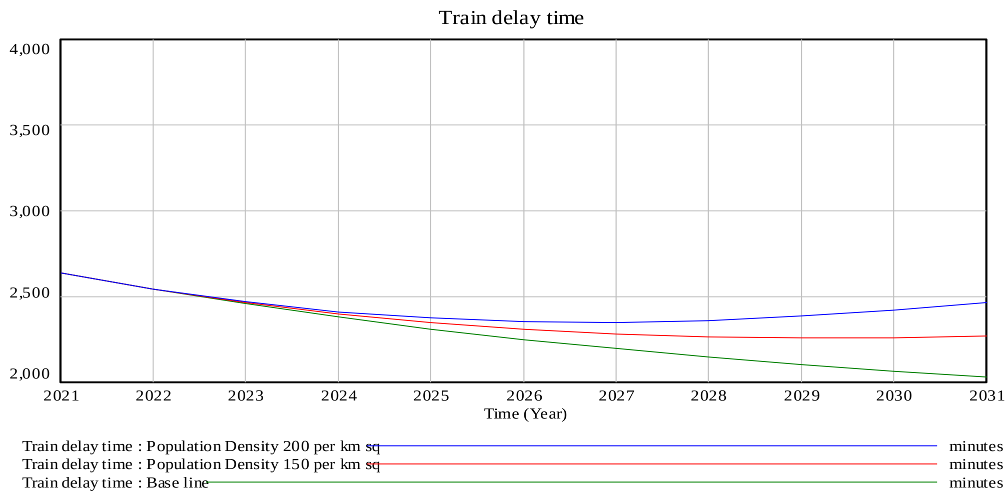

Figure 6.10:Simulation result of Train delay time by varying population density with 150 /km² and 200 /km²

Moreover, the initial value of train blockings also affected by an increase with higher population density. A change in population density to 150 per square kilometer results in an initial increase in train blockings from 196 to 272. Similarly, for a population density of 200 per square kilometer, the train blockings rise to 321.

Figure 6.11:Simulation result of Train Blocking by varying population density with 150 /km² and 200 /km²

In summary, the simulation results demonstrate that as community empowerment and awareness creation increase over time, the outcomes improve significantly. Specifically, train delay time, the number of facilities stolen and damaged, and train blockages all decrease, ultimately enhancing infrastructure safety and protection. Conversely, by further altering the constant exogenous variable values, it is possible to minimize the number of stolen and damaged facilities, train delay time, and train blockages. Neglecting these factors could have led to extended safety and security issues for the rail infrastructure. Additionally, increases in accidents involving domestic animals can lead to community dissatisfaction and emotionally-driven infrastructure damage along the railway. Therefore, this factor warrants close attention. Higher population density also impacts these endogenous variables. Implementing security measures in highly populated areas can help minimize thefts, vandalism of facilities, train delay time, and train blockages. Improving these safety and security dimensions is crucial, as shown in the causal loop diagrams.

CHAPTER SEVEN

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusion

This research focuses on developing a system dynamics model for improving the safety and security of railway infrastructure. The literature review indicates that CPTED is a relevant theory for enhancing the protection of rail infrastructure. Many researchers are working to safeguard critical infrastructure using CPTED principles. However, there is a lack of studies that address this issue through system dynamics modeling. Therefore, it is essential to study the application of CPTED principles in conjunction with system dynamics modeling. This study tried to demonstrate different safety and security factors influencing railway infrastructure using a system dynamic modeling approach. By combining CPTED strategies with system dynamics analysis, the research provides a comprehensive framework for enhancing the overall safety and security of rail networks.

Through a comprehensive literature review, a survey, and interviews, several key variables affecting railway infrastructure protection were identified. Building upon this foundational research, a system dynamics model was developed to capture the interrelationships between these influential factors. By modeling the complex relationships between the identified variables, the study able to analyze and understand the dynamics in the safeguarding of railway infrastructure.

In conclusion, the system dynamics modeling and the casual loop diagram illustrated that surveillance has a great impact on rail infrastructure. The diagram shows that implementing different mechanisms of surveillance with the help of technology has a great impact on infrastructure resilience. Similarly, as a strategy, working on community empowerment and awareness creation is helpful to improve the protection of the railway infrastructure by minimizing train delay times, train blockings as well as facilities thefts and vandalisms. Also, preventing the occurrence of accidents involving domestic animals by creating awareness in the community and implementing the aforementioned security measures has a great impact on the entire train operation by minimizing train delays and blockings as well as theft and vandalism.

On the other hand, as shown in the simulation results, population density has its own impact on infrastructure security. According to the data collected and the simulation results, in highly populated areas the frequency of theft and vandalism increases. This also leads to increased train delays caused by such incidents; therefore, it is important to focus on highly populated areas by implementing proposed protective measures.

Connectivity with stakeholders and focusing on target hardening by improving the previously mentioned security measures like —gate locks, fences, and interior doors—have a major positive impact on infrastructure protection.

7.2. Recommendations

To enhance the protection of railway infrastructure, it is crucial to implement technologically advanced surveillance systems. As demonstrated in the SD model casual loop diagram, surveillance has a vital role in the protection and mitigation of the entire railway infrastructure. Investing in such advanced surveillance will minimize the maintenance cost as well as eradicate motives for theft and vandalism. Particularly, as a big transportation provider in the country, EDR should focus on community empowerment and awareness creation as well as inviting the active involvement of local stakeholders in the protection of the infrastructure. By following this strategy, it can be possible minimizing train delays and blockings as well as theft and vandalism, also the company can strengthen the security of its railway infrastructure. Furthermore, the government should review and update its policy framework to leverage modern technology in safeguarding such critical transportation infrastructure. This could include incentives for the company to adopt cutting-edge surveillance and monitoring solutions, as well as clear guidelines for public-private collaboration in infrastructure security. Lastly, the following recommendations are provided on the basis of the research's results:

- Through system dynamics modeling and simulation, this study attempted to examine and illustrate multiple aspects linked to railway infrastructure utilizing a variety of data sources, including literature reviews, surveys, and observations. For some of the variables the study makes an assumption because there is a lack of complete data. Therefore, more study needs to be conducted by considering accurately recorded data on railway infrastructure protection.

- In reality, there are various issues for the safety and security of railway infrastructure. It is possible to effectively model the dynamic behavior of railway infrastructure protection by extending the issues with the SD model. Therefore, this study strongly recommends that future research on decision support mechanisms for railway infrastructure resilience be done so that operators may choose the best approach and strategy.

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APPENDIX

A Survey on Railway Infrastructure Protection

<u>This Survey is for Academic Research Only</u>

This survey is being conducted as a component of my Addis Ababa University thesis. The goal is to compile information on data gathering procedures that pertain to the protection of railway infrastructure. Rest assured that all answers will be kept private and used only for Academic purposes. There are no right or incorrect responses, and participation is completely voluntary. I respect your honest input and are grateful for the time you have taken to provide it. I appreciate your contribution to the research.

1. Highest level of education:

☐ Doctoral degree ☐ Master's degree ☐Bachelor's degree ☐ Diploma Other

2. What is your Level of position:

☐Director ☐Manager ☐Team Leader ☐Expert ☐Other

3. How many years of experience do you have in EDR:

☐1 Year ☐2 Years ☐3 Years ☐4 Years ☐5 Years ☐6 Years

4. Your Workshop:

☐Indode ☐Adama ☐Metehara ☐Meiso ☐Bike ☐Dire Dawa ☐Adigala ☐Dawanle

		1	2	3	4	5
No.		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	EDR is effective in the implementation of security measures to protect railway infrastructure?					
2	EDR is using security protocols or guidelines in place within the company to protect railway infrastructure.					
3	EDR conduct a frequent security assessment to evaluate the vulnerabilities and risks associated with railway infrastructures?					
4	There are dedicated security teams responsible for monitoring and safeguarding railway infrastructures.					
5	The security teams are dedicated, trained and equipped to handle security incidents and emergencies related to railway infrastructures.					

6	EDR experienced several security incidents related to railway infrastructures in the past year in my working section.					
7	There are surveillance systems (such as CCTV cameras) in my workshop/station to monitor railway infrastructures.					
8	The surveillance systems have good coverage and effectiveness.					
9	There is a proper access control measures (such as Fences, Gates, Barriers, Guards... etc.) implemented to restrict unauthorized entry into railway infrastructure areas.					
10	The security measures integrated with other safety systems (e.g., signaling, emergency response) for railway infrastructures.					
11	There are regular exercises conducted to test the effectiveness of the security measures and response protocols for railway infrastructures?					
12	EDR has a cooperation and collaboration with external stakeholders (e.g., government agencies, law enforcement) in ensuring the security of railway infrastructures.					
13	There are mechanisms in place for reporting and investigating security incidents or suspicious activities related to railway infrastructures?					
14	EDR invested on advanced technologies to enhance railway infrastructure protection.					
15	EDR has good level of integration between security systems and technologies used in railway infrastructure protection within my working area?					
16	There are ongoing projects or initiatives within EDR to improve railway infrastructure protection through technological advancements.					
17	Implementing technological solutions on EDR is cost-effective for railway infrastructure protection?					
18	EDR has conducted assessments of the existing security measures and technological systems for railway infrastructure protection.					

19	EDR has a commitment to investing in technological advancements for railway infrastructure protection.					
20	EDR actively collaborate with technology providers or research institutions to explore and implement innovative solutions for railway infrastructure protection.					
21	EDR makes effective technological advancements for the improvement of the overall security of railway infrastructure.					
22	There are collaborative initiatives between EDR and the community for railway infrastructure protection?					
23	The collaboration can be rated as good and effective between EDR and society for railway infrastructure protection.					
24	The activities of collaboration between EDR and society include information sharing on security threats and incidents, strategy development, and advocacy.					
25	Collaboration between EDR and the society for railway infrastructure protection occur consistently and frequently.					
26	EDR has a high level of engagement and participation in the activities of providing support for the community along the line.					