BENCHMARKING OPERATION READINESS OF THE HIGH-SPEED RAIL (HSR) NETWORK

BY

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ABSTRACT

At present, HSR networks have been significantly extended to accommodate increased passenger demand because the service is believed to unleash social benefits. Nevertheless, the investment in the HSR project is substantially higher than in other transportation projects. Also, most of the HSR network has faced unavoidable issues during operation, such as lack of passenger demand, low operating profit, and non-safety issues. Despite issues addressed, HSR organisations could not maintain their performance to reach the standard and the globe’s directions, especially the sustainability pillar. Those issues become ineffective for HSR organisations, impacting the passenger’s quality of life and socio-economic.

This thesis aims to develop a systems-based benchmarking framework for all HSR networks to enhance operating costs, punctuality, productivity, risk and uncertainty, sustainability, and urbanisation efficiency. Those six KPIs are necessary for the sustainable development of the upcoming HSR network. The thesis has made several significant contributions to developing a benchmarking framework for long-term improvement.

First, this thesis is the world’s first to integrate a Bayesian distribution and Python programming to improve safety across the railway network. As a result, the created model shows higher accuracy than previous models due to the combination of long-term data sets. Moreover, this thesis reveals the decision tree and the Petri-net models to identify the risk level. Thus, it is an advantage for the rail authorities to evaluate and enhance safety performance.

Next, the thesis focuses on life cycle assessment (LCA) and life cycle cost (LCC) frameworks. The LCA model reflects the environmental perspectives of each rail network. This thesis provides an in-depth analysis of each life cycle stage that shows the energy consumption rate and CO_2 emission rate. The outcome can point out energy consumption and CO_2 emission performance. In addition, this thesis is the world's first study concerning uncertainty costs during HSR operations regarding the LCC analysis. The net present value calculation with a discount rate has been added with the Monte Carlo Simulation. In this section, the developed model allows HSR authorities to firmly manage the budget under uncertain conditions, especially during an operating stage.

Lastly, this thesis concentrates on the social impacts of HSR service, particularly on a living quality, educational benefits, and economic opportunities. The long-term datasets have been analysed by using K-nearest neighbour and Pearson correlation techniques. The result can point out the company's performance toward social advantages. By adopting the models in practice, people can obtain more benefits from the HSR service.

By promoting the novelty framework into practice, benchmarking through diversification of current HSR networks is addressed. The selected routes and networks are chosen using a range of factors. For illustrate, the collected networks must be stable and trustworthy, as determined by their long-term operation for at least ten years. Furthermore, the selected HSR lines are mixed in geography, technology, and relevant conditions to avoid bias. The five noteworthy networks and routes consist of Beijing-Shanghai (China), Paris-Lyon (France), Tokyo-Osaka (Japan), Madrid-Barcelona (Spain), and Seoul-Busan (South Korea).

The analysis results indicate that none of the HSR networks illustrates high performance in all pillars. An overview result demonstrates that the CR’s networks perform the best performance following the Renfe, SNCF, JR Central, and Korail networks. In addition, the thesis has provided policy implications for long-term development, in particular, safety services, social impacts, environmental impacts, and technology and innovation. Those suggestions can be applied practically to both existing and upcoming HSR networks.

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LIST OF ABBREVIATIONS

°C	The degree celsius
°F	The degree farenheit
km	kilometre
pkm	passenger-kilometre
hr	hour
tkm	tonne-kilometre
AHP	Analytical hierarchy process
BDA	Big Data Analysis
BN	Bayesian Network
CBD	Central Business Districts
CFRP	Carbon Fibre Reinforced Plastic
CH_4	Methane
CO_2	Carbon dioxide
CR	China Railway Company
DEA	Data Envelopment Analysis
DMU	Diesel Multiple Unit
DT	Decision Tree
EI	Environmental Impacts
EMU	Electric Multiple Unit
ETA	Event Tree Analysis
FMEA	Failure Mode Effect Analysis

FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GJ	Gigajoule
HESS	Hybrid Energy Storage System
HSR	High-Speed Rail
JR	Japan Railway Group
JR Central	Central Japan Railway Company
Korail	Korea Railroad Corporation
KNN	K-nearest neighbour
KPIs	Key Performance Indicators
LCA	Life cycle analysis
LCCA	Life cycle cost analysis
$LCCO_2$	Life cycle of carbon dioxide
LCE	Life energy consumption
MCMC	Markov Chain Monte Carlo
MCS	Monte Carlo Simulation
NO_2	Nitrogen dioxide
NPV	Net Present Value
PCC	Pearson's Correlation Coefficient
PT	Petri-net
SDG	Sustainability Development Goal
SNCF	The Société nationale des chemins de fer français

SPAD	Signals Passing into Danger
RSSB	Rail Safety and Standards Board
RT	Railway turnout
UIC	International union of railway
UN	United Nations
UNEP	United Nations Environment Programme
UNSDGs	United Nations Sustainable Development Goals

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Attended workshops and conferences

▪ 2nd RISEN 2017- ECR Workshop and International Symposium on Rail Infrastructure Systems Engineering (i-RISE 2017), July 2017, UPV, Valencia, Spain.

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▪ 3rd RISEN 2018, - ECR Workshop and International Symposium on Rail Infrastructure Systems Engineering (i-RISE 2017), 3-5 June 2018, Brno University of Technology, Brno, Czech Republic.

▪ The 3rd World Multidisciplinary Civil Engineering Architecture Urban Planning Symposium (WMCAUS 2018), 18-22 June 2018, Prague, Czech Republic.

▪ The Fourth International Conference on Railway Technology Railway 2018 (Railway 2018), 3-7 September 2018, Sitges, Barcelona, Spain.

▪ 12th World Congress on Railway Research (WCCR), 28 October – 1 November 2019, Tokyo International Forum, Tokyo, Japan.

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CHAPTER 1

INTRODUCTION

This chapter introduces the thesis and presents a statement of the problem and the significance of the research, both of which help readers, whether internal or external to the high-speed rail (HSR) sector, to understand in-depth and current issues. The limitations, aims, objectives and structure of the thesis are also introduced. An outline of the KPIs for a new benchmarking framework is then given, allowing an understanding of the following chapters.

1.1 Introduction

1.1.1 Background

At present, the competition for public transportation has shown a high level. Public transportation is commonly regarded as an essential catapult for the well-being of societies, since it offers tremendous value to both residents and business. Many researchers have pointed out that highly efficient and seamless public transportation has indeed increased the quality of life (Spinney *et al.,* 2009; Balal and Cheu, 2019).

Nevertheless, there are clear differences in transportation networks between developed and developing countries. For instance, public transportation costs in developed countries have been well subsidised by local governments to encourage their citizens to use it instead of private cars. On the other hand, public transportation in developing countries has not properly received funding (Kaewunruen *et al.,* 2016).

Since the 20th century, the rapid development of technologies has played a crucial role in public transportation, especially in HSR. The transformation of railway networks has seen a rapid increase in the lengths of networks in many countries. As shown in the UIC report, HSR networks have grown dramatically from 4,620 km to 52,000 km over the past 20 years (UIC, 2020). One key driver is that many experts believe that an HSR service is inevitably essential to expanding their unlimited potential (Korail Sustainability Report, 2018; JR Central, 2019).

The advent of HSR services has genuinely impacted society and people's lives in terms of both short-term and long-term benefits. Some scholars revealed that HSR networks show huge benefits in countries with a vast territory. For instance, Russia has promoted the trans-continental network across its borders. One HSR line, the Moscow-Kazan route, shortens travel time from 13 to 3.5 hours, with an operating speed profile of up to 400 km/hr (Brunello, 2017). This massive reduction in journey times can truly connect Russians living in non-urban areas with civilisation. China, another vast country, launched the '8+8 HSR project', consisting of eight vertical and eight horizontal HSR lines. As is well known, China is the world's most populous country; therefore, this project aims to link people across the country and to expand the capability of the country's economy and externalities (Song *et al.,* 2018; (Ato) Xu and Huang, 2019; Rungskunroch *et al.,* 2020).

In addition, the growth of the HSR network is reflected in long-term benefits for society, especially socio-economically. The advantages of HSR are noticeable in terms of population dynamics between city centres and urban areas. Population growth rates have been found to be higher in the catchment areas of HSR lines. The rate of population in cities with HSR stations have been 22% higher than in cities without HSR (Hirota, 1985). In addition, in Spain, HSR represents great opportunities for passenger travel between Ciudad Real and Madrid, which is the centre for business (Shen *et al.*, 2014). HSR services also offer job opportunities for rural residents.

By following the reasons above, HSR companies attempt to increase their levels of service to achieve customer satisfaction by improving the railway system. HSR operators have upgraded their levels of services for the fulfilment of passenger requirements in terms of a broad range of issues, e.g. reliability of services and network safety of (Hirsch *et al.,* 2007). However, customers' needs can depend on the types of journeys they make; for example, a business trip requires a high level of service, reliable timetable and comfortable seat, whereas a leisure trip requires space and luggage storage (ORR, 2015).

1.1.2 Sustainable development on railway networks

The idea of improving a sustainability railway network has received a lot of attention. Effective railway operation planning is the most important factor in improving a company's success. The efficiency of a system is determined by a variety of factors. Railway performance, for example, is influenced by a number of elements, such as infrastructure, rolling stock, schedules, and service quality (Lucchini *et al.,* 2001).

Rail networks have become a significant form of public transportation propelling societies and the global economy since the first train was operated in the 16th century. Plenty of issues have been solved after the launching of rail services, including decreases in dust and CO_2 levels and reduced traffic congestion in big cities (Peng *et al.,* 2015). In 1964, the first HSR service was launched in Japan. The Shinkansen service has brought more advanced technologies than commuter rail services, especially in terms of better safety and greater velocity. Moreover, the integration of the Shinkansen and conventional rail networks ultimately offers benefits in terms of economic competitiveness, the environment and energy usage (Tanaka and Monji, 2010; Han *et al.*, 2012; Kojima *et al.,* 2017). The Shinkansen service has benefited not only its passengers but also the people of an entire country.

The success of the Shinkansen network has attracted other countries to invest in national HSR networks. Proposals to establish HSR services have been unveiled in many regions. For instance, South Korea has intended to connect each city via HSR with journey times of less than 90 minutes (Railway Gazette, 2011). In France, the amount of HSR track has doubled, from 2,000 km to 4,000 km, while the Spanish government has set a goal of building 10,000 km of HSR tracks (Burnett, 2009; Delaplace and Dobruszkes, 2015). In Great Britain, 'High-Speed 2' (HS2) will reduce the time it takes to travel from London to Birmingham from 81 to 49 minutes (Department for Transport, 2011). Additionally, the plans for the Chinese network have been dramatically increased from 30,000 km in 2020 to 45,000 km in 2030 (CARS, 2017). Additionally, HSR networks have been built and are operating in other countries, such as Austria, Belgium, Germany, Portugal, and the US.

While the advantages of HSR services are publicly displayed, many projects have confronted major problems regarding construction and operational processes. Most HSR lines experience a lack of operating profit due to low passenger demand and inappropriately priced services. Some HSR routes have faced a high degree of competition from other modes, such as cars and aeroplanes. Such problems impact quality of service and affect long-term development.

It is extremely difficult for HSR projects to achieve financial success or profitability due to reliance on many uncontrollable factors. Nevertheless, it is necessary to maximise the advantages of HSR for social benefits. To overcome this problem, the sustainability framework for HSR networks has been adopted to achieve success for HSR services. The sustainability concept can be applied at both local and global spatial levels to improve the benefits of HSR in supporting people in terms of their residential areas, the economy and the environment.

1.2 Statement of problems and significance of the research

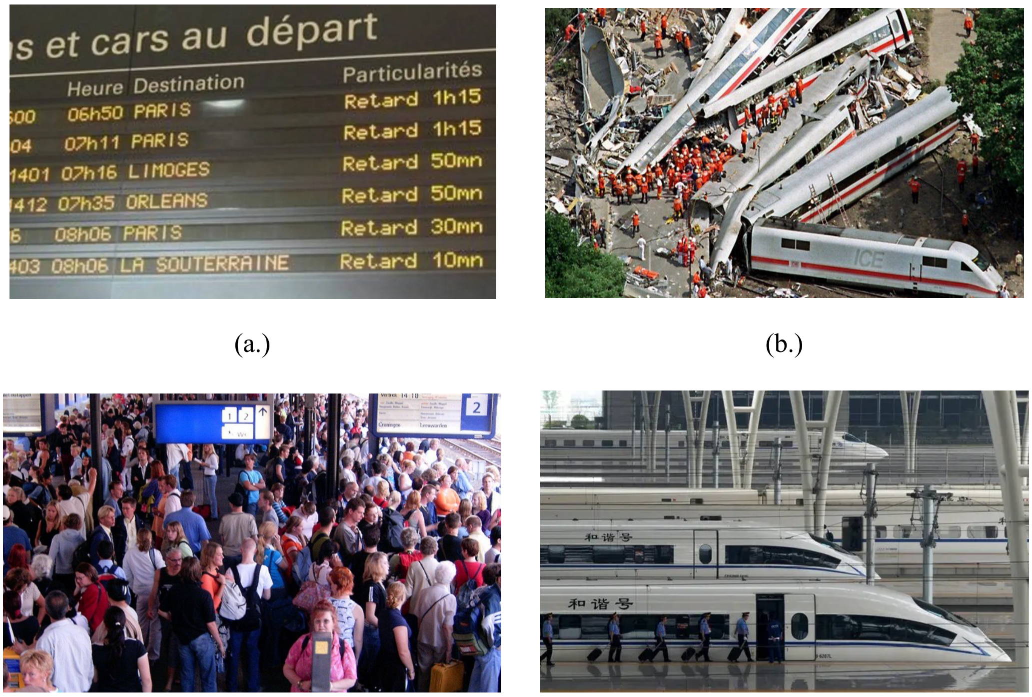
Todays, HSR networks have been widely expanded to support high passenger demand. Many countries firmly believe that an HSR network can ultimately bring benefits and opportunities to society (de Rus and Nombela, 2007; Yang and Zhang, 2012). Nevertheless, this turns out to be even more problematic because of the lack of overall operation readiness of the HSR network. These problems may wreck the railway sector, causing unsuccessful operation of their services.

First of all, the construction of a HSR project requires a high volume of investment compared with other transportation (Barringer *et al.*, 1995). Therefore, loss of profit becomes a critical problem across the HSR sector because HSR projects generally take a long time to achieve a positive return on investment. Even though HSR services receive subsidies from local or regional governments, it is worth discussing the exciting fact that only a few HSR lines are profitable, such as the Tokyo-Osaka and Paris-Lyon routes (Finger *et al.,* 2016).

Secondly, the role of HSR has become more important due to rising passenger demand. Giving an example of HSR networks in the EU, its infrastructure and station platforms have become highly crowded, particularly at peak times. As a result, some of the track and platform capacity has reached a saturation point. Also, some HSR lines have almost reached their maximum capacity (Lindfeldt, 2015). It implies that the passenger demand for overcrowded services affects the safety standards of the networks. This issue can also affect the robustness of schedules. Therefore, the operator should include an efficient tool to increase the efficiency of HSR's resources to support future demand.

Lastly, having staff with multidisciplinary backgrounds in HSR companies affects operating performance. The companies involve multiple sections, such as infrastructure, rolling stock, operations, maintenance, and human resources. Improper communication systems lead to safety and reliability issues across networks. The data recorded for 25 UIC members indicates that human, technical, and organisational failures are responsible for 13% of major accidents (UIC, 2017). As a result, an integrated high-performance work plan is required as a critical organisational driver.

The HSR network contains multiple internal and external organisational problems. One way to overcome these problems is to eliminate those issues to spread the benefits of their services throughout society. However, to our knowledge, there are no previous public policies or standardised frameworks that commonly evaluate HSR networks to make them more successful. For this reason, this doctoral research develops a new system-based framework to measure the HSR network performance comprehensively. The framework's outcomes are to precisely point out and minimise issues and support HSR companies in achieving sustainable goals.



(a.) (b.)

(c.) (d.)

Figure 1.1 Frequent problems for railway operations: (a.) non-robust timetables; (b.) poor safety performance; (c.) overcrowded platforms (d.) lack of railway infrastructure (la Nouvelle, 2012; Online focus, 2013; NL Times, 2019; The New York times, 2011)

1.3 Research scope and limitations

The research primarily focuses on HSR networks, defined as those networks with a minimum velocity of 250 km/hr for new lines or 200 km/hr for upgraded or existing lines. Hence, the thesis's framework is suitable to HSR networks rather than other types of rail service, such as conventional rail, intercity trains or freight trains.

Regarding data collection process, most of the datasets have been conducted during 2000 – 2019, while some public information has been collected in 2021. Therefore, outdated information was not taken into account.

1.4 Research aims and objectives

This research aims to develop a systems-based framework for HSR to enhance its efficiency in terms of life cycle cost, punctuality, productivity, risk and uncertainty, sustainability, and urbanisation. From these research aims six objectives follow as described below:

- To assess the HSR system performance in terms of life cycle cost, punctuality, and productivity, as well as risk and uncertainty, sustainability, and urbanisation.
- To establish data-driven and consistent measurement for future HSR projects.
- To gain a better understanding of best practices via case studies and to provide recommendations for improving current HSR systems.
- To better understand unpredictable scenarios in HSR accidents, strategies are advised to reduce the number of fatalities and injuries.

- To compare the amount of carbon emissions produced by each HSR network and make recommendations for addressing those emissions.
- To investigate the influence on newly accessible locations following the introduction of HSR lines, and to discover beneficial impacts in terms of living quality, educational benefits, and economic opportunities.

1.5 List of contributions

The contributions of this thesis are illustrated below:

- The research develops a novel benchmarking framework for the long-term development of HSR networks. Moreover, the study compares five HSR networks: CR, JR Central, SNCF, Korail, and Renfe.
- This thesis is the first study to develop a novel Bayesian model for railway operations based on prior belief and probabilistic methodologies. The accuracy of the non-uniform distribution model ($\propto$ = 4:4:1) developed is more than a 95% confidence level.
- The research combines both the decision tree (DT) and Petri net (PT) models to measure risk level across railway networks. The model can be applied by any rail authority.
- The research adopts a life cycle perspective on HSR networks by merging the life cycle assessment (LCA) and life cycle cost (LCC) frameworks. Additionally, the model includes net present value (NPV) analysis and Monte Carlo simulation (MCS). The outcome leads to precise budget management and control of environmental impacts, especially in uncertain circumstances.

- The thesis also benchmarks the socio-economic impacts of HSR networks. Long-term data has been analysed through K-nearest neighbour and Pearson correlation coefficient models through Python programming.
- The study is the world's first to review the whole of society, focusing on all generations, as the research outcomes point precisely to aspects of both society and the economy that can be developed.

1.6 An overview of the conceptual framework of the thesis

With the research aim at increasing the overall performance of HSR networks, a new systems-based framework has been developed. Six key performance indicators (KPIs) are considered: life cycle cost, productivity, punctuality, risk and uncertainty, sustainability, and urbanisation.

The framework is adopted from the balanced scoreboard model, a tool for strategical evaluation in industry and business (Kaplan and Anderson, 2005). The balanced scoreboard is used to monitor an organisation's performance and to closely compare this with its targets. This tool offers an organisation a deep understanding of its current situation, leading immediately to managing and making decisions for better performance (Bhagwat and Sharma, 2007; Neely, 2008; Sharma, 2009). Moreover, the scoreboard can benefit internal communication, allowing everyone to understand the organisation's current status.

Regarding railway operation research, the balanced scoreboard has been applied to support railway companies in managing each project KPI. In Figure 1.2, the railway organisation's scoreboard contains four main criteria: internal business process, financial perspective, learning and growth, and customer perspective (Anderson *et al.*, 2003; Kaplan and Anderson, 2005). These factors are mandatory for a railway organisation to operate its business successfully.

The application of the balanced scoreboard has been found to improve railway infrastructure management companies (Hirsch *et al.,* 2007). The research integrated the balanced scoreboard and seven success dimensions of railway organisation, as shown in Figure 1.2. The dimension is required to measure the organisation management performance.

In this thesis, a new system-based framework of has been integrated with balanced scorecard. The aforementioned KPIs have been illustrated in all dimensions, as shown in Figure 1.3.

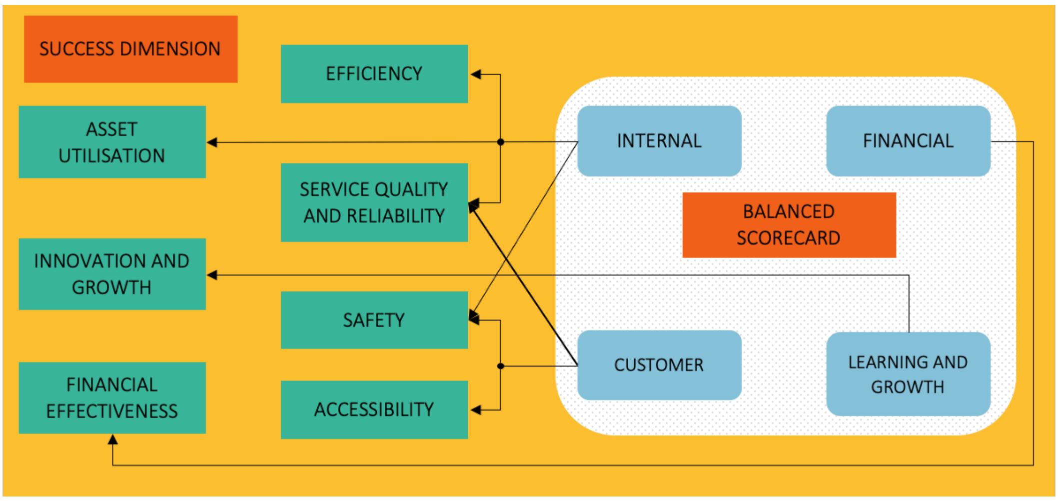


Figure 1.2 The development of the success dimension in a railway organisation through applying a balanced scorecard (Source: Kaplan and Norton, 2001; Hirsch *et al.*, 2007)

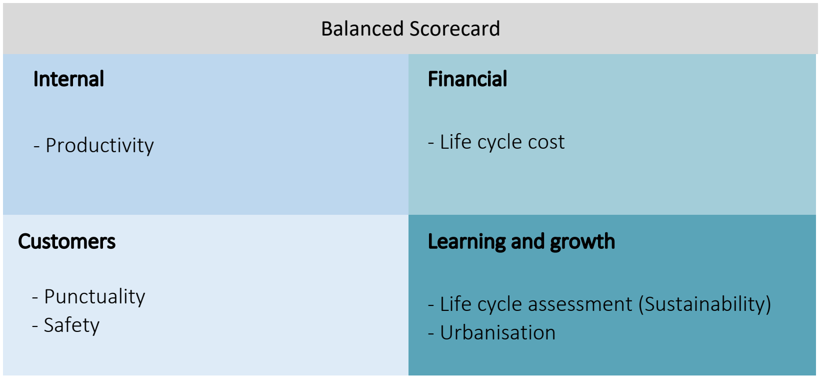


Figure 1.3 The integration of a new system-based framework's KPIs with a balanced scorecard

As mentioned, the thesis has adopted and modified the previous framework into six KPIs containing the balanced scorecard's three fundamentals (life cycle cost, productivity, and punctuality) and three novel frameworks (risk and uncertainty, sustainability, and urbanisation). The descriptive list of KPIs is illustrated as follows;

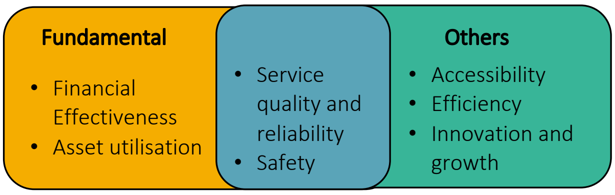
1. Life cycle cost: The factor measures the financial performance of HSR networks along four stages of the HSR's life cycle. The thesis focuses profoundly on the HSR's rolling stock and infrastructure. The KPI focuses on budget management and highlights the problem of lacking operating profit.
2. Productivity: The factor measures operating and service performance in HSR organisations by using six essential sub-indicators. The KPI highlights resource management in HSR organisations.
3. Punctuality: The factor measures operating and service performance in terms of punctuality and cancellation rates. The KPI addresses the effectiveness of HSR services.

4. Risk and uncertainty: The factor measures operating and safety performance by evaluating the risk level throughout the novelty model. The KPI reflects risk probability and leads to maintaining safe service for passengers.
5. Sustainability: The factor measures sustainability performance along the four life cycle stages of HSR's infrastructure and rolling stock. The KPI addresses the amount of energy consumption and CO_2 emission from HSR services.
6. Urbanisation: The factor measures sustainability and socio-economic performance of HSR services by evaluating three dimensions: quality of living, education, and employment. The KPI can enlarge the benefits of HSR to society.

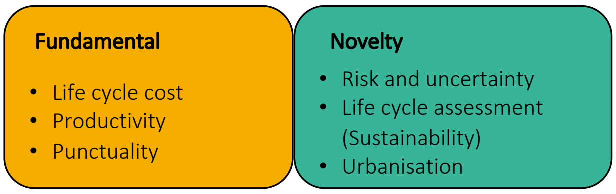
1.6.1 Weighted scores for KPIs

Compared with Hirsch *et al.,* (2007)'s KPIs, the research aimed at developing railway infrastructure management companies. Seven KPIs have been suggested as an improving direction. Nevertheless, this thesis aims at improving operational readiness to reach sustainable development; therefore, the combination of Hirsch *et al.,* (2007)'s KPIs (financial effectiveness and asset utilisation) and the aforementioned novelty KPIs are adopted into a new system-based framework, as shown in Figure 1.4 (b).

The fraction of Hirsch's fundamental and other KPIs shows a ratio of 2:3 (financial effectiveness and asset utilisation versus accessibility, efficiency, and innovation and growth), as shown in Figure 1.4 (a) (Hirsch *et al.,* 2007). For this reason, the fundamental and novelty frameworks' weights of this thesis are broken into a weight of 40%:60%, which is a similar ratio of 2:3.



(a)



(b)

Figure 1.4 The comparison of (a.) Hirsch's and (b.) the thesis' framework.

The weighted score of KPIs has been applied in a system-based framework to adopt into practice. According to the fundamental framework of this thesis, the life cycle cost and punctuality KPIs involve external and third-party stakeholders such as local government, and passenger. On the other hand, the productivity KPI relates to only internal management. As a result, the weighted score of the fundamental framework is distributed to life cycle cost (15%), productivity (10%), and punctuality (15%).

The total weight score of the novelty framework of the thesis is set to 60%. Those KPIs are necessary for a driven railway operator; therefore, the weight of risk and uncertainty, sustainability, and urbanisation are equally distributed at 20%. Overall weighted scoring is illustrated in Table 1.1.

Table 1.1 The summarisation on KPIs of the thesis' system-based framework

KPIs	Weighted score	Insight definitions	Weighted (%)
Life cycle cost	15	Manufacturing (Infrastructure)	3
		Manufacturing (Rolling stock)	3
		Operational	3
		Maintenance	3
		Demolition	3
Productivity	10	Overall productivity	10
Punctuality	15	Punctuality rate	7.5
		Cancellation rate	7.5
Risk and uncertainty	20	Overall risk across network	20
Sustainability	20	Life energy consumption (LCE)	10
		Life cycle of CO_2 ($LCCO_2$)	10
Urbanisation	20	Education	6.67
		Employment	6.67
		Quality of living	6.67
Total weight			100

Concerning the in-depth calculation of weighted scores, a mixed method is used that combines linear interpolation and the weighted scores model. The linear interpolation method is a powerful tool in mathematical analysis. It is widely adopted to solve issues related to missing values in the data processing stage, especially in data science (Blu *et al.,* 2004). Linear interpolation theory is clearly illustrated in Figure 1.5. Calculation in linear interpolation is illustrated in equation 1.1 below. This method is applied to the life cycle cost, risk and uncertainty, sustainability, and urbanisation criteria.

$$\frac{y_i - y_0}{x_i - x_0} = \frac{y_1 - y_0}{x_1 - x_0} \tag{1.1}$$

where: $y_0 = 0$; y_1 = maximum weighted score; x_0 = minimum value among the five networks or routes; x_1 = maximum value among the five networks or routes; i = set of benchmarking networks or routes {CR (Beijing-Shanghai), JR Central (Tokyo-Osaka), SNCF (Paris-Lyon), Korail (Seoul-Busan), Renfe (Madrid-Barcelona)}.

On the other hand, a fundamental aspect of the weighted score model is that it is a powerful technique that fits with the system-based framework. This method is necessary in deciding between many options, multiple criteria, and similar levels of options. The weighted score technique is applied to the productivity and punctuality criteria.

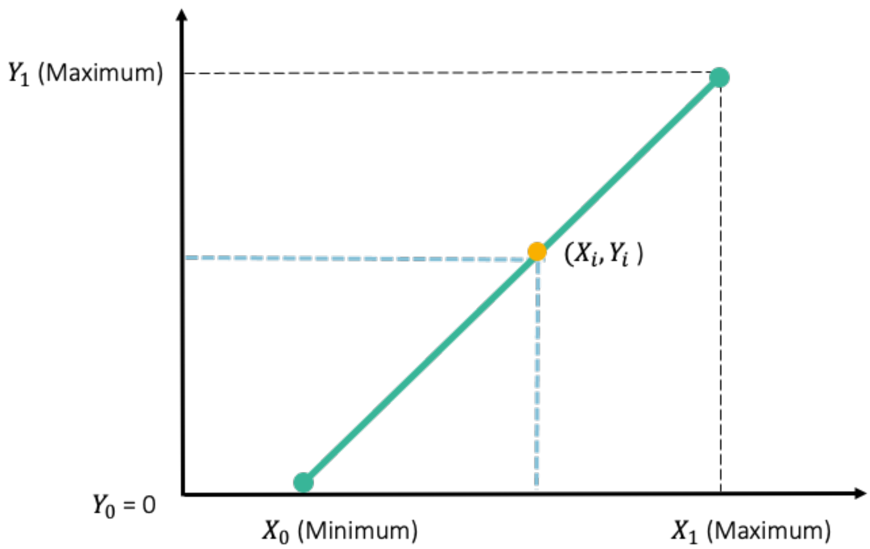


Figure 1.5 The concept of linear interpolation

1.7 Structure of the thesis

The structure of this thesis is arranged to help readers clearly understand its outcomes. The thesis has strictly followed the format of a collection of articles collection (also called a 'compilation thesis'). Additionally, the thesis is formatted according to the 'alternative format thesis guidelines' based on the University of Birmingham's regulation 7.4.1. This doctoral thesis consists of eight chapters with a total of 49,206 words, excluding figures, tables, appendices and materials.

Chapter 1, 'Introduction', includes the research background, general views and the idea of sustainable rail networks. The literature reviews (Chapter 2) include the backgrounds for the five notable HSR networks in five different countries that are taken into account in this study. This chapter leads to a standardised development of the benchmarking framework for future improvement in HSR networks.

The benchmarking framework has been created to determine the operational readiness of HSR networks, as mentioned in the research aim. The overall framework can be divided into two groups: fundamental and novel frameworks. The fundamental

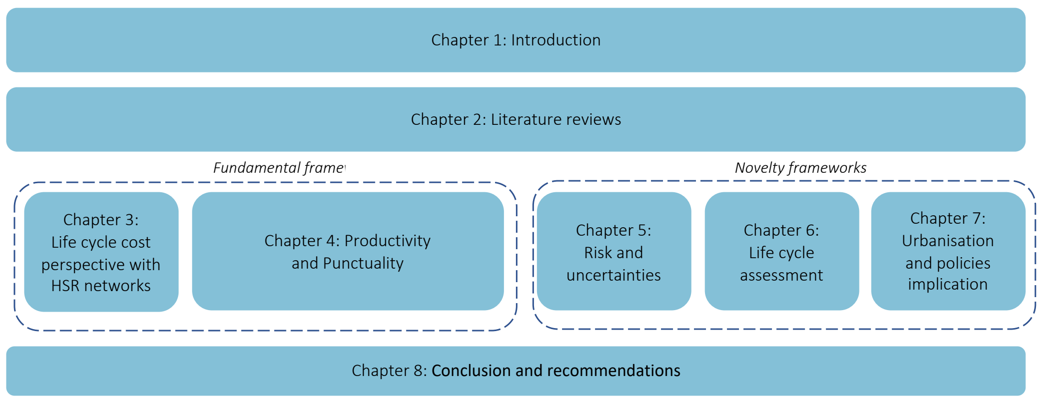


Figure 1.6 An overview of thesis structure

framework is a mandatory requirement for railway companies, consisting of life cycle cost (LCC) (Chapter 3), productivity, and punctuality (Chapter 4).

Although the fundamental frameworks have been mainly applied to all railway companies, they are essential keys for success that should be included. In Chapter 3, LCC is discussed regarding the rail network performance. The overall cost of each LCC stage has a net present value (NPV) with a 6% discount rate. Additionally, this chapter applies the Monte Carlo simulation (MCS) in the sensitivity analysis. The outcome from this chapter provides a benefit to railway companies in estimating cost even through uncertain events. In Chapter 4, the productivity and punctuality factors are covered to help railway companies to maintain their standards.

In addition, novel frameworks have been established and added to the fundamental frameworks. Our novel frameworks can apply to all railway companies leading them to provide long-term sustainable development. The novel frameworks are composed of three parts: risk and uncertainty (Chapter 5), life cycle assessment (Chapter 6), and urbanisation and policy implications (Chapter 7).

Chapter 5, on risk and uncertainties, aims to analyse and predict railway accidents across railway networks. This study presents Python-based models to evaluate risk level. The outcome is a massive advantage for railway companies in a definite reduction in railway accidents, thereby reducing injuries and fatalities. Chapter 6 illustrates LCA perspectives, focusing on energy consumption and CO_2 emission along with HSR life cycle. This research discusses both rail infrastructure and rolling stock in detail. The outcome from this chapter produces environmental benefits. Chapter 7 discusses the benefits of HSR services for urbanisation. This research takes long-term official data sets and compares the social benefits for all generations, especially in terms of education, the economy and quality of life. The outcomes can provide proper guidance to each HSR network for the improvement of its service and can ultimately benefit society.

Each individual chapter contains in-depth analysis of the five selected HSR networks, benefiting readers by clearly understanding both the pros and cons of each network. Furthermore, the benchmarking of the selected HSR networks gives insight into KPIs and weighted scores. Also, the conclusion and recommendations from this research that are suitable for the railway sector, policymakers and researchers to adopt into practice are illustrated and discussed in Chapter 8.

1.8 Chapter summary

The growth of HSR networks has offered positive impacts on society in both developed and developing countries. The success of these networks mean they have become role models for others countries in building new networks. On the other hand, HSR operations have unavoidably faced various problems from inside and outside of railway organisations.

Chapter 1 gives an overview of HSR and a perspective on sustainability development. The thesis also points out operational problems in the sector; thus, the framework for the long-term development of HSR networks has been adopted along with six criteria.

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CHAPTER 2

LITERATURE REVIEW

This chapter presents an in-depth literature review of urban public transport, linking it to the advent of HSR networks, global HSR trends, and the market share for HSR services. Also, the five selected HSR networks and routes are reviewed. Additionally, there is a three-part review of system-based frameworks in railway research divided as follows: tools and programming, railway operational performance, and railway infrastructure. This chapter demonstrates the knowledge gap and how the new framework developed in this thesis relates to other previous studies.

2.1 Urban public transport

Public transportation is currently essential to society as it offers tremendous benefits for both residential and business users. Many researchers have pointed out that highly efficient and seamless public transportation have indeed increased quality of life (Spinney *et al.,* 2009; Balal and Cheu, 2019). Nevertheless, there is a difference in the transportation networks of developed and developing countries. For example, public transportation costs in developed countries have been subsidised by local governments to encourage citizens to use services instead of private cars (Sáadin *et al.,* 2016). On the other hand, public transportation networks have not been widely supported in developing countries.

Likewise, travel passes for public transit in Madrid are subsidised for younger passengers, while ticket prices have been cut by up to 72.8%. As a result, passengers with medium incomes have increased opportunities to access public transport (Arranz *et al.,* 2019). Also, in the United Kingdom (UK), railcards with a discount of up to 33.33% of the regular ticket price are available to young people (16-25 years old), students and senior passengers (over 60 years old) (Harvey *et al.*, 2014). In Stockholm, moreover, with the Swedish railway network being increasingly subsidised by the government, this has led to a noticeable growth in the rail passenger market (Alexandersson *et al.*, 2018).

In developing countries, conversely, most public transportation has been operated as informal services, such as mini-buses, jeeps, taxis or tricycles, as shown in Figure 2.1. The vehicles used for informal transport services may not be fit for purpose, since their owners can be rather complacent about, and highly tolerant of low performance and low-level technologies. Informal transport service operations usually lack profit, and the vehicles take a longer than average time to reach passengers' destinations (Cervero and Golub, 2007). For instance, a Filipino with a low income always uses an informal form of transportation that includes door-to-door service (Guillen *et al.,* 2013). There are various types of informal transport services in Jakarta, Indonesia, such as pedicabs, motorcycle taxis, and mini-buses, all of which are based on fares and scheduled timetables controlled by the local government. In addition, these informal forms of transport service are often regarded as unsafe, and in need of government subsidy (Cervero, 2000; 2010).

Figure 2.1 (a) A mini-bus service in Nigeria, and (b) a tricycle service in Manila, Philippines (Source: Dahur, 2019; Felonco, 2018)

2.1.1 The advent of the high-speed rail (HSR) era

It has been mentioned in a report by the World Bank that the rehabilitation and development of the public transportation system are regarded as one of the key drivers of urban transport (World Bank, 2006). Another World Bank report, in addition, strongly believes that transport infrastructure, especially HSR infrastructure, has contributed to, and influenced social and economic development (Amos *et al.,* 2010). At the moment, building of HSR lines has accelerated worldwide, resulting in an infrastructure of more than 52,000 km (UIC, 2020). Numerous countries have made significant investments in both infrastructure and technology linked to HSR operation, believing that a HSR service is necessary for the endless extension of their potential (Korail Sustainability Report, 2020; JR Central, 2017).

HSR has been considered to be one of the intelligent and historical inventions of the 20th century, dramatically improving society and people's lives. In 1964, the Tokaido Shinkansen was commercially operated between Tokyo and Osaka with an operating speed of 210 km/hr and, increasing to 250 km/hr in 1969. Since the beginning of this first HSR service, a large number of rail networks have provided and invested in high-speed services for customers who expect faster services. However, the investment in HSR infrastructure and operations requires a large amount of money compared with other transportation projects. At the beginning, some of HSR services were partially operated on conventional lines.

Nowadays, HSR can broadly be defined depending on the specific location. Giving an example of a European rail network, the International Union of Railways (UIC) states that HSR includes new lines that are specially built for a speed of at least 250 km/hr, as well as existing lines that allow a speed of at least 200 km/hr (UIC, 2012). On the other hand, the definition in the American rail sector mentions that emerging rail (as HSR is known) should allow speeds of between 144.84 and 177.03 km/hr (Feigenbaum, 2013; US Department of Transportation, 2009; Cantos and Maudos, 2011).

The success of the Tokaido Shinkansen has opened minds in many other countries for high-speed transportation developments. Some scholars state that the key success of the Shinkansen service relies on various technical and operational factors, such as using a standard gauge, linking to conventional lines and major prefectures, and avoiding level crossings (Takai, 2015). Moreover, the networks have continually developed technologies by replacing old bogies with new ones, launching tracking systems, reducing train car weight, and providing a safe service, in particular an earthquake prevention system. Not only does the Shinkansen service provide advanced technologies in, but it has also offered advantages to society in terms of reducing environmental impacts.

HSR is well-known as a complex system compared to other public transportation modes. HSR operations commonly consist of various sections, as shown in Figure 2.2.

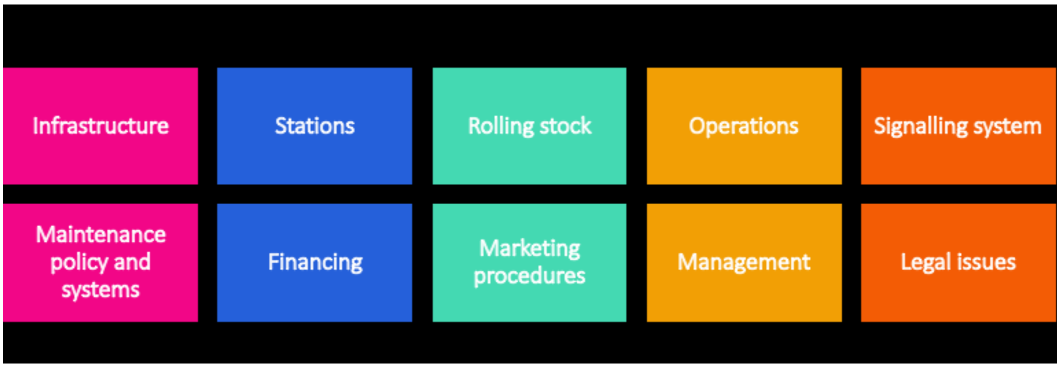


Figure 2.2 An overview on internal sections of HSR organisation

Additionally, the system can be more complicated in terms of international services (UIC, 2012). On the other hand, differentiation in each network's background is also impacted by the performances of their services. Because they consist of multiple sections and involve staff with backgrounds in multiple disciplines, HSR network operations have commonly faced both internal and external issues, leading to unsuccessful and high-risk networks. Therefore, a highly effective operational plan is strongly required for a HSR service.

2.1.2 The global trend in HSR services

Today, the growth of HSR services has been dramatic in both developed and developing countries. As shown in Figure 2.3, the growth of HSR networks has been substantial increased from 11,230 km to 52,418 km between 2009 and 2019 (UIC, 2020).

Apart from the economic benefits, some scholars have revealed that HSRs could generate huge benefits for society, especially in countries with vast territory. Russia, the county with the largest area in the world, has launched a trans-continental HSR network across the country to shorten travel times. Due to Russia's vast geographical area, the HSR lines link its major cities, such as Moscow, St Petersburg and Kazan, with a speed profile of up to 400 km/hr. For example, the Moscow-Kazan HSR line is hugely beneficial since it shortens the journey time from 13 to 3.5 hours (Brunello, 2018).

China has invested in the construction of HSR across the country under its 8+8 project, which consists of eight vertical lines and eight horizontal lines. China is well-known as the third biggest country by area, and the biggest by population. The attempt to build an HSR network across the country will not only benefit the Chinese, but will also link big cities and expand the capability of the country's economy (Song *et al.*, 2018; Xu and Huang, 2019; Chi *et al.*, 2020).

In European countries, HSR networks have not only smoothly linked major cities, but they also connect to neighbouring countries across borders. For example, the Perpignan-Barcelona HSR line connects this southern French area with Barcelona, Spain. The Eurostar service links the United Kingdom and three EU countries: France, Belgium and the Netherland (Vickerman, 1997; Masson and Petiot, 2009; Crozet, 2013).

2.1.3 Market share compared with other modes of transportation

One of the critical issues for HSR authorities is the lack from primary revenues. As mentioned, construction of infrastructure requires a large budget, and it takes a long time to obtain a return on investment. Additionally, the high operational costs of services are significantly larger than those of conventional train services. For these reasons, most rail authorities must have their operational costs subsidised by the local government, which leads to network ticket prices being restricted. One way to overcome this problem is for rail authorities to focus on effective routes to gain passengers and expand income.

With the aim at providing effective routes, rail authorities must put forward complete proposals and feasibility studies. It is noteworthy to consider, for example, the market shares in Japan's transportation sector compared for different journey

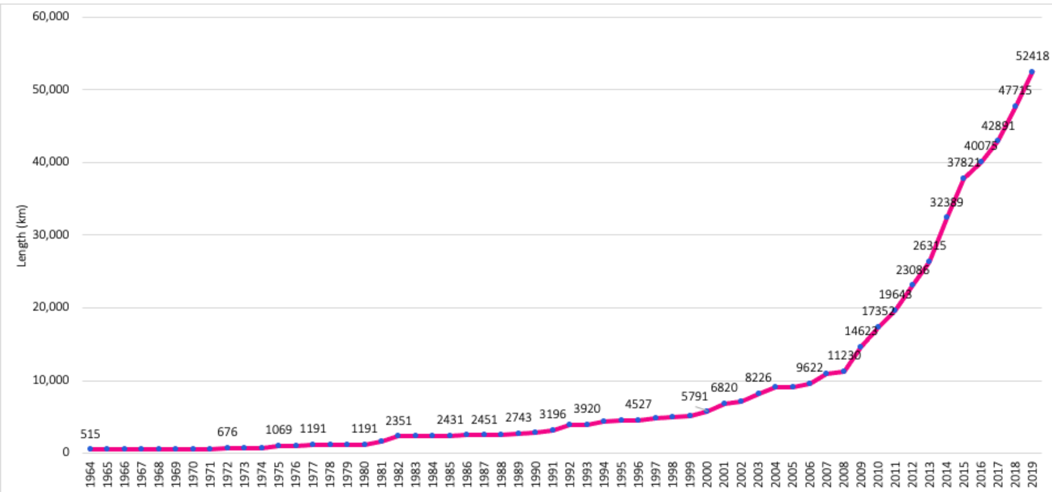


Figure 2.3 An overview of the global HSR network in operation during 1964-2019 (Source: UIC Atlas, 2020)

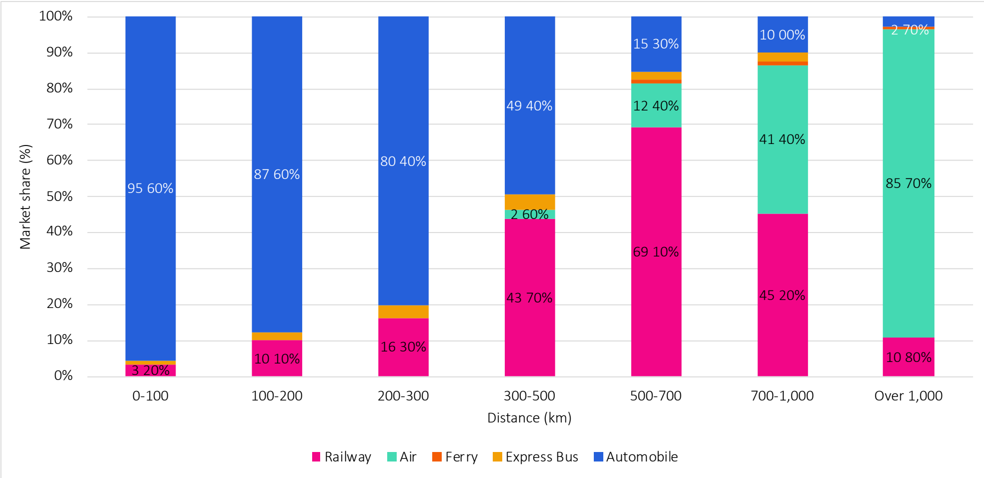


Figure 2.4 A comparison of market shares according to distance (km) for different modes of transportation (Source: Kojima *et al.*, 2017)

lengths. It should point out an interesting fact that HSR services suit specific distances, especially medium distances. As seen in Figure 2.4, services have grown more competitive than other modes of travel between 500 and 700 km, capturing 69.1% of the overall market share. Moreover, rail services almost have the largest share of travellers for operating distances of 300-500 km. To gain more passengers for these highly competitive distances, rail authorities should offer special promotions or discounted tickets to targeted customers.

In terms of a comparison within the HSR sector, the UIC report reveals that the Chinese network has the largest market share, containing 65% of the global HSR market, as shown in Figure 2.5. This is because the Chinese network is the world's longest, operating over 38,000 km across the country. The service has been recorded as serving 3.37 billion passengers or 1,470.66 billion pkm (Wang *et al.*, 2021), whereas the Japanese, French, and German networks have obtained 14%, 7% and 4% of global market share respectively.

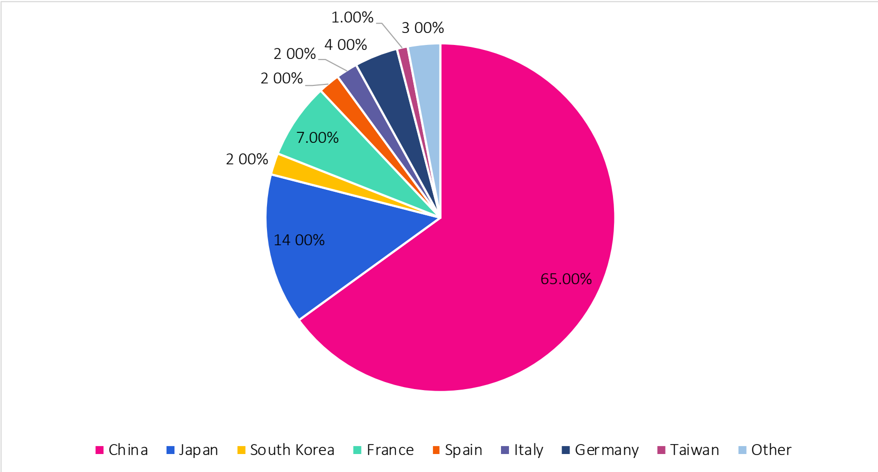


Figure 2.5 The commercial HSR market share by country in 2016 (Source: Wang et al., 2021; UIC, 2018)

2.2 A review of selected HSR networks and routes

In order to benchmark the key success of HSR networks, this research has selected HSR operators from around the world as case studies. The new system-based framework is composed of both fundamental and novel indicators. The selection criteria rely on a successful business model, operating plan, national economy and other related factors. On the other hand, previous research illustrates the gaps in the sustainable development of HSR networks, as shown in Chapter 1. In fact, HSR companies have faced various problems from both internally and externally. Also, the outcomes of HSR projects take a long time to measure.

This research expects to take the key successes from existing HSR companies. The five HSR companies selected for this study come from China, France, Japan, Spain and South Korea. The selection of five noteworthy routes is based on a variety of criteria. First, the network and service must be stable and dependable, as evaluated by their long-term operation over a period of at least 10 years. To minimise any prejudice and bias, the HSR routes chosen should be diverse in terms of geographical location, technology, and pertinent conditions. Additionally, these routes may comprise of both successful and unsuccessful practices. The diversity in existing HSR networks is expected to provide the best practices for developing new HSR projects.

Moreover, a particular route from each HSR network is analysed in depth in Chapters 3 and 6 to provide more accurate results for evaluation. The chosen HSR routes from the five networks are: Beijing-Shanghai (CR), Paris-Lyon (SNCF), Tokyo-Osaka (JR Central), Madrid-Barcelona (Renfe), and Seoul-Busan (Korail). Brief details of these HSR route are given below.

2.2.1 CR network: the Beijing-Shanghai route

Since China covers a vast territory, HSR projects are expected to reduce disparities among its province, and the network offers rapid inter-regional flows. In 2016, the Chinese government announced the ‘8+8 grid’ project, consisting of eight vertical and eight horizontal HSR lines, with a total length of 150,000 km expected to be completed by 2030 across mainland China (Jiang *et al.*, 2010; Degen, 2014).

The Beijing-Shanghai, or ‘Jinghu’, HSR is a part of the 8+8 grid project, and is owned by the China Railway company (CR). The service is already operational and connects the big cities along the east coast of the mainland along an entire length of 1,318 km. With 24 stations, the line links major economic centres, such as Tianjin, Jinan, Nanjing and Suzhou. The service offers an operating speed of at least 350 km/hr, which is much faster than existing conventional rail, reducing the travel times from ten hours to four hours. This shortened travel time has dramatically increased urbanisation and economic activity across the Chinese mainland’s coastal regions.

Today, the route services over 500 million passengers per year with a daily rate of more than a million passengers (Chen and Haynes, 2015; Statista, 2019b). It is noted as the most profitable line in China, producing 16.6 billion yuan or 1.85 billion pounds (Ji and Xu, 2021).

2.2.2 SNCF network: the Paris-Lyon route

In 1981, the first French HSR line was announced with the Paris-Lyon route to service an operating distance of 450 km. This line is also noted as the first HSR line in Europe. With a high operating speed in the range 270-320 km/hr, the service has become a success for the French rail network and is the foundation of the LGV network. Moreover, it has inspired the extension of local French rail network services to neighbouring countries, such as the UK, Germany and the Netherlands.

Today, the French HSR service is owned by the SNCF (French National Railways Company), which is a state-owned organisation (SNCF, 2020). The achievements of the Paris-Lyon route come from the seamless connection it provides between these cities, leading it to be a profitable route compared with other French HSR, or TGV, routes. However, the service is not accessible to society in its entirety due to only 15% of the French being able to afford it (Bigras and Roy, 2020).

2.2.3 JR Central network: the Tokyo-Osaka route

Japan has been noted as the leader of HSR services since it first launched the Shinkansen service in 1964. The Tokyo-Osaka route, namely the Tokaido Shinkansen, has been operated by the Japan Railway Central Company (JR Central) over a total distance of 515.40 km (Rungskunroch *et al.,* 2019). With an operating speed of 285 km/hr, the service ultimately brings benefits to Japanese society in terms of the economy, tourism and urbanisation. The success of the Tokaido Shinkansen as provoked demand for HSR services in other countries.

As a leader in HSR technologies, JR Central has also achieved the greatest operational success among HSR services. The Tokaido Shinkansen is one of a few profitable HSR lines in the world (Ishii *et al.,* 2019), and known as the world's busiest line. One of the service's key successes is that the route has connected Tokyo with other charming prefectures such as Nagoya and Osaka.

2.2.4 Renfe network: the Madrid-Barcelona route

The Madrid-Barcelona line was constructed during 2013-2018 and the service has been operated by Renfe Operadora, which is a state-owned company (Guirao *et al.,* 2016). The line has been operated with the aim of connecting Madrid and other Spanish cities with Perpignan, the French border city. With an operating speed of up to 330 km/hr, the service links Madrid and Barcelona in 150 minutes, compared with the 328-minute service offered by conventional rail (Gutiérrez, 2001; Gutiérrez *et al.*, 2015; Guirao *et al.,* 2016). Spanish HSR services give passengers the great advantage of having an alternative choice for travel between Spanish cities. Additionally, the service increases accessibility to travel, boosts the local economy and saves travel time (Pagliara *et al.,* 2012).

The Renfe network is very important to the Spanish. Accordingly, some authors have compared the Madrid-Barcelona HSR with the air service, with the result showing that the HSR service has reduced the number of airline passenger by 17%

(Jiménez and Betancor, 2012). During its six years of operation, the line has served a total of 33.36 million passengers (UIC, 2014).

2.2.5 Korail network the Seoul-Busan route

The Seoul-Busan HSR line, or Gyeongbu high-speed railway, is known as South Korea's first HSR (UIC, 2010; Korail Sustainability Report, 2020). The line has been fully operated since 2004 by the Korea Railroad Corporation (Korail). The route aims to connect Seoul, the capital, with other urban areas, especially in the southwest of the South Korean mainland. Nevertheless, the financial crisis that hit Asian countries during 1997 caused the South Korean government to break the Gyeongbu project down into three phases (Yun *et al.,* 2006; Kim *et al.,* 2013). The first phase of the Gyeongbu line ended at Daejeon, and the service between Daejeon and Daegu was the next phase to be added. The HSR service co-operated with conventional rail services until 2010, when the final phase seamlessly connected Daegu and Busan. The full connection brought the operating distance to 346.40 km, along which there are nine stations.

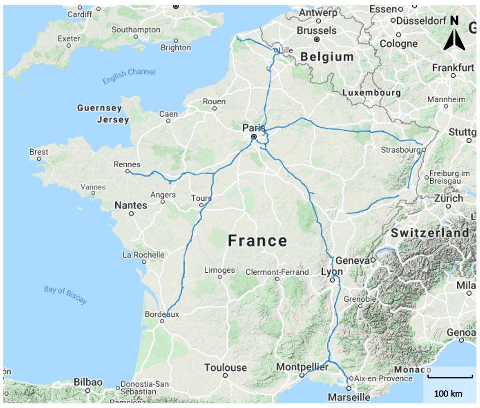
During its operational phase, the HSR service has been known as the KTX service, providing operating speeds of up to 350 km/hr. The service has increased demand among travellers for railway transportation (Park *et al.,* 2009; Kim *et al.,* 2018). Today the network can serve 162,000 passengers daily. However, it is interesting to mention that the Gyeongbu KTX has been revealed to have obtained the highest modal share in only a part of its service, particularly in the intercity range. Due to HSR providing benefits over medium distances, it is difficult for the service between Seoul and Dongdaegu to achieve a greater market share than other modes of transportation.

Table 2.1 A detailed summary of the five selected HSR networks.

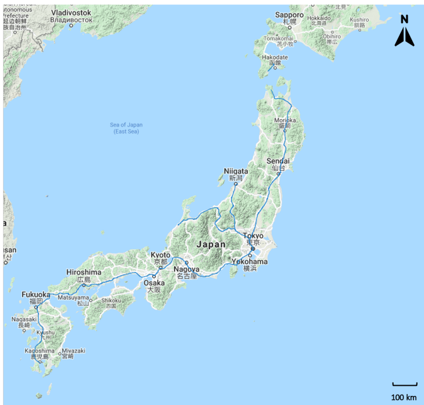
Operator	CR[a,b]	SNCF[c]	JR Central[d]	Renfe[e,f]	Korail[g,h,i]
Country	China	France	Japan	Spain	South Korea
Line	Jinghu HSR	TGV Sud - Est	Tokaido Shinkansen	AVE Madrid - Barcelona	Gyeongbu HSR
Route	Beijing - Shanghai	Paris - Lyon	Tokyo - Shin Osaka	Madrid - Barcelona	Seoul - Busan
Opened	2012	1981	1964	2008	2004
Length (km)	1318	450	515.4	621	346.4
Speed (km/h)	350	270-300	285	250-330	305-350
Number of ridership (million per year)	210 (in 2019)	44.4 (in 2017)	174 (in 2019)	4.3 (in 2019)	41.7 (in 2018)
Occupancy	77.52% (in 2019)	80% (in 2015)	90% (in 2021)	78.8% (in 2014)	96% (in 2013)
Maximum number of stops	23	1	16	8	10

Source: [a]Statista (2019a), [b]Jiang et al., 2010, [c]SNCF Réseau (2017), [d]JR Central (2020), [e]Renfe (2014), [f]Statista (2021), [g]Kim et al., (2018), [h]KNRA (2010), [i]Korea National Statistical Office (2015)

China

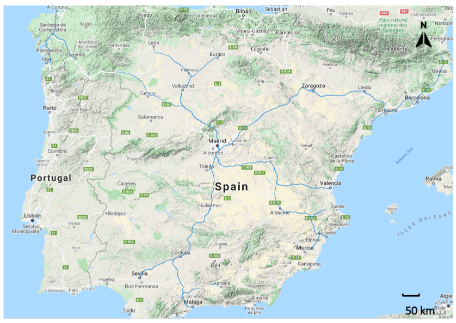


France



Japan

South Korea



Spain

Figure 2.6 An overview of HSR networks by country

2.3 A review of benchmarking frameworks in railway research

With respect to railway operations, these have been inevitably faced with unexpected problems, and operators have continually improved their performance in terms of safety, maintenance and overall efficiency (JR Central, 2017; Network Rail, 2017; Banverket, 2004). Advanced technologies and various standards have been applied by railway companies to increase their performance levels over other competitors.

Benchmarking is a great technique for improving an organisation's performance, and the practice is extensively used to improve the performance of railway companies (Anderson *et al.*, 2003). The approach typically investigates the experiences of others, allowing railway operators to compare their current efficiency to that of other railway operators. By using this method, the rail operator can quickly find the gaps, leading to direct continuous improvement in efficiency and achievement of best practices.

Application of the benchmarking method can be classified into three levels: internal, external and best practice. Internal benchmarking is the origin of an organisation's plan. In contrast, the method generates competitive pressures on the organisation's infrastructure caused by increasing productivity while reducing cost, time and waste in the process. Additionally, it is believed to be the best process for determining best practice, innovation, and efficient operational planning (McGaughey, 2002). According to some scholars, benchmarking is a strategic process for steadily improving firm performance and reaching goals (Pin Lee *et al.,* 2006; Hansen *et al.,* 2013; EEA, 2014). On the other hand, the limitation of benchmarking is that it is not effective for manufacturing processes because these contain miscellaneous factors from external sources. Thus, it is unable to compare such processes within their peer group (Joshi *et al.*, 2006).

Benchmarking of railway network performance seems to offer apparent benefits; hence, rail authorities take this method as a mandatory tool. The Rail Safety and Standards Board (RSSB), a British organisation, states that "Britain's railway sets the benchmark for service quality, customer satisfaction, and value for money by being safe, reliable and resilient, meeting capacity and service requirements and contributing to the growth of the economy" (RSSB, 2012). Additionally, Network Rail, Britain's railway company, compares its annual progression in terms of the number of passengers, punctuality and the amount of freight (Network Rail, 2017). Maintaining railway service performance is more difficult than for other modes of transportation. Railway networks are complicated, and their operation occasionally requires sharing of infrastructure (e.g. track and stations) with other companies. The service is operated by staff with backgrounds in multiple disciplines, and some railway services operate between countries, particularly in Europe. Therefore, maintaining its levels of performance is necessary for a railway company.

Benchmarking methods have been applied to government projects. These methods allow local governments to intently monitor, compare, analyse and report throughout the schedule for new railway projects (Envisio, 2017). By using a benchmarking method, governments are able to manage projects within deadlines and budgets. Additionally, this method allows policymakers to look forwards to the socio-economic impacts after a service comes into operation, and to predict the advantages in terms of sustainability development and residential areas.

2.3.1 An application of tools and programming

Improving overall performance is one key for rail operators in being more competitive in the transport sector, especially with respect to other railway companies. Benchmarking research has been widely discussed among railway companies over several decades, while frameworks and methodologies differ according to each company's strategies, policies and status.

A benchmarking framework has been used to enhance the efficiency of transactions across 43 British, German and Swedish railway companies (Merkert *et al.,* 2010). The research aimed at enhancing users' experiences of rail services, particularly at the transaction stage. It applied five models of Data envelopment analysis (DEA) and Tobit regression methods along with a framework, covering transactional, institutional and environmental factors. However, the outcomes from the research outcomes did not provide practical suggestions to the rail companies.

The efficiency of public transportation in 52 major cities worldwide has also been evaluated by using DEA (Hilmola, 2011). With the aim at enhancing the use of services and space, the results from this research reveal that city size impacts differently on transport services. Transportation systems are shown to perform better in mega-cities than for other sizes of city. Nevertheless, the size of a city is not the major factor in improving transport services.

Although railways in India form one of the world's largest rail networks, this network is faced with a complicated operating system. The performance of 23 service areas within Indian Railways has been compared using the DEA method (George and Rangaraj, 2008). Operating cost, tractive effort, equivalent track kilometre, number of staff, passenger carriages, and waggons are among the six operational elements examined in this study. The outcomes point to a lack of maintenance of operational performance on the network. Nonetheless, the chosen factors do not cover a majority of operational factors.

Another research study evaluated the efficiency and performance of Asian and European HSR networks by using DEA to benchmark fleet capacity and network length (Doomernik, 2015). In examining how to improve freight train performance, particularly on Swedish railways, Cullinane *et al.* (2017) used DEA as the main methodology in a study that mainly concerns charges for access to rail track. Additionally, some authors have also suggested the DEA method for benchmarking in railway research, including Coelli and Perelman (1999); Driessen, Lijesen and Mulder (2005); Growitsch and Wetzel (2009). From this standpoint, DEA can be considered as one of the potential methods to solve the problems addressed in this research. DEA models allow a combination of extraneous factors for model inputs. Nevertheless, using the DEA method can generate efficient and satisfactory outcomes for current railway networks, although the method is not suitable for predicting uncertainties regarding future railway networks.

Some authors have recommended computational-based programming and simulation models, such as ARENA Simulation, HERMES, MATLAB, RailSys, and Simu8, for benchmarking research. For example, an application of the ARENA simulation has been used in the measurement of Spanish railway track performance. The study focuses on the utilisation of track, stations and other factors. The outcomes reveal that the Spanish network has lower utilisation than other European countries (Woroniuk and Marinov, 2013). Also, the combined use of the ARENA simulation is also found in Taiwanese railway research. Cheng (2010) focused on the optimisation of numbers of seats and passenger demand. The research suggested that optimising seat demand leads to increases in operating income of about 7%. However, it is notable that the ARENA simulation suits the generation of real-time results, but it complicates the scenario for finding best practices. To address the research problems in this study, the benchmarking framework cannot be achieved by using the ARENA simulation by itself.

HERMES, another simulation model, has been applied in railway research to decrease primary traffic disturbance (Nicholson *et al.*, 2015). This study used seven KPIs: volume of transportation, travel duration, connection, timeliness, resilience, energy consumption and resource use. The robustness of the railway schedule is developed by using a traffic simulator which allows a reduction in disruption to primary traffic.

A research study that uses RailSys, a railway simulation software package, to increase the performance of rail services in Egypt (Aly *et al.,* 2016), analyses various factors, including benefits, costs and other factors associated with trains. By using RailSys, the study generated a new model that can cut journey times by approximately 17% compared with the existing method.

As mentioned, previous studies have exclusively applied a computer-based programming method. Various computational methods have been adopted using factors associated with railways in order to find weaknesses. Although there are many studies, research on the benchmarking of railway performance remains limited to software. It can be concluded as using only computational methods cannot achieve the goals of this research study. Therefore, computer-based programming will be integrated with a big data method, as mentioned in section 2.4.

2.3.2 Benchmarking of railway operation performance

Railway operation covers all of the major activities in a network, such as organising, planning, and managing resources. There have been numerous studies to evaluate railway operation performance in terms of enhancing a network's efficiency. Since railway services have frequently faced issues of non-robustness with their timetables, prior studies have improved network punctuality by understanding incidents that cause delay and thereby reducing disruption (Nicholson *et al.*, 2015).

Operating cost has become an essential factor in the success of a network. Previous research has compared physical transaction cost indicators (Merkert *et al.,* 2010). Comparing among European rail networks, the authors believe that improving technical efficiency can strengthen rail operators with respect to their competitors. Some scholars have benchmarked the construction costs of railway projects across European countries (Trabo *et al.*, 2013). Rail companies have inevitably faced construction costs that exceed their budgets. This research benchmarked nine European rail projects, including the Copenhagen-Ringsted route, the first Danish HSR line, which is found to offer the best practice, generates the lowest construction cost.

Some studies have targeted the increased social impact from providing high-efficiency networks. It is inevitable to claim that HSR services stimulate impressive socio-economic effects, particularly in suburban regions. In terms of socio-economic impact, it has been popular to focus on this as the main indicator that drives HSR services. Fardella and Prodi (2017) offered an Italian perspective regarding the construction of the Belt and Road Initiative, which is a global road and rail project (Fardella and Prodi, 2017). Their study analysed the effects of the project, especially in northern and central European areas, in terms of developing a connection with the Italian railway network. Other research has created a conceptual framework for increasing the socio-economic impact of Indian Railways because some of the service areas are inefficient (Sharma *et al.*, 2016). In Russia, the evaluation of the socio-economic impacts of urban railways has been proposed in research aimed at providing long-term planning in Moscow (Namiot *et al.,* 2018). Additionally, the relationship between railway and socio-economic impacts has been conducted for 278 railway stations in South Korea (Lee *et al.*, 2015). This study revealed that the effective catchment areas are within a range 300 metres and 500 metres respectively from light rail and heavy rail transit stations. This ultimately benefits policymakers in increasing the efficiency of the South Korean rail network, and it provides an advantage for passengers.

Another factor that plays an essential role in further development is the environment. The use of green energy has been adopted in all transport sectors. Also, many countries have encouraged people to use public transportation instead of private cars to reduce traffic congestion and CO_2 emissions. Ha *et al.,* (2011) considered natural damage due to transportation. The research evaluated the amount of CO_2 emissions from air and rail transport by using data sets from 1999 to 2007 JR companies. The results indicated that rail transport has a much lower impact on the environment than air transport. Other research assessed the energy-environment efficiency of the road and railway sectors in 30 Chinese provinces (Liu *et al.,* 2016).

The findings pointed to the most efficient areas as constituting best practice for less efficient areas.

Owing to its high-efficiency methods and ability to compare among selected groups, benchmarking has been applied at multiple levels, such as company, city, region and country levels. Various studies have benchmarked within a country or across multiple regions.

For example, Indian railways, the fourth largest network in global terms, has faced the problem of improving logistics performance. Some scholars have compared performances within the Indian container sector by using multiple indicators. An analysis of the strengths and weakness of the logistics system for a brand-new company, namely CONCOR, was conducted to aid future development (Napa, 2006). Another study compared among 15 freight competitors by focusing on their policies and environmental practices (Gangwar and Raghuram, 2010). Also, analysis to compare Indian railway and port services in terms of logistical competitiveness has led to increase operational efficiency (Pillania *et al.,* 2008; CARE, 2009; TERI, 2008). From the review above, benchmarking within countries can point out weaknesses in internal networks. It is suitable for enhancing the efficiency of an existing railway network in terms of quality of services, environmental impacts and socio-economic impacts.

On the other hand, the benchmarking of train performance across rail networks and countries is the most studied area. Railway services are noted as a highly complex mode of transportation due to their limited resources and facilities. Additionally, some services operate across borders, especially EU borders. Therefore, improved overall performance is especially required.

For example, the measurement of freight performance between 1980 and 2004 has been conducted in North America, China, Russia, Israel and the Baltic states in order to enhance logistical efficiencies (Hilmola, 2009). The strength of the study was its broad comparison of multiple countries and regions, which allowed the best performance to be adapted for future frameworks. Swedish and Norwegian rail networks have also been the focus of evaluation in terms of their maintenance performance (Åhrén and Parida, 2009).

There is also research that compares sustainable urban logistical plan among the UK and four Scandinavian rail networks in order to reveal the best framework (Fossheim and Andersen, 2017), rail freight companies across European countries have been benchmarked to reveal their levels of efficiency (Wiegmans and Donders, 2007). The study examined various key performance indicators, such as employee productivity, sales productivity, and rail car productivity. The outcomes indicated that productivity performance for freight companies had developed during the period of study.

2.3.3 Benchmarking of railway infrastructure

Inevitably, infrastructure is a significant asset in railway operation, particularly in cross-region railway service. So, the allocation, charging, and monitoring of the railway infrastructure is marked necessary. The benchmarking of railway infrastructure is a key development, especially for international train services. It allows rail authorities to understand their current performance, provides an in-depth understanding of the costs and revenues needed to be profitable, and closely monitors other external companies (Åhrén and Parida, 2009).

Benchmarking of railway infrastructure has been broadly discussed by a great number of authors. The procurement process for railway infrastructure projects has been benchmarked for five European countries: Germany, Norway, Sweden, the Netherlands, and the UK (Eriksson *et al.*, 2017). These rail networks use a 'design-in-bid' contract, for which the research points out in detail the strengths and weaknesses for each network. Espling and Kumar (2008) benchmarked the maintenance process across the Swedish national rail network. The research provides an effective method for improving operational and maintenance processes. Similarly, the benchmarking of maintenance performance indicators between the Swedish (Banverket) and Norwegian (Jernbeneverket) HSR networks has revealed the best practices (Åhrén and Parida, 2009).

One approach to becoming a successful network involves applying an effective framework to an operational system. Despite decades of benchmarking in railway research, there remain a number of gaps that may obstruct success.

First, most published research has been based on business perspectives towards enhancing the efficiency of railway operation. As shown in the previous section, both productivity and profitability factors are determinedly emphasised. Nevertheless, the long-term development of rail networks strongly requires sustainability development alongside network profitability.

Second, much of the published research has not chosen rail companies or networks for benchmarking processes properly. This has been previously assessed only to a very limited extent because of the unavailability of information from the rail sector. Hence, many researchers have inevitably faced data restrictions causing benchmarking across rail networks to become challenging. To solving these problems of lack of information and restricted data, in this research big data analysis is applied in order to fill this gap.

2.4 The application of big data in railway research

Since big data has widely impacted on academia and business, many scholars have proposed a definition for this concept. In general, 'big data' means a large and more complex data set, particularly from new data sources. The big data concept involves volume, velocity, variety, veracity, and value (Madden, 2012; Wamba *et al.*, 2015). It has been stated that big data usually features a range of different concepts in the collection process of vast amounts of data (Favaretto *et al.*, 2020). George *et al.* (2016) defines big data as deriving from the increased availability of sources such as online data, social media and mobile transactions. This growth of useful information meaningfully provides powerful impacts on many sectors. Large amounts of information need computational techniques and/or statistical methods in order to understand data trend and reveal hidden patterns.

The application of big data analysis (BDA) in railway research plays an important role in the railway industry. Big data is involved in four different railway research areas; configuration data, train schedule management, status data, and operational data (Ghofrani *et al.*, 2018). Various railway research has benefited from BDA in the processing, evaluating and interpreting of large amounts of information. These processes are usually combined with advanced methods, such as artificial intelligence (AI), machine learning, and other computational-based methods. The application of

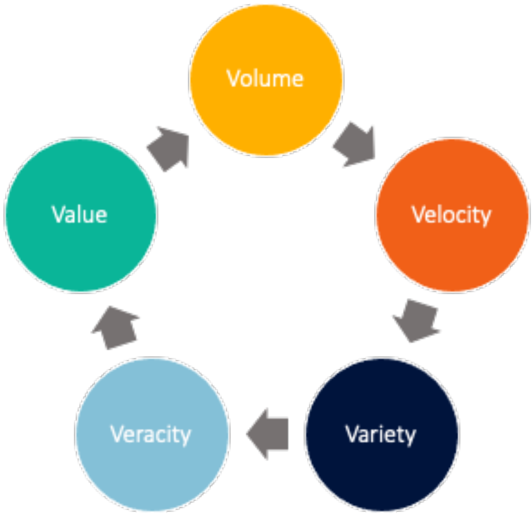


Figure 2.7 A big data's conceptual including '5V' (Volume, Velocity, Variety, Veracity, Value)

these methodologies lead to improved railway operation performance, reduced risks across rail networks, and the growth of passenger demand.

There have been numerous studies that apply BDA in railway research. BDA has been adopted to create decision-making regarding asset management that is specific to the railway industry (Thaduri *et al.,* 2015; McMahon *et al.,* 2020). Additionally, BDA has been used in the analysis of the monitoring of sensors, which are an important asset for the implementing of maintenance systems in order to avoid disruptions during operations (Fumeo *et al.,* 2015). Similarly, the Dutch railway also uses BDA to make effective decisions on the maintenance of railway track by using historical information. As a result, the network can closely monitor all failures and reduce maintenance costs (Núñez *et al.*, 2014). Researchers have also merged BDA with MapReduce, a model on the Hadoop platform, to allow life-cycle management of Chinese HSR equipment (Shao *et al.*, 2014). Also, Zhang and Gong use BDA with the Hadoop platform in order to launch marketing decision support in the freight train market in China (Zhang and Gong, 2014).

Moreover, BDA is also applied to decrease risk across rail networks. Rungskunroch *et al.,* (2021) use BDA to benchmark risk level across five HSR networks, revealing the different impacts from each type of accident, leading to a reduction in the number of fatalities and injuries to passengers (Rungskunroch *et al.,* 2021). Other research is combined with the new internet-driven data revolution to increase safety benefits across the UK rail network (Figueres-Esteban *et al.,* 2015). The research suggests addressing new techniques in safety policies. There is also research that focuses on decreasing risk in railway stations by using BDA and machine learning (Alawad *et al.,* 2019). The benefit of this is to support higher passenger demand across the railway industry while dealing with limited assets. Additionally, BDA is used with respect to HSR infrastructure to predict bridge deformation. Track geometry inspection datasets have been combined with a bridge dynamical deformation (BDD) model (Wang *et al.*, 2021), the outcome of which is to indicate a low-cost and effective method of improving safety performance.

Previous studies have emphasised the use of BDA with other computational based-models, such as machine learning and the Hadoop platform. However, the capabilities of such methods do not fit the aims of this research. Regarding this thesis, the application of BDA with Python, a computational-based programming language, is used in Chapters 6 and 7. This research aims to develop a novel framework for the development of HSR networks. Long-term datasets from each of the selected countries are collected from the World Bank, official reports from HSR operators, and other related sources. Various methods and statistical models are applied with BDA. In

Chapter 6, the aim is to improve railway safety performance and to reduce risk. BDA is applied with Bayesian inference and Dirichlet distribution. The datasets collected are then evaluated using the DT and PT models. In contrast, the goal in Chapter 7 is to evaluate the socio-economic impacts across the five rail networks. Here, BDA is combined with the KNN and PCC methods via Python.

2.5 Key performance indicators (KPIs)

With the aim at developing a system-based framework for HSR which can enhance its efficiency from multiple perspectives, this study takes six KPIs as important key drivers for railway organisations. The framework consists of three fundamental KPIs (life cycle cost, punctuality, productivity) and three novel KPIs (risk and uncertainty, sustainability, urbanisation).

As shown in Figure 2.8, the research is conducted with data from five HSR networks for five specific routes in order to evaluate the KPIs by using various computational techniques. Additionally, relevant mathematical models and statistical methods have been applied in this study. The integration of big data analysis with selected KPIs gives highly accurate results which leads to effective policy implications for upcoming rail networks.

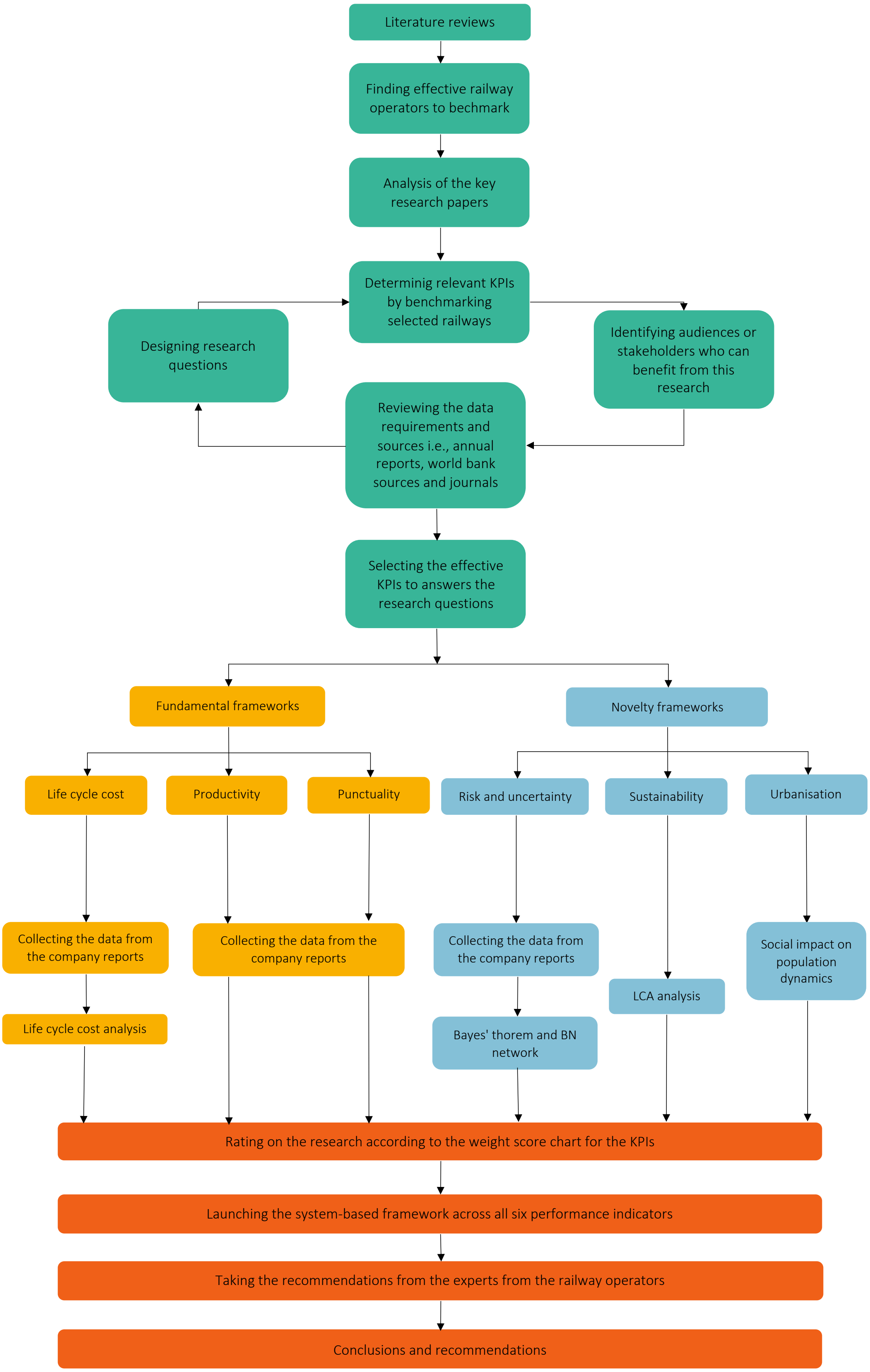


Figure 2.8 An overview of the KPIs in this research

2.6 Conclusions

Several theories have been proposed to improve overall HSR performance, focusing on HSR's infrastructure and others on its service. In addition, many authors have developed a system-based framework for HSR services. However, a closer look at the literature on benchmarking on HSR operation reveals several gaps and shortcomings.

First, previous frameworks allowed rail authorities to improve only limited performance. In other words, the developed framework has focused on a single factor such as maintenance plan, traffic disturbance, logistics and other related factors. However, only a few pillars of development cannot lead HSR networks to achieve sustainability targets. Second, most of the previous models have conducted only internal and limited datasets. As a result, the model suits solving internal issues. Also, it leads to inefficient performance benchmarking with its competitors. Lastly, only a few studies have shown benchmarking with other rail companies within the region. However, this thesis compares five notable HSR networks from five countries. Therefore, this novelty framework represents high diversity, which is suitable to be a practical framework.

To fill those gaps, this thesis demonstrates a novelty system-based framework for any HSR service to improve its efficiency in terms of life cycle cost, productivity, punctuality, risk and uncertainty, sustainability and urbanisation. It is advantageous for all rail authorities to measure their current performance with noteworthy HSR networks.

2.7 Chapter Summary

Chapter 2 provides background information about urban public transport and HSR services. With the aim at developing a system-based framework, a review of five selected HSR networks and routes is presented, the selection criteria for which included a diversity of geographical regions, technologies, and other conditions.

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CHAPTER 3

LIFE CYCLE COST PERSPECTIVE

This chapter presents a review of the railway network's life cycle cost, including railway infrastructure and rolling stocks. This thesis provides an in-depth four-stage life cycle cost consisting of manufacturing, operational, maintenance, and demolition processes. The long-term analysis of a total of 70 years in operation is applied with a 6% discount rate. Also, the Monte Carlo Simulation is added to the sensitivity analysis section to examine unusual events.

3.1 Introduction

A life cycle cost analysis (LCCA) is a methodology used to gauge the success of a project over the course of its lifetime. It takes into consideration budget and includes the total financial expenses incurred during the life cycle. Furthermore, LCCA is commonly used to analyse and control valuable operational conditions in order for owners, project managers, and stakeholders to have complete comprehension of the project's viability and the essential long-term profitability (Barringer *et al.*, 1995; Asiedu and Gu, 1998; Norris, 2001). The LCCA idea was extensively proposed in both the public and commercial sectors at the dawn of the industrial age. The LCCA is based on the idea that all assets should be valued based on their lifetime cost (Woodward, 1997).

The LCCA is defined in a variety of ways; for example, “The life cycle cost of an item is the total of all expenditures invested in support of the item from its conception and manufacturing through its operation to the end of its useful life,” (White and Ostwald, 1976). The idea aids a company's manager in clearly understanding future costs and advantages related to complicated financial factors such as initial cost, cost life cycle, operating and maintenance expenses, and sensitivity analysis.

The importance of LCCA has grown significantly in recent years as the global economy has expanded. Complex materials and labours were used in the manufacturing process. Furthermore, certain product components are manufactured in many countries; as a result, shipping, taxes, and other overhead expenses must be included (Arditi and Messiha, 1999; Fuller, 2010). Therefore, calculating profitability without applying LCCA may lead to unprofitable project. In practice, LCCA represents an organization’s annual cash flow, payback duration, internal rate of return, and future value, all of which are required for an organization to successfully market its plans and products or services. As LCCA is applicable to projects that may have other paths, it is obvious that this approach is well-suited for benchmarking net profits.

3.1.1 An application of LCC with railway research

Owing to the construction of a railway track needs a large investment and a long return period, LCCA is then critical in railway infrastructure management for railway companies. Infrastructure managers use it as a guide when making maintenance choices. Some researchers have used LCCA for railway bridges since they are considered long-term assets with poor upkeep. The study benefits bridge managers by enhancing high precision decision-making toward life cycle cost (LCC) of infrastructure assets, allowing them to precisely monitor, maintain, repair, and modernise a railway bridge (Nielsen *et al.,* 2013).

The LCC application was used in the Swedish railway's maintenance decision to support railway for track maintenance. Uncertainty in dependability and maintenance factors, particularly in the railway's track, have plagued the Banverket railway system. The study used LCC and Monte Carlo Simulation (MCS) to improve railway maintenance decision-making (Patra *et al.,* 2009).

Giunta *et al.* (2018) published a paper that details the many benefits of LCCA. The study's goal was to develop a novel track-bed maintenance approach (Giunta *et al.,* 2018). The LCC of bitumen stabilised ballast (BSB) and regular ballast was compared (TB). The results of sensitivity analysis and discount rate show that the BSB's technology provides considerable economic advantage over others (Michas, 2012). Another researcher uses LCCA and MCS to optimise and prepare materials for the Lisbon-Oporto railway line's renewal operation. Due to a financial constraint, a research proposes to reduce LCC on rail components and assist infrastructure managers in making decisions (Caetano and Teixeira, 2013).

Another researcher used LCCA to manage the railway traffic management system's cost structure. In reality, the railway traffic system was complicated, and it necessitated RAMS (reliability, availability, maintainability, and safety). As a result, the LCCA was a critical instrument for budget management optimization and effectiveness (Ciszewski and Nowakowski, 2018). Other studies used LCC and RAMS to assess the life-cycle cost of railway infrastructure. Calle-Cordón *et al.* (2017)

conducted a sensitivity study on maintenance expenditures in relation to long-term risk situations. A LCC with RAMS programme has been discovered in remote condition monitoring across Network Rail in the United Kingdom. Train delays had been seen on the British network as a result of necessary penalty payments. Furthermore, from 2008 to 2020, passenger demand was expected to quadruple, making LCCA a vital instrument for managing the financial cost-benefit of replacing new technology (Márquez *et al.*, 2008).

The LCCA had also been used to assess the cost-effectiveness of the European railway control system, which provided seamless cross-border services. The LCCA may implement an effective migration plan across the network, which can immediately minimise Life cycle costs (Obrenovic *et al.,* 2006).

3.2 Methodology

Within this chapter, the LCCA method is used in this study to benchmark economic consequences using the time value of money. The life cycle cost (LCC) may be computed according to the following equation 3.1. In addition, the equation 3.2 uses NPV analysis to get the exact life cycle cost.

3.2.1 Availability of data

The datasets have been conducted from HSR companies' reports, sustainability reports, and publications. This included specific information of each network such as standard staff' salary and bonus.

In contrast, the material costs and building equipment costs are collected from Global Source (2020). The standard electricity cost relies on the electricity rate of 09

December 2020 (Statista, 2021). And, the exchange rate is derived using the January 2021 standard conversion rate (GOV.UK, 2021). Also, the research intensely focuses on infrastructure and rolling stock due to the limitation of the reliability datasets.

3.2.2 The calculation of HSR's LCC

The whole life of HSR vehicle and infrastructure is addressed in this section. Manufacturing, operating, maintenance, and demolition stages are shown in Figure 3.1 based on the entire life cycle phases. Raw materials, shipping fees, taxes, and employee compensation are all factored into the production and pre-assembly stage calculations. Second, all expenses such as employee wages, gasoline and energy, logistic charges, and other relevant expenditures are included in the operational stage.

Following that, the cost of maintenance covered all maintenance costs for both rolling stock and infrastructure for the life of their lives. Finally, overall demolition expenses include all expenditures and energy expended for recycling, disassembly, and shredding.

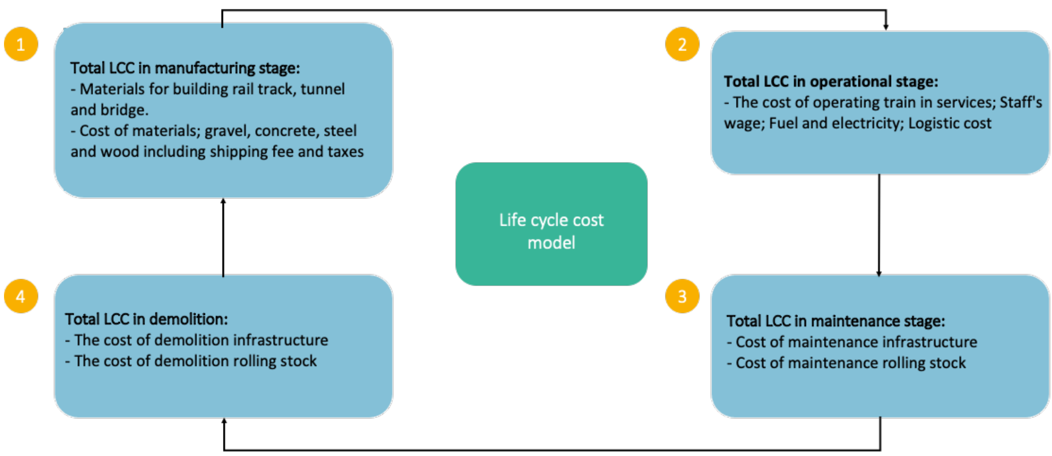

Figure 3.1 A detail framework of LCC

$$LCC = \sum_{i=1}^{n} C_i \quad (3.1)$$

Equation 3.1 shows the LCC calculation for each level. The comparison of LCC throughout the HSR network is standardised in pound/km unit as part of one of the research projects aimed at measuring financial performance. The exchange rate is derived using the January 2021 standard conversion rate.

3.2.3 NPV analysis

A Net Present Value (NPV) analysis is often used in a capital investment to assess a project's profitability over time. An important aspect of NPV is that it depicts the time value of money over various time periods, which is critical throughout the investment stage of any project. The notion of time value of money may be summarised as the current worth of money is insufficient to account for its future value (Van Groenendaal, 1998; Berkovitch and Israel, 2004). The NPV analysis is a critical tool for determining the overall cost of a project and comparing it to alternative solutions.

As indicated in equation 3.2, the NPV analysis of a HSR project includes each stage of LCC, cash flow, initial investment, discount rate, and time period. The infrastructure's life time is defined at 70 years in this research, whereas the train and rolling stock's life time is set at 35 years. The calculated life time is followed by their average life cycle. Additionally, a standard discount rate is placed at 6% annually (Kiani *et al.,* 2008; Åkerman, 2011, Kilsby *et al.*, 2017; Shinde *et al.*, 2018; Rungskunroch *et al.*, 2021).

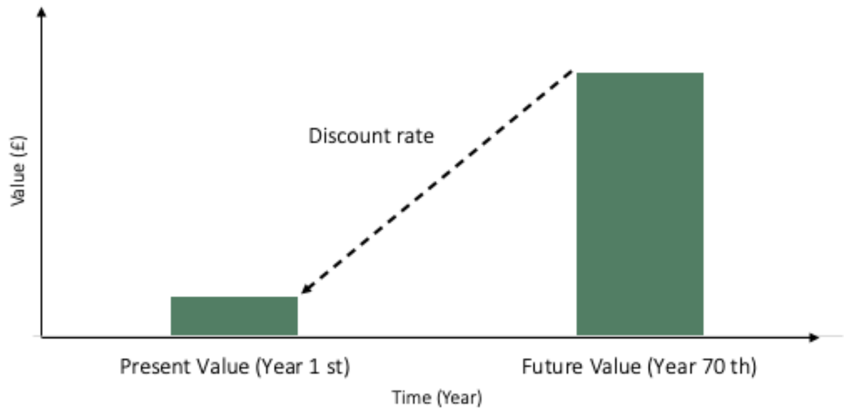

Figure 3.2 The conceptual of discount rate

$$NPV = \sum_{k=0}^{n} \frac{A_i}{(1+r)^i} - A_0 \tag{3.2}$$

where C_i = the entire cost of the life cycle at stage i; i = a set of life cycle stage {manufacturing and pre-assembly, operation, maintenance, demolition}; A_i = cash flow at year i; A_0 = initial investment; r = discount rate; k = the time period in unit years.

With the goal of benchmarking life cycle cost performance throughout the railway network, this study prioritises power costs. It relates to an energy consumption rate in January 2021. The energy cost is determined by the power rates in each country. In addition, every five years, a significant track maintenance is estimated (Rungskunroch *et al.,* 2021).

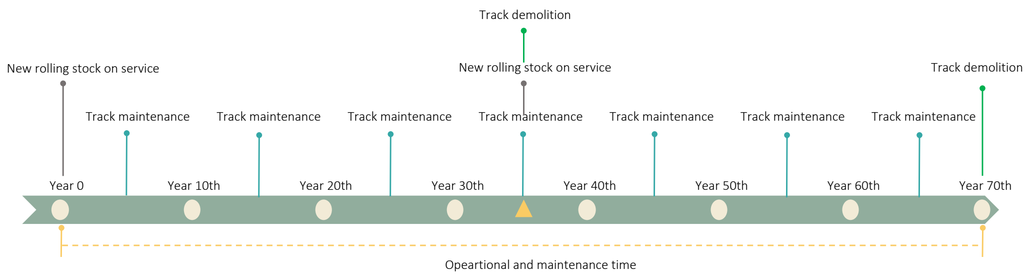

Figure 3.3 Overall timeline of a HSR operation

3.2.4 Monte Carlo simulation

Monte Carlo simulation (MCS) is based on the notion of repeating random sampling to arrive at predefined or unknown outcomes (Mooney, 1997; Raychaudhuri, 2008). The MCS is a statistical instrument that is used to forecast the likelihood of certain events. One of the MCS method's distinguishing features is the ability to flexibly apply random sampling to input parameters in order to identify outputs.

MCS has a wide range of applications in science, engineering, and applied science research. Financial engineering, risk management, and economic research have combined the MCS (Sadeghi *et al.,* 2010; Brandimarte, 2014). The MCS has been used in railway studies to assess risk to infrastructure. For example, some researchers could improve the level of service safety on the SCNF network. To characterise the behaviour of railway track geometry, MCS has been included into a maintenance procedure (Quiroga and Schnieder, 2012). Another study used MCS and even tree-based approaches to assess danger in railway tunnels. This was due to an increase in cases of derailment, accident, and fire in railway tunnels. As a consequence of the research, an excellent approach for closely monitoring mortality in railway tunnels has been developed (Vanorio and Mera, 2012).

In addition, the MCS has been used to improve the efficiency of railway operations. Some academics predict that railway timetables can become more reliable, particularly in Japan's metropolitan regions. The study discovered that train delays during morning rush hours directly affect over 2,000 people every day. As a consequence, the MCS was used to analyse network dwell durations across 26 trains in service, resulting in a total delay reduction of 1,420 seconds (Ushida *et al.,* 2011). Another example study was Hong Kong, where the mass transit railway reached peak capacity with 2,500 people each train, which was above existing capacity. The MCS plays a crucial role in determining dwell duration, ensuring safety and timeliness across Hong Kong's subway system (Lam *et al.,*1998).

In terms of the economic advantages of railways, some authors have used MCS to assess the long-term cost of international rail development projects. In reality, the cost of building railway infrastructure was higher than that of other modes; also, the project might be subject to construction market fluctuations. This research provided an accurate cost-estimating risk model to help managers better comprehend the benefits of investing in railway projects (Yuan *et al.*, 2020). In addition, the MCS has environmental and economic advantages. It was discovered in a study of the LCC of Turkey's HSR networks. The study uncovered the environmental costs of both networks' railway operations and infrastructure; as a consequence, the study could support future Turkish railway projects lower their environmental consequences (Banar and Zdemir, 2015).

An effective operational strategy, which included financial liquidity, invariably leads to good railway service. As previously stated, the majority of railway companies have struggled to make a profit. In this study, the MCS is used to analyse LCC steps separately in order to provide an accurate pricing range. This product eventually benefits railway operators by allowing them to deal with unforeseen events; further, it provides detailed information on HSR operating expenses, allowing for a better understanding.

3.3 Data analysis

Table 3.1 depicts the selection of specific HSR routes from each network in this section, with the goal of presenting detailed results and recommendations for future HSR developments. The expenses of construction, materials, and operation have been derived from corporate papers, publications, and other credible sources. This research analyses each HSR network from its 1st year to its 70th year of operation. In order to compare current financial performance, the NPV analysis is applied to a normalised present value.

3.3.1 LCC of the manufacturing and pre-assembly stages

The materials necessary to construct a rail track are listed in Table 3.1. There are 11 critical materials to the building process, and the material information in the table is gathered from reputable sources, which is based on typical market pricing. However, import tariffs in various nations have a role in determining construction costs. Import taxes in European countries are often higher than in Asian countries; for example, goods import taxes in France are 18.6%, while import taxes in Spain are 21%. The initial construction cost in this research also includes 10% of the delivery price.

Table 3.1 A summary of the material costs associated with a single kilometre of HSR track (Global source, 2020)

Cost of material	Cost (£/km)				
	CRC	JR Central	Korail	SNCF	Renfe
Gravel/Sand	6,459,384.69	7,622,073.9	7,751,261.6	8,306,768.71	8,461,793.94
Concrete	23,389,306.8	2,747,892	117,361.05	444,235.62	688,148.79
Wood	653.25	3,047.8032	1,674.28	6,337.49	9,817.17
Steel	225,277.2	265,827.1	270,332.64	289,706.479	295,113.13
Steel low-alloy	13.32	89.79	152.40	129.22	200.18
Zinc	N/A	0.09	0.4	N/A	N/A
Copper	N/A	11.23	48.02	N/A	N/A
Ceramics	349.86	2927.79	6,438.47	3,394.16	5,257.77
Aluminium	N/A	0.486	2.079	N/A	N/A
PVC	N/A	0.92	3.94	N/A	N/A
Excavation of soil	N/A	332,351.1	1,421,724.2	N/A	N/A
Summary	30,074,985.12	10,974,222	9,568,999.1	9,050,571.69	9,460,330.98

In terms of operating equipment, the information on the costs of the 11 various types of construction equipment is based on the electricity rates in each country. As illustrated in Table 3.2, the expenses may be divided into two categories: track and earthwork expenses.

Table 3.2 The cost of building equipment for a single kilometre of high-speed rail (Source: Global source, 2020)

Construction equipment	Track			Earthwork			
	Working time (h)	Rated power (kW)	Working time (h)	Rated power (kW)	Working time (h)	Rated power (kW)	Working time (h)
Concrete distributor	45.6	22	1,003.2	N/A	N/A	N/A	1,003.2
Concrete mixing plant	45.6	160	7,296	219.9	160	35,184	42,480
CNC grinding machine	45.6	160	7296	N/A	N/A	N/A	7,296
Gantry crane	113	86.5	9,774.5	N/A	N/A	N/A	9,774.5
Two-way transporter	34.5	110	3,795	N/A	N/A	N/A	3,795
CA mortar truck	27.7	90	2,493	N/A	N/A	N/A	2,493
Track laying machine	6	396	2,376	N/A	N/A	N/A	2,376
Spiral drilling machine	N/A	N/A	N/A	311.2	90	28,008	28,008
Excavator	N/A	N/A	N/A	5,889	125	736,125	736,125
Loading machine	N/A	N/A	N/A	2,944.5	162	477,009	477,009
Concrete pump	N/A	N/A	N/A	439.8	115	50,577	50,577

3.3.2 LCC of the operational stage

The operating costs include rolling stock, crew salary, fuel and power, all of which are subject to fluctuating prices dependent on the nation in question. Staffed at 50 persons per km, the number of employees employed is approximated at 50 individuals. In this study, it is estimated that the network lifetime for the HSR is 70 years; and it utilises the first year of all HSR operation, on the basis of reality. A good example of this is the 'Paris – Lyon' HSR route, which has run since 1981 by SNCF. Therefore, the LCC calculations are performed from 1981 to 2051, as shown in Figure 3.4. Additionally, NPV calculation and discount rate are utilised when accounting for the LCC in that time period.

3.3.3 LCC of the maintenance stage

The LCC maintenance stage focuses mostly on keeping the track and rolling stock in a good shape. However, HSR operations, track maintenance and track monitoring are all essential to ensure the safety of the system. A significant amount of track maintenance work is projected to be done every five years (Ishida and Suzuki, 2005; Chrismer, 2008; Nimbalkar and Indraratna, 2016). The material and machinery costs are included in the maintenance costs, which are estimated to be 15% of the initial construction costs.

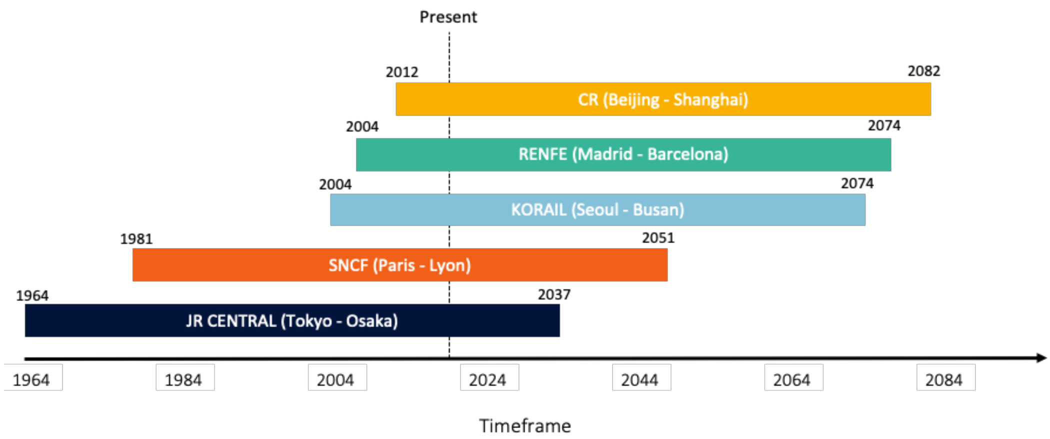

Figure 3.4 The LCCA's timeframe of HSR routes

3.3.4 LCC of the demolition stage

The LCC value for the demolition stage covers both demolition and landfill logistics expenses. It is taken into consideration the recycling rates, which vary by region. The end-of-life cost of rolling stock is computed in years 35 and 70, but the lifespan of rail tracks is computed in years 70 and up.

There are two stages to the HSR demolition stage: rail track demolition and rolling stock demolition. Rail track is made up of both recycled and non-recycled materials, whereas rolling stock is generally made up of recyclable materials like aluminium and steel. Non-recyclable components (such as wood, polypropylene, and nylon) are shredded and disposed. Contaminated or hazardous materials (such as ballast), on the other hand, must be cleaned to minimise their environmental effect. As a result, demolition costs for hazardous materials are greater than non-toxic materials. All recycled materials (such as steel, concrete, and soil) are taken from the rail track and reused.

3.4 Results

The LCC findings are normalised to the value of '£/km,' with Table 3.3 presenting a summary of the LCC data that comprehensively depicts the entire life cycle phases. A benefit of applying these outcomes is that their benefits are given with a 6% discount rate.

Table 3.3 The benchmarking of the LCC results

Details (units)	Total LCC				
	CR	JR Central	Korail	SNCF	Renfe
The cost of constructing the tracks (material and equipment) (£)	30,086,961.36	11,287,237.70	9,671,069.31	9,267,096.71	9,747,080.34
The cost of track operation (£)	11,976.25	313,015.45	102,070.28	216,525.02	286,749.38
Total cost of track construction (£/km)	**22,827.74**	**21,916.97**	**23,164.24**	**22,657.94**	**15,695.78**
1st year of rolling stock value (£)	2,110,618.95	249,255.43	1,238,051.23	148,168.28	250,679.77
36th year of rolling stock year 36 value (£)	17,195,744.44	2,030,746.77	10,086,715.33	1,207,164.30	2,042,351.30
Total cost of rolling stock (£/km)	**19,306,363.39**	**2,280,002.20**	**11,324,766.56**	**1,355,332.58**	**2,293,031.07**
Tariff (£/km)	2,488.00	11,248.00	7,328.00	9,896.00	7,776.00
Bonus (£/km)	99.52	-	290.00	402.16	300.00
Fuel and electricity (£/km)	11,976.25	313,015.44	102,070.25	216,525.03	286,749.36
Total cost of operation (£/km)	**14,564.00**	**324,263.00**	**109,688.00**	**226,823.00**	**294,825.00**
Total cost of maintenance (inc. mat & equip) (£)	362,053,536.40	135,446,852.30	116,052,831.70	111,205,160.60	116,964,964.10
Total cost of maintenance (£/km)	**51,362.42**	**49,313.17**	**52,119.54**	**50,980.36**	**35,315.51**
Track demolition (£)	30,190.00	606,815.00	314,367.00	246,954.00	374,960.00
Rolling stock demolition (£)	44,500.00	35,750.00	34,720.00	30,800.00	21,250.00
Total demolition cost (£/km)	**4,554.12**	**9,105.51**	**79,747.72**	**13,451.09**	**24,955.67**
Total LCC (£/km)	**19,399,671.67**	**2,684,600.85**	**11,589,486.06**	**1,669,244.97**	**2,663,823.03**

More than 90% of HSR's LCC is spent at the operating stage, as shown in Table 3.3. Furthermore, the manufacturing and maintenance stages of the LCC have shared roughly 1% and 3% of the total LCC, respectively. In the initial and 36th years, the majority of the operational costs are spent on rolling stock, whereas staff and energy expenses account for just a minor cost of the total operating expenditures. It is vital to remember that replacing new rolling stock charge high volume of money. In terms of manufacturing costs, this thesis simplifies and forecasts major rail track maintenance every five years, whereas rolling stock and train carriages are repaired once a year. Lastly, infrastructure demolition and demolition are demonstrated to account for less than 1% of overall LCC.

In terms of financial performance benchmarking, the older project has a higher potential for financial gain than the most recent network, according to the analysis results. The reason for this is because of the effects of the time value of money during the life cycle of the HSR. SCNF's route had the lowest LCC in our analysis, at 1,669,244.97 £/km. In addition, the LCC of the JR Central and Renfe lines is somewhat higher, at 2,684,600.85 £/km and 2,663,823.03 £/km, respectively. Because both SCNF and JR Central's routes were built before the year 2000, they benefit from the time value of money. On the other hand, the Renfe line, which began service in 2008, has the lowest construction costs due to an overall LCC that compares favourably to prior networks.

3.5 Sensitivity analysis

The LCC computation is based on actual data gathered for regular events and is estimated and supplied. As a result, a sensitivity analysis is necessary to examine unusual events such as natural catastrophes, vandalism, and unanticipated damages during operations. One practical benefit of this study is that it may be used to prepare reserve capital for new projects' financial planning.

To eliminate uncertainties, the ISO 14040 standard recommends using Monte Carlo Simulation (MCS) on the life cycle analysis. The LCA, which may minimise uncertainties in the recycling process, and the LCC, which reduces maintenance and operating costs, are examples of MCS use in railway research. The MCS in the LCC is used in this study to assess the uncertainty of unexpected events.

In terms of the MCS, the study uses a triangular distribution with a bottom limit of -10 percent of the standard cost and an upper maximum of +60 percent of the standard cost. Table 3.6 shows how the LCC's standard cost is estimated based on the regular circumstances. The thesis's sample size is set at 5,000 (n = 5,000). Figure 3.5-3.9 depicts the simulation results for each rail network. Equation 3.3 is the probability density function of the triangular distribution.

$$f(x) = \begin{cases} 0 & x < a \\ \dfrac{2(x-a)}{(b-a)(c-a)} & a \leq x \leq c \\ \dfrac{2(b-x)}{(b-a)(b-c)} & c \leq x \leq b \\ 0 & x > b \end{cases} \tag{3.3}$$

Where; a is the lower limit, b is the upper limit and c is the mode, where $a \leq c \leq b$

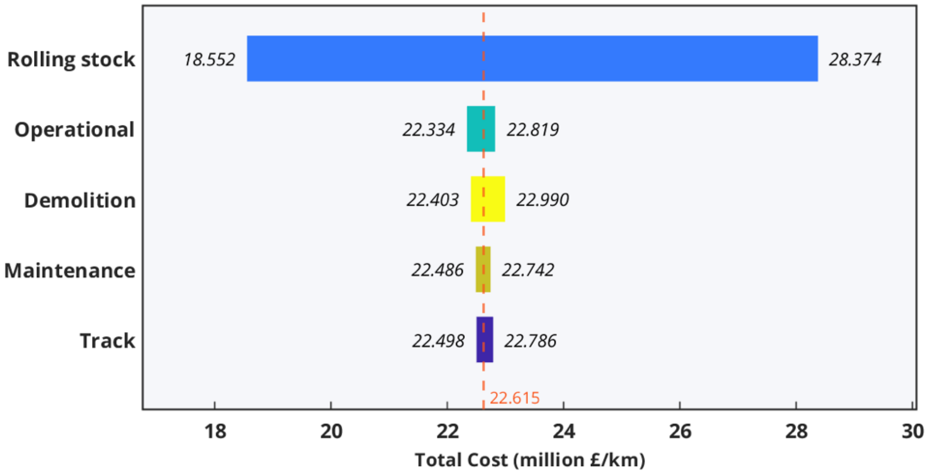

Figure 3.5 The MCS's impact on the CR network

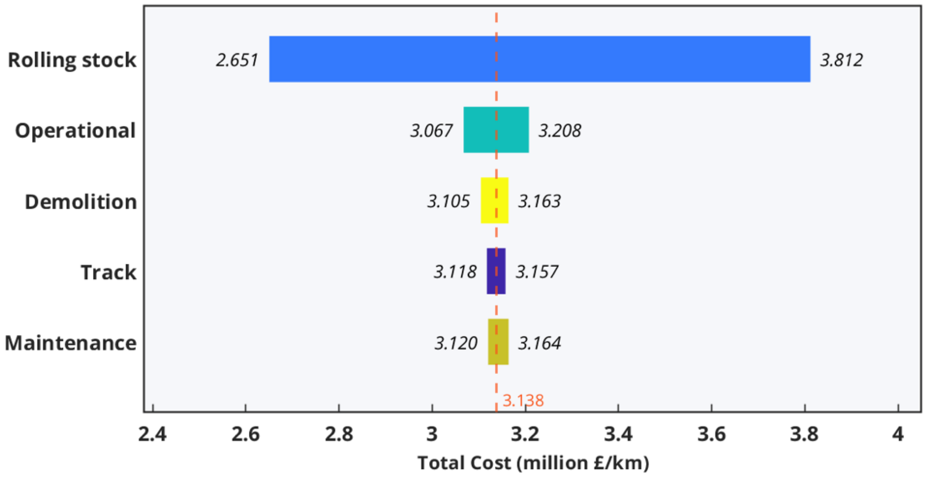

Figure 3.6 The MCS's impact on the JR Central network

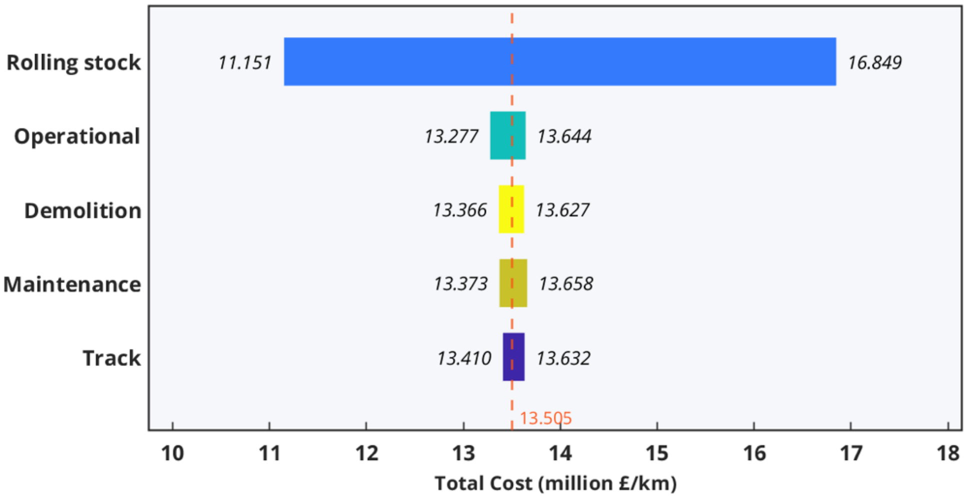

Figure 3.7 The MCS's impact on the Korail network

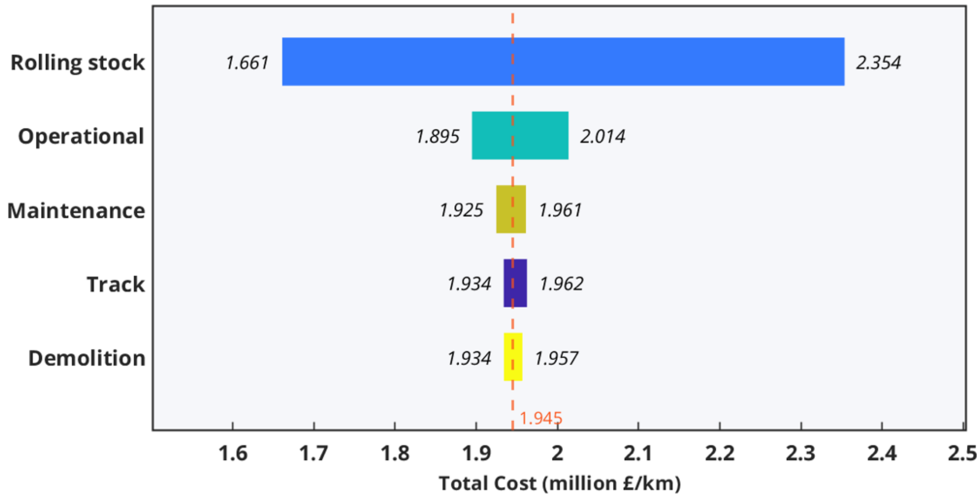

Figure 3.8 The MCS's impact on the SNCF network

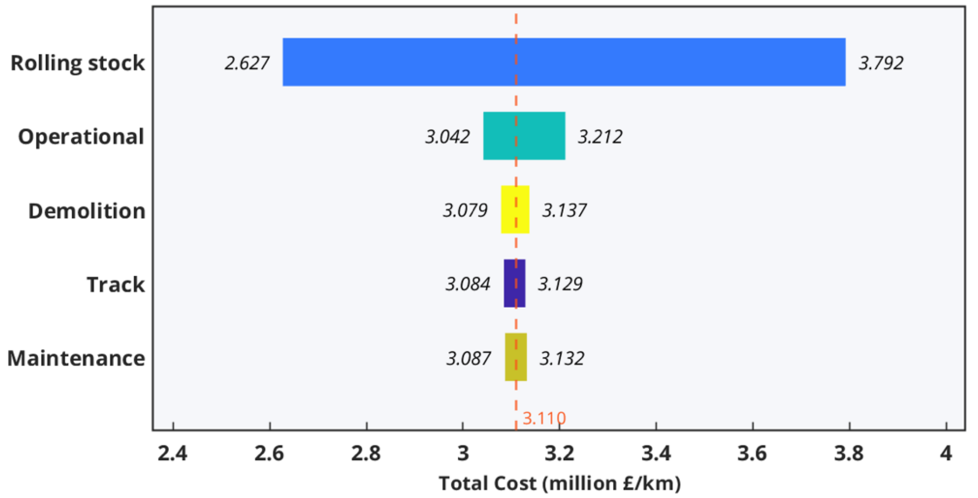

Figure 3.9 The MCS's impact on the Renfe network

The results of the MCS reveal about LCC uncertainties that can be altered from the typical scenario. The study examines five aspects of the LCC, including the production of rolling stock and tracks, as well as operational, maintenance, and demolition expenses. For example, lowering the LCC can be achieved by replacing old technologies with new ones that save energy and materials. The increase in LCC, on the other hand, is attributed to the replacement of track and rolling stock owing to

Table 3.4 The breakdown of the MCS's result from LCC investigation on each rail network

Rail authorities	Cost (million £/km)		
	Minimum	Mode	Maximum
CR	17.6	22.6	30.9
JR	2.5	3.1	4.1
KORAIL	10.5	13.5	18.3
SNCF	1.6	2.0	2.6
Renfe	2.4	3.1	4.1

severe damage. As seen in Figures 3.5 – 3.9, the rolling stock expense has the most variability in comparison to other parameters, as indicated by the wide range. On the other hand, the infrastructure and upkeep expenses are relatively stable over the course of the HSR's existence. The results demonstrate that the rolling stock is prohibitively expensive; it also needs replacement after 35 years.

The uncertainties associated with the HSR's LCC are shown in Table 3.4 in the unit 'million £/km'. The CR's network has the most uncertainty, indicating an LCC of 17.56 – 30.89 million £/km; however, the JR's network has the smallest uncertainty, indicating an LCC of 2.44 – 4.11 million £/km. The older network has less uncertainties than the newer network, because of the time value of money's effect on the LCC.

3.6 Conclusions

A literature review highlights the severe problem of lacking operating profit in various railway networks. This chapter aims to precise in-depth budget management. In this chapter, this thesis has highlighted gaps and provided solutions to enhance financial performance. First, most of the HSR's LCC models have been calculated in a short timeframe, which does not cover their whole life cycle. Also, the model has focused on neither HSR's infrastructure nor HSR operation; moreover, the net present value analysis has been omitted. Therefore, it results in an error in cost analysis. However, this thesis is the world's first to develop a new HSR's LCC model. In this study, the NPV analysis is used to determine the network's long-term life cycle. The expected life spans of rolling stock and HSR tracks are 35 and 70 years, respectively.

The major problems are that all HSR projects require a high investment volume compared to other transportation modes. For this reason, HSR projects face financial crisis during operational stages, particularly when facing uncertain events. To avoid this issue, this thesis proposes a sensitivity analysis for HSR's LCC by using Monte Carlo Simulation (MCS), which adheres to the ISO 14040 standard to the letter. It is advantageous for rail authorities to maintain control over their budgetary plans during times of uncertainty.

This chapter is quite useful for infrastructure managers when it comes to making the best maintenance and special event selections. Both expenditures are expected to be 15% of the initial construction cost, with the maintenance phase repeating every five years. Budgets have been lowered in periods when there is no significant repair, and a year's worth of running expenditures are included. According to the data, the LCC fractions in all of the nations investigated are the same. The LCC is split throughout the phases, with the repair stage accounting cost up to 45% of the total.

The running costs include typical provincial salary rates and electricity bills. The huge disparity in legal pay rates for track construction is illustrated; for example, JR Central's legal labour rate is 11,248 £/km, while the CR's legal wage rate is 2,488 £/km. Furthermore, during the operation and maintenance phases of a HSR service's life cycle, worker wages are considerable; in other words, the wide differential in pay rates has a considerable impact on the LCC report.

As a result, the SNCF's LCC is the smallest at 1,669,244.97 £/km, while Korail's LCC is the costliest at 11,589,486.06 £/km. The SNCF's LCC looks to be almost seven times that of Korail. The SNCF network has been in continuous operation since 1981, which is 23 years longer than Korail. The LCC of the older SNCF project is smaller than that of the late Korail network due to the time value of money (TVM). It is also worth considering the amazing statistics that the LCC summary discovered. Earlier HSR proposals have a greater chance of having a beneficial economic impact than later HSR projects.

The MCS is broken down into five categories in this study: rolling stock, operation, demolition, track (infrastructure), and rolling stock expenses. This section provides long-term advantages to rail authorities that have a thorough understanding of the industry's complicated cost structure. As a result, rail officials will be aided in planning new HSR projects and coping with unpredictable scenarios. As a result, the LCC of the CR network may reach a maximum of 30.89 million £/km and a minimum of 1.56 million £/km as SNCF.

3.7 Chapter summary

This chapter examines the whole LCC of HSR infrastructure and rolling stock over a 70-year period. All relevant costs, such as shipping fees and taxes, have been calculated using the LCA method in four stages: pre-assembly and manufacture, operation, maintenance, and demolition. Because this study is about the time worth of money, a discount rate of 6% per year is used. Finally, this component uses MCS to do a sensitivity analysis, allowing the rail authorities to gain a better knowledge of the cost structure.

Following the study in this part, Renfe is the leader in LCC management since the network clearly exhibits the lowest cost when compared to other networks. However, assessing insight performance should be fair and transparent, thus this research breaks out each level. Table 3.5 shows the results of the KPIs for each area.

The findings suggest that the upcoming HSR projects should be concerned about the impact of money's time value because early projects obtain more financial benefits than late projects. Another good practice is controlling budget management. For example, the CR network has perfectly limited its costs, especially operational costs, despite starting significantly later than other projects.

Table 3.5 The summary of KPIs of LCC

KPIs	Total weight (%)	LCC stages (details)	Weight (%)	CR	SNCF	JR Central	Korail	Renfe
Life cycle cost	15	Manufacturing (Infrastructure)	3	0.14	0.20	0.50	0.00	3.00
		Manufacturing (Rolling stock)	3	0.00	3.00	2.66	1.25	2.66
		Operational	3	3.00	0.94	0.00	2.08	0.29
		Maintenance	3	0.14	0.20	0.50	0.00	3.00
		Demolition	3	3.00	2.65	2.82	0.00	2.19

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CHAPTER 4

Productivity and punctuality

This chapter presents two mandatory indicators, namely productivity and punctuality. The productivity factor shows the performance of management staff, training, budget and other important factors. In contrast, punctuality reflects the operational performance the HSR networks. Within this chapter, qualitative analysis is applied by using information from official company financial reports, sustainability reports, and other reliable sources.

4.1 Introduction

4.1.1 A review of productivity

The chapter highlights productivity issues in order to promote the long-term development of HSR networks. Today, the sustainable development perspective is concerned due to global sustainability goals. The definition of 'resources' refers to a variety of different things, people, machines, and infrastructure. There are many resources that a company requires to successfully complete jobs and carry out activities. Resources are generally split into six types: labour, equipment, materials, investment, facilities, and time.

As resources are limited, controlling demand for them has become a crucial indicator in examining overall performance (Ichniowski *et al.,* 1995; Bratton and Gold, 2017). Sustainable resource management has been launched as a circular economic action plan that serves all EU member states. This leads to a long-term sustainable development goal that benefits both the economy and the environment (European Commission, 2021). The vision of diminishing resources includes energy, raw materials, and labour.

Regarding HSR organisation, sustainable resource management consists of multiple sub-sections, as shown in Figure 2.2. Therefore, the importance of resource management is that it enhances a company's performance and productivity. It enables businesses to use planning in relation to their employees as well as to their own limited resources. Additionally, resource management increases the transparency of the planning and management processes.

To measure productivity regarding resource management, six sub-indicators are applied as key measures: sales and marketing development, technology development, service development, human resource management, environmental management and financial overview, as shown in Figure 4.1. Detailed theories and frameworks are clearly reviewed in the following sections.

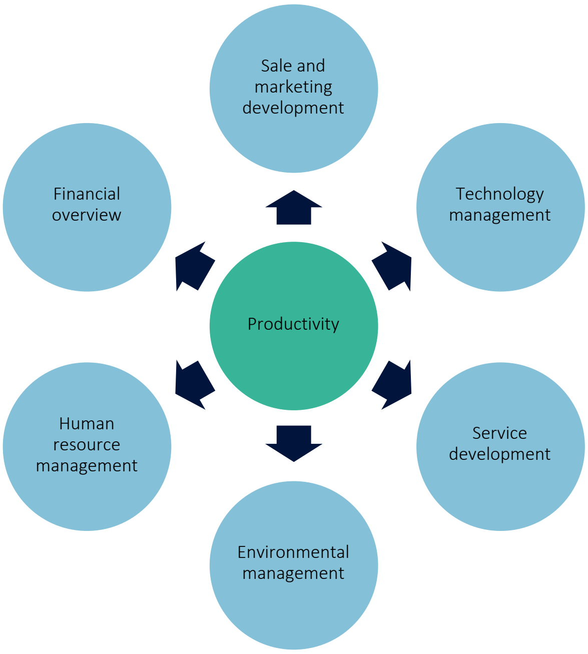

Figure 4.1 A summary of the six sub-indicators of the productivity KPI

4.1.1.1 Sale and marketing development

As mentioned in Chapter 1, most rail networks are experiencing a loss of operating profit caused by low passenger demand. The construction of HSR networks, on the other hand, necessitates a significant investment. In fact, HSR ticket prices are higher than those for conventional rail services. For this reason, some groups of passengers are unable to pay any fare for HSR services, so some local governments subsidise ticket costs for passengers. To increase passenger demand, some rail authorities have launched many campaigns to attract more passengers by offering special tickets and discounts to students. Also, special HSR tickets for foreign travellers have been proposed to stimulate national economies.

Qin *et al.,* (2019) have developed a pricing strategy model for HSR networks by using China as a case study. The study expects to maximise revenue and achieve sustainable development. To stimulate passenger demand, a differential pricing model is proposed during peak and off-peak periods. This was expected to increase passenger flow and revenue by approximately 8%-11%. This is because travelling during peak times may impact on passenger flow and worsen the rail travel experience. Using this strategy can directly improve service quality, raise passenger expectations, and lead to revenue growth.

Pricing strategies for the HSR electric multiple unit (EMU) were developed to stimulate HSR market. For example, the Chinese railway system has introduced a new service for night-time travellers, known as the ‘evening-morning’ service, which has been operated in the evening hours. The flexible pricing model has been suggested to support market supply and demand. Moreover, other strategies (e.g. ticket refunding systems) have been introduced to the service (An, 2019). The proposed model is intended to provide guidance in order to improve the competitiveness of this new service.

The ability to pay ticket prices has become an important factor in determining the price of a service. In some areas, the HSR passenger numbers reflect low demand due to HSR fares being extremely high, compared to other modes of transportation. Wang (2018) has evaluated marketing strategies for HSR with reference to passengers’ incomes. The study focused broadly on passenger incomes, purpose of travel, travel distance, seasonality, and region. The study’s goal was to provide flexible pricing strategies for all types of customers. As a result, the study recommended a fixed pricing model as well as flexible pricing strategies for the long-term development of the Chinese HSR (Shaw *et al.,* 2014; Wang, 2018).

Similarly, Delaplace and Dobruszkes (2015) examined ticket prices for low-cost HSR services (Ouigo) and airlines in France. The study focused in detail on production conditions, marketing strategies, passengers' experiences, and fares. The authors revealed that the French HSR provides at least a 50% discount for disabled people, children under the age of 12, people over the age of 61, and SNCF workers and their relatives. This has had a positive result, with increased numbers of passengers and more opportunities for the Ouigo service in the transportation market.

From this literature review, marketing strategies and promotions can truly increase passenger demand for HSR services. For this reason, sales and marketing performance is part of this study on the evaluation of HSR network performance.

4.1.1.2 Technology development

Technology development has become an important factor due to increased passenger demand and competition in the transportation market. Much of the research points strongly to technological development ultimately being able to benefit HSRs in a competitive market. Chuang and Johnson (2011) have mentioned that fares for Chinese HSR services were approximately 20%-30% more expensive than those for passenger trains because 80% of seats were unsold. The government wanted to improve HSR operational effectiveness and, as a result, the authors proposed various strategic technologies that the government could implement and adopt on a national scale.

Various technological advances and innovations have been integrated into every part of railway networks, including infrastructure and operating systems. As an example, improved boarding strategies have been introduced with the aim of increasing passenger flow. Tang *et al.* (2019) created simulation models and offered three optimised strategies for reducing boarding time, motion time, and blockages during boarding. Similarly, the UK government has expressed concerns about the accessible design of railway stations, particularly for disabled people who use wheelchairs. The majority of railway stations have security barriers in place. The installation of barriers, on the other hand, has resulted in increased boarding time for both passengers and wheel chair users. As a result, practical guidance on barriers has been issued as a directive across the UK rail network (DfT, 2015).

Uzuka (2013) highlighted the advantages of the Shinkansen network's technological advancement. The Shinkansen network has been gradually developing technologies, especially the replacement of older technology with electrification. Moreover, the improvement in pantographs has increased energy efficiency and reduced noise pollution. As a result of the switch to electrified trains and other innovations, Japan has emerged as the best-practice case of efficient urban transportation, which has a positive environmental impact. Similarly, Bettez (2011) studied glycol de-icing technology for rolling stocks and found that it can be most cost-effective during the winter period.

To summarise, technology development can enhance overall performance, offer safe services to all passengers, and reduce operating costs. Therefore, it is reasonable to include the measurement of technology and innovation development within this study.

4.1.1.3 Service development

It is unavoidable that the quality of HSR services influences passenger satisfaction and loyalty. A service-centred approach envisions an engaged consumer who communicates with staff, the service script, and/or supporting tangibles. This approach has suggested the need to develop deep and trusted connections with customers in order to raise their perceived worth (Vargo and Lusch, 2004). Customer satisfaction also relies on the quality of the product or service according to psychological research (Anderson and Sullivan, 1993).

As discussed in this section, the development of HSR services can directly address various operating problems, such as train delays, passenger flow, payment systems, and so on. In terms of the economy and customer expectations, the proper allocation of trains between peak and off-peak hours is critical. Chang and Lee (2008) studied the accessibility of the KTX service in Seoul and other metropolitan areas. According to the study, there were large gaps between the actual service and the ideal service demanded by KTX passengers. Overestimated forecasts of passenger numbers was detrimental to the company's operational profits. To address this issue, this study contributed an effective accessibility model for use in operational areas. The authors expected this to improve KTX's economic feasibility through benefitting from the opportunities from improved accessibility (Chang and Lee, 2008).

Customer relationship management, which is one type of service development programme, is widely recognised as critical for an enterprise's long-term profitability and success as it can increase customer satisfaction levels. Similarly, a reduction in customer complaints can be reflected in an increase in customer loyalty and retention rates, which are critical elements in the profitability of service-oriented firms (Eid, 2007). Therefore, new service development should be based on detailed understanding and forecasting of latent customer expectations of the service (Matthing *et al.,* 2004). For example, the American customer satisfaction index (ACSI) has clearly explained the relationship between perception of quality, expectation, and value of a product/service. The index has been created to assess customer satisfaction with both foreign and domestic firms' products and services in the United States. This has become a key factor in economic development a local and national level (ACSI, 2021). As illustrated in Figure 4.2, the factors considered in the ACSI have an impact on customer satisfaction because they can affect whether customers are satisfied nor dissatisfied with a product/service. Also, reduced customer complaints can result in increased customer loyalty and retention rates, which are critical elements in the profitability of service-oriented businesses (ACSI, 2021).

Similarly, Cascetta and Coppola (2014) studied passengers' behaviour and travel demands regarding HSR services in Italy. The research focused on trip frequency options for passengers with respect to each type of purpose, such as business, leisure, and personal trips. Trip-frequency models were designed to estimate passenger volumes in various scenarios involving improved service quality (Cascetta and Coppola, 2014). In addition, a study of service quality on the Taiwanese and Korean HSR networks found an increasing level of satisfaction and profit. The study addressed

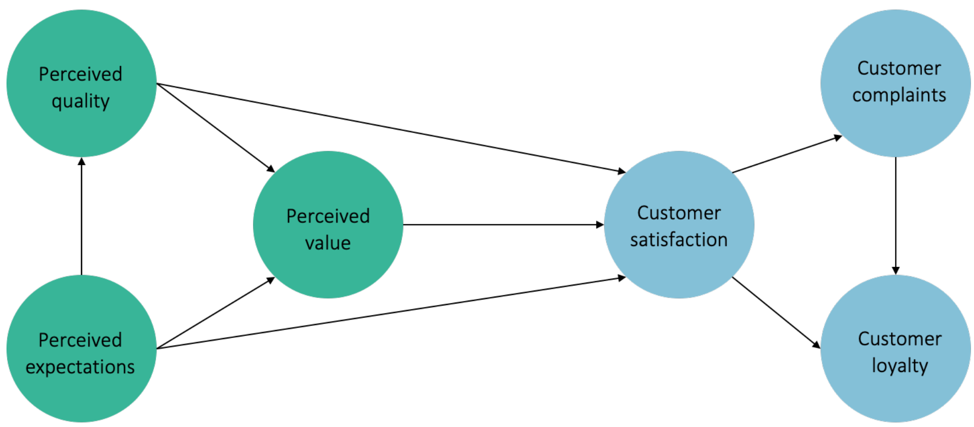

Figure 4.2 The ACSI customer satisfaction model (Source: ACSI (2021))

the importance of customer satisfaction and employed a priority performance assessment. The outcomes were expected to help improve rail organisations' operational performance and customers satisfaction (Chou *et al.*, 2011).

Ultimately, service development affects customers' expectations when they use HSR networks, as shown in previous research. It has direct positive impacts for rail authorities. The customer becomes the centre of everything due to the highly competitive transport sector. For this reason, service development is included as a sub-criterion for measure overall performance in terms of productivity.

4.1.1.4 Environmental perspectives

Through the Paris Agreement, the goal of reducing the environmental impact of transportation networks has been added to the global mission. Development in terms of environmental factors shows the perspective of rail authorities on the impact of global warming, towards which the transport sector has contributed approximately one-fourth of global CO_2. It is therefore necessary to reduce the environmental impact of HSR.

Various techniques have been used throughout the railway industry, including a transition from DMU (diesel multiple unit) trains to EMU (electric multiple unit) trains. The N700 Shinkansen train an EMU model that emits less CO_2 than DMU models and other modes of transportation. Sato *et al.,* (2010) found that, due to the performance of the N700 Shinkansen train, the traction system's weight/power ratio was halved and its energy usage was cut in comparison to the first series of Shinkansen trains. Similarly, Singh *et al.,* (2006) focused on the improvement of the quality of power from EMU AC-DC converters. The simulation results indicated that the model designed could increase the energy efficiency of trains during operation. Reduced energy consumption and CO_2 emissions have a positive impact on the environment.

Plakhotnik *et al.,* (2005) concentrated on the environmental and ecological consequences of Ukraine's railways, using the Ecotrans program to monitor their impact on the atmosphere, water, and waste. The results showed that the amount of pollutants in the atmosphere increased significantly between 1999 and 2002, measured according to solid pollutants, CO_2, NO_2, and SO_2. As a result, government policies have proposed to reduce the environmental impact of the railway network. Kurze (1996) pointed out the impact of railway noise and vibration on the environment, despite the fact that this is less than for road traffic. The research controlled the great impact of noise and vibration on train car parts such as disc brakes and elastic rail pads. Also, reductions in structure-borne sound have been made in various locations, such as the ballast mat within rubber tunnel mats on steel bridges (Kurze, 1996).

Furthermore, there have been widespread new developments in railway energy storage. de la Torre *et al.,* (2014) proposed that EMU trains be fitted with a hybrid energy storage system (HESS). The authors claimed that the merging of a HESS and the train's battery could increase the energy storage capability (de la Torre *et al.*, 2014). Another research study has looked into power regeneration braking technology for EMU trains. The EMU braking system uses dynamic braking, while kinetic energy becomes waste. In the meantime, the electricity produced can be utilised to power additional trains within the network or can be used to balance other power needs, such as lighting in stations (UIC, 2003). However, there are gaps in this improvement of energy storage technology on low-density district lines and during off-peak hours. As a result, the study proposed a high energy conversion rate for EMU trains, resulting in lower CO_2 emissions (Ogasa, 2010).

In conclusion, rail authorities must be concerned about long-term environmental consequences. As a priority, employees should be encouraged to pay attention to environmental effects and to use appropriate resources to mitigate the negative effects. For this reason, the measurement of environmental impact has been added to this section.

4.1.1.5 Human resource management

To achieve sustainable development in the railway industry, human resource management (HRM), or crew training development, is necessary because it is a process of learning and development of the relevant skills and knowledge for individual staff. Also, multi-tasking skills should be integrated into an expert training system. A significant amount of research on the performance of human resource management in railway services has been conducted by many scholars. Some positions, such as infrastructure manager, necessitate a high degree of professional experience in order to make the right decisions (Daniel, 2017).

Many rail organisations have prioritised employee development programmes. Morgan *et al.,* (2007) analysed the differentiation in staff effectiveness in terms of pre-training and post-training costs. The CRM programme was devised by the Texas Transportation Institute with the aim of enhancing performance across the railroad sector. The research results revealed that there were high levels of effectiveness and knowledge after training.

As mentioned in Chapter 1, railway authorities consist of employees with multidisciplinary backgrounds, so human resource management plays an important role in each section and throughout the workers' careers. It contributes to the efficiency of internal work plans, procedures, and company strategies. In fact, 20% of all railway accidents are caused by human errors, and most of these errors occur among railway company staff (Baek *et al.*, 2008; Rungskunroch *et al.*, 2021). Similarly, a study of human factors influencing railway accidents has been conducted on Australian railways. According to some studies, nearly half of all accidents were caused by human factors, such as equipment failure, lack of maintenance, and breakdown in communication. Furthermore, a lack of fundamental skill and attention has been linked to railway accidents which have resulted in a large number of fatalities and injuries (Baysari *et al.*, 2008). Likewise, Jehanzeb and Bashir (2013) mentioned that there was no one-size-fits-all approach to designing staff training, but that there are certain key methods that can be quantified. A successful employee training programme must incorporate elements of knowledge acquisition, career advancement, and goal setting. As a result, a staff training programme should play an important role in improving railway network safety performance.

In conclusion, staff are the most valuable asset in railway organisations. By offering training courses and providing fundamental knowledge related to staff roles, companies can ensure that staff activities can truly enhance their productivity. Consequently, human resource management is measured as part of determining overall performance in terms of resource management.

4.1.1.6 Financial overview

Lastly, financial status has evolved into an important key metric for measuring performance in resource utilisation. Financial analysis is concerned with identifying the financial strengths and weaknesses of HSR networks. The reason for this is that financial status directly indicates the performance of the organisation and refers to measures of company policies and operational activities (Jupe, 2009; Ravinder and Anitha, 2013). Strong financial health indicates that a company is likely to succeed due to a high potential for return on investment. Some signs of good financial health, among others, are a growing cash balance and a steady flow of income.

Accordingly, the financial status of a HSR company is evaluated over the previous five years. The outcome means that a company has an exact understanding of its financial situation and detailed costs. As a result, rail authorities can launch new campaigns or sell promotions to increase their financial viability.

4.1.2 A review of train punctuality

The punctuality KPI assesses how effective an operating plan is for both normal and unexpected events. It is a common indicator in the railway industry, explaining the root cause of train delays. The concepts of punctuality and delay are well-known, but there are subtle differences between them. The terminology of punctuality in railway research refers to a train operating within an accepted divergence time, including being behind and ahead of schedule. Delay, on the other hand, refers to a train running behind schedule. Both punctuality and delay are commonly measured in units of time (i.e., seconds, minutes and hours).

In fact, railway companies have combined various technologies to improve punctuality rates due to customers' expectations of their services. One definition of train punctuality is given as "the ability to achieve a safe arrival at a destination on an advertised timetable" (Gylee, 1994). Also, some scholars define punctuality as a percentage of trains arriving at and departing from a station in a specified range of time (Hansen, 2001). On the other hand, some researchers have mentioned that punctuality is a measurement of a train arriving at, passing through, and departing from a predefined point compared with a predefined time (Rudnicki, 1997).

The importance of punctuality in railway systems is identified as the primary criterion for measuring the performance of these systems. This KPI is commonly discussed across the industry and associated academic fields with the aim of reducing delays across railway networks. It is important to highlight the fact that there are various factors that cause train delays, such as weather conditions, wind speed, snow, leaves on track, the number of trains in a station, and traffic volume.

Furthermore, train delays can often be caused by planned maintenance. Maintenance, as is well known, is an important process in ensuring the safety of railway operations. Granström and Söderholm (2005) studied the effect of maintenance and reinvestment activities across the Banverket network. The study investigated existing train delay statistics and proposed a practical method to improve the operating system without causing train delays.

Fahlén and Jonsson (2005) investigated Sweden's railway network. A new European perspective on train punctuality recommended communication with traffic control about weather conditions, particularly in winter (Fahlén and Jonsson, 2005). Palmqvist *et al.,* (2017) suggested that train delays are primarily caused by weather conditions. Their study was based on big data, investigating nearly 90 million sets of weather data from Sweden, followed by an analysis of these data sets in relation to the 32.4 million Swedish train characteristics. The impressive results revealed details of delay times and compared them with weather conditions. As a result, the study provided a practical railway timetable to avoid train delays during inclement weather. In addition, this timetable can be applied to maintenance and planning projects (Palmqvist *et al.*, 2017).

Preston *et al.,* (2009) studied the impact of passenger train delays in Great Britain. According to the study, the average train delay in the United Kingdom was three minutes, and the causes of train delays included train operators (signal and other non-track assets), infrastructure (track) problems, and other external causes (excluding weather). Train delays may have an impact on passenger expectations; however, this study found interesting evidence that British rail passengers were very sensitive to them but have grown accustomed to them. To address this issue, the study suggested that rail operators provide better and more advanced information to customers so that they are aware of any new schedule (Preston *et al.*, 2009).

Jiang *et al.,* (2010) focused on the causes of train delays on the Beijing-Shanghai HSR network. Six causes of network delays are weather conditions, maintenance schedules, system failure, conflicts with other trains, passenger overflow, and external issues. According to the study, punctuality was critical for this HSR service, and it was recommended that the quality of service of the Chinese Train Control System should be improved because they believed that, in the long term, causes of delays could be improved.

Goverde (1999) researched Dutch railway safety performance in order to improve the network's issues with delay. The research found that a train schedule can be improved by reducing the buffer time. As a result, the research offered a new and efficient periodic timetable that could reduce train delays (Goverde, 1999). Similarly, D'Ariano *et al.* (2008) anticipated that train punctuality would improve and that delays on the Dutch network could be eliminated. Consequently, the research introduced new real-time traffic management by rearranging some of the trains in service. The results indicated a high likelihood of improving network punctuality (D'Ariano *et al.*, 2008). Another study suggested a way to reduce buffer time in the Dutch network, particularly on the Maarssen-Utrecht Centraal route. The study addressed this issue through mathematical models, with the outcome of a 5.25% reduction in buffer time (Yang *et al.*, 2019).

The impact of train delays has been clearly demonstrated to reduce customer satisfaction while increasing economic inefficiency. Blayac and Stéphan (2021) conducted a quantitative analysis of train delays and customer behaviour in different European countries. Results from an individual survey of 670 passengers showed that 67% of participants prioritised punctuality factors when planning a long-distance journey due to concerns about missing an appointment or missing connections with other trains (Blayac and Stéphan, 2021).

European Regulation No. 1371/2007 has been implemented to regulate the quality of train services throughout the EU. The regulation offers rights for both domestic and international passengers in terms of ticket information, compensation, journey assistance, and other passenger benefits (Gov.UK, 2020). As shown in Table 4.1, the comparison of train delay across European countries is recorded for both regional and long-distance services (Grechi and Maggi, 2018). The data indicates that train delay falls in a range from 30 to 1,800 seconds. Rail authorities are concerned about passenger rights as a result of delays in communication of information and in reimbursement to passengers in accordance with EU regulations.

Table 4.1 Summary of train delay across EU countries (Source: Grechi and Maggi,2018)

Country	Delay more than (seconds)	
	Regional service	Long-distance service
Austria	329	329
Belgium	359	n/a
Bulgaria	300	300
Croatia	60	60
Denmark	179	179
Finland	150	n/a
France	359	n/a
Germany	359	n/a
Hungary	30	30
Italy	n/a	900
Latvia	210	210
Lithuania	1800	1800
Netherlands	180	300
Norway	239	359
Poland	300	300
Portugal	300	300
Slovakia	300	300
Spain	180	180
Sweden	359	n/a
Switzerland	179	179
UK	n/a	600

Olsson and Haugland (2004) mentioned that a high degree of punctuality was a first priority that affects potential customers using rail services. Their research discussed strategies to improve train punctuality in Norway, revealing a key success in managing boarding and alighting queues, as well as reducing congested areas, with the goal of improving punctuality. One way of improving this problem is to eliminate time gaps and time headway. It is interesting to talk about the facts of ‘buffer time’, which is defined as a small-time difference between the standard operating time and the dwell time. Hansen (2010) stated that a railway operation timeframe consists of running time, dwell time, and headway time to the next stops (Hansen, 2010).

In addition, Chang and Sim (1997) have suggested an integration of the generic algorithm with the automatic train operation system as a way to reduce train delays for mass rapid transit (MRT). The authors created a mathematical optimisation model to improve overall performance in terms of punctuality, travel costs, and energy use (Chang and Sim, 1997). Similarly, Veiseth *et al.,* (2011) developed a punctuality improvement method system (PIMS) to improve interaction between rail authorities and new development projects. The authors believed punctuality to be the most important factor, so it is necessary to eliminate four types of delay: at terminals, from wheel damage, on single track, and at junctions (Veiseth *et al.*, 2011).

Rail authorities, on the other hand, have proposed rerouting and reordering strategies to eliminate delays. Carey and Carville (2000) highlighted the issue of a lack of railway infrastructure in Asia and Europe, as well as how train delays affect the complex of train characteristics (i.e., speed and capacity). The research focused in detail on a delay at a single platform station. To be clear, a single platform station has a higher chance of delay than multiple platform stations when trains arrive late or behind schedule, as they will be impacted by the previous and upcoming trains. To address this issue, the study proposed new schedules for the distribution of delays. The outcome could solve bottleneck problems in railway traffic (Carey and Carville, 2000).

The development of punctuality is also in the purpose of Kaas' (2000) punctuality model for railways. The research focused on the 'Copenhagen-Ringsted' route of the Danish national railway, which faced problems of traffic density caused by a lack of infrastructure. The study analysed long-term data and offered a new model to improve punctuality on the network (Kaas, 2000).

To summarise, a high level of punctuality has become an important factor in railway operations. This is due to the fact that it influences customer expectations of services. According to this research, therefore, it is reasonable to include the positive impact of robust measurement of punctuality performance within this study.

4.2 Methodology

4.2.1 Availability of data

The study conducts productivity and punctuality data during 2000 - 2019 from publication and HSR companies' sustainability reports and financial reports.

4.2.2 Research methodology

Following from the characteristics of information on productivity and punctuality, most of the collected data is in a non-statistical form, which differs from the rest of this thesis. Also, a small number of sampled groups, consisting of five HSR networks, is selected for benchmarking. For this reason, qualitative research is the main methodology applied in this section.

The qualitative analysis is more suitable than quantitative research for intangible, imprecise issues that are more social and experiential in nature. The qualitative method is predicated on the intelligence that machines lack, as factors such as positive associations with a brand, management trustworthiness, customer satisfaction, competitive advantage, and cultural transformations are difficult to represent through numerical inputs (Creswell *et al.*, 2007). Additionally, qualitative research methods can yield rich and thorough information, frequently in great details.

The application of qualitative research is widely found in various research areas, such as narrative research, phenomenology, case study, and grounded theory. Regarding research on railways, qualitative analysis has mostly been applied to the operational and service areas, especially in evaluating passenger behaviour and expectations. Farrington-Darby *et al.,* (2005) used qualitative analysis to identify the problems of recognising and correcting dangerous behaviour and poor safety culture prevalent in train maintenance. The study provided a qualitative examination of safety culture and unsafe behaviour throughout a railway organisation. As a result, practical strategies regarding railway maintenance were launched to support all of the staff involved (Farrington-Darby *et al.,* 2005).

Qualitative analysis is suitable for enhancing an organisation's performance. Mackenzie *et al.,* (2018) studied the causes of people committing suicides on the railways with the aims at reducing such suicide attempts. Qualitative analysis was the main tool for collecting information from a total of 79 potential witnesses, including railway authorities, staff, CCTV footage and other related information. The outcomes revealed several behaviours associated with suicide, leading to an effective degree of safety control by the rail authority and transport police (Mackenzie *et al.*, 2018).

Gelders *et al.,* (2007) targeted an improvement in communication performance between railway staff and customers across the Belgian railway network. This brought a long-term benefit for the company which was able to precisely enhance its performance and understand customer expectations in details. The qualitative research involved an in-depth interview with a total of 11 persons, including internal staff and external customers with some relation with the Belgian railway system. Consequently, the positive impacts of a counter-balanced communication performance on corporate reputation and brand equity are examined in order to ascertain the mediating function of business credibility and trust in the company (Gelders *et al.*, 2007).

4.3 Results and discussion

Within this chapter, the qualitative analysis method has been adopted to examine the productivity and punctuality KPIs. The analysis of productivity is reviewed by network through six criteria of resource management, while the analysis for the punctuality factor is also separately reviewed by country.

4.3.1 An analysis of productivity results

4.3.1.1 CR network

The CR network has operated the world's largest network, currently covering 37,900 km across China. Therefore, resource management has played an essential role for the company. Regarding the sales and marketing section, CR has not offered any discount on tickets for foreign traveller and non-adult groups. In terms of technology development, CR has established a national high-speed train technology innovation centre, which enables the firm to carry out extensive scientific and technical research initiatives.

Regarding human resources and staff benefits, CR has established a strategy plan and an annual talent training programme to increase its innovativeness and efficacy in nurturing talents. In 2020, approximately 275,000 employees attended workshops or training courses provided by the company. However, other benefits for staff and their families have not been mentioned in public.

CR has claimed that they strictly follow both national (Xi Jinping's ecological civilisation) and international (Paris Agreement) environmental policies. The company has discharged low amounts of waste gas, SO_2, and hazardous waste and has reduced its environmental impact. Lastly, CR's financial status shows slight decreases in its cash and bank balance; on the other hand, the company has greatly improved its non-current asset value from 383,572,485,000 to 392,380,368,000 Yuan from 2019 to 2020 (CRRC, 2020).

4.3.1.2 SNCF network

Regarding sales and marketing development, SNCF in France has not provided any special tickets or discounts for foreign and non-adult passengers. However, SNCF has launched a railcard that offers discounts of at least 25% for passenger who travel within the country. The railcard can reduce the cost of international SNCF train tickets across EU countries.

SNCF provides a variety of convenient services, including Ouigo (conventional rail) and TGV services. Delaplace and Dobruszkes (2015) compared low-cost airline, Ouigo, and TGV services. The TGV service offers a total of 510 seats, with two classes, and a buffet car. The service has supported passenger demand with a mix of trunk routes and inter-regional services. The SNCF sales and marketing section offers various methods to buy tickets, such as online booking, self-booking via mobile phone, and booking through agencies. Moreover, SNCF had earlier allowed passengers to use e-tickets and self-printed tickets (Delaplace and Dobruszkes, 2015). In terms of technology development, the TGV technology has been acquired by other countries and has become a role model for Korail's service.

SNCF collaborates with academic partners for training in technical skills for its staff. SCNF has developed a doctoral training programme via the Industrial Research Training Agreement under the National Association for Research and Technology. The collaboration programme enables staff to directly connect with university research centres, leading to the sharing of technology and innovation for future projects. For this reason, 81.7% of SNCF staff have enrolled on at least one training course.

Regarding CO_2 emissions, SNCF has followed the global target of reducing CO_2 in the atmosphere. SNCF has reduced energy consumption from 17.899 GWh in 2019 to 14,069 GWh in 2020, bringing a reduction in GHGs emission from 3,349 ktCO_2 to 2,556 ktCO_2. Moreover, SNCF has planned to launch the Dual-mode hybrid train from 2020. The new train is expected to reduce by at least 20% total energy consumption and pollution compared with the current train. On the other hand, SNCF has shown an uncertain financial status. The trend in the company's revenue shows an apparent decrease from 35,120 to 29,975 million euros from 2019 to 2020 (SNCF, 2019; 2020).

4.3.1.3 JR Central network

The analysis of the Shinkansen network's productivity illustrates that the rail authority has met all the requirements. JR Central has launched the 'JR Pass', which is a joint ticket with six companies in the JR group, for foreigners to travel across Japan by rail. Customers can use any standard car with the JR pass, which is available in packages of 7, 14, and 21 days (Japan Rail Pass, 2021). Liu and Chang (2019) have indicated that JR rail passes are the most cost-effective way to travel across Japan via public transportation. As a result, passenger identification for JR passes has developed into a common and widely used smart-card-based application (Liu and Chang, 2019). In addition, the Shinkansen service promotes online reservations called 'express reservations', with discounts for passengers who use the Shinkansen frequently.

In terms of technology development, JR Central is deeply concerned with innovation in order to provide a high-quality service to passengers. Movable platform fences have been installed to prevent customers from falling onto the rail track. Moreover, the fence can be removed for wheel chair users to allow seamless movement between the platform and the rail cars. Another impressive innovation is the natural disaster detection system, which has been gradually developed to ensure safety and

Figure 4.3 A movable platform fence on the Tokaido Shinkansen platform in Tokyo (The Japan Times, 2021)

increase service reliability. Many natural disasters have struck Japan, most notably massive earthquakes. As a result, the company has continued to innovate, such as the introduction of Maglev trains and the use of braking distance.

Regarding service development, the company has followed passenger demands and prepared a suitable number of trains for service. This can be confirmed by the growth in the total number of trains per day from 231 to 378 during the period 1987-2019. In terms of environmental impact, JR Central created the 'N700A' Shinkansen model, which consumes and emits less than the previous model (Series 700). When compared to 1990, energy consumption by rail cars has decreased by 33%. By comparison with airline services, the Shinkansen consumes eight times less energy and has 12 times fewer emissions. This great accomplishment demonstrates true accountability in terms of the global environmental goal.

With respect to human resource development, the company has established the Komaki research centre as an official training centre to develop human resources. According to the official report of JR Central, the training programme is designed to develop staff capabilities, particularly in the areas of technology, innovation, and safety. Finally, the financial situation has improved over the last five years (JR Central, 2020, 2019, and 2017).

4.3.1.4 Korail network

Korail also shows a high level of efficiency in terms of productivity and management. This research finds that Korail has distinctive technologies across its network. Moreover, the network has launched the 'Rail+Win-Win Funding System' to raise funds for a railroad technology commercialisation initiative. This campaign encourages SMEs, who have outstanding technology, to suggest new products, projects, and processes. Additionally, Korail's railway technology is acknowledged as outstanding, surpassing that of other international railway organisations. Korail's technology has been promoted and has become a model for overseas HSR projects. Also, Korail provides special tickets (i.e., family tickets) and discounted tickets for disabled, foreign traveller and non-adult groups (Jung and Yoo, 2014).

Korail has increased its service levels by improving the convenience provided for its passengers on lines to remote areas. By following passenger feedback, the company plans to launch new unique tours, and develop low-cost trains to remote areas. Furthermore, in response to passenger demand, Korail has increased KTX service on weekdays. From the environmental perspective, Korail has obtained 'low carbon product certification' for the ITX-Saemaeul Seoul-Busan, which is an intercity express train service. Moreover, Korail has placed the environmental perspective within its social value framework. The company is deeply concerned with its environmental impacts on society, especially in terms of dust pollution. Moreover, Korail has shown its environmental awareness following the Paris Agreement and the sustainability development goals (SDGs), particularly on climate change, by launching its 'renewable energy 2030' policies. As a result, a reduction of 13.9% in GHGs was achieved during the 2018-2019.

Regarding HR development, Korail has won a prize for developing HR from the Human Resource Development Association of Korea. Also, Korail mentions that none of its staff complains about their roles. Moreover, the firm promotes an organisational culture that enables employees to maintain a healthy balance between work and family life. Regarding its financial performance, Korail has performed well in the last five years, showing a good financial health status (Korail Sustainability Report, 2019).

4.3.1.5 Renfe network

The Renfe network's area of business area is widespread both nationally and internationally. The company is well known for advanced technology. Thus, the joint HSR projects have been rolled out in many countries, including the USA (Texas) and Saudi Arabia. Renfe has gradually developed its services and has a level of customer complaints on its AVE service of less than three per 1,000 passengers. However, there are no special tickets or discounts for foreign and non-adult passengers.

Regarding the environmental perspective, the company has set a target to reduce the environmental impact from its activities, which has also led the company to achieve sustainability goals. Renfe has improved its working environment to limit environmental effects by assisting relevant businesses to reduce impacts on surrounding nature, giving suggestions for optimisation and, in any event, strictly adhering to current ecological protection measures. Additionally, the company has reduced the use of poisonous, polluting or dangerous goods or products, replacing them with those that are less aggressive towards the natural environment. For this reason, Renfe had reduced CO_2 emissions annually by 73,519 tons on average during the period 2016-2018, which is 47.61% higher than its emissions in 1990.

In terms of human resource development, Renfe has offered proper training opportunities, provided precise information, and raised awareness among all staff. Staff now have more benefits, such as flexible working hours, discounted tickets, work insurance, and other social security benefits. Furthermore, Renfe is intensely

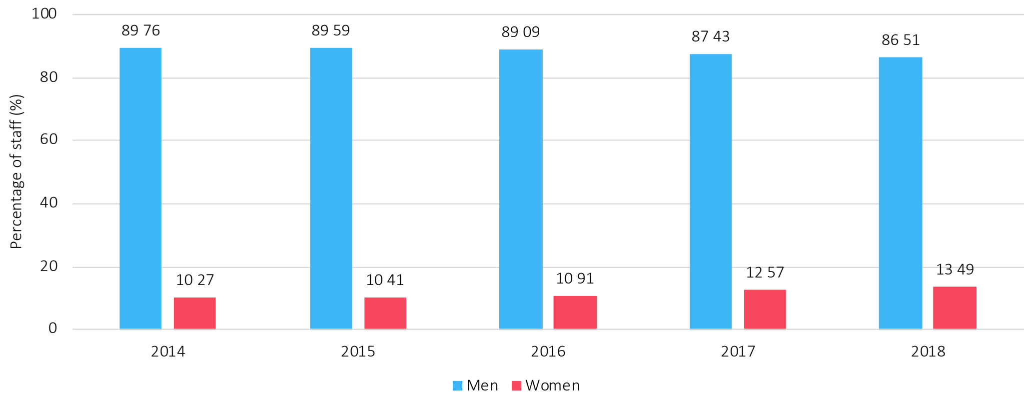

Figure 4.4 The proportion of male and female staff in Renfe during 2014-2018 (Source: Renfe, 2018)

concerned with gender equality by managing the company's structure and allocating job positions to women. As seen in Figure 4.4, the trend in female staff in the company been slightly upward. Female staff are mostly assigned to administration, commercial, and management positions. Moreover, the company offers 222 job positions to disabled people. Lastly, Renfe has continually received subsidies from the local government, and this research finds that the company has had a good financial status in the last five years (Renfe, 2018).

4.3.2 An analysis of punctuality results

This analysis has been conducted on long-term evidence regarding punctuality found in HSR company reports, sustainability reports, and other related documents. There is apparent limitation in terms of data restrictions in the Chinese, French, and Spanish company's reports. However, this research has collected sufficiently reliable information from other publications.

First, Japan's HSR network has impressively revealed a sustainable development plan through the company report. As mentioned in Chapter 2, an analysis of punctuality rate has been recorded in JR Central's reports during 2015-2020. For

Table 4.2 Comparison of train delay for JR Central (Source: JR Central, 2021)

Punctuality rate	Year					
	2015	2016	2017	2018	2019	2020
Delay (mins)	0.2	0.4	0.7	0.9	0.2	0.2
Delay (second)	12	24	42	54	12	12
Delay (mins)	0.2	0.4	0.7	0.9	0.2	0.2
Delay (second)	12	24	42	54	12	12

example, the Tokaido Shinkansen's train delay figures (minutes), as shown in Table 4.2, are within an acceptable range of 0.2 to 0.9 minutes per train. In other words, JR's train delay is in the range 12 to 54 minutes per train or 24 minutes on average.

Second, the Korail sustainability report reviews the punctuality rate of both KTX (HSR) and regular rail services. KTX has a high operational performance because the punctuality rate is more than 99.75% during the period 2016-2019. Meanwhile, the punctuality rate of the standard train service was at least 98.14% within the same period, as shown in Table 4.3.

In addition, Lee (2017) has provided a detailed analysis of the KTX network. It is important to note that there is plenty of evidence that strongly points to a punctuality rate of at least 97% across the KTX network (Lee, 2017). Another research recorded KTX's cancellation and punctuality rates during April 2004. The study was conducted based on 126 daily round trips on the KTX network; the research found no train cancellations and a 97.8% punctuality rate. Also, a comparison with the three

Table 4.3 Comparison of train delay for KTX (Source: KTX, 2019)

Punctuality rate	Year			
	2016	2017	2018	2019
Punctuality rate of HSR train operation (%)	100	99.76	99.79	99.8
Punctuality rate of regular train operation (%)	99.87	98.14	99.30	99.50

following months showed rates of 98.5%, 98.8%, and 98.8%, respectively (Kim, 2005).

Next, the delay and punctuality information for the CR network is not mentioned in official company reports. As a result, the evaluation of the CR network's punctuality is based on other reliable publications. The Chinese rail networks, which operate over a large area, require a high degree of punctuality in order to reduce delays to other trains. Research was conducted to record train delays at Guangzhou and Changsha stations, which are significant HSR hubs, from March to November 2015. It was found that the total delay at Guangzhou and Changsha was 77,802 and 54,327 minutes, respectively (Yang *et al.,* 2019).

Similarly, some scholar investigated train delays on the Wuhan-Guangzhou HSR network used a statistical method, applying the Weibull distribution to estimate the occurrence of delays (Wen *et al.,* 2017). As a result, the study revealed a 98.5% punctuality rate across the network.

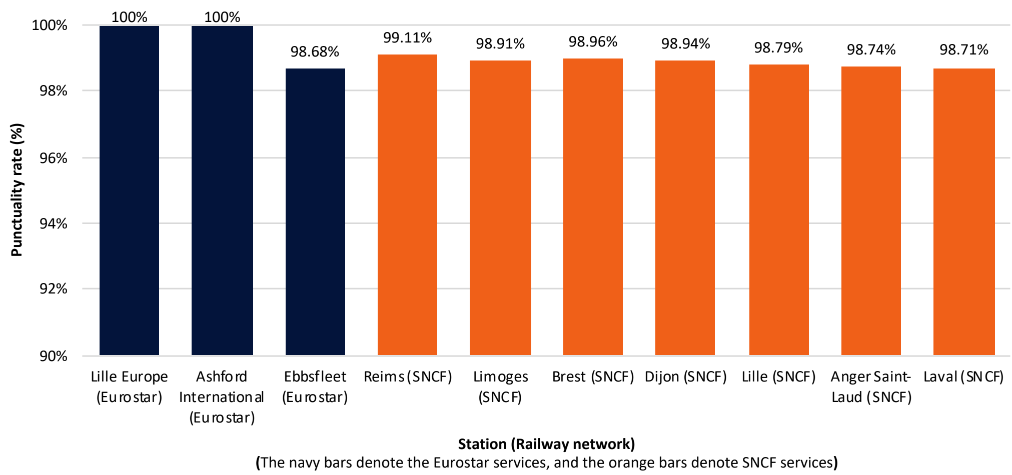

Figure 4.5 The comparison on the most punctuality of station and HSR network (Source: Statista, 2016)

Also, in a research focusing on network disruption between east China and the Hong Kong corridor during the COVID-19 pandemic, Jiao *et al.,* (2020) mentioned that massive disruption always occurs between 10.00 a.m. and 3.00 p.m., reducing overall punctuality by 14.5%.

The SNCF and Renfe networks' delay information has not been mentioned in the official company reports. Therefore, this information is collected from publications and other reliable sources such as annual reports. Figure 4.5 depicts a comparison of the most punctual trains in European countries in 2016. Seven of the destinations serviced by SNCF show slight delays: Reim, Limoges, Brest, Dijon, Lille, Anger Saint-Laud, and Laval (Statista, 2016). Another publication has stated that the French HSR service's (LGV) punctuality rate is at least 93% (Glickenstein, 2015).

Meanwhile, the AVE punctuality rates for services on the Renfe network have been recorded by Pisonero (2010). The study reveals the punctuality rates of four AVE routes between 2007 and 2010: Madrid-Sevilla, Madrid-Zaragoza, Madrid-Barcelona, and Madrid-Malaga. The punctuality rate of the Renfe network is at least 97.8%, as shown in Figure 4.6.

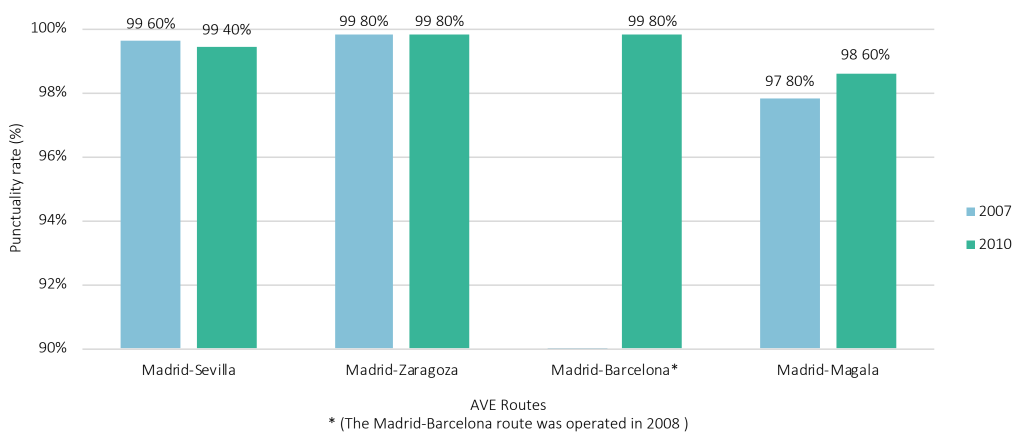

Figure 4.6 Comparison of punctuality rates for AVE routes (Source: Pisonero, 2010)

4.4 Conclusions

Managing an organisation's resources and maintaining a punctual of services have become critical successes in the rapid expansion of HSR demand. The lack of concern about these factors has led to a negative impact on the satisfaction of a company's customers and stakeholders, and on its safety levels and operating profit.

Regarding the productivity KPI, six sub-indicators have been applied to measure performance regarding railway resource management. The JR Central and Korail networks show the best performance, meeting all criteria. In addition, the company pays profound attention to technology and innovation development due to offering high-quality service. Also, the networks launched special tickets and discounts. As a result, it enhances both Japanese and foreign passengers' satisfaction levels. While the Renfe network also perform at a high level. On the other hand, the Renfe should improve technology and sales and marketing developments. For long-term development, rail authorities should offer special tickets and discounts to foreign travellers and non-adult groups, which would enhance accessibility rates.

With respect to the punctuality KPI, the delay and punctuality rates have become necessary indicators. By using a qualitative approach, this chapter has found that all of the selected HSR authorities are above a standard of at least 95% punctuality, and show a small number of train cancellations. Note that punctuality is determined by an average on-time arrival rate of at least 95% of the scheduled arrival time. However, the train cancellation rate should not exceed 5% of all trains in service, which is an acceptable cancellation rate in severe weather conditions (Xia *et al.,* 2013).

4.5 Chapter summary

This chapter has examined the productivity and punctuality factors. First, productivity has been split into six categories: sales and marketing development, technology development, service development, environmental development, human resource development, and financial overview. All of the productivity factors reflect railway companies' capabilities in resource management, which are linked to long-term development in technology, innovation, and financial benefits.

Tables 4.4 and 4.5 illustrate the results for the productivity and punctuality KPIs. The benchmarking results for productivity clearly show that the JR Central and Korail networks are the leader in resource management, with policies in place to meet all six criteria. Whereas, Renfe also illustrates high performance. The thesis suggests that the forthcoming HSR should follow all the productivity criteria to reach the best performance. It helps the HSR company better manage its limited resources. Also, communication with their customers is essential to gain trustworthiness.

Another KPI is punctuality, which measures the likelihood of train delays and cancellations. The thesis suggests that the average punctuality rate should be at least 95% of the actual arrival time. However, the train cancellation rate should be no more than 5% of total trains in operation, which is an acceptable cancellation rate under bad weather conditions. The results indicate that all of the selected networks have met these requirements.

Table 4.4 Summary for productivity KPI

Productivity (details)	Weight (%)	CR	SNCF	JR Central	Korail	Renfe
Sales and Marketing development						
Tickets and promotions for students & adults, and other special tickets	1.25	0	0.625	1.25	1.25	1.25
Tickets for foreign travellers	1.25	0	0	1.25	1.25	0
Technology development						
Reduced time in service / Increase train speed profiles	1.25	1.25	0	1.25	1.25	0
Other innovations (e.g. movable fencing for increasing passenger flow, ticket application methods)	1.25	1.25	1.25	1.25	1.25	1.25
Service development						
More trains in service	1.25	0.625	1.25	1.25	1.25	1.25
Environmental development						
Use of green energy or new train cars; environmental perspective	1.25	1.25	1.25	1.25	1.25	1.25
Human Resource development						
Staff training and other staff benefits	1.25	0.625	1.25	1.25	1.25	1.25
Financial overview						
Financial status in prior five years; liquidity status	1.25	1.25	0.625	1.25	1.25	1.25
Total	10	6.25	6.25	10	10	7.5

Table 4.5 Summary for punctuality KPI

Punctuality	Weight (%)	CR	SNCF	JR Central	Korail	Renfe
Delay (Punctuality at least 95%)	7.5	7.5	7.5	7.5	7.5	7.5
Train cancellation	7.5	7.5	7.5	7.5	7.5	7.5
Total	15	15	15	15	15	15

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CHAPTER 5

RISK AND UNCERTAINTY

This chapter presents an evaluation of the cause and effect of railway accidents, the applications of Bayesian statistics, uncertainties in risk assessment, and risk classification. This chapter leads to an in-depth understanding into the fundamentals of railway risk and uncertainty. The review of risk assessment models is illustrated to determine the pros and cons of existing models. Then, the development of a novel risk assessment model using Python programming is shown in this chapter. This thesis also establishes the Decision tree (DT) and Petri-net (PT) models to evaluate risk levels. It enriches benefits of benchmarking safety performance across the railway networks.

5.1 Introduction

Railway networks are required to provide passengers and other related people with superior transport services and safety. Although the railway industry has the lowest accident rate in comparison with other modes of transport, the EU-27 study revealed that more than 1,200 railway accidents happened across the EU in 2010 and the number of fatalities was reduced to 853 in 2018. (ERA, 2018, EC, 2020). Significant decreases in the number of accidents have prompted rail authorities' efforts to achieve zero accidents on all rail networks worldwide.

Uncertainties are well-known to have a great importance in railway risk control and safety procedures. The researchers obtained long-term accident data sets from railway authorities, which included the causes and consequences of each event over a 20-year period. The thesis examines primary data sources to ascertain the influence of railway incidents on the number of fatalities and injuries. Using a modified Bayesian technique, this thesis builds a novel Python-based model for predicting railway accident rates. A significant benefit of this new customised model is a better understanding into how incident unpredictability propagates, which offers better insight into the possible accident rate.

A major concern about the unified safety performance assessment is that the railroads have established their own safety rules and performance criteria. Rail organisations often assert that they operate a low-risk network. Nevertheless, a systemic bias may exist as a result of the imbalanced safety performance standards employed in a specific railway system or even within an operating business. A novel approach to this issue is to establishes a new framework for benchmarking balanced safety performance across railway networks using decision tree (DT) and Petri-nets (PT) frameworks. The result proposes new standardisation criteria based on four distinct risk categories. This study's unique contribution has a wide variety of applications in terms of comparing risk performance across all HSR systems. Additionally, this research emphasises new risk prediction and benchmarking models capable of measuring uncertainties and balancing performance requirements for systems. Both models will result in the sustainable development of future rail networks, assisting rail authorities in developing risk management plans and assessing the implications of current rail policies. This strategy will improve safety, which is critical for social values, which are a pillar of sustainable development.

5.2 Background

5.2.1 Cause and consequences of railroad accidents currently in existence

The rapid development of HSR technology has resulted in a drop in railway accidents during the last 10 years. According to the EU-27 report, there were 666 railway accidents across European nations in 2018, with 748 people suffering serious injuries. Nevertheless, the number of hospitalised passengers decreased by 30% from 2010 levels (ERA, 2018). Similarly, London Underground reports that the number of incidents somewhat dropped during a five-year period from 2013 to 2018, while the total number of accidents decreased by 30.83% (ORR, 2019).

When compared with other modes of transportation, research indicates that railway services have the fewest passenger wounds and deaths. According to the European Transport Safety Council's (ETSC) research, railway deaths occur at a rate of just 0.035 individuals per 100 million person-kilometres (pkm). By comparison, the overall death rate from road accidents (i.e., motorcycle, foot, bicycle, automobile, bus, and coach) is 0.95 individuals per 100 million pkm, as seen in Figure 5.1 (ETSC, 2003). Another research notes that 75% of railway accidents in the EU are caused by trespass; 15% of these occur at level crossings (UIC, 2018).

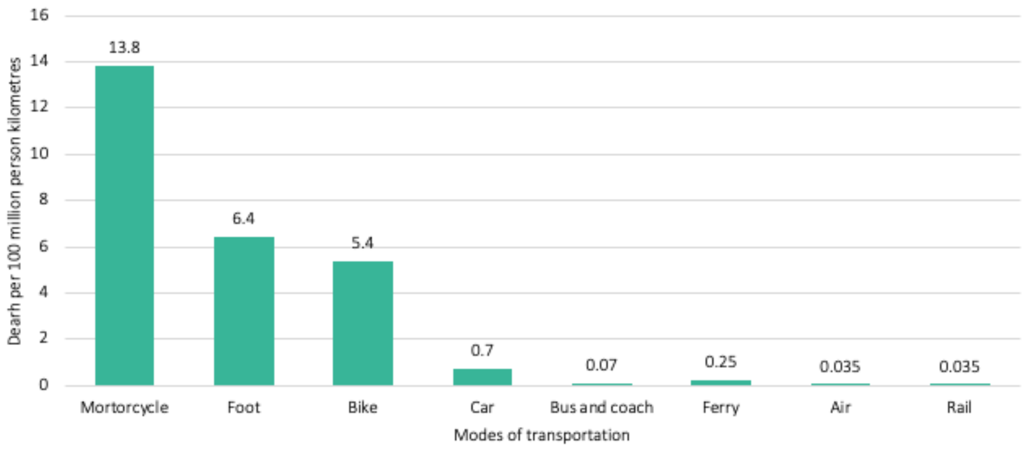

Figure 5.1 Comparison of fatality rates throughout the EU transportation (unit: 100 million pkm) (Source: ETSC, 2003)

As a result, the US National Safety Council determined that rail has a minimal risk of injury and death. According to Figure 5.2, the mortality rate for heavy duty vehicles is 0.01-0.12 fatalities per 100 million passenger-miles (pm), in comparison to the rate for light vehicle cars is 0.46-0.66 fatalities per 100 million pm (National Safety Council, 2020).

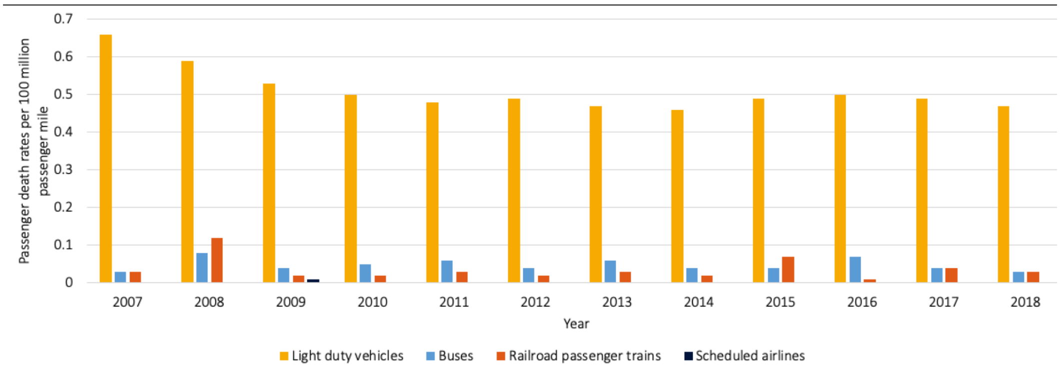

Figure 5.2 Comparison of death rates throughout the EU for motorcycles, pedestrians, cyclists, cars, buses & coaches, ferries, air and rail (unit: 100 million pm) (Source: National Safety Council, 2020)

In summary, the number of railway accidents has been down, with railway services registering a low rate of injuries and deaths compared to other types of transportation. However, the goal of achieving zero accidents and minimising damage are critical motivation of railway organisations.

5.2.2 The use of Bayesian statistics in the study of railway accidents

Bayesian statistics (also known as Bayesian network, Bayes belief network, BN) has been developed to compute conditional probability in complicated models. Fault tree analysis (FTA), event tree analysis (ETA), and failure mode effect analysis (FMEA) are examples of probability-based methodologies that have not been able to tackle this problem (Zhang *et al.*, 2014; Dindar *et al.*, 2018; Wang *et al.*, 2018). The BN model is extensively used in railway risk assessment, safety analysis, and other risk assessments. The model can be used to forecast the probability of accident causes based on previous experience using current data. Multiple dangers and uncertainties may be entered into BN, making it suited for sophisticated causes of railway accidents. The results of the BN model combined with railway accidents demonstrate a greater level of risk assessment accuracy than in other models.

Some scholars modelled railway incidents in the United Kingdom using a Bayesian network in conjunction with risk evaluation. The research highlights the problem of signals passing into danger (SPAD), which occurs when trains illegally pass stop lights. The study findings have resulted in certain modifications to the driver training programmes offered by the UK railway sector in an attempt to reduce rail accidents (Marsh, 2004). Similarly, research is being conducted in the United Kingdom on three kinds of level crossings: railway-controlled, automated, and passive. The data indicates that, between the three types of level crossings, automated crossings have a greater accident rate than the other kinds of level crossings (Evans, 2011).

Additionally, BN has been used to examine train derailments induced by severe weather at railway turnouts (RTs) that are crucial components of railway infrastructure. The findings result in enhanced railway operations under unpredictable climatic circumstances (Dindar *et al*., 2018). Similarly, the model for predicting RT failures has been launched, which is impacted by meteorological conditions. Furthermore, the BN model was used in the study to assess the effect of the RTs in harsh weather. The data enables appropriate RT maintenance choices, which can result in considerable cost savings and improved safety efficiency (Wang *et al*., 2017). Additionally, the BN was combined to follow the state of RTs, and the method is capable of precisely accounting for track deterioration (Wang *et al*., 2018).

5.2.3 Uncertainties in risk assessment for railway

Safety risk assessment is a critical factor in railway operations, and uncertainty analysis for railway systems is critical in rare instances. Railway systems can experience uncertainty as a result of both internal and external occurrences. Internal events, for instance, occur in the train's cars or systems, whereas external events arise as a result of external forces, such as natural catastrophes. Fukuoka (1999) notes that assessing railway risk is difficult due to the low frequency of accidents. This demonstrates the issue that a lack of knowledge (or a lack of data) significantly impairs railway operators' ability to estimate risk and uncertainty within railway networks.

Alternatively, several numerical methods have been devised to address the issue of insufficient and trustworthy data. de Miguel *et al*., (2019) investigates uncertainties at railway turnouts using the outcome of a Monte Carlo simulation (MCS). Ultimately, this strategy generates complete sensitivity indices. In Austria, a life cycle analysis of rail and road level crossings are conducted with the goal of optimising upkeep costs (Grossberger *et al*., 2017). Although the research encountered complications in terms of time and parameter circumstances, the MCS was used to build a probabilistic situation and evaluate uncertainty. Another rail lifespan evaluation resulted in the decision to renew maintenance of support infrastructure. Such the research showed that rail track maintenance costs have risen considerably. Hence, the MCS was used to quantify the uncertainty associated with the track lifespan (Vandoorne and Gräbe, 2018). Similarly, an MCS model was used to produce probability distributions for a study of dangers in railway tunnels. According to this study, probability distributions provided realistic representations that were useful for railway risk evaluation (Vanorio and Mera, 2012).

5.2.4 Classification of railway accidents

To identify the risk of the railway network, this thesis categorises each risk based on the underlying cause of accidents. Understanding the impacts and fundamental causes

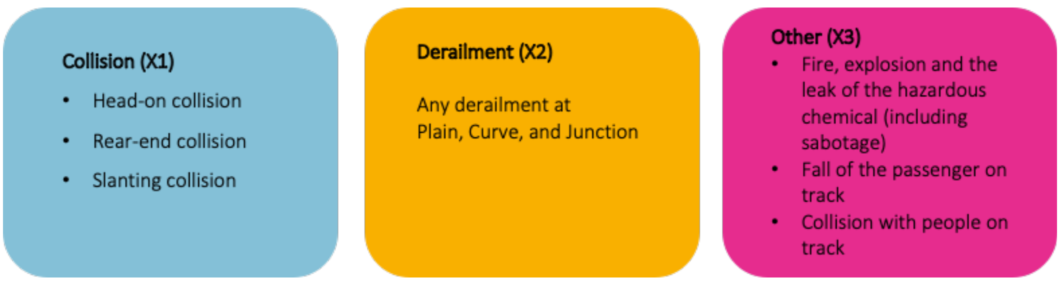

Figure 5.3 The categorisation of accident causes including collision, derailment, and other

of accidents is critical because it contributes to the sustainability of rail network safety rules. The obtained data is divided into three categories depending on the impacts of an accident on the train, which include (i) collision, (ii) derailment, and (iii) additional impacts. As illustrated in Figure 5.3, the ‘other impacts’ on trains are mostly caused by human.

Additionally, seven categories of causes of accidents exist: (i) driver error, (ii) signal operator error, (iii) infrastructure failure, (iv) equipment failure, (v) human error, (vi) natural causes and (vii) contributory factors. With respect to the human error, this means the fault of staff other than drivers and signal operators. Likewise, as seen in Table 5.1, the sub-causes of accidents are categorised into seven categories.

Table 5.1 Summary of types of accident, sub-causes of accidents

Cause of accident	Sub-cause of accident
Y1: Driver's error	Inadequate release of the hand brake Failure to maintain control of the vehicle's speed
Y2: Signalmen's error	Failure of signal equipment Disabling a communication device
Y3: Infrastructure failure	Geometry of the track Equipment such as frogs, switches, and track Failure in design of bridge and construction Joint bar for rails Roadbed
Y4: Equipment failure	Journal bearings and axels Coupler and ventilation system Doors Mechanical and electrical malfunctions Locomotives Wheels Body Brake On flatcar, trailer or container
Y5: Human error (Exclude Signalmen's and driver's error)	Cab signals Physical condition of workers Signals via flagging, fixed, hand, and radio General switching rules Authority responsible for the main track - inability to halt the Train in a safe manner Miscellaneous Train speed Switches Train management or train make-up

Cause of accident	Sub-cause of accident
Y6: Natural causes	On track: snow, ice, sludge, gravel, coal, and sand Tornado, torrential rain, and landslide Flooding and tsunami Dense fog, smog, or other substances that obscure visibility Extreme wind speed
Y7: Contribution factors	Trainload or overburdened vehicle Highway Tracking an object Vandalism or damage to the track

5.3 Model for risk assessment

Risk analysis is the method for determining the danger characteristics of railway systems with the goal of eliminating or minimising the risk of railway accidents. Numerous risk assessment models have been developed in connection with railway accidents.

In the United Kingdom, risk safety models developed by the RSSB are the gold standard for evaluating the degree of safety and damage on the country's main routes. The unit of measurement is called 'fatalities and weighted injuries' (FWI), with one FWI equal to one fatality, ten major injuries, 200 notifiable minor bruises, or 1,000 non-reportable minor bruises (Gilmartin, 2010). Using the FWI unit, some researchers also analyse railway-related risks on Slovak train systems. Such a study was primarily concerned with the number of casualties (Leitner, 2017).

In contrast, some research integrated risk assessment models into other variables such as vulnerability, capacity to cope, and hazard frequency. For instance, in the evaluation of risk corridors for Canadian railways, hazard and risk are integrated. Both aspects were critical in evaluating without relying on injury and fatality statistics. The reason for this were because the majority of trains that go through these routes are freight trains. As a result, the danger to passengers and crew should be smaller than that associated with passenger trains. Business issues can also contribute to railway network risk. Xue *et al.,* (2020) investigated the commercial aspects at play in Chinese HSR risk coupling model. The study examined the flaws in innovation, investment, and administration, concluding that isolated risk categories may result in accidents.

Additionally, big data analytics is used to uncover problems and analyse infrastructure risks (Li *et al.,* 2010). Jamshidi *et al*., (2017) derive posterior distributions for risk models using the MCS approach in Bayesian data analysis. This model is capable of accurately estimating failure due to infrastructure flaws, allowing for the long-term prevention of railway accidents.

On the contrary, numerous risk assessment techniques (i.e., Bayesian statistic, DT, ETA, FTA, Fuzzy logic, Human factor analysis, PT, Risk evaluation) have been applied to risk assessment models. Table 5.2 summarises the risk analysis methods used in previous studies.

Table 5.2 An overview of notable railway risk assessment models, authors, and research gaps

Authors	Risk models / Risk assessment model	Gaps
Leitner (2017), Gilmartin (2010)	The key criteria for this research are 'fatalities and weighted injuries.' The FWI is defined as one mortality, 10 serious injuries, 200 reportable small injuries, or 1,000 unreported minor injuries.	Using the FWI index may be incompatible with cross-country benchmarking. For instance, incidents with fewer injuries or deaths cannot be quantified.
Alexander (2012), Westerman (2020)	$R = \frac{H \times V}{C}$ where 'R' means risk, 'H' means hazards, 'V' = mean vulnerability, 'C' means capacity to adapt to changes diminishes.	The paradigm is applicable to both natural and human-caused disasters. While natural disasters are a factor in railway accidents, the framework cannot account for all possible causes.
CsChe (2017)	Risk = Hazard × Vulnerability Hazard = The probability of a derailment occurring on a single mile section is determined by incident history, infrastructure, and operating procedures. Vulnerability = The monetary value of exposure to physical conditions.	Only danger and vulnerability factors are considered in the model. It is used to measure the risk posed by freight trains. The model is unsuitable for benchmarking passenger trains or for other passenger-related effects.
Xue *et al.* (2020)	$\varepsilon R = \frac{(LR \times WR)}{\sum(LR \times WR)}$ $\mathrm{CE(A-B)} = \frac{(X \parallel t = j - XCE(A-B) \parallel t = j)}{X \parallel t = j}$ CE (A − B) is the result of the interaction of risk factors A and B The overall risk level at the end of the jth year is given by X‖t = j, Risk factor A and B have been removed from the equation, such that XCE (A − B) ‖t = j reflects the overall risk level at the end of the j^{th} year after eliminating their coupling impact.	This research is particularly interested in the technical, capital, and managerial aspects of railway risk. Additionally, the paper explores the economic consequences and organisational issues in detail.
Jamshidi (2017)	$\pi\,(\theta\,\vert\Delta L) = \frac{f\,(\Delta L\;\theta)\pi_0\,(\theta)}{f(\theta)} \propto$ $f\,(\Delta L\vert\theta)\pi_0\,(\theta)\;\pi_0\,(\theta) = probability\ density\ function$ $f\,(\Delta L\vert\theta)$ = likelihood from statistical observation $\pi = posterior\ distribution$	This research employs posterior distribution techniques to forecast railway infrastructure failures or fractures. An appropriate technique is posterior distribution.

According to the assessment of the literature, previous studies were mostly conducted to improve railway network performance. Dindar *et al*., (2020) made recommendations to railway operators about how to operate in the event of extreme weather. Their study focused on improving railway sector dependability through the application of fuzzy logic and Bayesian networks (Dindar *et al.,* 2020). Certain studied apply the MCS, DT, and ETA models to assess the hazards associated with human error, which includes train staff, passengers, and road users (Zhou and Lei, 2020; Khalid *et al.,* 2019; Vileiniskis *et al.,* 2017). Additionally, DT and other techniques were used to resolve infrastructure and maintenance issues on train networks (Zhou *et al.,* 2020; Eisenberger and Fink, 2017; Jia *et al.,* 2011).

In terms of safety policies, several studies advocated for policies that incorporate measurement to aid in the prevention of railway accidents. The analytical hierarchy process (AHP) was offered, as are the maximum absolute weighted residual (MAWR) and maximum entropy method (MEM) methods for calculating the harmful failure rate of equipment (Liu *et al.*, 2020). Song and Schnieder (2018) proposed employing the FTA and PT approaches to reduce head-to-tail collisions. The DT approach was used to build the driving model, which assessed drivers on a scale from low risk to high risk (Ochiai *et al.,* 2019). As a result, the danger of human mistakes has been diminished. A similar approach has been obtained by utilising subtree models in conjunction with high-demand railway. These findings indicated that safety performance may be improved by up to 48.05% (Chen *et al.,* 2018). Numerous authors have tackled the subject of accident analysis. In quantitative investigations, fuzzy FTA has been used to forecast railway accidents on HSR networks. The results demonstrate that it was beneficial for decision-making when there was an element of incompleteness or complexity (Liu *et al.,* 2015). Also, the railway accidents caused by passing warning signs have focused on using risk variables to reduce incident costs (Kyriakidis *et al.,* 2019; Li *et al.,* 2019).

Similarly, Zheng *et al.,* (2016) used historical accident data to anticipate profit decisions in rare instances. Additionally, FT, fuzzy belief models, and a variety of other modelling techniques have been used to estimate freight train risk. The findings may result in an improvement in logistical performance when it comes to harmful goods (Huang *et al.*, 2020; Huang *et al.*, 2021). Previous studies have concentrated only on the number of incidents, wounds, and deaths, as well as other contributing complications (vulnerability, hazard level). Additionally, many models cannot be used on different railway networks. As a result, this study employs novel risk assessment methods to compare railway networks. These novel models can be assessed as instruments for improving safety performance while avoiding the problem of information limitation.

Table 5.3 The summarisation of risk analysis in existing railway research

Author (s)	**DT**	**ETA**	**FT**	**PT**	**Risk evaluation**	**Human factor analysis**	**Others**
Szabó & Tarnai, 2000			✓				
Žarnay, 2004				✓			
Flammini *et al.,* 2008					✓		
Yildirim *et al.,* 2010				✓			
Jafarian & Rezvani, 2012			✓				
Iwata & Watanabe, 2010					✓		
Arai *et al.,* 2012					✓		
Yaghini *et al.,* 2013	✓						✓
Zhang *et al.,* 2014					✓		
Ma *et al.,* 2014			✓				✓
Yianni *et al.,* 2016				✓			
Giglio & Sacco, 2016				✓			
Lee *et al.,* 2016	✓						
Ruijters *et al.,* 2016			✓				
Dinmohammadi *et al,* 2016					✓		
Le *et al.,* 2017				✓			✓
Zhu & Wang, 2018	✓						
Song & Schnieder, 2018			✓	✓			
Chen *et al.,* 2018		✓					
Bukhsh *et al.,* 2019	✓						
Vorobyov *et al.,* 2019						✓	
Khalid *et al.*, 2019		✓					
Stoilova, 2020	✓						
Huang *et al.,* 2020			✓				
Rungskunroch *et al.,* 2021	✓			✓			✓

5.4 Research framework

Bayesian inferences are one method for resolving the information scarcity problem. This study compiles long-term secondary data sets on passenger train accidents from railway operators' official records. To begin, data collecting and purification techniques are necessary, with a particular emphasis on passenger rail incidents. The data purification method for railway accidents consists of three stages: removing incorrect data sets, matching public documentation from rail authorities, and rechecking missing data sets.

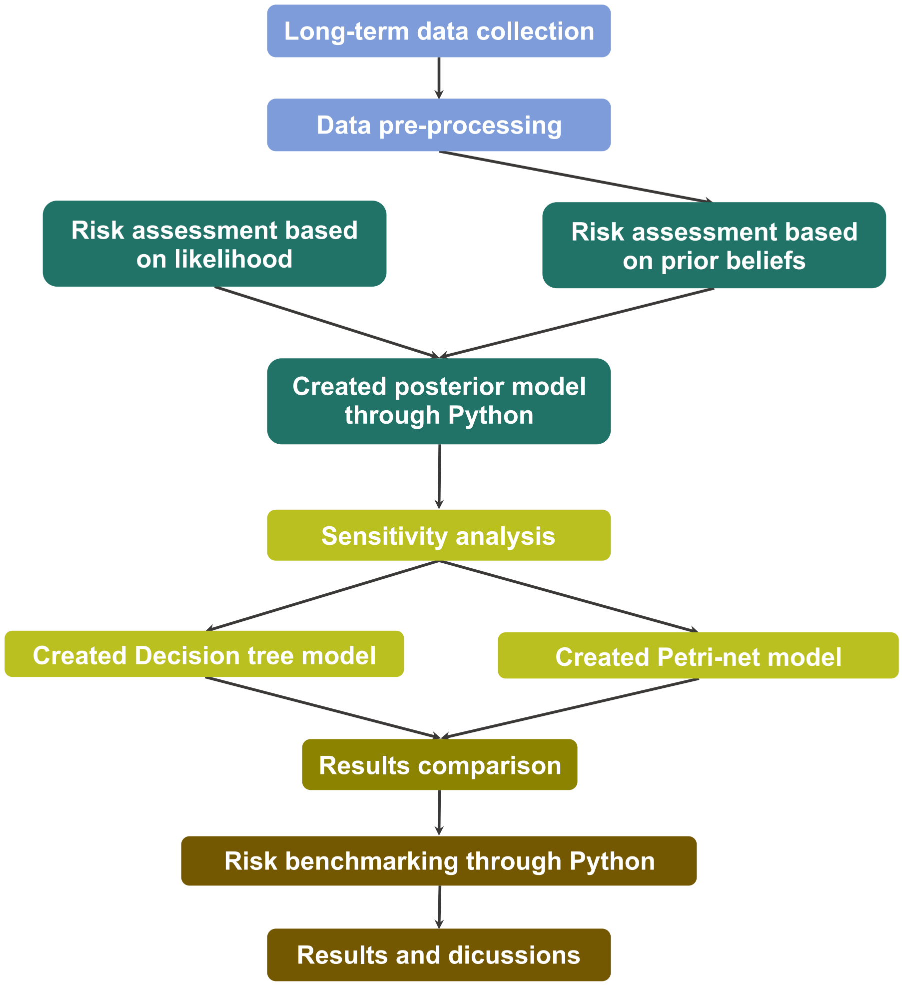

Figure 5.4 The framework of risk and uncertainty assessment

Bayesian statistics are used to conduct a risk assessment analysis. This stage is critical in estimating the likelihood of railway accidents. Determining the posterior probability of each consequence of a train following an accident is a critical factor. Uncertainties can be inferred from acquired data based on expert judgments, as such data is typically unclear. As previously stated, many types of accidents occur rarely and cannot be analysed without the use of mathematical models. As a result, the thesis offers posterior probability estimates for the events at this step.

Following that, the approach predicts the posterior probability for X1, X2, and X3 using a non-uniform distribution ($\propto$ = 4:4:1). This is because research indicates that the risk of adverse consequences following rail accidents is not uniform. Additionally, the study set the 'confidence interval' to 95%, which results in more exact predictions and interpretation outcomes than prior papers. Finally, risk levels are benchmarked for five railway networks. The data has been analysed using Python, and the DT and PT models are built based on the posterior likelihood of effects following an event, as well as the degree of injuries and fatalities. Additionally, a better knowledge of long-term risk and the uncertainty inherent in databases can eventually result in an increase in rail network safety.

5.5 Methodology

5.5.1 Availability of data

The data for this thesis has been adopted from official companies' report, government, and rail authority records. The study examines passenger rail incidents that happened during 2000 - 2019. This study includes 650 suitable data sets, which contain injury and mortality statistics.

5.5.2 A Bayesian network application

A Bayesian network has been constructed in this study to assist readers in comprehending the causes and effects of railway incidents in uncertain settings. This has resulted in a better understanding of railway accident causes and a reduction in casualties. (Heckerman *et al.,* 1995; Uusitalo, 2007).

The FRA (Federal of Railroad America) and other railway agencies provided a list of all possible reasons, as depicted in Tables 5.1 and 5.2 (FRA, 2019). As seen in Figure 5.5, the fundamental model establishes the link between (X) the consequences of accidents, (Y) the causes of accidents, and (Z) the sub-causes of accidents. It is possible to assert that ‘Z’ is conditionally reliant on ‘Y’ and ‘X’ (P(Z | X,Y)), whereas ‘Y’ is conditionally reliant on X (P (Y | X)). All variables beginning with the letter ‘X’ correspond to the impacts of railway accidents, with X1 referring to collisions, X2 to derailments, and X3 to other types of accidents.

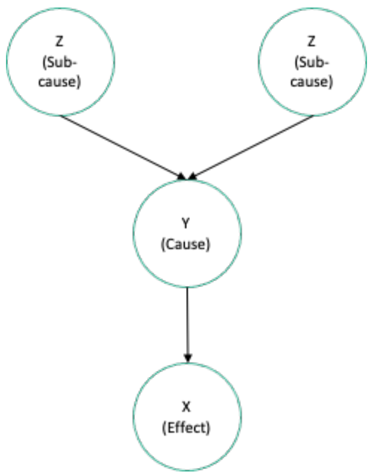

Figure 5.5 Overall Bayesian network framework for railway accidents

5.5.3 Theorem of Bayesian statistic

Bayesian statistics are probabilities that represent a degree of confidence or information about an occurrence, referred to as ‘prior knowledge’. It is a conditional probability distribution over two occurrences, X and Y. Additionally, as seen in equations 5.1 and 5.2, Bayes’ theorem may be reversed to determine the probability of a single occurrence (Briggs *et al.,* 2003; Sobradelo *et al.,* 2014).

$$P\,(X\,|\,Y) \quad \frac{P\,(Y\,|\,X)\,*\,P\,(X)}{P(Y)} \tag{5.1}$$

$$P\,(Y) \quad \frac{P\,(Y\,|\,X)\,*\,P\,(X)}{P(X\,|\,Y)} \tag{5.2}$$

Referring to Tables 5.1 and 5.2, the probability distribution of the consequences, X, provided the causes, Y, may be computed using equation 5.1. Alternatively, one may obtain the probability of the causes, Y, using equation 5.2. As a result, the aforementioned equations are used to deduce the underlying link among Tables 5.1 and 5.2. For instance, given the likelihood of a train derailing, X1, as a result of a driver’s mistake, Y1, Bayes’ theorem may be expressed as the following equations.

$$P\,(Train\ derailment\,|\,Driver's\ error) = \frac{P\,(Driver's\ error\,|\,Train\ derailment)\,\times\,P\,(Train\ derailment)}{P(Driver's\ error)} \tag{5.3}$$

$$P\,(\,Driver's\ error) \quad \frac{P\,(Driver's\ error\,|\,Train\ derailment)\,\times\,P\,(Train\ derailment)}{P\,(Train\ derailment\,|\,Driver's\ error)} \tag{5.4}$$

The likelihood of the cause of an accident may be computed by following the mathematical arguments for equations 5.3 and 5.4. Along with Bayes’ theorem, Bayesian inference is utilised. This is a kind of statistical reasoning in which the probability of a hypothesis is updated when new data and information becomes accessible (Payzan-Lenestour and Bossaerts, 2011; Dindar *et al.*, 2018). In particular, Bayesian inference is performed by (i) selecting a prior distribution, which is a likelihood function P(θ) expressing one's beliefs about a parameter prior to seeing any data, (ii) selecting a statistical model P(x) that reveals one's opinions about data x given parameter, and (iii) revising the opinions and computing the posterior distribution P(X) after observing data X. The posterior distribution may be expressed as follows using Bayes' theorem:

$$p\ (\theta|X) = \frac{p\ (\mathrm{X}|\theta)\ *p(\theta)}{p(X)} \tag{5.5}$$

Where $p\ (\theta|X)$ denotes the posterior distribution that conveys uncertainty after the prior distribution and data have been considered; $p\ (X|\theta)$ denotes the likelihood function; $p(\theta)$ denotes the datasets of prior knowledge; and $p(X)$ denotes the normalising constant, commonly known as the evidence. Figure 5.6 provides a summary of Bayesian inference.

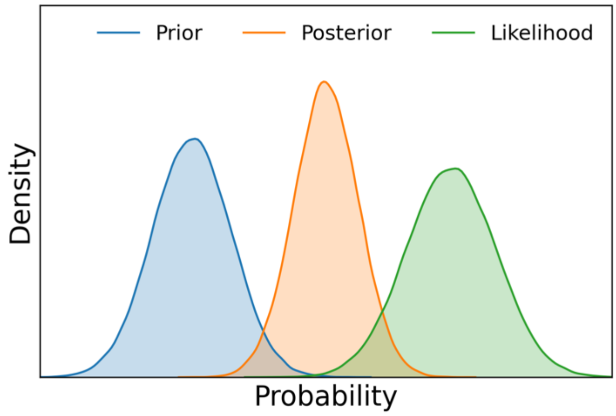

Figure 5.6 A summary of Bayesian inference, which illustrates how one's beliefs are changed in response to data observation.

5.5.4 Introduction to Bayesian statistics in Python and other programming languages

As posterior probability is intended to be the outcome of the investigation, this study makes use of 'PyMC', a popular Bayesian statistics tool written in Python. This project develops a unique model for calculating the odds of railway accidents using Python. The outcome of this approach includes the posterior distribution and statistical data, including the mean, median, and standard deviation. These can clearly illustrate the ambiguity inherent in the data produced.

Many researchers employed a Bayesian network model in conjunction with programming languages (Pol, 2003; Patil *et al.,* 2010). The Bayes function was implemented in coding languages because it was capable of solving complex conditional probability issues and visualising the results. Additionally, it can be expanded to include other relevant areas, such as analytics. PyMC is founded on the Markov chain Monte Carlo (MCMC) technique, a class of algorithms for selecting from probability distributions. The MCMC methodology is advantageous for acquiring knowledge about distributions, particularly for predicting posterior distributions for Bayesian inference, which are often difficult to calculate analytically.

5.6 Data analysis

Using hypothesised prior distributions, Bayesian inference is employed in this study to analyse the uncertainty in the obtained data. This chapter analyses and discusses the Dirichlet distribution, which is a non-uniform distribution. This is critical for interpreting the outcomes acquired from expert beliefs and data collecting accurately. The result reveals that probability density functions can be discovered, allowing for the accurate prediction of future accidents.

Dirichlet distributions, often known as multivariate beta distributions, are a special type of continuous probability distribution with k types. Assume that x represents the probability of each parameter $\theta = \{\theta_1, \theta_2, \dots, \theta_k\}$, where $0 \leq \theta_i \leq 1$ for $i \in [1, k]$ and, $\sum_{i=1}^{k} \theta_i = 1$. The Dirichlet distribution's probability density function is given by:

$$Dir(\theta|\alpha) = \frac{1}{B(\alpha)} \prod_{i=1}^{k} {\theta_i}^{\alpha_i - 1} \tag{5.6}$$

where $B(\alpha)$ denotes the multinomial beta function, $B(\alpha) = \frac{\prod_{i=1}^{K} \Gamma(\alpha_i)}{\Gamma(\prod_{i=1}^{K} \alpha_i)}$; and α denotes a vector of positive actual values called a hyperparameter, $\alpha = (\alpha_1, \alpha_2, \dots, \alpha_k)$. A Dirichlet distribution's expected value may be computed directly from its vector α, which is $E[X_i] = \frac{\alpha_i}{\alpha_0}$; $\alpha_0 = \sum_{s=1}^{k} \alpha_s$.

To estimate the posterior distribution (p) using Dirichlet distributions (α) as priors (X), this research used the Dirichlet-multinomial model that is a multinomial distribution with Dirichlet prior X. According to Bayes' rule, the posterior distribution is as follows:

$$P(p|X, \alpha) = Dir(N + \alpha) \tag{5.7}$$

Equation 5.7 refers to the Dirichlet distribution with parameters $N + \alpha$, where N is the occurrence count. Thus, the anticipated value may be represented analytically as:

$$E[p_i|X, \alpha] = \frac{N_i + \alpha_i}{N + \sum_{s=1}^{k} \alpha_s} \tag{5.8}$$

where N_i represents the recorded count for each type, whereas α represents the pseudo-observations at each kind.

With respect to the long-term data obtained, the Dirichlet distribution analysis is conducted on the premise that the fractions for X1 and X2 are equal and that the fraction for X3 is less than the fractions for X1 and X2 (P(X3) < P(X1); P(X3) < P(X2)). This statement is based on gathered data, which indicates that the proportion for X3 is just 13%. As a result, the Dirichlet forms for non-uniform distributions are denoted by the following formulas; X1: X2: X3 = 4:4:1.

This study compares the FRA data set to the real number of railway accidents in order to validate the developed model. The 63,770 data sets are analysed within the Python model that has been built with a confidentiality level of 95%. Based on the statistics, the chances of a train collision, derailment, and other impacts are equal; in other words, the probability of this event should be expressed as ∝= 1:1:1. However,

Table 5.4 Comparison of the actual values: model ∝ 4:4:1 and model ∝ 1:1:1

Model/Type of accident	X1-Collision	X2-Derailment	X3-Others
Actual result	0.549	0.341	0.110
∝ 4:4:1	0.546	0.352	0.102
∝ 1:1:1	0.536	0.351	0.112

the model developed suggests that the percentages for previous belief should be ∝ = 4:4:1 rather than ∝ = 1:1:1.

The findings in Table 5.4 demonstrate that the model constructed using prior belief portions of ∝ = 4:4:1 is very efficient and more accurately forecasts the actual X1, X2, and X3 values than the model constructed using prior belief proportion of ∝ = 1:1:1. These results indicate that the likelihood of adverse consequences after an accident is not equal. It is sufficient to state that the non-uniform distribution type '∝ = 4:4:1' is the best-fitting model for this thesis.

5.7 Evaluating the risk level of railway accidents

Following section 5.6, the study shows that a non-uniform distribution (∝ = 4:4:1) is the best-suited model for this study. The purpose of this section is to compare the risk of railway accidents on the five selected networks. The analysis is based on accident databases that include the impacts of trains as well as the number of deaths and injuries during a 20-year period.

According to the identification of train-related effects following incidents, this chapter demonstrates that effect type 'X3' is much more connected with injuries and deaths than effect types X1 and X2. X3 causes roughly four times the normal amount of harm. The statistics collected in the 5 nations of concern indicate that effect type X3 happened 14 times, resulting in 2,354 injuries and 438 deaths. On the other side, ‘X1’ and ‘X2’ happen 47 and 45 occasions, respectively, with injury and mortality numbers comparable to ‘X3’. As a result, it may be stated that ‘X3’ causes much more harm than other sorts of effects.

5.7.1 Result of posterior probability distribution

The study applies a non-uniform distribution model ($\propto = 4{:}4{:}1$) to calculate the posterior probability of collision, derailment, and other impacts. The analysed data are illustrated in Table 5.5 and are used into the evaluation process. Figure 5.7 compares the posterior distributions for collision, derailment, and other impacts by nation, as well as the overall posterior distributions.

Table 5.5 Comparison of the results of non-uniform distribution by network

Network	Type	mean	sd	hpd_2.5%	hpd_97.5%	mcse_mean	mcse_sd	ess_mean	ess_sd	ess_bulk	ess_tail	r_hat
	X1	0.425	0.098	0.234	0.62	0.003	0.002	1447	1442	1443	1057	1
CR	X2	0.462	0.098	0.281	0.656	0.002	0.002	1557	1546	1551	1299	1
	X3	0.113	0.06	0.023	0.24	0.001	0.001	1730	1562	1751	1219	1
	X1	0.407	0.095	0.225	0.588	0.003	0.002	1252	1252	1239	1144	1
SNCF	X2	0.517	0.096	0.338	0.704	0.003	0.002	1406	1406	1396	1207	1
	X3	0.076	0.051	0.001	0.173	0.001	0.001	1571	1530	1449	974	1
	X1	0.357	0.118	0.154	0.603	0.003	0.002	1500	1495	1464	1033	1
JR Central	X2	0.585	0.119	0.345	0.804	0.003	0.002	1548	1538	1534	1278	1
	X3	0.058	0.054	0	0.168	0.001	0.001	1629	1576	1483	884	1.01
	X1	0.424	0.113	0.203	0.629	0.003	0.002	1474	1392	1484	1144	1
Korail	X2	0.473	0.115	0.267	0.702	0.003	0.002	1600	1600	1605	1333	1
	X3	0.103	0.067	0.004	0.235	0.002	0.001	1538	1437	1440	1042	1.02
	X1	0.492	0.063	0.374	0.619	0.002	0.001	1468	1461	1469	1444	1
Renfe	X2	0.327	0.061	0.218	0.457	0.002	0.001	1609	1604	1607	1559	1
	X3	0.181	0.05	0.085	0.279	0.001	0.001	1507	1428	1533	1035	1
	X1	0.444	0.045	0.36	0.533	0.001	0.001	1830	1809	1843	1313	1
Overall	X2	0.426	0.045	0.335	0.511	0.001	0.001	1928	1918	1933	1326	1.01
	X3	0.129	0.031	0.072	0.189	0.001	0.001	1808	1781	1817	1416	1

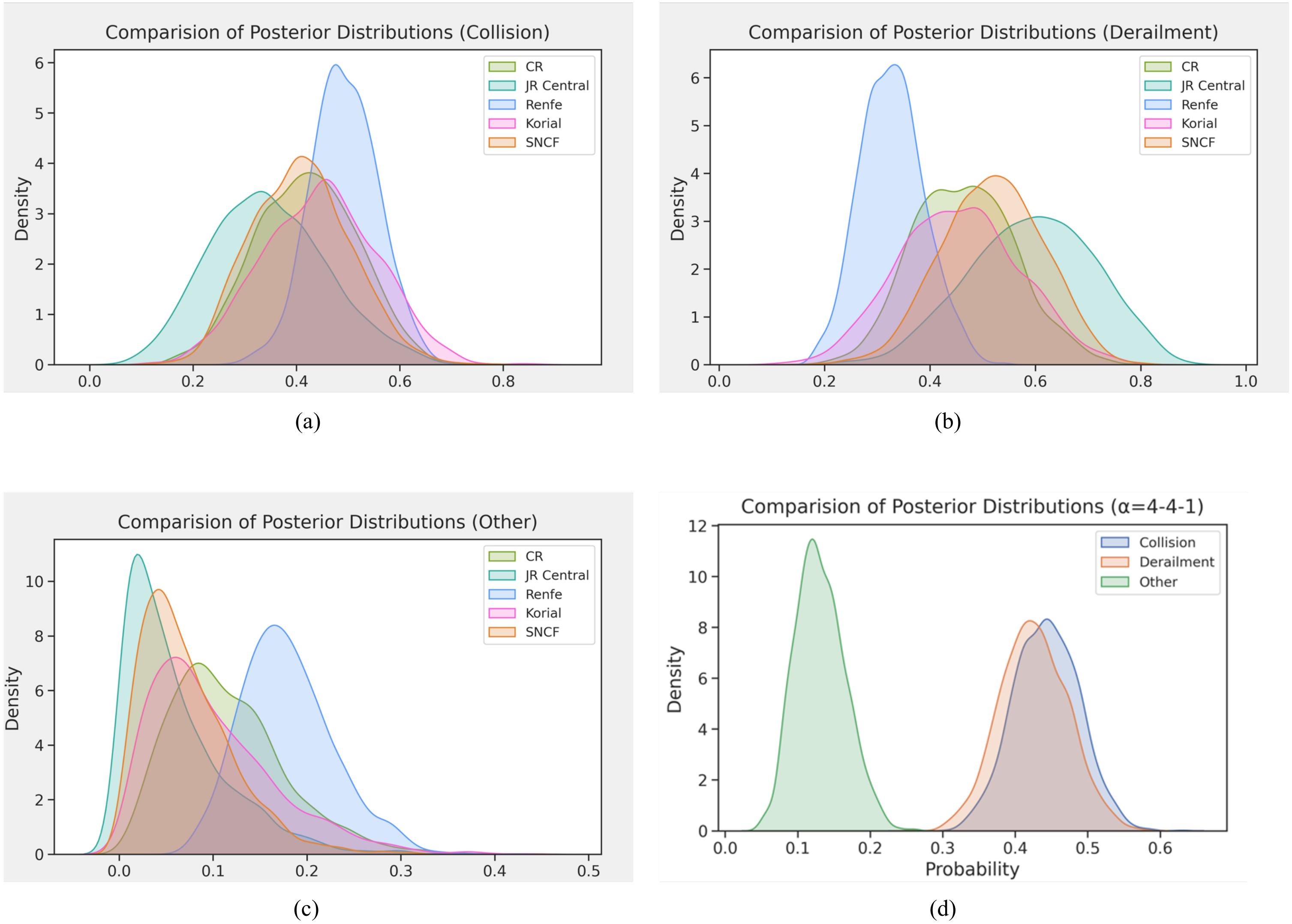

Figure 5.7 Comparing posterior distributions for (a.) collisions, (b.) derailments, (c.) other events by nation, and (d.) overall posterior distributions.

5.7.2 Models for railway risk assessment

By examining the current risk models in Table 5.3, it is clear that no prior study has been conducted to compare railway network risk levels using posterior probability. Posterior probability forecasts with great accuracy using long-term data and expert opinions. In contrast, current models are mostly used to predict susceptibility and hazards. This research examines the damage caused by railway accidents (numbers of deaths and injuries) and the posterior probability of their consequences (X1, X2, X3). To compare risk levels across the five selected rail networks, the thesis employs a combination of the DT and PT models.

5.7.2.1 The design of the DT model

The DT model is a forecast structural flowchart that is used to classify characteristics after they are entered. The DT model is used in this research to determine the risk levels associated with rail networks. This study establishes results for each branch as either 'yes' or 'no'. The leaf nodes indicate decision rules that include five criteria: death rate, injury rate, and X1, X2, and X3 values. The model's end nodes are decomposed into 32 outcomes that reflect risk levels, with the lowest score indicating the smallest risk and the highest score indicating the most danger.

5.7.2.2 The PT model

The PT model is a proposed mathematical model with three components: location, transition, and arc. The framework is most widely used to describe the flow of materials in a manufacturing system. The method is also utilised to assess risk level in this study, as stated in Equations 5.9 – 5.13.

Assume S is an integer reflecting the degree of risk, which is an expected consequence. S is dependent on two parameters, as seen in Equation 5.9.

$$S\ (\overline{e}, \overline{w}) \tag{5.9}$$

where; $\overline{e}$ *denotes events and* $\overline{w}$ *denotes weighted score*

The vector $\overline{e}$ represents events or model's conditions, which consist of fatalities rate, injuries rate, X3, X1 and X2 values.

$$\overline{e} = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \end{bmatrix} = \begin{bmatrix} death\ rate \\ injury\ rate \\ X3 \\ X1 \\ X2 \end{bmatrix} \tag{5.10}$$

where; $e_n\ equals\ to\ 1$ if $Input\ value > threshold$ and $e_n\ equals\ to\ 0$ if $Input\ value \leq threshol$

Given the vector $\overline{w}$ is the weight of vector $\overline{e}$, as shown in Equation 5.11.

$$\overline{w} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \end{bmatrix} = \begin{bmatrix} 16 \\ 8 \\ 4 \\ 2 \\ 1 \end{bmatrix} \tag{5.11}$$

Then, as stated in equation 5.12, the dot product of the 'w' and 'e' vectors is a critical operation when working with vectors in geometry. Additionally, the risk level (S) may be determined using equation 5.13.

$$S = \overline{w} \cdot \bar{e} = \begin{bmatrix} 16 \\ 8 \\ 4 \\ 2 \\ 1 \end{bmatrix} . \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \end{bmatrix} \tag{5.12}$$

$$S = 16e_1 + 8e_2 + 4e_3 + 2e_4 + e_5 \tag{5.13}$$

The structure of the PT model, as known as 'Synchronisation', is as seen in Figure 5.9. The benefit of the PT model is that it accurately captures the complicated discrete event model. Although the model's shape can be simplified, it retains a continuous flow of information and consequences. The PT model is utilised to determine risk levels in this investigation. The results of DT and PT are then compared.

5.7.3 Sensitivity analysis

This thesis carries out a sensitivity analysis to determine the appropriate decision-making threshold for railway hazards. Additionally, it seeks to ascertain the confidence of the DT and PT models developed as a result of modifications in X1, X2, and X3. According to the early investigation, the model has a high degree of confidence, as seen by the sharp edges in the graphs in Figure 5.5. Thus, the sensitivity analysis varies by a standard deviation between ± 1 and ± 2 standard deviations (s.d.), and the injury and mortality rates vary with Q_1 (quartile 1), mode value, Q_3 (quartile 3), and mean values ($\bar{x}$).

Six analytic models have been developed, and each has been verified at between the ±1s.d. and ± 2s.d. To assess and choose the optimal model, the 'total absolute error' is an important parameter to consider. The model with the smallest total absolute error can be considered as having the greatest degree of certainty.

As indicated in equation 5.14, the total absolute error is obtained by adding the '% altered' to the mean value. Additionally, equations 5.15 and 5.16 represent the absolute error and total absolute error.

$$Percentage\ \text{changed}\ (\%) = \frac{X - \bar{x}}{31} \times 100 \tag{5.14}$$

$$Absolute\ error\ (\%) = \sum_{i=1} (\%\ changed_i) \tag{5.15}$$

$$Total\ absolute\ error\ (\%) = \sum_{j=1} (Absolute\ error_j) \tag{5.16}$$

where x is a result of the model analysis, i is an index in the sensitivity analysis, $i \in \{$*-2s.d., -1s.d., +1s.d., +2s.d.*$\}$; and j is a network index, $j \in \{$*CR, SNCF, JR Central, Korail, Renfe*$\}$.

In conclusion, Table 5.6 summarises the model findings and the overall absolute error. Model 2, which employs Q_3 thresholding for both injury and death rates, has a minimal total absolute error of 61.29%. As a result, as seen in Figure 5.8, the sensitivity analysis for model 2 by nations produces graphs with modest levels of variation.

Finally, Figures 5.9 and 5.10 illustrate the PT and DT models developed in this research.

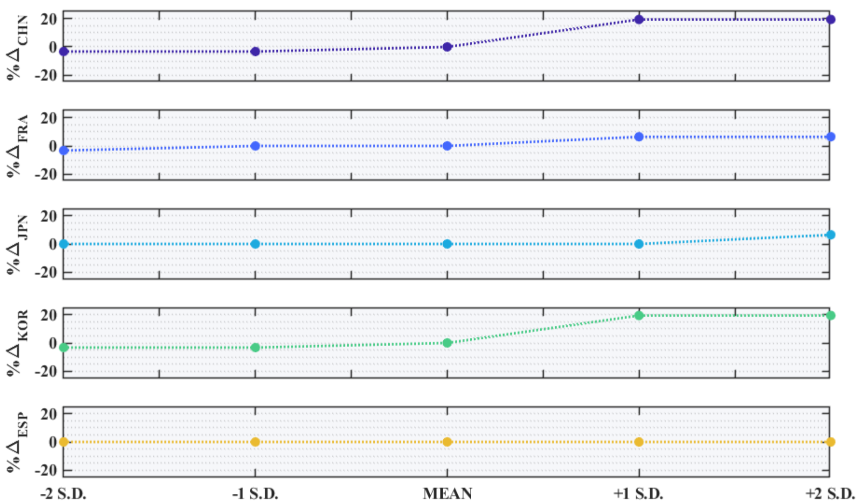

Figure 5.8 Sensitivity analysis of Q3 thresholding for injury and fatality rates

Table 5.6 Summary of the model and the total absolute error

Model	Sensitivity analysis	Total absolute error (%)
1	Mean value thresholding with wounds and death tolls	112.90
2	Q_3 thresholding with wounds and death tolls	61.29
3	Mode thresholding with wounds and death tolls	64.52
4	Q_1 thresholding with wounds and death tolls	119.35
5	Q_3 thresholding with wounds and Q_2 thresholding with death tolls	71.29
6	Q_2 thresholding with wounds and Q_3 thresholding with death tolls	74.19

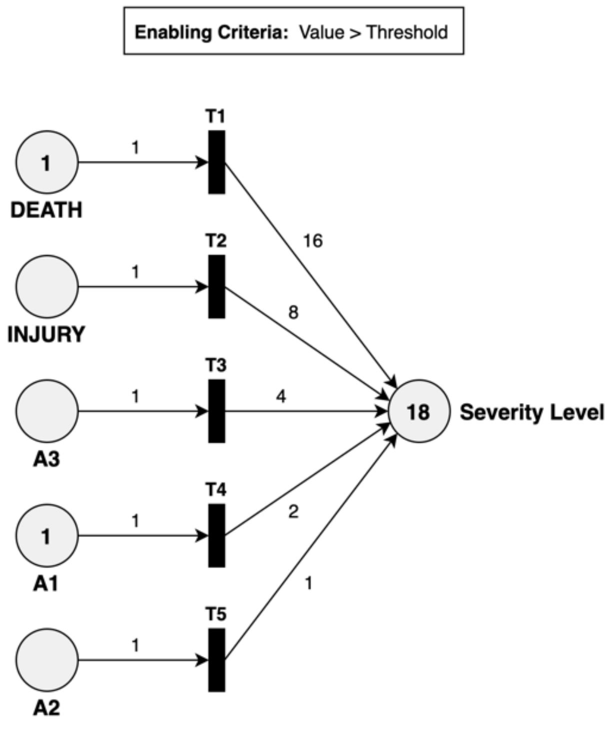

Figure 5.9 An overview of PT framework for evaluating risk score

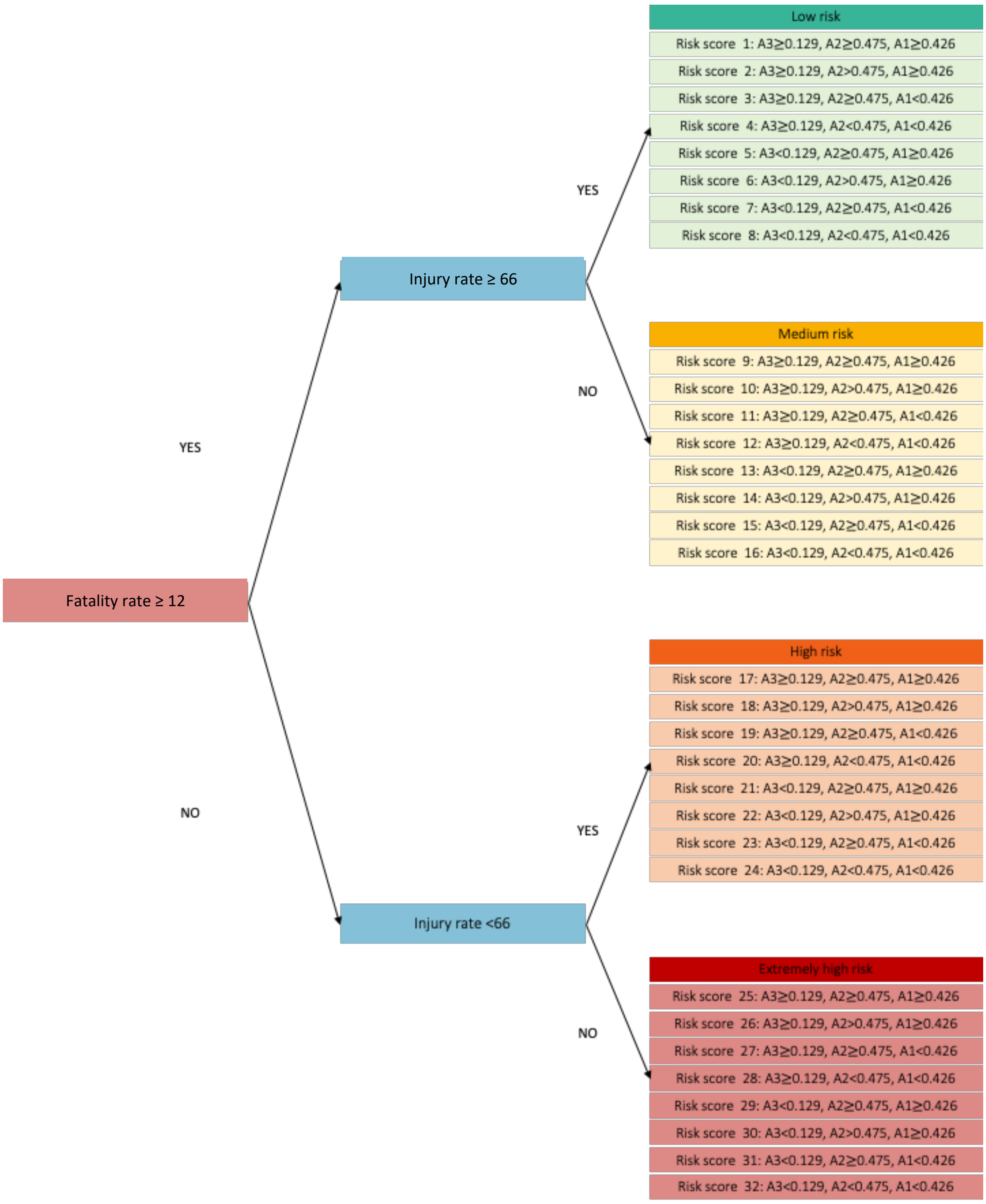

Figure 5.10 Overall DT framework for evaluating risk score

5.7.4 Results and discussion

The analysis of the various sets using the DT and PT models yields discrete values ranging from 1 to 32. According to the risk rating, the risk level may be categorised into four categories. A risk score of 1-8 indicates minimal danger, 9-16 indicates moderate danger, 17-24 indicates high danger, and 25-32 indicates extremely high danger.

Table 5.7 summarises the benchmarking findings for the five HSR networks. These findings provide a substantial benefit since safety standards for prospective projects may be modelled after individuals associated with ‘low-risk’ networks. The findings of the risk level study indicate that Korail network poses the most danger of any of the examined networks. The network has a safety score of 18, which is classified as ‘high risk’, whilst French network has a score of 10, which is classified as ‘moderate risk’. CR, JR Central, and Renfe each have railway systems with ratings of 2, 2, and 7, which are regarded to be ‘low risk’.

According to the most thorough analysis of CR and JR Central networks, both networks have a low accident rate and low injury and fatality rates per accident. As a result, the risk associated with these systems is deemed ‘minimal’. Additionally, these

Table 5.7 The result of risk level analysis

Network	Risk score	Risk level
CR	2	Low
SNCF	10	Moderate
JR Central	2	Low
Korail	18	High
Renfe	7	Low

systems have been strengthened in terms of security. For example, in Japan, high-magnitude earthquakes have caused train derailments, forcing the HSR network to install an emergency earthquake detection system on the track to cut off power. This has resulted in an overall enhancement in safety issues and the avoidance of train damage over time.

Likewise, the Renfe network has a risk level of ‘low’, earning a score of 7. The majority of them are neither fatal or result in minor wounds. These low injury and death rates are linked to the Renfe network’s classification as a ‘low’ risk. Meanwhile, SNCF network has a risk rating of 10 indicating ‘moderate’. Incidents happen at a threefold higher rate than in Renfe network. Despite this, the average death toll and hospitalisation per incident is 15 and 96, which is greater than the world average.

Korail, on the other hand, faces a greater threat than other networks. Despite the low frequency of railway accidents, their severity is ‘severe’. The data obtained indicates that the average death toll and hospitalisation per accident is between 18 and 41. This increases Korail’s severity level over the global average, resulting in the highest projected risk rating for Korail’s network.

It is worth examining the fascinating facts highlighted by this risk benchmarking model’s outcomes. Due to the high accident probability associated with extensive and congested train networks, this benchmarking model indicates that risk levels associated with other relevant factors should be examined rather than the accident rate. The risk scores in the outcomes may be described in conventional terms using the case studies mentioned above, and the framework can be evaluated against other networks.

The causes of accident type ‘X3’ (other related causes) are classified into two categories: mechanical failures and contributory factors. In order to minimise risk, the research strongly advises railway operators to implement sufficient maintenance programmes for train's cars, tracks, and systems, as well as to strengthen safety regulations and employee training in the aftermath of catastrophic incidents.

5.8 Conclusions

With the expansion of HSR networks globally, safe train services are a critical component of railway operators' efforts to facilitate passenger trips. Rail accidents may be divided into three categories based on long-term accident data sets: collisions, derailments, and other consequences. According to this study, the category of 'other impacts' causes four times as much damage as accidents and derailments. As a result, the study analyses accident data sets using new models and identifies best practices. According to the findings, the non-uniform distribution of a ratio of $\propto =$ 4:4:1 produces the most precise results.

This chapter seeks to better understand the uncertainties associated with railway accidents in order to accurately mitigate the effect of fatalities. Five nations have been chosen as benchmarks for risk levels. The study creates a model for 'benchmarking risk' that is a linear transform model on posterior probability and damage and death severity levels. Additionally, the analysis is performed using DT and PT techniques. The systems of CR, JR Central, and Renfe are classified as low risk while the networks of SNCF and Korail are classified as moderate risk, and high risk respectively.

To enhance railway network safety, this research proposes that 'other impacts – X3' should be removed or reduced. The X3 is caused by mechanical failure and other contributing factors. Future research should productively pursue this problem by delving deeply into the underlying causes of accidents utilising posterior distributions. Our results on posterior probabilities can potentially be used to develop a new metric for politicians and railroad businesses.

5.9 Chapter summary

This chapter examines the risks and uncertainties of the HSR networks to evaluate risk levels, leading to preventing railway accidents in the future. First, the thesis categorises the types of railway accidents into three groups. The distribution of railway accidents is shown in non-distribution uniform ($\propto = 4{:}4{:}1$).

This study then codifies the Bayes' model using Python to create a model that could be applied to other rail networks. The precise outcomes contribute to a better understanding of the railway accident's uncertainty. This chapter also demonstrates the model's application to DT and PT models.

Following this study, CR and JR Central networks are the leaders in risk management. On the other hand, Korail's network is at an extremely high-risk level. Table 5.8 illustrates the results of KPIs for each area.

In light of the industrial era, high-technologies and innovations have been applied across the rail industry and networks. Adopting new technologies can genuinely protect passengers' lives, diminish accidents' impact, and enhance safety performance.

Table 5.8 The summary of KPIs for risk and uncertainty

KPIs	Total weight (%)	Insight definitions	CR	SNCF	JR Central	Korail	Renfe
Risk and uncertainty	20	Overall risk in network	19.39	14.48	19.39	9.58	16.32

New designs are shown in many sections related to the rail networks, including rolling stocks, infrastructure, operational plans and policies. The thesis suggests the upcoming HSR strictly follow the practices below to increase safety performance.

Firstly, the new design of rolling stock is concerned with the safety of the passengers. It covers the rolling stock's body, software, gear, break, and train doors (ORR, 2017). The Shinkansen, for instance, has installed safety equipment to protect passengers from the earthquake (Nishimura *et al.,* 2010; Evans, 2010).

Secondly, the safety system has been improved significantly on the railway's infrastructure, especially at the level crossing (LX). Some rail networks avoid building tracks across the LX. Thus, they build railway bridges or rail tunnels to prevent an incident between trains and road vehicles. On the contrary, railway bridge and tunnel construction costs and time are significantly higher than standard track (Zoeteman, 2020; Craighill and Powell, 1996; Das, 2011).

The practical operational plan plays a critical role in increasing the safety level on the railway network. The plan includes a signalling maintenance scheme to reduce accidents between the train and obstacles (UIC, 2019). The replacement of the standard signalling system and traffic control system has been enlarged across the EU countries. Moreover, the new maintenance issue concerns passengers' risk. For example, in Great Britain, the regulation for maintenance on the railway network to develop safety issues was vastly discussed among industry, regulators, and stakeholders (ORR, 2019).

Finally, safety policies on the network have varied across countries, with the exception of shared rules among 29 EU countries, which are based on the International Union of Railway Standards (UIC). For instance, Regulation No. 1371/2007 of the European Parliament and the Council, which relates to rail passengers' rights and obligations, has partially concerned safety during rail service (Petit and Puetz, 2016). The regulations influence the 51 railway authorities to apply new policies to the incoming projects (Schaefers and Hans, 2000; Hoffmann and True, 2006).

5.10 References

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CHAPTER 6

High-speed rail and sustainable development

This chapter examines a life cycle assessment of the entire HSR network, including its infrastructure and rolling stock. The life cycle assessment is reviewed in-depth in four stages. Also, the focuses of this chapter are on energy consumption and CO_2 emissions. The outcomes are clearly revealed by each stage, leading to achieving sustainable development of upcoming HSR projects.

6.1 Introduction

Global warming has deteriorated significantly over the last several decades, necessitating a response from all sectors to reduce Carbon dioxide (CO_2). Transportation is responsible for a quarter of world emissions (UIC, 2017). Many initiatives to minimise emissions have resulted in novel designs for rolling stock, construction, and operating systems as rail networks have grown dramatically. Only a few businesses, however, have yielded positive results.

One major issue with CO_2 emission is that the majority of railway operators have not paid close attention to emissions during the HSR's lifespan. Additionally, the manufacturing process of the infrastructure and rolling stock produced a significant amount of CO_2. The purpose of this research is to highlight the environmental impacts (EIs) of HSR networks in terms of reducing ecological consequences. Furthermore, it appears that a prevalent difficulty encountered by railway enterprises is financial difficulties as a result of the exorbitant cost of investment and operations. This study also looks at the economic implications of sustainability as well as the lifecycle of a rail network.

By comparison to other research, the benchmarking technique enables emerging networks to take into account the HSR's whole-life lifetime and implement practical tactics from established rail networks.

6.2 Background

The construction of the HSR track has extended around the world, resulting in a network of about 52,000 km (UIC, 2020). This development is founded on the conviction that HSR service is unquestionably critical to the eventual country's prospective expansion (Wang *et al.,* 2018). In reality, fast urbanisation may have an effect on the environment, as it may cause climate change, which has resulted in a rise in the average world temperature of roughly 0.8°C (1.4°F) since 2000. (Braganza *et al.,* 2004). Numerous organisations have undertaken efforts to combat global warming's causes; for example, Greenpeace has called for the replacement of coal, oil, and gas with alternate green and clean energy sources (Katz-Kimchi and Manosevitch, 2015). The United Nations Environment Programme (UNEP) is actively engaged in global, regional, and national programmes spanning seven distinct themes, including global warming (UNEP, 2019).

Transportation is a major producer of CO_2 in the atmosphere due to growing demand for transportation, which results in increasing energy usage from petroleum and other fossil fuel sources. Transportation utilises 28.8% of energy and emits 28.3% of total CO_2 through combustion process (IEA, 2017; UIC, 2017; UIC 2015). Additionally, the railway industry has undertaken efforts to minimise energy use and CO_2 emissions. The European railway sectors have committed to halving CO_2 emissions from passenger and freight trains by 2030. (UIC, 2015). In comparison to other modes of transportation, HSR has the potential to significantly reduce EIs due to the low volume of pollutants it releases. According to some analysts, HSR might reduce environmental pollution in China by 7.35% (Yang *et al.,* 2019). In Japan, the Shinkansen class ‘N700’ generates just 8.34% of an airplane’s total emissions (JR Central, 2019). Additionally, the UIC research examined data from European nations and determined that HSR emits just 17 g CO_2 per pkm, compared to buses, private automobiles, and aeroplanes, which emit 30, 115, and 153 g CO_2 per pkm, respectively, as seen in Figure 6.1 (UIC, 2017).

Although some academics have argued that HSR is environmentally beneficial, economic viability must be considered due to the high cost of HSR operations. Indeed, investment in HSR involves a long return time, and the majority of HSR projects require local government subsidisation. As a result, technology changeover in new systems should be approached from a budgetary standpoint. Numerous efforts are being made to grow HSR networks sustainably, including the use of innovative

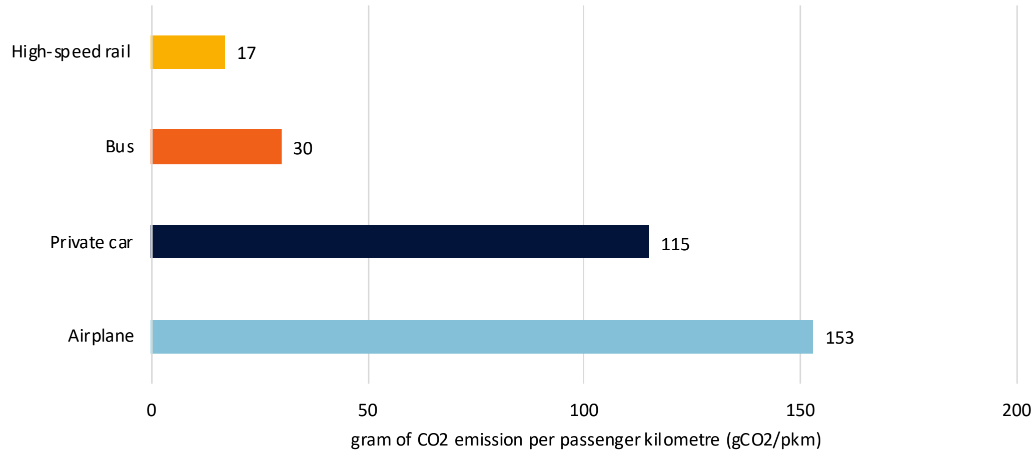

Figure 6.1 CO_2 emissions from high-speed rail in comparison to other modes of transportation in European nations (Source: UIC, 2017)

technology. Several studies have described and contrasted each country's railway systems in terms of new technology, economics, and emissions (Lin *et al.,* 2020; Vuchic and Casello, 2002; He *et al.,* 2017).

6.2.1 Sustainability perspective on HSR network

Since the Industrial Revolution, a significant amount of greenhouse gases (GHGs) has been produced into the atmosphere as a result of the expansion of commercial, industrial, home, and transportation sectors. The produced GHGs have contributed to climate change, which has had detrimental consequences for humans and species. Following the promotion of the Paris Agreement in December 2015, a focus on sustainable development has been emphasised. The pact compels all public and business sectors worldwide to take steps to keep global temperatures below 1.5°C above pre-industrial levels. Additionally, as stated in the United Nations' (UN) sustainability objectives, conserving the environment and preventing climate change are critical development goals to achieve by 2030 (Searchinger, 2008).

In terms of transportation, it has been estimated that it accounts for one-fourth of worldwide CO_2 emissions due to increased demand. Indeed, HSR has the lowest emissions of any method of transportation, as seen in Figure 6.1. Additionally, the long-term and sustainable development of HSR is substantially greater than that of public transportation. According to some scholars, public transit exactly decreases CO_2 and harmful pollutants by lowering the usage of private automobiles (Schipper, 2011; Shapiro *et al.,* 2016). Furthermore, some study indicates a link between public transportation and some health concerns. It has been demonstrated that having a high-quality transportation infrastructure with easy access to public transportation correlates with people having improved health conditions as a result of reduced travel and waiting times (Anwar *et al.*, 2020; Badland *et al.*, 2017).

HSR has emerged as a viable solution for the transportation sector's sustainable growth in both developed and developing countries. HSR, as a result of rapid technological advancement, provides a more sustainable and efficient use of energy than other modes. Today, HSR utilises natural resources and renewable energy sources, resulting in decreased energy consumption and minimal CO_2 and air pollution emissions (Campos *et al.,* 2007). In terms of energy usage, some scholars believe that using composite and lightweight materials on the body of railway cars (i.e., carbon fibre reinforced plastic (CFRP)) can help reduce GHG emissions (Hou *et al.,* 2019; Kaewunruen *et al.,* 2019). Indeed, lightweight materials reduce drag by conserving energy and enabling high velocity. Additionally, End-of-life rolling stock made of CFRP material requires less energy during the recycling process.

6.2.2 Life cycle assessment (LCA)

A life cycle assessment (LCA) or life cycle analysis is a method capable of determining the environmental impact of a product's manufacturing, transportation, and disposal. The LCA idea was found in the 1960s and 1970s and has since been steadily expanded and utilised in a variety of areas (Guinee *et al*., 2011). In the first period, LCA has been used to solve problems related to energy efficiency, pollution, and wastes (Sundström, 1979; Assies, 1992). Following this, the life cycle assessment played a significant part in the worldwide organisation for standardising (ISO). The foundation for life cycle assessment was specified in two international standards (ISO 14040 and ISO 14044). Since 2010, the LCA has been largely incorporated into a framework for sustainability. The advantage of an application was broad in scope, ranging from product to sector to economy (Ortiz *et al.,* 2009; Heijungs *et al.,* 2010).

Several previous studies had emphasised the need of applying LCA to railway infrastructures. Several studies have evaluated the LCA performance of railway bridge designs with the goal of assessing environmental performance. The research examined procedures ranging from construction through recycling and disposal. It enabled infrastructure managers to make decisions, particularly when passenger demand has increased (Thiebault, 2010; Evangelisti *et al.*, 2017). Similarly, another researcher incorporated LCA into the design of railway bridges. The research analysed two different designs for the Banafjäl Bridge in Sweden and concludes that the fixed slab bridge, which requires less maintenance, performs better environmentally than the ballast design (Du and Karoumi, 2013; Bressi *et al*., 2018).

Additionally, several researchers have recommended the incorporation of LCA into railway vehicles. Three railway vehicles were compared in the study: an electric metro, a diesel commuter, and a high-speed electric model. The result indicated that all models have a high recyclability rate, owing to the fact that the majority of cars were constructed of metals (Helmers *et al.,* 2017). Similarly, some studies advocated replacing six major components of HSR's rolling stock with CFRP. The use of lighter materials resulted in a decrease in CO_2 emissions during the life of the rolling stock (Rungskunroch *et al.*, 2019).

However, the application of LCA to an entire HSR network has yet been investigated in detail. A majority of studies have been focused on either infrastructures or rolling stocks. It results in unquantifiable EIs over the lifecycle of the HSR network. Additionally, the HSR network may be unable to achieve its sustainability target. Therefore, an integration of the LCA of HSR's rolling stocks, infrastructures, and operations is addressed in this study. The contribution has broad applicability in terms of precisely evaluating EIs from HSR operations. This study focuses on environmental sustainability by developing LCA frameworks for HSR networks. The success of HSR services depends on numerous variables. This chapter summarises the performance of five HSR networks under various technology, regulations, and other pertinent variables. These findings can be incorporated into new guidelines for future HSR projects.

6.3 Research methodology

6.3.1 Availability of data

The datasets have been conducted from HSR companies' reports, sustainability reports, and publications. For example, the information of material and energy requirements in rail track is collected from the publication of Maibach *et al.,* (2003) and Von Rozycki *et al.,* (2003). And, the material and energy requirements in the rail tunnel are taken from the report of Ecoinvent (2007).

As mentioned in Chapter 2, the following five HSR networks have been taken to in-depth evaluate the LCA. A summary of those selected networks, route, rolling stock models, and weight are shown in Table 6.1.

Table 6.1 A summary of HSR rolling stocks' model and volume

Network	Series of rolling stock	The rolling stock's volume (tons)
JR Central	N700	715
CR	CRH380A	890
Korail	KTX-II	694.4
SNCF	TGV	616
Renfe	AVE	850

In this study, the benchmarking has adopted the data, which can be updated. The result is based on the data in the timeframe 2000-2019. Therefore, the results can be updated after changing the timeframe of benchmarking.

6.3.2 Methodology

Future HSR services have the potential to provide an ultimate number of advantages for society, particularly in terms of environmental and economic implications.

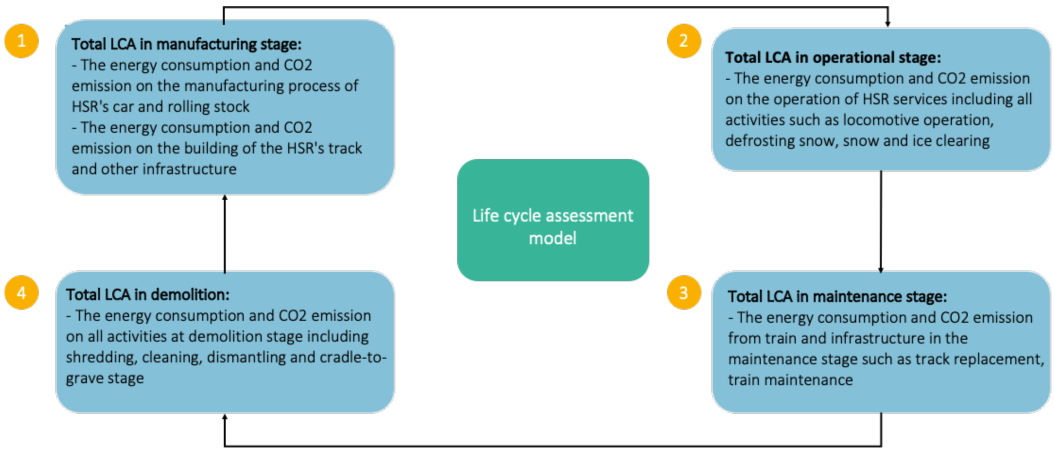

Figure 6.2 An overview of the research framework

Numerous HSR networks have garnered widespread admiration in comparison to other modes of public transit and vehicle types. The reason for this is because HSR networks consume the least energy and emit the fewest greenhouse gases (GHG) per passenger per kilometre-travel (Wilkerson, 2005; Chester and Horvath, 2010; Yue *et al.*, 2015).

Regarding the HSR networks' sustainable development goals, environmental evaluations are critical techniques that consider systematic thinking and the whole life cycle of HSR networks. The LCA study is used to identify environmental advantages. The LCA models are estimated for four stages of the life of a HSR network, namely production, operation, maintenance, and destruction, as illustrated in Figure 6.2. The outputs of energy consumption and CO_2 emission are discussed to establish best practices that would enable stakeholders to develop sustainable strategies for future HSR projects.

6.4 LCA for HSR networks

One of the study's primary aims is to examine the EIs associated with the operation of HSR services. The life cycle assessment (LCA) indicates the amount of energy consumed and CO_2 emitted at each step of the life cycle. According to previous studies, the outcomes of LCA analyses can result in a reduction in long-term impact on humans and wildlife, an increase in product quality, and a drop in GHG emissions (Rungskunroch *et al*., 2021; Kaewunruen *et al.,* 2020). As illustrated in Figure 6.3, the life cycle of a HSR network is classified into four phases: (i) the manufacturing, pre-assembly, and logistics of materials, rolling stocks, and infrastructure; (ii) the operational stage of HSR services; (iii) the maintenance stage of vehicles and infrastructure; and (iv) the vehicle demolition stage. Each stage of a railway operation's life cycle involves a variety of energy inputs (oil, electricity), raw materials, emissions outputs (CO_2, GHGs, NO_2, CH_4), and other trash. In terms of outputs, this study addresses and contrasts solely CO_2 emissions, which account for over 80% of total outputs (Zimmermann *et al*., 2018; IPCC, 2014).

A whole energy consumption (LCE) and CO_2 emissions ($LCCO_2$) are computed using EIs, as specified in equations 6.1 and 6.2:

$$LCE = \sum_{i=1}^{n} EC_i \tag{6.1}$$

$$LCCO_2 = \sum_{i=1}^{n} CE_i \tag{6.2}$$

where LCE = life cycle of energy consumption; $LCCO_2$ = life cycle of CO_2 emissions; EC_i = total energy consumption (GJ) in stage i; CE_i = total CO_2 emission (t) in stage i;

i = set of life cycle phase {manufacturing and pre-assembly, operation, maintenance, demolition}.

This study concentrates on the service providing time of HSR networks. Infrastructure construction is seen as an initial investment that has already been made and cannot be retrieved (Kaewunruen *et al*., 2020). This section entails the material information that go into the construction of HSR vehicle and rolling stock used in operations.

6.4.1 LCA of manufacturing and pre-assembly stage

The amounts of energy used and weights of rolling stock are collected from the HSR company's annual reports. This study is particularly interested in mass and energy usage figures that are exact. Therefore, the LCE and $LCCO_2$ emissions, which are estimated for the 16-car rolling stock model, are defined in equations 6.2 and 6.3, respectively:

$$EC_{manufacturing} = \sum_{m=0}^{n} (E_m \times W_m) \tag{6.2}$$

$$CE_{manufacturing} = \sum_{m=0}^{n} (C_m \times W_m) \tag{6.3}$$

where C_m = CO_2 emission from material 'm'; E_m = Consumption of energy by materials m; W_m = The mass of material 'm' that makes up a vehicle; m = {lists of material components used in the manufacture of rolling stock}.

The computation of the LCE and $LCCO_2$ emissions is given in this study for three distinct types of rail track infrastructures: rail track, rail tunnel, and rail bridge. The reason for this is because different types of infrastructure need varying amounts of materials and energy, as seen in Tables 6.2–6.5 (Maibach *et al.,* 2003; Von Rozycki *et al.,* 2003).

Table 6.2 The summarisation of material and energy requirement in rail track (Source: Maibach *et al.,* 2003, Von Rozycki *et al.,* 2003)

Material / Energy	Unit	Use	Amount
Gravel / Sand	kg/(m*a)	track bedding	530
Concrete	kg/(m*a)	Sleeper	34.3
Steel	kg/(m*a)	Sleeper	1.3
Wood	kg/(m*a)	Sleeper	0
Steel	kg/(m*a)	rail	9.4
Steel low-alloyed	kg/(m*a)	mast	0.74
Zinc	kg/(m*a)	protective coating mast	0
Copper	kg/(m*a)	overhead contact line	0.42
Transport lorry 28t	tkm/(m*a)	track bedding	423.862

Table 6.3 The summarisation of infrastructure type

Network	Types of rail infrastructure (km)			Total distance (km)
	Rail track	Rail tunnel	Rail bridge	
CR	50	0	1,268	1,318
JR Central	216	45	254	515
Korail	116.5	189	112	417.5
SNCF	409	0	0	409
Renfe	621	0	0	621

Table 6.5 The summarisation of material and energy requirement in rail tunnel (Source: Ecoinvent, 2007)

Material / Energy	Unit	Amount
gravel	kg/(m*a)	696
concrete	kg/(m*a)	465
steel low-alloyed/iron	kg/(m*a)	1.58
steel	kg/(m*a)	14.7
ceramics	kg/(m*a)	1.6
zinc	kg/(m*a)	0.006
Aluminum	kg/(m*a)	0.05
copper	kg/(m*a)	0.055
PVC	kg/(m*a)	0.0653
electricity	kWh/(m*a)	569
diesel, building machine	MJ/(m*a)	135
transport lorry building materials	Tkm/(m*a)	103.87
excavation soil	kg/(m*a)	4,850
transport lorry landfill	Tkm/(m*a)	48,500

Table 6.4 The summarisation of material and energy requirement in rail bridge (Source: Maibach *et al.,* 2003, Von Rozycki *et al.,* 2003)

Material	Absolute material consumption	
	Concrete	Steel
Unit	t/km bridge	t/km bridge
Glen bridge	55,000	3,000
Road/railway bridges	89,000	4,900
Material	**Specific material consumption**	
	Concrete	**Steel**
	kg/(m*a) bridge	**kg/(m*a) bridge**
Unit	550	30
Glen bridge	1,780	98
Road/railway bridges	673	36.8

6.4.2 LCA of the operational stage

In calculating HSR operations, this study makes the assumption that an average vehicle's life cycle is 35 years. Additionally, as in equations 6.4 and 6.5, the total time in service is determined based on one round trip each day:

$$EC_{Operation} = \sum_{n=0}^{70} (0.9 \times O_n) \tag{6.4}$$

$$CE_{Operation} = \sum_{n=0}^{70} (EC_{Operation} \times C_n) \tag{6.5}$$

where O_n = output energy at year n; n = {0,1,2…,70}; C_n = CO_2 emission from electric power.

Energy consumption may be calculated as in Equation 6.4 by multiplying the quantity of output energy by 0.9, which is the average conversion efficiency of electrical energy to mechanical power. This analysis makes the assumption that the HSR car has 16 carriages. The electric power rate of 9,450 KJ/kWh is combined with the CO_2 emission rate of 0.392×10^{-3} t/kWh^2 in this study (Herfatmanesh *et al.*, 2013; Gao *et al.*, 2018; Yousefi *et al.*, 2019). Both of these numbers are used in equation 6.5, which calculates CO_2 emissions during the operating stage.

6.4.3 LCA of the maintenance stage

Both rail infrastructures and vehicles are subject to regular maintenance. Infrastructure maintenance include a number of tasks on the rail track, involving work on the ballasted track, track renewal, and rail and other track component replacement

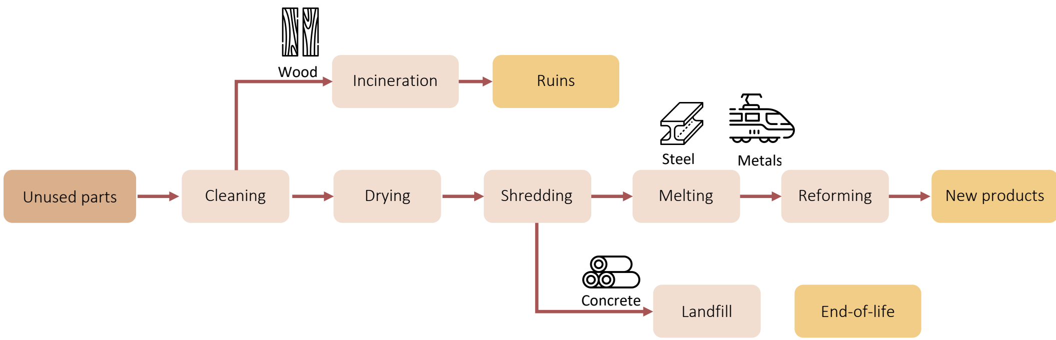

Figure 6.3 An overview of the demolition stage of the railway's infrastructure and rolling stock

(Chester and Hovart, 2010; Rungskunroch *et al.,* 2021). Additionally, the lifespan of train track is set be 70 years. On the contrary, this operation takes into account the upkeep of vehicles with a life expectancy of year 35^{th}. Vehicle replacement is consequently fixed at year 36^{th}.

The amount of LCE and $LCCO_2$ in this section belong to track maintenance, vehicle maintenance, and staff tools used throughout the maintenance operation (machines and cars). According to the estimations, the energy consumption of 16 carriage rolling stock is around 12,500 kWh each maintenance, while the carbon footprint throughout the two rounds of the HSR lifetime is around 190 tonnes (von Rozycki *et al.,* 2003).

6.4.4 LCA of the demolition stage

The demolition stage is the last step of the life cycle of a HSR network, with end-of-life rolling stock and rail infrastructure removed or deleted after 35 and 70 years of operation, respectively. The majority of HSR car bodies are constructed of lightweight materials such as aluminium and alloy, which enables the reuse and recycling of some rolling stock components (Kaewunruen *et al.*, 2018; Rungskunroch *et al.*, 2019). Components that cannot be recycled are shredded and discarded (Yue, 2013).

Similarly, the end-of-life infrastructure components include recyclable and non-recyclable components. The recyclable components are repurposed; for instance, steel scraps can be melted and reshaped for use in building projects. Nonetheless, non-recyclable components, such as ballast, are not recyclable and may contain contaminants. This must be sanitised and disposed of. In terms of the demolition stage, the total life cycle LCE and $LCCO_2$ values comprise the demolition of railway network (track, bridges, and tunnels) and two lots of carriage decommissioning.

6.5 Results

To facilitate comparisons of environmental and economic consequences across HSR networks, all LCA results are standardised to two units: 'GJ/km' and 'tCO_2/km'. Table 6.6 and Table 6.7 indicate the LCE and $LCCO_2$ percentages for each stage of the LCA process; further, Figure 6.4 illustrates the average LCE and $LCCO_2$ at each life cycle stage.

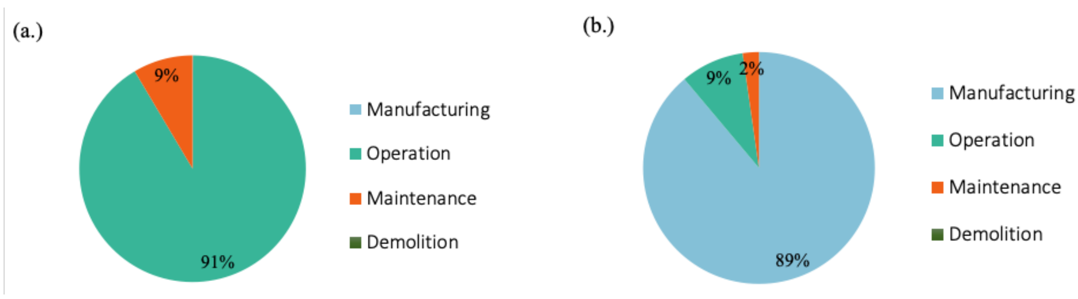

Figure 6.4 The average fractions of (a.) LCE and (b.) $LCCO_2$ from HSR LCA stages

Table 6.6 Summary of LCE results

Life cycle stage	Source	Total LCE				
		JR Central	**CR**	**Korail**	**SNCF**	**Renfe**
Manufacturing	Rolling stock	121.18	150.84	117.69	104.60	72.03
	Infrastructure	4,091.83	8,493.85	2,440.29	1,538.68	2,336.23
Operation	Whole system	4,947,783.22	5,554,449.97	3,059,415.30	1,977,384.81	4,989,760.67
Maintenance	Rolling stock	283,500.00	567,000.00	226,800.00	226,800.00	340,200.00
	Infrastructure	49,101.97	101,926.18	29,283.45	18,464.13	28,034.79
Demolition	Whole system	756.00	360.00	720.00	720.00	720.00
Total LCE (GJ)		5,285,354.20	6,232,380.84	3,318,776.73	2,225,012.22	5,361,123.72
Total LCE per km (GJ/km)		10,262.09	4,728.53	7,948.30	5,439.25	8,632.53
Annual LCE per km (GJ/km)		146.60	67.55	113.55	77.70	123.32

Table 6.7 Summary of $LCCO_2$ results

Life cycle stage	Source	Total $LCCO_2$				
		JR central	**CR**	**Korail**	**SNCF**	**Renfe**
Manufacturing	Rolling stock	5,211,113,050.00	6,486,560,300.00	5,060,974,688.00	4,489,574,320.00	3,097,514,750.00
	Infrastructure	16,504,870.00	950,782.00	8,599,722.00	6,847,677.00	10,394,851.00
Operation	Whole system	566,237,072.20	635,665,579.10	350,127,377.40	226,297,016.80	571,041,079.80
Maintenance	Rolling stock	9,270,000.00	18,540,000.00	7,416,000.00	7,416,000.00	11,124,000.00
	Infrastructure	198,058,444.30	11,409,383.24	103,196,658.60	82,172,127.86	124,732,622.90
Demolition	Whole system	26,040.00	12,400.00	24,800.00	24,800.00	24,800.00
Total $LCCO_2$ (tCO_2)		6,001,209,476.50	7,153,138,444.34	5,530,339,246.00	4,812,331,941.66	3,814,832,103.70
Total $LCCO_2$ per km (tCO_2/km)		11,652,808.65	5,427,262.70	13,246,291.85	11,766,062.45	6,143,028.89
Annual $LCCO_2$ per km (tCO_2/km)		166,468.70	77,532.32	189,232.74	168,086.61	87,757.56

Table 6.8 Summarisation on LCE fraction in each LCA stage

Network	Amount of LCE (GJ)	The percentage of LCE in each of the four phases (%)			
		Manufacturing	Operation	Maintenance	Demolition
JR Central	5,284,976.20	0.08	93.61	6.29	0.01
CR	6,232,200.84	0.14	89.12	10.73	0.01
Korail	3,318,416.73	0.08	92.19	7.72	0.02
SNCF	2,224,652.22	0.07	88.87	11.02	0.03
Renfe	5,360,799.72	0.04	93.07	6.87	0.01

Table 6.9 Summarisation on $LCCO_2$ fraction in each LCA stage

Network	Amount of $LCCO_2$ (tCO_2/km)	The percentage of $LCCO_2$ in each of the four phases (%)			
		Manufacturing	Operation	Maintenance	Demolition
JR Central	6,001,196.46	87.11	9.44	3.45	0
CR	7,153,132.24	90.69	8.89	0.42	0
Korail	5,530,326.85	91.67	6.33	2	0
SNCF	4,812,319.54	93.44	4.7	1.86	0
Renfe	3,814,820.94	81.47	14.97	3.56	0

6.6 Conclusion

The purpose of this chapter is to benchmark EIs and to analyse the overall LCA of HSR networks. The research findings can be incorporated into practical plans for the long-term development of any future HSR project. The chosen networks are evaluated on a variety of parameters, including network performance, technology, location, and service, and include the CR, JR Central, Korail, SNCF, and Renfe networks.

The findings of the LCA study indicate that the majority of LCE occurs during the operational stage, accounting for around 91%. Meanwhile, the majority of the

$LCCO_2$ fraction is formed during the manufacturing step, accounting for about 88 percent of the total. Benchmarking LCE statistics reveals that the CR's HSR network consumes the least energy at 67.55 GJ/km and emits the least CO_2 at 77,532.39 tCO_2/km annually. Whereas the networks of Renfe, JR, SNCF, and Korail release a negligible amount of CO_2.

Notably, our findings demonstrate how to lower the LCE and $LCCO_2$ levels. By utilising EMUs, the LCE value for the operating stage can be minimised owing to lower energy usage. In comparison, CO_2 emissions may be reduced immediately at the rolling stock production stage. This thesis advises that future HSR networks be created responsibly in light of global regulations.

6.7 Chapter summary

This chapter includes a comprehensive life-cycle assessment of HSR's infrastructure and rolling stock over a period of 70 years of service. An in-depth examination of LCE and $LCCO_2$ has been conducted. This part is extremely beneficial for rail authorities and asset owners who need to properly understand their network's performance in comparison to other networks. Additionally, a long-term analysis at each LCA step can serve as a benchmark for any network to take prompt action, regardless of whether it is in the construction, pre-operation, or operation phases.

CR is a leader in energy consumption, consuming 67.55 GJ/km across its full life cycle, according to this chapter's study. In addition, CR is the best at releasing a very minimal CO_2 into the atmosphere, with a CO_2 emission rate of 77,532.32 tCO_2/km. The chapter's KPIs are summarised in Table 6.10 below.

Table 6.10 The summary of KPIs of sustainability pillar

KPIs	Total weight (%)	In-depth analysis	Weight (%)	CR	SNCF	JR Central	Korail	Renfe
Sustainability	20	LCE	10	10.00	8.72	0.00	4.18	2.94
		$LCCO_2$	10	10.00	1.89	2.04	0.00	9.08

The KPIs of sustainability pillars such as LCE and $LCCO_2$ are based on the assessment criteria in Figure 1.5 (Chapter 1). This benchmark is based on the data provided on an annual basis. The success of HSR projects is contingent on a variety of factors and requires a lengthy return on investment. Our findings provide outstanding environmental consequences. The thesis suggests that future HSR projects should be implemented responsibly in accordance with global policy, particularly in light of the climate change challenge. Additionally, the implementation of LCA assessments is a critical factor in ensuring that HSR projects fulfil their objectives. The thesis' outcomes identifies the following significant events and policy suggestions for policymakers.

Whilst HSR networks are claimed to be the cleanest polluting mode of transportation, its emissions account for 14% of global emissions. Efforts to minimise CO_2 emissions may be bolstered by switching to electric multiple unit locomotives (EMU) and utilising alternative low-emission energy sources such as biofuel, hydrogen, and other renewables. As a result of the large shift in energy needs across the HSR lifespan, the amount of LCE in operational stage can be lowered. In terms of sustainable development, flawless connections can encourage travellers to switch from private vehicles to HSR and public transit. This move can result in a direct reduction in CO_2 emissions in long term.

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CHAPTER 7

Urbanisation and policy implications

This chapter evaluates the socio-economic impacts of the HSR services of the five selected networks. This thesis employs large data analytic approaches and analyses using Python models, a computationally intensive programming language. Additionally, the model is coupled using KNN (K-nearest neighbour) and PCC (Pearson's correlation coefficient) methods. 30 HSR experts in railway networks, either academic or industrial have been interviewed in this study's analysis. The policy implications for the long-term development of new HSR networks are discussed profoundly, with the goal of enhancing social and economic sustainability.

7.1 Introduction

Today, the growth of HSR services is perceived as a catalyst for enhancing cities' potential and unleashing societal benefits. HSR networks are viewed as a novel and intelligent form of public transportation since they have the potential to stimulate economic growth in both rural and urban areas (Kojima *et al.*, 2017; Rungskunroch *et al.*, 2020). The HSR service functions as a stimulus for urban-suburban connection. The extensive and seamless connection afforded by HSR networks generates enormous national interest in passenger transport. For example, the Chinese HSR network facilitates domestic travel within the country and links China to its borders, resulting in boosted commercial opportunities. China's GDP is anticipated to increase by roughly 1-3% as a result of the HSR network (Xu and Huang, 2019). Similarly, tremendous expansion of HSR networks can be witnessed in European countries. Since 2000, the EU has invested about 23.7 billion euros in HSR infrastructure, leading in a network expansion from 643 km in 1985 to 9,226 km in 2020 (EEA 2014; Statista, 2020). The expansion of HSR networks has increased the number of passengers utilising HSR services from 15 billion pkm in 1990 to 124 billion pkm in 2016. (EC, 2018). HSR services provide smooth cross-border travel for passengers and promote the economies of EU member states through increased productivity, job development, and market expansion.

While the socio-economic consequences have undoubtedly been reflected in society, particularly through the perspective of adults, such advantages cannot fully represent the ideals of the whole population. Thus, this thesis fills a knowledge gap by assessing the socio-economic consequences on all stakeholders, including children and the elderly, in terms of quality of life (QoL), educational opportunities, and socio-economic advantages. The findings highlight both the strengths and limitations of each HSR network. This research utilises World Bank's primary data sources to ascertain the socio-economic consequences of a variety of critical HSR networks. The new insights from this study are broadly relevant to policymakers in order to conduct an assessment of existing HSR networks and build an effective strategy for future HSR networks.

This study created novelty Python models by combining the KNN and PCC techniques. The results are then categorised by socio-economic factor into three categories: QoL, educational factors, and economic and employment variables. This chapter's new contribution has a wide variety of applications in terms of assessing the socio-economic advantages of various HSR networks. Additionally, this research conducted a detailed survey of 30 worldwide HSR specialists in academics and industry sectors to gather expert comments to supplement the data analysis.

7.2 Background

HSR networks appear to have benefited society in both direct and indirect ways. Socio-economic circumstances, such as population increase and area economic development, are recognised as indirect advantages of HSR services. Many studies have been conducted to determine the influence of HSR networks in a variety of areas as follows;

7.2.1 Shortening journey time

The impact of shortened travel time has been systematically reviewed due to vast developments in technologies. According to existing studies, the time reductions from HSR services clearly offer benefits over other transportation modes. HSR services drastically reduce journey times between cities compared with conventional railway services. Decreasing travel time is the most important effect from HSR because massive savings in time attract passengers to use HSR services (Yin *et al.,* 2015); in other words, HSR can change passengers' behaviours and attitudes towards this mode of transportation.

Since HSR services have become a travel choice, they have gained market share from competing transportation modes, especially airlines. This is because it is capable of delivering high-frequency rail services, which reduce travel times, connect major cities, and provide comfortable service. Additionally, the reduction of trip times is the single most important aspect of meeting consumer expectations (Pepy and Leboeuf, 2005; Hall, 2007). As a result, several studies have discussed the effective range of HSR services. Nevertheless, the precise distance has not been disclosed because it is dependent on uncontrollable circumstances. Some scholars state that the most efficient distance for HSR services is in the range 483-692 km

(Albert and Bel 2012), whereas others mention distances in the range 500-700 km as appropriate for services (Kojima *et al.,* 2017; MLIT, 2010).

The reduction in travel times comes not only from HSR operating speeds, but also from the accessibility of HSR stations. Most HSR projects have been compared with airline services in terms of travel time and cost. As an example, the California High-Speed Rail Authority (CAHSR) plans to launch a HSR project along the USA's west coast. The project aims to linking downtown San Francisco and Los Angeles, which are two of California's economic centres. Studies have compared HSR, airplanes and private cars in terms of travel time, revealing that HSR services offer a minimum travel time of 3.10 hours, while airplane and car journey times are 5.20 and 7.20 hours respectively (US High Speed Rail Association, 2015).

Another example of the study is Europe, where HSR appears to be more competitive with medium-haul airline services than with short- and long-distance travel, owing to its effective route duration (Albalate *et al.,* 2015). For instance, Eurostar's market share on the London-Paris route has grown significantly in comparison to aircraft services (Behrens and Pels, 2012). In conclusion, HSR reduces the amount of time spent on airline check-in, security, and waiting operations. Additionally, HSR services save travel time between cities and airports due to convenient access to HSR stations.

7.2.2 Population dynamics

Another significant aspect of HSR services is their regional accessibility. According to Geurs and van Wee (2004)'s research, transportation is one of four elements that determine accessibility, along with land use, temporal, and individual components. It promotes long-term regional development and benefits residents in catchment areas.

Population dynamics is related to urbanisation's accessibility, relocation, and other significant aspects in human existence, such as housing and employment. After the Tokkaido

Shinkansen began operation, population growth was slightly more significant along HSR lines (Amano and Nakagawa, 1990). Also, it was 22% higher in cities with HSR stations than in cities without stations (Hirota, 1985). Moreover, half of the prefectures with at least one HSR station had population growth more than the national average. These effects of HSR were also shown on the Tohoku line, representing a population growth of 32% in cities close to HSR stations; in contrast, areas without HSR services showed no significant population growth (Obermauer and Black, 2000).

In Spain, people were attracted to live in Ciudad Real. Some scholars find that there is a high demand among people to live near to HSR stations. The HSR service has provided opportunities for passenger travel between the city and Madrid (Coronado *et al.*, 2019). Additionally, the impact of Swedish HSR indicated that the service had prompted an increase in the number of inhabitants living in Eskilstuna, an area city with a HSR station that provides excellent connections to Stockholm (Fröidh, 2005).

Some research demonstrated the advantages of expanding regional accessibility as a result of the time-space convergence effect (Spiekermann and Wegener, 1994). Additionally, HSR services exacerbate regional spatial imbalance (Jin *et al.*, 2017; Monzon *et al.*, 2019), since long-term connection favours residents of locations with HSR stations via improved QoL.

Employment and the labour force both have a significant role in population dynamics. Some scholars mentioned that HSR services have a direct influence on the employment rate and economics of an area. Additionally, the labour force has risen after the coming of HSR because the service offers accessibility between industry and residential areas. In Japan, several job sectors, such as retail food and lodging, benefited significantly from Shinkansen networks (Okabe and Miki, 1984; Hirota, 1985; Brotchie *et al.,* 1991). Meanwhile, the economic effect of China's HSR has been revealed with the enlarging of the network. Some scholars state that the Chinese HSR network was designed more with the intention to support a high volume of passenger demand than a concern with an economic impact, as in other countries (Xu and Huang, 2019). However, the network has also reformed the landscape of China's economic distribution. In Europe, most HSR stations are located in city centres and are integrated with those cities' internal transit systems (Banister and Berechman, 2001). For this reason, European networks are more accessible. Also, this leads to very positive impacts on employment in these areas.

Similarly, in Europe, HSR services have been associated with urban job possibilities. By 2026, the High-Speed 2 (HS2) line will provide around 22,000 employments in the United Kingdom (Eyles, 2013). Additionally, an additional 100,000 jobs are anticipated with the opening of Spain's Atlantic HSR (Fernandez-Macho *et al.*, 2012). Several researchers have examined the influence of the French HSR on urban economies, including research that quantifies suburban job density (Chen *et al.*, 2014). The findings indicate that while job possibilities are clearly increasing in towns with HSR services, non-HSR areas have also experienced development in the labour market. As a result, growing work possibilities might be attributed to a variety of other reasons.

Previous studies have mentioned that HSR services bring positive effects for local business and economy. The opening of HSR lines provoke investment in various businesses such as real estate, tourism and community facilities. Some authors point out that HSR services actually support short-term supply more than air services (Blanquart and Koning, 2017). This is not only through savings in travel costs, but these services also reduce travel time. This becomes a crucial tool for increasing the potential of local markets, especially for the services sector, such as marketing. According to some research, acceptable travel expenses can amplify local advantages. This is because urban productivity and economic activities can be spread to neighbouring areas, where people can be reached by HSR services (Combes and Lafourcade, 2012).

7.2.3 Property and land prices

With respect to property and land prices, the coming of HSR services increases the quality of residential areas because they support people's accessibility to visit other places. This can be confirmed by increased property prices around stations. Building obviously gains a positive impact from the location of stations, with commercial properties within 0.25 miles of stations shown to be 12.2% more expensive than residential properties. Also, there is a variation of 4.2% in the price gap between area around railway stations and other zones (Debrezion *et al.*, 2007). In addition, area with railway stations that are close to central business districts (CBD) have seen the greatest impact on property costs (Bowes and Ihlanfeldt, 2001).

Additionally, many studies have revealed a statistically positive impact on land and property values near to HSR stations. In another case study, Le Mans in France, transactions of buildings and land doubled in number within three years after the opening of a HSR station; in the same period, the land and accommodation prices also doubled (Sands, 1993). In Taiwan, however, access to HSR has shown no significant effects on property values and land prices (Andersson *et al.,* 2010). Therefore, the study of the impact of HSR on property value focused on further development. The comparisons of land prices before and after the opening HSR of stations has become a necessary part of finding out the most influential factor.

Several scholars have examined the probable influences on property values in eight HSR stations in eight European nations (de Jong *et al.,* 2007). The research's findings indicated that regional economies were the most critical element. Moreover, transit accessibility and the availability of public resources have had a significant influence on property values. In 10 nations, a benchmarking study of the impact of HSR's stations discovered that the placement of HSR stations was the most significant factor impacting property values and societal influence (Gargiulo and De Ciutiis, 2008).

Table 7.1 The summarisation of research areas regarding the effects of HSR and social impacts

Author(s)	Year	Socio-economic factors				In-depth analysis	
		Travel time	Population Dynamic	Employment and Economic	Property and Land price	Worker group	All age groups
Albalate *et al.*	2015	✓					
Albert and Bel	2012	✓					
Amano and Nakagawa	1990		✓				
Andersson *et al.*	2010				✓		
Banister and Givoni	2013			✓		✓	
Behrens and Pels	2012	✓					
Blanquart and Koning	2017			✓		✓	
Bowes and Ihlanfeldt	2001				✓		
Brotchie	1991			✓		✓	
Chen	2014			✓		✓	
Combes and Lafourcade	2012			✓			
de Jong	2007				✓		
Debrezion *et al.*	2007				✓		
Dolinayova *et al.*	2018			✓			
Eyles	2013			✓		✓	
Fernandez-Macho *et al.*	2012			✓		✓	
Fröidh	2005		✓				
Gargiulo and De Ciutiis	2008				✓		
Garmendia *et al.*	2008		✓				

Geurs and van Wee	2004		✓				✓
Hall	2009	✓					
Hirota	1984			✓			✓
Högdahl *et al.*	2019	✓					
Hunt	1971			✓		✓	
Jin *et al.*	1989		✓				
Kojima *et al.*	2017	✓					
MLIT	2012	✓					
Monzon *et al.*	2019		✓				
Nakamura and Ueda	1989			✓		✓	
Obermauer and Black	2000		✓			✓	
Okabe	1980			✓		✓	
Pepy and Leboruf	2005	✓					
Pepy and Perren	2006	✓					
Sands	1993				✓		
Spiekermann and Wegener	1994		✓				
US High Speed Rail Association	2009	✓					
Yang *et al.*	2018			✓			
Yin *et al.*	2015	✓					

As shown in Table 7.1, many research has established that HSRs have certain effects on social benefits. The majority of them concentrated on a single socio-economic pillar, which favoured a concentration on adults. This fascinating statistic highlights a significant information gap in terms of defining the socio-economic of a whole society, which should affect all demographic groups. Additionally, a research area has been quite narrowly defined inside a particular city, region, or nation. For this reason, the published research remains limited in terms of benchmarking among rail networks or nations, resulting in a lack of long-term sustainable development success.

To address the aforementioned knowledge gaps, this chapter evaluates the impacts of HSR networks while also revealing their social consequences in terms of population dynamics, access to education, employment opportunities, and other factors, with the goal of ensuring the long-term sustainability of HSR networks.

7.3 Methodology

7.3.1 Availability of data

In order to analyse the social consequences of HSR services, the research draws on long-term social factor data sets published by the World Bank, a reputable source (World Bank, 2020). The collection timeframe has been set during each network's first year of operation to 2019. Twelve social variables of population dynamics, educational, economic, and workforce variables are all included in the data sets.

These factors have been split into three groups, including QOL, education and employment factors. It can be examined to find correlations between social impact and the growth of HSR operations since they came into service. The social factors are illustrated as follows:

- **Population growth** – The factor reflects a country's sustainability under strain. Significant population expansion will have a detrimental effect on agricultural land availability and will exacerbate demand for food, social services, and infrastructure.
- **Age dependency ratio for the young generation** – The factor shows the ratio of younger dependents (under 15 years old) to the working-age population (15-64 years old).
- **Age dependency ratio for the old generation** - The factor shows the ratio of older dependents (over 64 years old) to the population of working-age (15-64 years old).
- **School enrolment in three levels (primary, secondary, tertiary)** – The factor is the ratio of registered student of compulsory school age to the number of compulsory school age equivalents. The education factor is included in the development plan of the UN and UNESCO.
- **Progression to secondary school** – The factor shows the number of new students admitted to the secondary school in a certain year represented as a proportion of the entire student population.
- **Primary completion rate** – The factor shows the total number of new students in the final grade of primary school divided by the total student at the final year entrance age.

- **Labour force** – The factor shows the number of individuals aged 15 and older, who provide labour for the production of goods and services over a specified period of time.
- **Employment to population ratio** – The factor shows the percentage of the population that is employed in a country.
- **Unemployment rate** – The factor shows the percentage of the labour force that is unemployed but available for and seeking work.
- **Women's representation in national legislatures** – The factor shows the proportion of women who hold seats in parliament. It is related to employment and gender inequalities.

The outcomes can give a true reflection of how the growth of HSR networks impacts all generations, leading to long-term sustainable development.

7.3.2 Research methodology

After the data collection stage, a pre-processing data stage is implemented to verify the acquired data, as shown in Figure 7.1. According to the analysis of long-term data, certain values in the gathered social factor information are missing. Therefore, Python is used to construct the k-nearest neighbour (knn) model for predicting this missing data. Then, correlation analysis is used to determine the effect of social variables on the growth of the HSR network. Finally, the 30 HSR expert's reviews have been attached to discover practical policy implications.

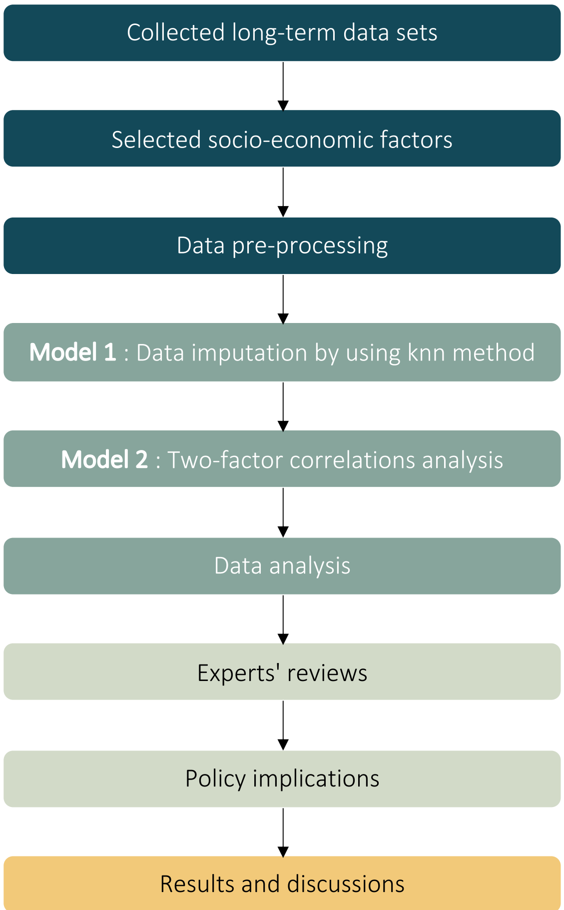

Figure 7.1 An overview of research methodology including collecting long-term data sets, creating novelty models, interviewing HSR's experts, and providing policy implication.

7.3.3 K-Nearest Neighbour

The K-Nearest Neighbour (KNN) algorithm is a supervised machine learning technique that is frequently used to fill in gaps in data sets. The KNN idea is straightforward: it simply fills in missing data with the most precise or closest values. The value of k varies according to the quantity of full data contained in the data set. For instance, if k is set to 5 (*k=5*) the five nearest data points are then utilised to compute a new value to replace the missing value using specified functions.

On the other hand, selecting the k value incorrectly might result in an erroneous assessment of the new data point value. A k-value that is too small misses the data set's trend, but a k-value that is too large causes disruption in other values (Guo *et al.*, 2003; Mani and Zhang, 2003; Wong *et al.*, 2009). According to some scholars, the optimal fit for the k-value may be attained by testing several k-values against the data set in order to minimise arbitrary errors (Wong *et al.*, 2009; Beretta and Santaniello, 2016). As seen in Equation 7.1, this research employs the conventional Euclidian distance form.

$$d(a,b) = \sqrt{(a_1 - b_1)^2 + (a_2 - b_2)^2 + \cdots + (a_n - b_n)^2} \tag{7.1}$$

where: d = Euclidean distance between the point a and b, a = $\{a_1, a_2, \ldots, a_n\}$ and b = $\{b_1, b_2, \ldots, b_n\}$.

7.3.4 Pearson's correlation coefficient (PCC) analysis

In statistical studies, Pearson's correlation coefficient (PCC) is critical. This technique is used to determine the connection between two variables or data sets (Benesty *et al.,* 2008; Sheugh and Alizadeh, 2015; Akoglu, 2018). An analysis indicates a value of between -1 and 1. Numerous elements of PCC data analysis are relevant to this field of study. The PCC is interpreted differently in different disciplines, as shown in Table 7.2, with the range for weak connections in psychology being less than 0.3, 0.2 in politics, and 0.5 in medicine (Akoglu, 2018).

In this thesis, scores between 0.1 and 0.3 indicate a weak relationship, 0.3 and 0.5 indicate a moderate relationship, and 0.5 and 1.0 indicate a significant relationship (Rungskunroch *et al.*, 2021). A positive number indicates that both variables are in direct correlation, whereas a negative value indicates that both variables are in inverse correlation.

The PCC is used in this study to analyse the link between social variables and the expansion of HSR networks, as indicated in equation 7.2.

$$\mathbf{P} = \frac{\sum(\boldsymbol{P_i} - \boldsymbol{p})(\boldsymbol{Q_a} - \boldsymbol{q})}{\sqrt{\sum(\boldsymbol{P_i} - \boldsymbol{p})^2 \sum(\boldsymbol{Q_a} - \boldsymbol{q})^2}} \tag{7.2}$$

where: P = Correlation coefficient, P_i = values of the social factors i, p = mean of the values of the social factors i; Q_a = the length of the HSR network in year a; q = mean of the length of the HSR network.

Table 7.2 The interpretation of the Pearson correlation coefficient in different research areas (Source: Akoglu, 2018)

Interpretation	Research areas			
	Engineering [a]	**Psychology [a]**	**Politics [a]**	**Medicine [a]**
Perfect relationship	-1 (negative) or 1 (positive)			
Strong relationship	± 0.5 - ± 1.0	0.7 – 0.9	≥ 0.4	0.8 – 0.9
Moderate relationship	± 0.3 - ± 0.5	0.4 – 0.7	0.3	0.7 – 0.6
Weak relationship	± 0.1 - ± 0.3	< 0.3	< 0.2	< 0.5
No relationship	0			

7.3.5 Applications of PCC to railway research

Due to the vast range of benefits associated with PCC, several studies in railway research have used this approach as the primary methodology. PCC is used to increase the efficiency of railway operations. It has contributed to long-term improvements in safety performance. Liu and Markine (2019) used PCC to assess the safety of railway crossings during severe weather. The research discovered that some indicators (i.e., fatigue area, vertical acceleration) need to be modified to accurately assess the condition of railway crossings. Additionally, some study was conducted on the circumstances of railway track monitoring by using PCC (Balouchi *et al.*, 2019). Sadeghi and Hasheminehad (2016) also discovered a link between rail curvature and tangent track roughness in order to investigate rolling stock noise. PCC has also been used to forecast ground-borne vibration situations. This study revealed a way to mitigate the environmental impact of unavoidable vibration (Ntotsios *et al.*, 2020; Ntotsios *et al.*, 2017).

Additionally, the PCC has been widely utilised in railway studies to improve technical services. Hazal and Zübeyde (2020) evaluated vertical and lateral rail wear by examining traffic loads and track characteristics. Traffic loads are imprecise data based on unknown passenger counts and material quantities. Consequently, a correlation study is performed to determine the predictive ability of the models developed throughout the research. Another research examined relationships between track geometry and variable settlement, particularly the association between track stiffness and variable settlement. By incorporating PCC into the research, it was possible to acquire exact measurements of track vertical stiffness, resulting in improved maintenance performance and less environmental impact (Nielsen *et al.,* 2020).

Additionally, PCC has been used in railway studies for land use categorization. The findings resulted in the long-term enhancement and management of regions next to train stations. Zemp and *et al.*, (2011) analysed 1,700 Swiss railway stations using PCC, taking into account contextual variables such as station density and intended usage of train services. PCC provides categorization within the context of the system structure, resulting in strategic planning for railway stations to accommodate variable passenger demand. Huang and *et al.*, (2018) investigated the influence of network dynamics in China, using PCC to examine the correlations between various networks. The findings suggested the existence of successful policies worthy of further research.

PCC is not only used to boost technical performance. Some researchers used PCC to boost service capabilities. Miranda and *et al.*, (2018) emphasised the importance of service quality and customer satisfaction in the railway sector's development. The study surveyed passengers and used PCC to determine the correlations between eight critical variables, including convenience, connectivity, and dependability. This technique directly benefits the railway sector by allowing them to meet customer expectations ahead of their competition.

To verify the correctness of the models used in this work, those models are compared to a PCC analysis of the economic impact of French HSR investment on metropolitan agglomerations. Another study utilised the same approach to determine the correlation between HSR networks and the population from 1981 to 2009, yielding a PCC-value of 0.981 (Chen, 2014). Similarly, this study analyses the identical data set and arrived at the same PCC conclusion.

7.4 Results and discussion

The purpose of this section is to examine the social consequences of the expansion of five selected HSR networks. The study makes extensive use of PCC to establish correlations between the elements that contribute to future gains.

As seen in Figure 7.2, the expansion of HSR network operations has obviously varied between nations due to their respective growth goals and policies. Japan, for example, is the first country to use HSR, beginning the Shinkansen service in 1964 and progressively expanding the network in response to passenger demand. The Shinkansen network provides a superior level of comfort and reliability. For these compelling reasons, the Shinkansen network has grown in stature, having a substantial influence on Japanese life (Evans, 2010; Rungskunroch *et al.*, 2019). As a consequence, the network has established itself as a model for other nations.

Another case of interst is China, which launched its HSR network in 2008 and now accounts for roughly two-thirds of all HSR networks worldwide (Chen and Haynes, 2015; Chen *et al.*, 2016; Rungskunroch *et al.*, 2020). The overall length of the

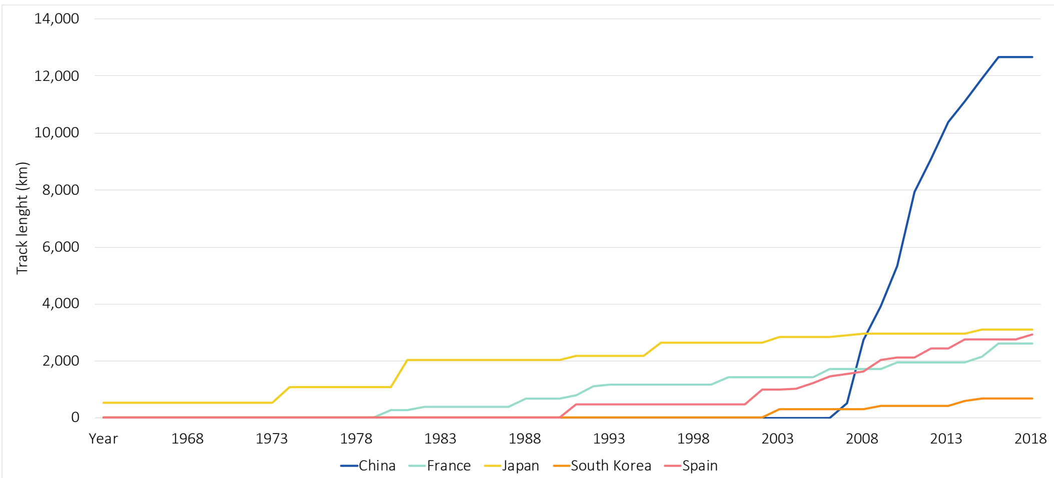

Figure 7.2 Comparison of growth of rail networks operating in five countries during the

Chinese network in service was 12,699 km in 2019. Moreover, the government has proposed building another 38,000 km by 2025 (He *et al.,* 2021). This is because many analysts believed the Chinese network has boosted the country's economy significantly by promoting commercial linkages with its neighbours. As a result, the magnitude of each HSR network's societal effect is determined by a variety of internal elements.

This chapter focuses on three categories of social factors: the QoL, education, and employment. The twelve factors are as follows: population growth, age dependency ratios for the young and old generations, school enrolment at three levels (primary, secondary, and tertiary), progression to secondary school, primary completion rate, labour force participation rate, employment to population ratio, unemployment rate, and proportion of women in national paliament. These variables are analysed for correlations with the expansion of HSR operations from their inception. The findings may provide an accurate representation of how the expansion of HSR networks affects all generations.

The PCC analysis reveals the results related to these 12 variables by nation, as shown in Table 7.3. PCC results are in the range of -1 to 1, which explains the link between HSR network expansion and PCC results. Additionally, Figure 7.3-7.7 depicts the entire correlation analysis for all nations.

Additionally, the variables in this study are classified into three pillars, with the average findings shown in Table 7.4.

7.5 Overall social impacts of HSR networks

In terms of the pillars of the QoL, this includes population growth and the age dependence ratios of the young and elderly generations. To begin, one of the variables that contributes to the description of population dynamics is population growth. According to the United Nations (2015) study, population dynamics include changes in population growth rates, age structure, and population dispersion. In all five nations,

Table 7.3 The summarisation of PCC results of 12 social factor of each HSR network

Social factors	Abb.	PCC's results				
		CR	SNCF	JR Central	Renfe	Korail
Population	PD1	0.97	0.97	0.94	0.93	0.93
Age dependency ratio, young	PD2	-0.03	0.75	-0.94	-0.88	-0.27
Age dependency ratio, old	PD3	0.89	0.97	0.88	0.95	0.92
School enrolment, primary	ED1	0.92	-0.77	0.24	-0.82	0.08
School enrolment, secondary	ED2	0.89	0.6	0.96	0.8	0.93
School enrolment, tertiary	ED3	0.94	0.94	0.92	-0.37	0.94
Progression to secondary school	ED4	-0.71	0.5	0.69	0.21	0.55
Primary completion rate	ED5	-0.68	-0.17	0.24	-0.41	-0.35
Labour force participation rate	EC1	-0.95	0.17	-0.75	0.66	0.84
Employment to population ratio	EC2	-0.96	0.34	-0.78	0.62	0.38
Unemployment	EC3	0.52	0.27	-0.66	-0.47	-0.25
Proportion of seats held by women in national parliaments	EC4	0.89	0.9	0.6	0.91	0.89

the PCC findings for population dynamics are at least 0.93. This might be regarded as an exceptionally favourable association between HSR networks and population trends.

On the other hand, the age dependence ratios between the young and elderly generations quantify the HSR's impact on life quality. Regarding the seamless connectivity of HSR networks, several studies emphasise on how HSR services improve accessibility to essential locations such as schools, hospitals, and community malls (Tian *et al.*, 2011; Tian *et al.*, 2012). This improves the QoL for those living near train stations and in their catchment regions.

The average PCC-value for the elederly group is at least 0.88, but the average value for the younger group is -0.27, as shown in Table 7.4. It implies that HSR services appear to have a stronger favourable association with older groups than younger groups. However, the idea of accessibility to HSR services is different, since the elderly are able to travel independently, while young people are typically accompanied by their parents. In other words, the HSR network has a significant impact on the elderly than younger groups.

Table 7.4 The summarisation of PCC results in QoL, education, employment categories.

HSR Network	QoL	Education	Employment	Average
CR	0.61	0.27	-0.13	0.25
SNCF	0.90	0.22	0.42	0.51
JR Central	0.08	0.41	0.14	0.21
Korail	0.34	-0.12	0.43	0.22
Renfe	0.53	0.43	0.47	0.47

Obtaining a proper education is one of the key factors that has driven society forwards. This study measures the opportunity for children to attend schools at three levels: primary, secondary and tertiary. These attendance rate factors point exactly to the impact of HSR services for the young generation. In fact, children in developing countries have a lack of access to education (UNESCO, 2020). Some studies reveal that many children must walk to/from school for up to six hours daily, because their homes are so far away from school. Additionally, the same issue is still found in the suburban areas of developed countries, because children living in remote rural areas need as high a standard of education as children living in cities. Therefore, the coming of HSR has potentially brought equivalence to people who had difficulties in accessing a proper education system. The PCC results show that the average enrolment rate in primary school is -0.07, which means HSR services have a low negative correlation with this factor. On the other hand, the enrolment rates in both secondary and tertiary levels surprisingly show a strong positive correlation, at 0.84 and 0.68 respectively, with growth of HSR networks. It can be implied, therefore, that HSR services can truly improve educational opportunities for the younger generation.

From previous studies, it remains unclear to what degree HSR services are attributed as having an education benefit for the young generation. In this research, data sets for progression to secondary school and primary completion rates have also been collected. These factors are used to evaluate the advancement of enrolled students and to reflect their capabilities. The PCC outcomes show a positive correlation for progression to secondary school in all five countries, except China, whereas, the result for average primary completion rates is -0.28, a negative correlation. In conclusion, HSR services offer a truly positive impact for the young generation, especially in terms of the education pillar. The research impressively reveals that HSR networks can stimulate strong student enrolment rates for schools at all levels. However, the impact of HSR services on student performance has not been clearly measured due to the values indicating weak relations.

Expanding the national economy and stimulating local markets are targets that countries aim for when launching HSR networks. This thesis has investigated data sets for labour force participation rates, employment, unemployment and proportions of seats in national parliaments taken by women. The outcomes are expected to justify the size of the impacts from HSR networks on the countries' economies. By using long-term data, this thesis finds that the HSR has greatly stimulated the labour market in Spain and South Korea, and partially stimulated it in France. These countries show a positive correlation between labour market factors and growth of HSR networks. With respect to the employment and unemployment rates, these factors are reflected in the economy both locally and nationally.

As many studies have stated, the coming of HSR can enlarge business areas and truly increase job opportunities, while tourism and local business should also benefit directly from growth in passenger demand (Kojima *et al.,* 2017). Nevertheless, the Japanese job market shows a weak negative relation with the growth of the Shinkansen network. This can be interpreted as the network not being the key development factor for Japan's economy, but is merely a supporting factor.

Lastly, women's job opportunities are believed to be improved with the coming of HSR. The research has analysed the proportion of seats held by women in national parliaments as a factor that not only reflects the position of women, but also measures gender equality. The outcomes show an average value of 0.838, which means a very strong positive relationship with HSR network growth.

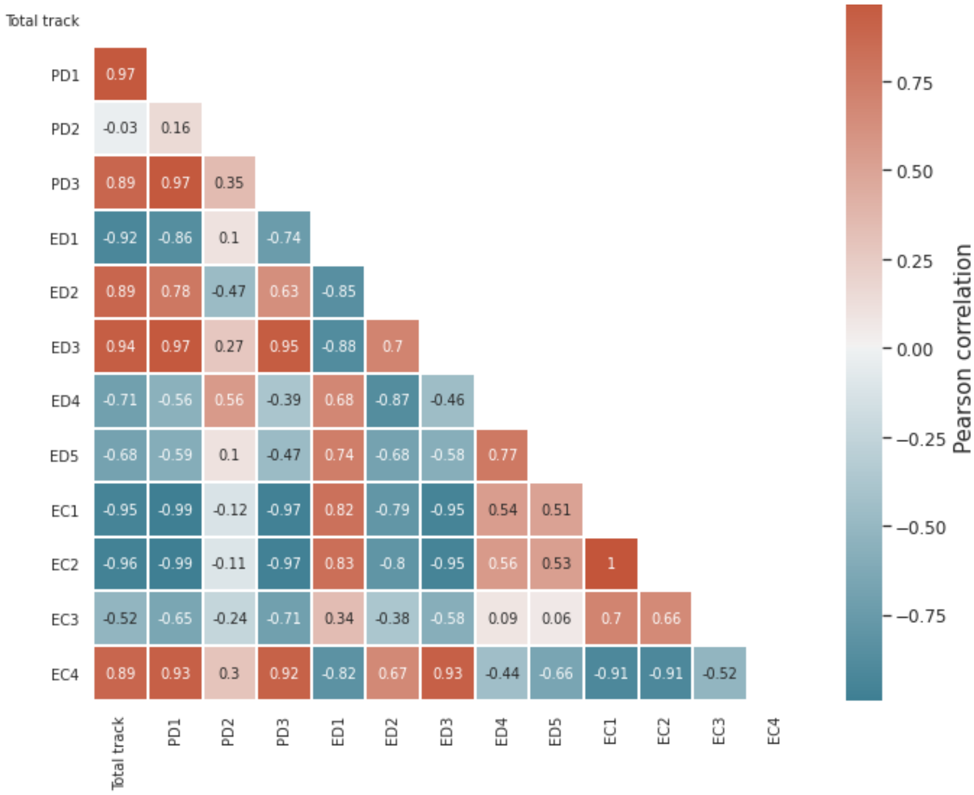

Figure 7.3 The PCC's result of CR network and social impacts in China

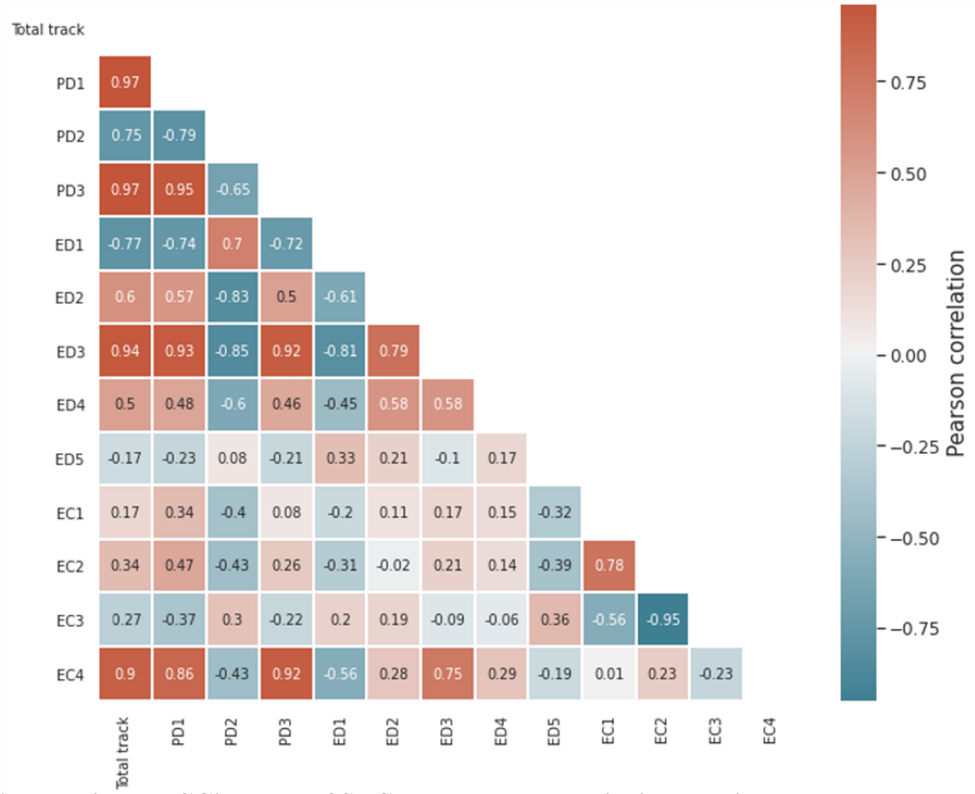

Figure 7.4 The PCC's result of SNCF network and social impacts in France

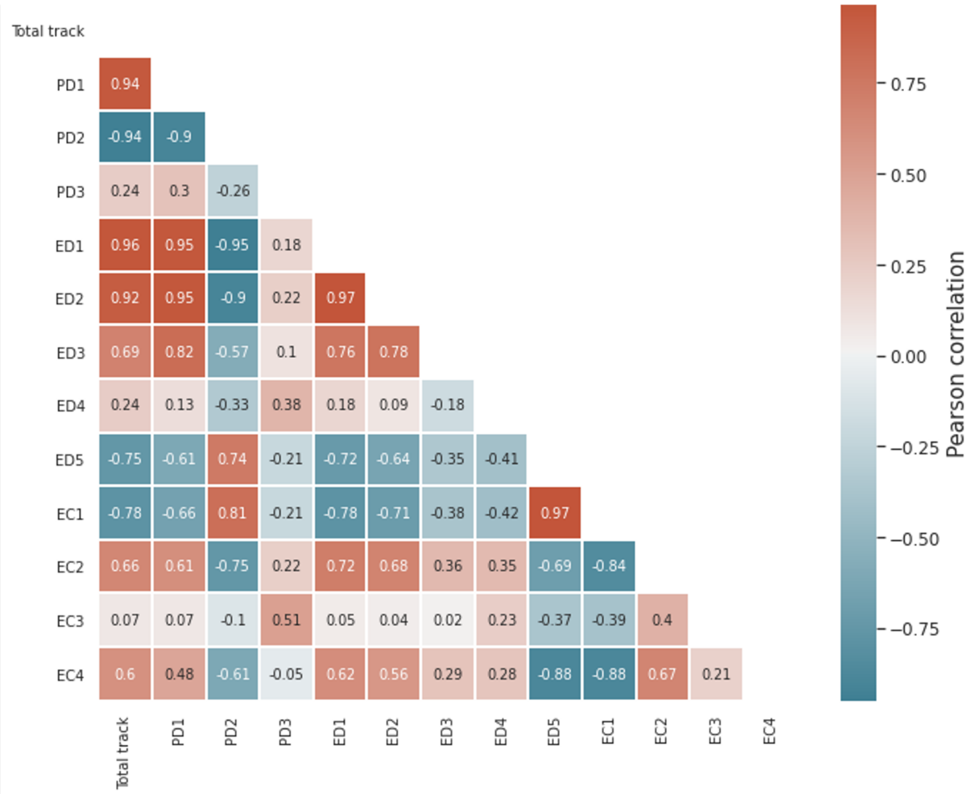

Figure 7.5 The PCC's result of JR Central network and social impacts in Japan

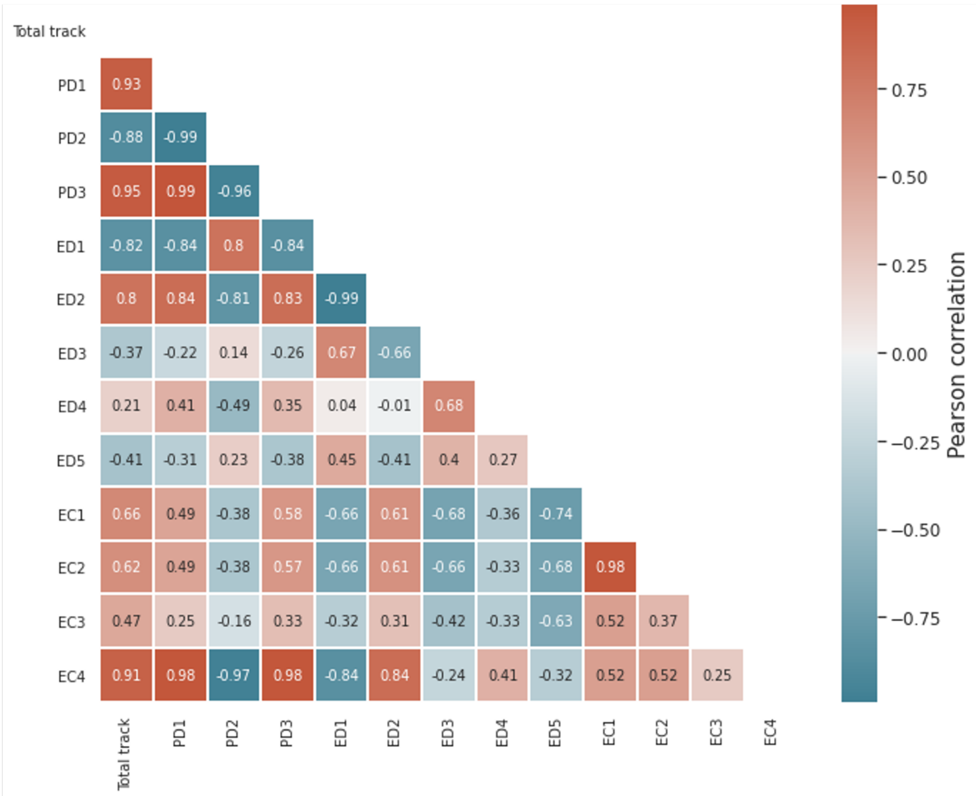

Figure 7.6 The PCC's result of Korail network and social impacts in South Korea

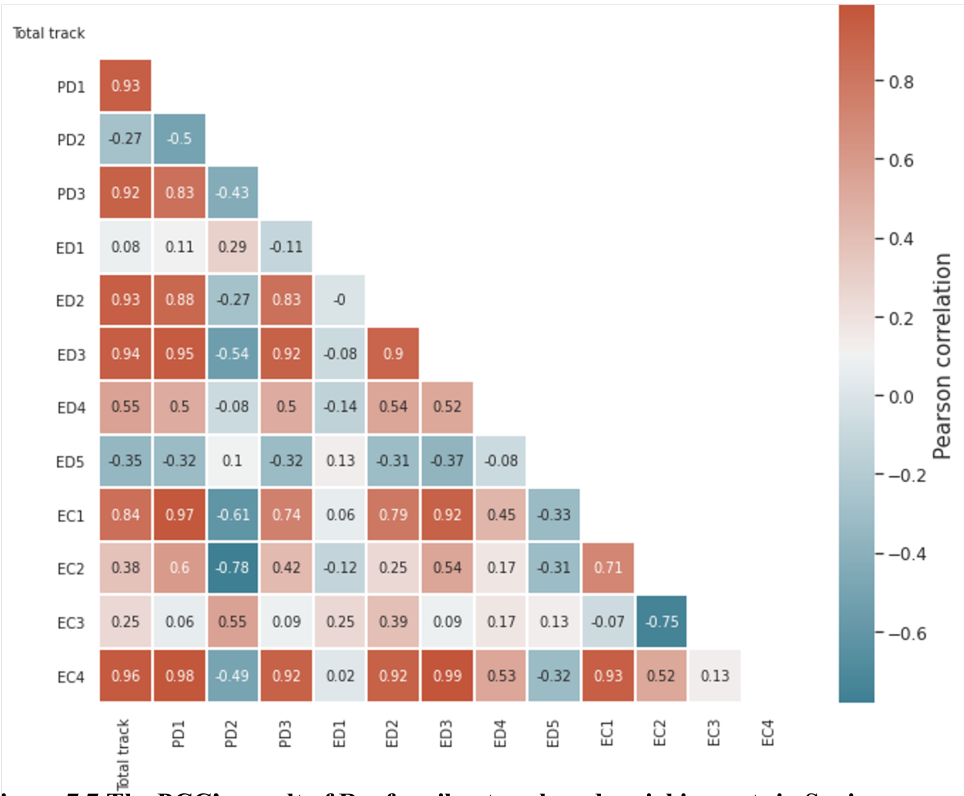

Figure 7.7 The PCC's result of Renfe rail network and social impacts in Spain

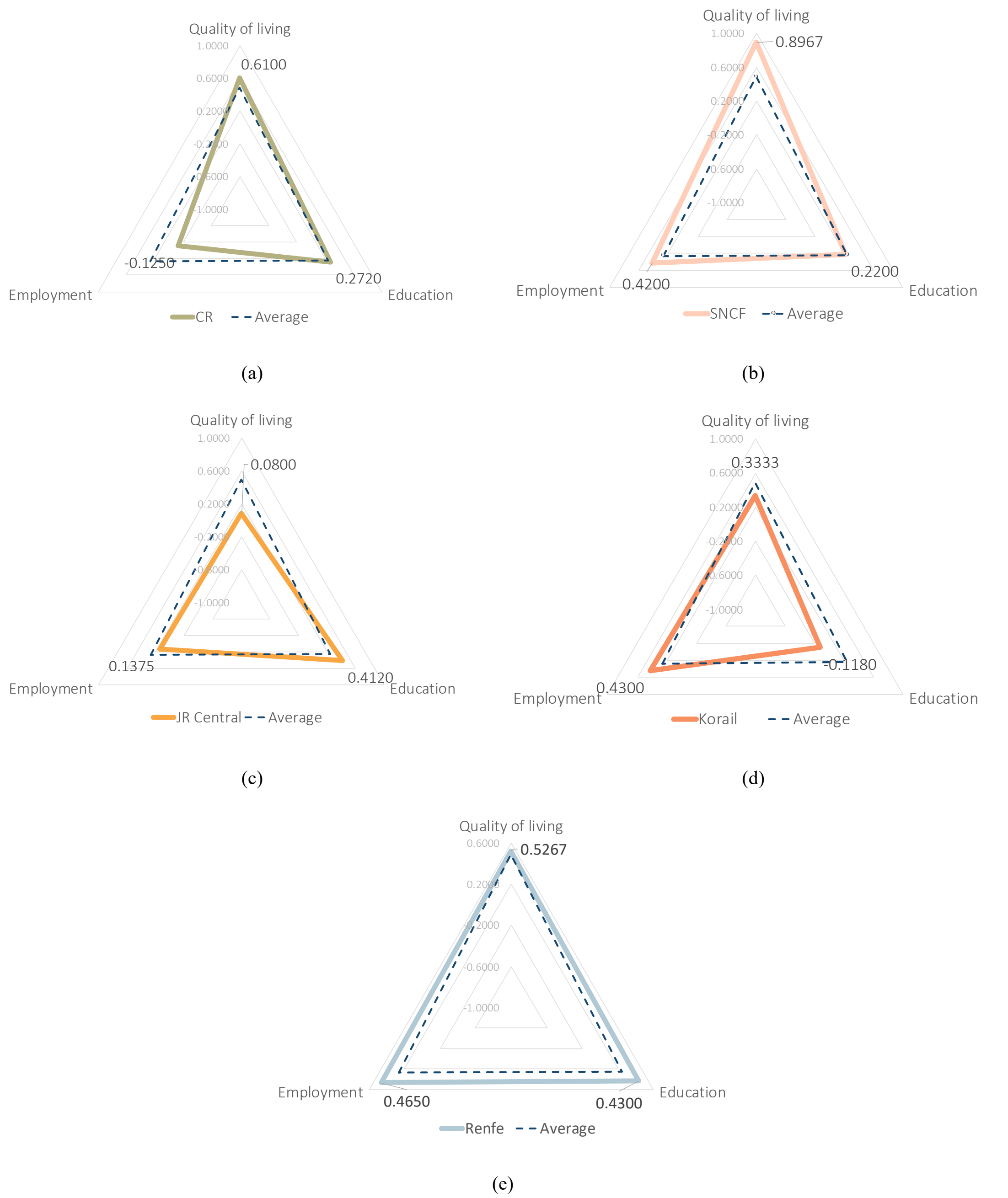

Figure 7.8 The comparison on the radar charts of quality of living, education and employment from (a.) CR (b.) SNCF (c.) JR Central (d.) Korail and (e.) Renfe networks

7.6 Overall impact of HSR networks by nation

Examining the social impacts of HSR networks, this section discusses the correlation analysis results of five nations that are broken into three key pillars, including quality of living, employment, and education.

7.6.1 The SNCF network

The French HSR, or TGV network has had the greatest impact with an average of 0.51. The analysis of the French network in terms of its social impact has found that QoL has distinctly seen the greatest impact among the three pillars. This statement can be confirmed with the analysis of the low-cost French HSR, namely "Ouigo", which has become a more attractive service than low-cost travel. Ouigo's services are mostly intended for passengers who want to book leisure trips. Also, the service truly supports the high volume of passengers in France's big cities (Delaplace and Dobruszkes, 2015).

The benefits of TGV services over those of airlines have been praised in terms of shortening travel time. Passengers can save 30 minutes in security checking-in time; in other words, people can reduce round trips by at least an hour by using HSR services (Dobruszkes and Givoni, 2013; Dobruszkes *et al.,* 2014). It is important to highlight the fact that HSR offer services for affordable prices using various marketing strategies (e.g. early booking of tickets, return tickets, and discounted tickets). For these reasons, this study finds that the French QoL has been improved, as indicated by the PCC result of 0.9.

In terms of employment, the correlation between education and HSR network growth is 0.42, which indicates a moderately positive relation. The spread of French HSR stations not only reduces travel time, but also stimulates mobility and supports urban economies (Facchinetti-Mannone, 2009, 2019). The shorter travel time may help enterprises to distribute their products and services more readily in France (Preston, 2009). Increased accessibility to HSR services comes from journey times, train frequency and reasonable prices. As an example, the current rail travel time on the Reims-Paris route has been shortened from 95 to 45 minutes, while the advance ticket price is only €10.53 (SNCF, 2020).

Some scholars state that HSR enhances new businesses in Paris, which has become a more important factor for business, especially for trading services (Beckerich *et al.,* 2019). This is because French HSR services have allowed businesses to increase their visibility and accessibility to customers because they have obtained positive effects from greater activity and productivity. Therefore, the French network has been able to stimulate the job market and the country's economy in both direct and indirect ways.

Lastly, the education pillar is averaged 0.22 for the French HSR network. In fact, there has been no research that has intently studied the relations between French education and the HSR service. The PCC results show that school enrolment rates at both secondary and tertiary levels are very strongly correlated with the growth of the network, but the correlation is weak at primary level. It remains unclear how HSR truly affects France's education system. Overall, the French HSR network has had a great impact on society, mostly offering benefits in terms of QoL, the economy and education.

7.6.2 The Renfe network

Regarding the Spanish HSR network, it also offers great benefits to society as shown by the PCC average of 0.47. The Spanish HSR network has developed into the country's primary transportation network (Betancor and Llobet, 2016). Additionally, the Spanish government has initiated a plan to expand the initiative across the country, which would need significant expenditure.

Concerning this point, many experts oppose the HSR project as they think HSR cannot offer social profitability. There have been scholarly studies on both the financial and social profitability of four major Spanish HSR lines (Albalate and Bel, 2010, 2012). These studies have found that accessibility has been improved across Spain since HSR services have been operating. Spatial distribution has been analysed, indicating that Spain's accessibility value has risen almost 50% (Monzon *et al.,* 2019). Additionally, some researchers discovered that HSR services enhance territorial cohesiveness, which is one of the EU's development priorities. Likewise, seamless connectivity can help decrease regional inequalities (Ortega *et al.,* 2012). Similarly, this thesis's findings indicate HSR services show the greatest benefits for large territories, rather than small countries. The average PCC result for QoL and the Spanish network is 0.53. The results also highlight that older groups have obtained positive benefits, with a PCC value of 0.92, while the network is not relevant to young people.

With respect to the employment pillar, our findings show a PCC value of 0.47, which is almost a highly positive correlation. Research has revealed that mobility resulting from the Spanish HSR network impacts on the labour market. Studies of the metropolitan areas of Madrid, Barcelona, Seville and Malaga have found that the network is associated with temporary migration, including for short-term contract and consultancy jobs (Guirao *et al.*, 2018). Also, the location of stations supports labour mobility and increases the size of the labour market. Research has also found a positive effect on local tourism sectors (Albalate *et al.,* 2021).

Regarding the education pillar in Spain, there has been no research that specifically mentions benefits from rail networks. This study has surprisingly found that there is a very strong correlation with the economy. The correlation between Spanish education and the employment rate is shown in Table 7.5. Additionally, the PCC average value for the education pillar is 0.43.

In fact, Spain's unemployment rate has been found to have decreased due to the rising enrolment rates in education. Approximately 60% of the unemployed have not received a proper education or are unskilled workers. Also, most of them used to work in the construction field (Jansen *et al.,* 2016). The Renfe network offers high frequency services at low prices, which are suitable for workers' schedules. For these reasons, the Spanish network has ultimately offered benefits to the whole of society in terms of the education, employment and QoL pillars.

Table 7.5 The correlation analysis between educational and economic factors

Factors	**PCC result**	**Interpretation**
Labour force rate - Secondary school enrolment	0.79	Strong positive correlation
Labour force rate - Tertiary school enrolment	0.92	Strong positive correlation
Employment rate - Tertiary school enrolment	0.54	Strong positive correlation
Proportion of seats in parliament held by women – Secondary school enrolment	0.92	Strong positive correlation
Proportion of seats in parliament held by women – Tertiary school enrolment	0.99	Strong positive correlation

7.6.3 The CR network

Given its extremely vast geography spanning 23 regions, HSR services had been described as China's primary transportation method. Before the launch of the HSR network, people were concerned about its abilities to speed up economic growth. This is because new projects come with uncertain economic benefits and need high levels of investment (Zhu *et al.*, 2015).

Some people do not believe that the social impacts in China would be as high as seen in Europe (Chen and Haynes, 2015). However, the Chinese network shows satisfactory service in terms of fares, journey distance, and on-board amenities. Moreover, price is the most important factor that has caused a shift to the Chinese HSR network (Pan and Zhang, 2008). The most notable Chinese HSR services have mainly appeared in the east coast corridor where the network seamlessly links the majority of cities, such as Shanghai, Beijing and Guangzhou. The Chinese network commands up to approximately an 80% share of the transportation market for short-distance routes between big cities (Chen, 2017). Furthermore, the network has extensive links with other countries, including Kazakhstan, Mongolia, Russia, Taiwan, and Hong Kong. This is advantageous for long-term growth in neighbouring markets.

The service is believed to have been a key driver in speeding up the country's economic growth, providing a long-term positive impact on Chinese society. Average income and GDP figures are indicators for evaluating economic impact in a country. Studies of the impact on household income in China during 2009-2012 show that the positive impact offered by HSR provoked regional economies (Sun and Mansury, 2016). However, the network may not only help society directly, but may also function as a stimulant for the country's economy. As is well known, HSR services significantly cut travel times; in other words, they can improve tourism, labour, productivity, innovation growth, and service mobility. Some scholars have found that CR network has increased the accessibility, attention and political relevance of tourism, because it fuels local and regional economic growth (Cao *et al.*, 2013; Chen and Kingsley, 2015). HSR services seem to reduce disparity; however, they do not enhance overall tourism revenues.

In terms of supporting the business sector, CR network services play an essential role in the allocation of industrial resources, such as staff, products and services, and they can truly promote company agglomeration (Shao *et al.,* 2017; Li *et al.,* 2019; Guo *et al.,* 2020). HSR is especially ideal for business travellers who need high-convenience services and wish to save time on their journeys. Some research mentions that low-income groups, students and non-business groups may not be willing to pay for HSR tickets as the service is expensive compared with their incomes (Guo *et al.,* 2020). For this reason, the thesis's PCC result for QoL is -0.13, indicating that the network can sustain only a limited number of users. Similarly, the PCC result for education of 0.27 also indicates a weak relationship with the growth of Chinese HSR. To improve CR network in the long term, affordable prices for middle class people should be a first priority. New strategies and promotions should be introduced for services in order to attract more passengers, such as student discounts, advance tickets and return prices.

Regarding the QoL in China, the PCC result of 0.61 shows that it is strongly correlated with the growth of the HSR network. As mentioned, conventional rail was the key transportation system in China, but the HSR network has offered faster services. Considering the major cities in China, most of them are located long distances apart on the east coast of the mainland. For instance, Beijing and Shanghai, both of which are among China's main commercial areas, are separated by 1,200 km. To travel between them, HSR services take only 4.18 hours, instead of a 12 hour journey by private car. The HSR network has also become a competitor for airplane services. Travel by airplane takes two and a half hours on-board, but passengers must spend additional time travelling to/from airports, checking in with security, and waiting on standby at the gate. Moreover, the airplane tickets are slightly more expensive than for HSR services. Therefore, Chinese HSR operations not only offer people QoL, but they also stimulate the transportation market.

Similarly, research on the effect on airline passenger demand in China reveals that it has reduced by 27% within two years of the HSR network becoming operational (Yang *et al.*, 2018). Some scholars suggest that HSR and air services in China could be integrated. According to the 62 case studies carried out in China and Japan during 2007-2015, linking airports and HSR stations can bring positive impacts, as it increases HSR connectivity and accessibility (Liu *et al.*, 2019; Li *et al.*, 2020). Increases in land values around HSR stations may also be used to gauge the quality of living. Rungskunroch *et al.* (2020) has studied the socio-economic impacts of China's HSR network. The study has found that the trend in property prices near to the Hongqiao transportation hub has been sharply rising due to increasing demands for places to live. The factors above all support the enhancement of China's QoL.

7.6.4 The Korail network

The Korail network appears to benefit South Korean society (Park *et al.,* 2009; Jeon, 2010; Kim and Baek, 2010). A study of the favourable impact of KTX on accessibility in South Korea during 2004 - 2018 discovered that the network could help the country achieve more spatial fairness (Kim and Sultana, 2015). Similarly, some scholars have mentioned that Korail network have a positive impact on urban economic activities. However, the location of stations is a key factor in the success of the HSR, as stations that are further than 10 km from city centres are less beneficial for households and local markets (Kim *et al.*, 2018).

With a deep consideration for its infrastructure, the Korail network has been developed based on South Korea's balanced development strategy. It seems that, because KTX has come into service later than networks in other developed countries, its infrastructure has, in fact, been planned in detail by experts from the French SNCF and Japanese Shinkansen, especially in terms of station locations (Korean National Statistical Office, 2019). Many studies have focused intently on station location as this has become a catalyst for successful urban and economic growth (Givoni, 2007; Priemus *et al.*, 2008; Yin *et al.*, 2015). Regarding increased mobility, the KTX shows huge advantages in linking big cities and stimulating population mobility in Korea. The Korean National Statistical Office's (2015) data reveals that the market share of passengers on HSR has greatly increased since the opening of the Korail network. For instance, the Gyeongbu KTX has a 60.3% share of the passenger market compared with airlines, which have only 23.8%. Moreover, other important routes have higher proportions than other means of transportation, for instance Seoul-Daegu (59.8%).

Other published research, meanwhile, has found that population mobility has been affected within a 200 km radius of Seoul. A study of population mobility along the Honam KTX lines has found that average mobility flow is 40 km (Eom *et al.*, 2020). Also, the most crowded area is within a range of 20-25 km around the Seoul station. From the arguments above, the key finding emerges that Korail has a potential impact in substantial areas, such as the capital and central business district, and that the service can be highly effective for distances of over 500 km. However, most KTX lines are shorter than 200 km due to passenger mobility not being as high as expected. For these reasons the QoL PCC- result is 0.33, while that for employment is 0.43, so both factors can be interpreted as having a moderate correlation with the growth of the HSR network.

As the same time, findings for KTX's development and spatial distribution on the Seoul-Busan route reveal that population and employment distribution are impacted on the micro-level (Kim and Sultana, 2015). Additionally, the rise in mobility was a temporary impact, waning after 2011. The reason for this was because job centres are located outside of city centres. As a result, the Korail network has impacted a limited group of people and shows a low correlation with the country's economy. In terms of the educational benefit, the PCC result of -0.12 shows a low negative relation with the KTX network. This thesis is the first research to reveal educational benefits from the Korail network.

7.6.5 The JR Central network

Since the opening of the Shinkansen network, the trend in travel by HSR has significantly increased compared with other transportation modes. In fact, the geography of the mainland is a good fit for efficient operating distances. Based on Japanese transportation market shares, research has found that Shinkansen has gained a higher market share than other modes of transportation for distances of 300 km to 1,000 km.

JR Central network has justifiably been labelled as a socio-economic catalyst in this era due to its services having both direct and indirect effects on society. Some scholars have mentioned that the network is one of the critical factors that has induced passengers to make trips, leading to increased local economic benefit (Yao *et al.*, 2003). Other research has found that short-term mobility in Japan has increased by 10%, and that travel time is reduced around HSR corridors by 20% (Litman, 1997). Hence, socio-economic conditions, such as population and regional economic growth, have been improved by Shinkansen services.

In regard to driving the country's economy, the JR Central network seems to have had an impact on the labour market at the beginning of its operations. Many researchers have evaluated the Shinkansen network's impacts on population dynamics, including employment and labour force factors. Some scholars have found that cities with HSR stations showed 16-34% higher employment growth (Hirota, 1985). The growth rate was found to be 1.8% in areas near to stations, but only 1.3% in non-HSR station areas. The employment rate was found to have decreased in the years that followed. In 1989, the overall employment rate reduced by 2.8%, while in the areas without HSR, it reduced by 3.6%. Additionally, the IT sector has grown by 22% (Nakamura and Ueda, 1989). This suggests that the network has a limited influence on specific segments of the labour economy. Businesses engaged, such as food retailing and the lodging industry, require a high degree of station accessibility (Okabe and Miki, 1984; Brotchie *et al.,* 1991). The network's overall benefit to Japan's labour market has dwindled, as seen by various sectors and regions. Similarly, this thesis's PCC result for employment of 0.14 shows a low positive correlation with the growth of the JR Central network.

The PCC result for QoL is 0.08. Additionally, the PCC findings for the young and elderly age dependence ratios are -0.94 and 0.24, respectively. It can be implied that the JR Central network offers more QoL benefits to older groups than younger groups. However, younger groups obtain great educational benefits as the PCC result for education is 0.41, which is also a higher value than for the other four countries. To our knowledge, there has been no research that evaluates the details of the Shinkansen network's impact on educational benefits in depth. It is worth discussing the exciting facts revealed by the student enrolment rates for primary, secondary and tertiary schools, which have PCC results of 0.96, 0.92 and 0.70, respectively. These show a significant relationship with the expansion of the Shinkansen network.

7.7 Perspectives from professionals on a realistic HSR system

Although this study has considered long-term socio-economic factors and analyses them through highly efficient models, the experts' reviews of the study's analysis are added, in order to adopt this valuable feedback into practice. Our expert feedback has been collected by following the general data protection regulation (GDPR).

A total of 30 global HSR experts (or six specialists from each network) are participated, including academia, industry, and research expertise. They must have experience of at least 15 years and currently hold at least one position connected to the railway sector. Regarding the selection criteria for participants, they had to have experience in at least one of the selected railway networks. Before participating, they must read through the in-depth network's data analysis, as shown in Section 7.4. At any point during the survey, the participant may refuse to participate or leave blank any questions they do not wish to answer.

A five-point Likert scale is used to quantify expert responses, with 1 representing 'strongly disagree' and 5 representing 'strongly agree'. The first question is 'How much do you agree with the analysis?'. As seen in Figure 7.9, the aggregate expert agreement findings are compared to the data analysis for each rail network. The average score for experts on the CR, SNCF, Korail, and Renfe networks ranges from 4.2 to 4.8, corresponding to 'agree' to 'strongly agree' with our assessments. On the other hand, the result for JR Central network specialists is 3.2, indicating that they neither dispute nor agree with the Shinkansen network study. Notably, one of

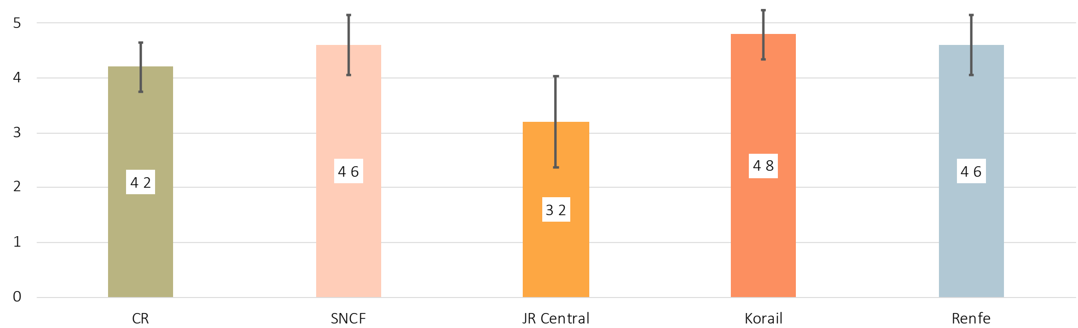

Figure 7.8 Results for the degree of expert agreements with this study's benchmarking analysis across selected HSR networks

Shinkansen's industry specialists asserts that the network has benefited education, employment, and business in Japan for decades. However, the disruption to Japanese society caused by numerous waves of the COVID-19 epidemic has had an effect on the HSR services.

On the other hand, the majority of academic experts concur with the study of the Shinkansen network in this chapter, stating that the network advances technology in terms of safety, timeliness, and rapid delivery in order to accommodate future societal changes. Additionally, the experts believe that the Shinkansen does not normally operate during the pandemic. For this reason, it is effective through strengthening linked public transportation systems such as buses, light rail, and municipal trains that connect users to the network.

Additionally, the next part of the feedback concerned effective policy goals for sustainability development, each of which has been individually rated on a five-point Likert scale. The eight policy objectives are as follows: providing reasonable ticket prices, providing special or discounted tickets, extending early and late tickets, connecting to major cities, connecting to business areas and attractions, expanding business areas near HSR stations, increasing social value near HSR stations, and connecting to other public transit or transportation modes.

All eight variables inevitably contribute to the socio-economic benefits of HSR and are required for the construction of the HSR network. Nonetheless, the background impacts of the various networks on the suggested policy implications are distinct. Table 7.6 summarises the aggregate average of the 30 global experts' opinions and suggestions (Costa *et al*., 2013; Saunders and Townsend, 2016). With regards to the enhanced socio-economic effect of HSR networks, the highest priority for rail services

Table 7.6 Overall averaged results for expert feedback regarding policy implications to drive long-term development

Policies implications	Average (± standard deviation)	Ranked
Offering reasonable ticket prices	4.52 ± 0.44	6th
Offering special or discounted tickets	4.68 ± 0.41	3rd
Extending early and late tickets	4.48 ± 0.95	7th
Connecting to major cities	4.80 ± 0.24	1st
Connecting to business areas and attractions	4.60 ± 0.35	4th
Increasing business areas near to HSR stations	4.44 ± 0.30	8th
Increasing social value near to HSR stations	4.60 ± 0.24	4th
Linking to other public transit or transportation hubs	4.76 ± 0.26	2nd

is given to ‘connection to large cities’, which receives an average score of 4.8. Numerous experts feel that the most critical component of improving socio-economic benefits across all demographic segments is seamless and widespread connectivity. Moreover, connecting to other public transit or transportation hubs, providing special or reduced tickets, and connecting to commercial districts and attractions, all contribute to the success of HSR services.

Nonetheless, policy consequences should be prioritised in accordance with a network’s internal characteristics and history. The comparability of average scores for each policy implication for each of the chosen networks is shown in Figure 7.10. When compared with other methodologies, expert feedbacks have the advantage of accurately disclosing practical solutions to be used on specific networks.

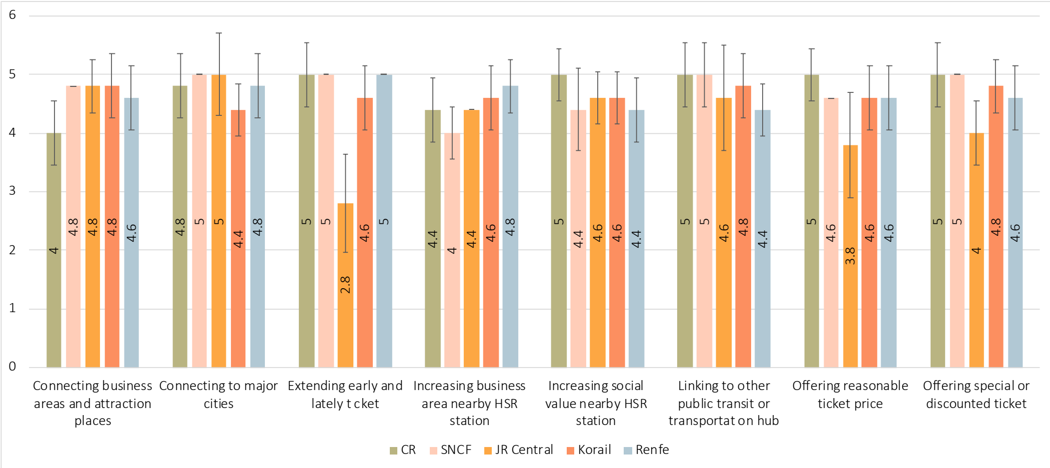

Figure 7.9 Overall analysis of the results for long-term development compared by network

7.8 Conclusion

As the operation of HSR services is ultimately believed to offer benefits for society, the growth of HSR has dramatically extended into many countries. It is inevitable that HSR services provokes definite socio-economic benefits; however, the effect of HSR networks can be overrated and they do not represent the whole of society. This study revealed a knowledge vacuum in that there has been no prior research on the impact of HSR on younger and older generations. As a result, our research utilised unmatched large data sets to ascertain socio-economic consequences using innovative Python models. The findings indicate that both younger and older generations in some nations will receive a lesser degree of advantage from HSR networks.

By promoting a worldwide sustainable development policy, this study seeks to quantify and enhance the socio-economic advantages of HSR services, therefore ensuring the long-term growth of both present and future networks. This study compares the socio-economic consequences of five HSR networks in China, France, Japan, South Korea, and Spain. Additionally, the KNN and PCC techniques have been used to estimate the magnitude of social impacts using new models. The benchmarking results indicate that France and Spain's networks provide the highest social benefits to all demographic segments, followed by China, South Korea, and Japan, providing substantial advantages to the young and older generations in order to get a specific degree of benefit.

To provide practical recommendations based on our results, expert advice and comments have been collected from 30 HSR specialists worldwide whose work is directly connected to the five selected railway networks. Overall, the results indicate that, with the exception of the Japanese network, all analyses scored higher than the 'agree' threshold. Additionally, these specialists prioritise policies and programmes aimed at increasing the efficiency of HSR networks by connecting them to large cities, connecting them to transportation hubs, and selling special tickets. These policies emphasise the advantages and viability of enhancing a society's socio-economic benefits.

7.9 Chapter summary

Not only have HSR services boosted economic growth in several nations, but they have also considerably improved the QoL for countless individuals, particularly in HSR catchment regions. For many decades, both industrialised and developing countries have aggressively pursued the building of HSR networks. With the best safety record and the least environmental effect of all forms of transport, HSR networks have unavoidably become a symbol of civilisation.

Following the United Nations Sustainable Development Goals (UNSDGs) 3, the goal is to “ensure healthy lives and promote well-being for all at all ages”. The chapter’s objective is to analyse the socio-economic consequences of HSR networks and to map out policy implications for future HSR networks. Regarding the analysis and survey results, only a few effective HSR networks can genuinely affect their countries’ socio-economic well-being. Nevertheless, the benchmark demonstrates that socio-economic consequences appear to be widespread. The SNCF and Renfe networks contribute to social impact more than the CR, Korail, and JR networks. The breakdown results of each KPI are illustrated in Table 7.7.

The Spanish network is the leader in social impact among selected HSR services, demonstrating better overall socioeconomic values, particularly in the QoL pillar. Regarding increasing social impact, one of the best practices is to enhance the accessibility of the HSR services to reach more passengers. In addition, launching a low-cost service of HSR as SNCF’s strategies is also an effective solution.

Table 7.7 The summary of KPIs of urbanisation

KPIs	Total weight (%)	Urbanisation	Weight (%)	CR	SNCF	JR Central	Korail	Renfe
Urbanisation	20	Education	6.67	4.24	4.07	5.37	2.94	4.77
		Employment	6.67	2.92	4.74	2.01	4.77	4.89
		Quality of life	6.67	5.37	6.33	4.31	4.45	5.09

7.10 References

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CHAPTER 8

Conclusion and recommendations

This chapter presents an evaluation of the overall results of the operation readiness framework across the five HSR networks. Likewise, the discussion of selected HSR networks is provided by country. This chapter gives readers an in-depth understanding of the pros and the cons of each network. Concerning the application of the system-based framework, it is also advantageous for all rail authorities to compare their performance with that of other leading HSR companies. Lastly, the thesis presents policy implications for future development. The insights will be advantageous for policymakers, governments, and other related sectors for the implementation of new HSR policies in the future.

8.1 An evaluation of the HSR operation readiness framework

As mentioned in Chapter 1, the benchmarking criteria used in this study are divided into six broad categories, three of which are fundamental and three of which are novel, and lead to sustainable development of railway networks. The weighted score fractions used to calculate KPIs are shown in Table 8.1.

The evaluation of the performance of five HSR networks is based on six pillars. This thesis clearly states the insightful definitions of each KPI, and the results from the system-based framework are illustrated in Table 8.1. In each section, for

Table 8.1 The benchmarking results of analysis on HSR performance through the thesis' system-based framework.

KPIs (% weight)	Insight definitions	Sub-weight (%)	CR	SNCF	JR Central	Korail	Renfe
Life cycle cost (15%)	Manufacturing stage (Infrastructure)	3	0.14	0.20	0.50	0.00	3.00
	Manufacturing stage (Rolling stock)	3	0.00	3.00	2.66	1.25	2.66
	Operational stage	3	3.00	0.94	0.00	2.08	0.29
	Maintenance stage	3	0.14	0.20	0.50	0.00	3.00
	Demolition stage	3	3.00	2.65	2.82	0.00	2.19
Productivity (10%)	Overall productivity	10	6.25	6.25	10.00	10.00	7.50
Punctuality (15%)	Punctuality rate	7.5	7.50	7.50	7.50	7.50	7.50
	Train cancellation	7.5	7.50	7.50	7.50	7.50	7.50
Risk and uncertainty (20%)	Overall risk across network	20	19.39	14.48	19.39	9.58	16.32
Sustainability (20%)	LCE rate	10	10.00	8.72	0.00	4.18	2.94
	$LCCO_2$ rate	10	10.00	1.89	2.04	0.00	9.08
Urbanisation (20%)	Education pillar	6.67	4.24	4.07	5.37	2.94	4.77
	Employment pillar	6.67	2.92	4.74	2.01	4.77	4.89
	Quality of life pillar	6.67	5.37	6.33	4.31	4.45	5.09
Summary		100	79.44	68.46	64.60	54.25	76.73

comparison among the HSR networks, the lowest scores are given in red while the highest scores are given in green.

8.2 Discussion of HSR operating performance

8.2.1 CR network

As shown in Figure 8.1, the CR network shows good performance in life cycle cost, especially in the operational and demolition stages. As the average workforce in China is relatively low, the whole life cycle cost of the CR network performs well. Although CR network is the largest HSR network in the world, it is found to be the safest network and is labelled as low-risk. This is because the CR network is concerned with safety policies. Compared to other networks of a similar distance, the CR network has consumed the lowest amount of energy, and emitted the smallest volume of CO_2 into the atmosphere. It is the most environmentally friendly network.

However, the CR network should improve its productivity management plans. An in-depth analysis finds that the company has not suitably arranged the sales and marketing section. Because the company has not offered any special tickets or sales promotions, some groups of passengers are unable to use the HSR service. Furthermore, the CR Company has struggled with human resource management and service development. The company's profits may suffer as a result of a lack of good performance in these areas.

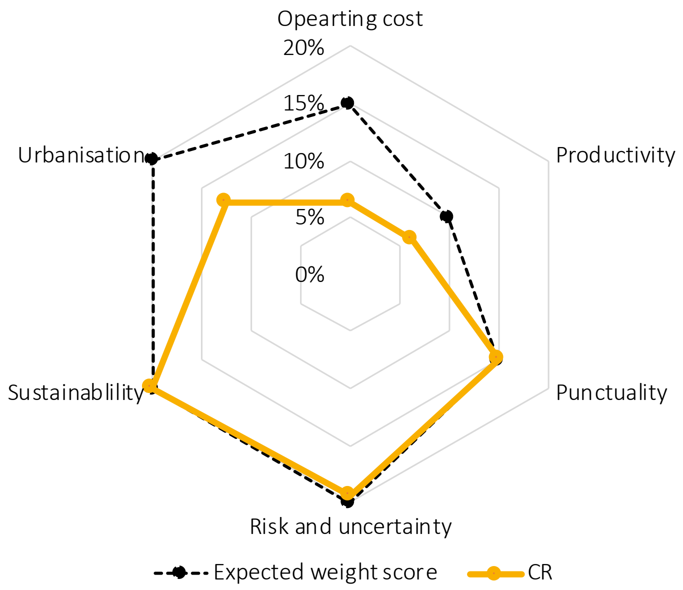

Figure 8.1 Overall performance of the CR network through the thesis' system-based framework.

8.2.2 SNCF network

As illustrated in Figure 8.2, SNCF has performed well in life cycle cost management, especially in the rolling stock manufacturing process. This is very important because the life cycle of rolling stock is limited to 35 years, and it is the joint largest fraction of the total life cost of a HSR network. Therefore, the managing of the costs of rolling stock manufacture can lead to a success in overall financial performance for a company.

In terms of energy consumption rate, the SNCF network has exhibited a low energy consumption. The thesis finds that the SNCF's energy consumption is only 77.70 GJ/km. This is a very impressive achievement and matches the goals of the Paris agreement. Furthermore, the SNCF has offered the greatest impact on urbanisation, especially for the quality-of-life pillar. This means that SNCF has a positive impact on

French society. This is because the network offers various types of service to passengers.

On the other hand, the thesis finds some faults with the SNCF service. The SNCF lacks adequate productivity in terms of its sales and marketing development, and technology development. For this reason, the company has shown and unhealthy financial status, obtaining lower profits in the past five years. To fill these gaps, the SNCF should immediately enhance its sales and marketing development for its long-term benefit.

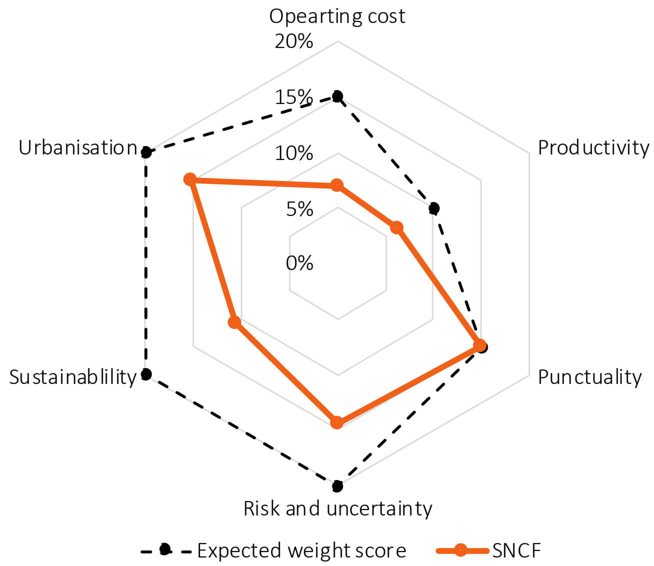

Figure 8.2 Overall performance of the SNCF network through the thesis' system-based framework.

8.2.3 JR Central network

As shown in Fig 8.3, JR Central has shown the best performance in productivity as the company has met all the requirements for productivity management. The company is unmistakably different from other businesses. The introduction of the JR Pass for foreigners is one of the most impressive strategies. It enables them to use an unlimited number of Shinkansen services throughout the country, demonstrating a long-term socioeconomic benefit to the local government.

Furthermore, the network's risk management is reflected in its low-risk status. Japan has the safest rail network in the world, with no fatalities from rail accidents. This is a very impressive outcome since Japan have unavoidably faced many natural disasters, especially massive earthquakes.

In terms of social impact, the results show that the Shinkansen has a positive impact on the education sector, which means that the younger generation benefits from the service. On the other hand, the quality of life and environmental benefits remain among the lowest. However, the Japanese have reaped the benefits of other modes of transportation.

Regarding the sustainability pillar, the outcomes have been normalised in the unit 'GJ/km' and 'tCO_2/km', as shown in Tables 6.6 and 6.7, and benchmarked with other countries. The JR central's results illustrated low scores on LCE and $LCCO_2$. It is interesting to highlight the fact that the network was the first HSR service. Beginning in the 1900s, JR Central has had disadvantages as a pioneer in technology adoption, especially in the construction stage. Nevertheless, JR Central has gradually developed, and applied high-class technologies on infrastructure and rolling stock, resulting in becoming a leader and role model of success HSR.

However, the pillar has been calculated from the entire 70 years of HSR's life cycle timeframe; therefore, JR Central's sustainability performance has been negatively affected due to the technology limitation at the beginning of the service.

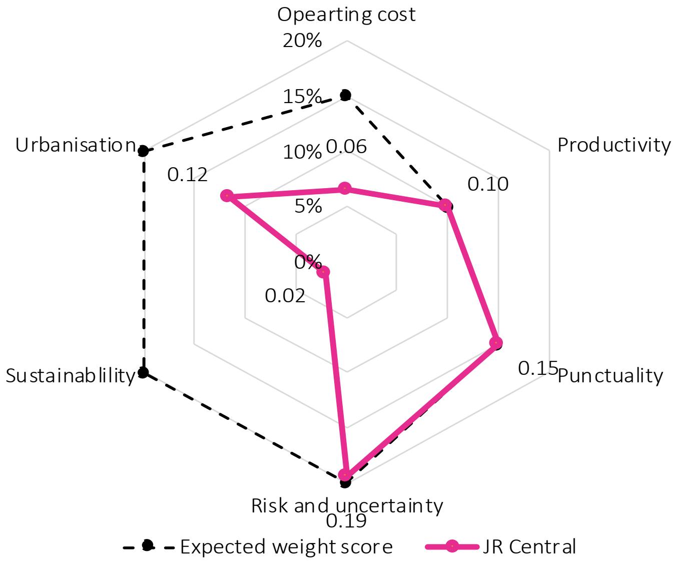

Figure 8.3 Overall performance of the JR network through the thesis' system-based framework.

8.2.4 Korail network

As shown in Figure 8.4, the life cycle cost management of the network has performed unwell. The Korail faced the Asian economic crisis in 1997 during the construction, causing the project to be extended. The cost of construction has also had an effect on the value of money resulting from recent projects.

The research finds that the Korail network shows the lowest performance in safety as it has a high level of risk. Some accidents have resulted in a large number of injuries, and their causes were due to a lack of maintenance. For example, the KTX train derailed due to a railroad switch system error that caused 15 of 196 passengers to be injured (The Korea Herald, 2018). In terms of sustainable development, Korail has invested highly in a new train model to reduce its environmental impacts. However, the overall result indicates that energy consumption and CO_2 emission rates, based on long-term datasets, are need some improvement. The thesis supports Korail's action of a KTX's Seoul-Busan service, which was awarded the first low-carbon certificate by the Korea Industry and Technology in 2019.

The Korail network is the best in the overall productivity pillar. In terms of urbanisation, the service has benefited Korea in terms of employment and quality of life. This will be a catalyst to enhance South Korea's socio-economic benefits.

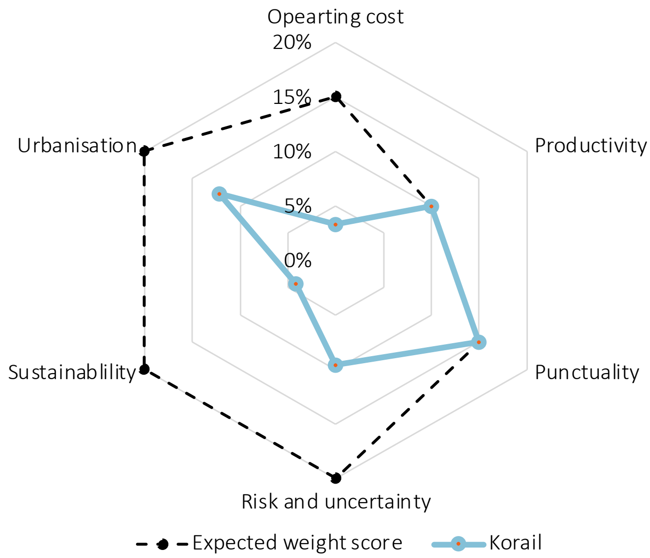

Figure 8.4 Overall performance of the Korail network through the thesis' system-based framework.

8.2.5 Renfe network

From the outcome of the research, Renfe has demonstrated the best performance in respect of the various pillars. The AVE service performs satisfactorily for the life cycle cost pillar, especially in manufacturing and maintenance costs. This is due to the network's early construction, which has benefited its value. Also, the service has the lowest CO_2 emissions.

According to an in-depth analysis, Renfe networks have the lowest CO_2 emissions in the manufacturing stage in relation to kilometres of track. As shown in Table 6.5, the type of Renfe's infrastructure is normal rail track. The infrastructure on other networks, on the other hand, include rail tunnels and bridges, which require more materials and energy to build.

Furthermore, the AVE has benefited Spanish society, particularly the employment rate. One of the main reasons for this is that the AVE links big cities in Spain and neighbouring countries. People have more options for cross-country travel once the AVE service became operational. Therefore, the Spanish labour market has obtained benefits from service.

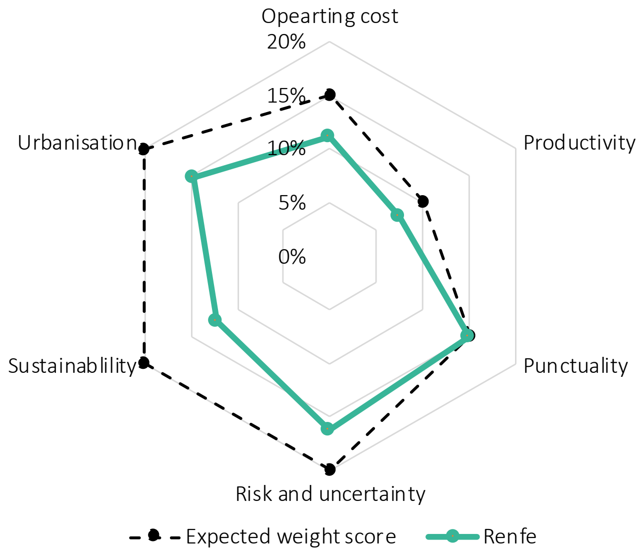

Figure 8.5 Overall performance of the Renfe network through the thesis' system-based framework.

8.3 An application of the framework

As mentioned in Chapter 1, the railway organisations have been inevitably faced with various operational problems, leading to an unsuccessful company. The system-based framework for HSR has been developed to achieve success for HSR service. Any railway corporation can adopt the application of the thesis's framework to improve their operating performance.

The distinctive point of the model is adaptable, allowing railway companies to adjust weight scores along with six KPIs. The reason is that using a model can lead to practical and immediate solutions in the organisation. For instance, the framework has provided a default on the ratio of fundamental and novelty at (40:60), as shown in Table 8.1. However, the railway organisations can reasonably adjust the ratio to fit their goals as long as the six KPIs are concerned.

In terms of LCC management, the railway organisations should entirely break down the costs into four phases. This method can point out the financial performance of each stage, leading the company to control the expenses wisely. Organisations must also consider the uncertainty cost of unexpected events. It can be a guide to reserve capital for their upcoming projects. On the other hand, the productivity and punctuality performances must be followed the framework criteria. In addition, the keys of improvement have been profoundly introduced in policy implications (section 8.4). On this basis, the system-based framework can be applied to the upcoming global HSR project.

Giving an example of the HS2, the project is planned to seamlessly link the UK's big cities with the HSR network. The first phase is set to connect London and Birmingham. With a large amount of investment and long-term construction, the project is mainly targeted at increasing job opportunities, providing accessibility, and reducing environmental impacts. The framework's application allows the HS2 project to prevent unsuccessful construction by comparing it with other networks. In addition, the integration with the LCC and MCMC models reduces the lack of financial and profit problems. In addition, the evaluation of the socio-economic impact of HS2 can be contemplated before launching Phase 1. The framework can serve as a guideline for the project to provide accessibility and social inclusion strategies to reach its goals wisely.

8.4 Policy implications

Policy implications are provided to enhance overall performance of existing and upcoming HSR networks. By evaluating HSR networks' performance, this thesis reveals that some of HSR operating areas must be immediately improved to ultimately provide long-term benefits to society.

Apart from constructing projects with suitable operating distances, which should be at least 500 km long, and stations are suitably located. There are four key factors that rail authorities should be concerned to include: a safe service, social impacts, environmental impacts, and technology and innovation. All of the proposed policy implications are linked to novelty frameworks, as shown in Figure 8.6.

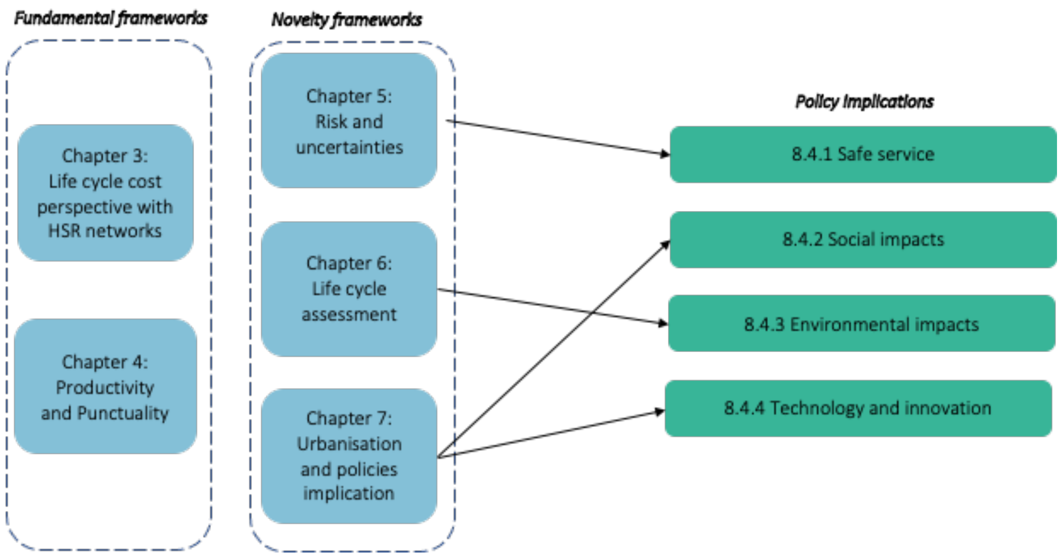

Figure 8.6 An overview of policy implications through the thesis' system-based framework.

8.4.1 Safe service

As mentioned in Chapter 5, the safety factor is one of the distinctive options for HSR services. In fact, railway service shows the lowest death rates compared to other modes of transportation. Nevertheless, the evaluation of risk and uncertainty for leading railway networks is partially characterised by high risk. For this reason, railway organisations' primary incentives are to achieve an accident rate of zero and to minimise damage.

The thesis has classified the causes of railway accidents into three types: collision (X1), derailment (X2), and other causes (X3). The results point to accident type 'X3' being mostly due to human errors, instigating greater damage than the other types of accidents. The thesis suggests the following three key improvements towards the provision of safe services by railway networks:

- **Using advanced technologies and new innovations** – In the past several decades, the safety technologies have been developed across rail networks including in terms of rolling stock, infrastructure, operational plans, and policies. Such effective technologies can reduce the severity level of railway accidents.
- **Replacing LX with railway bridges or tunnels grade separation** – As most railway accidents happen at LX, the building of railway bridges and tunnels can reduce accidents between trains and road users. This solution suits new HSR projects; however, the construction cost is significantly higher than the building of the rail track. In terms of existing railways, the installation of barriers and clear signalling are required.
- **Following maintenance protocol** – Lack of a proper maintenance plan is another frequent cause of railway accidents. The thesis suggests that all railway operators must communicate and encourage all staff to strictly follow these plans. The company should also launch safety training courses so operational staff can understand safety schemes and their importance in details.

8.4.2 Social impacts

As mentioned in Chapter 7, HSR projects have been primarily launched to increase social and economic benefits. By analysing the social impacts of HSR networks based on quality of life, education rates, and the employment rate, the thesis points out that most HSR network have not maximised their efficiency in providing a social service.

Therefore, addressing the inefficiency of HSR service can have the effect of increasing the potential of cities and spreading societal benefits.

This thesis provides in-depth analysis from 30 global HSR experts who were asked to prioritise eight important policies for enhancing railway performance. The experts' feedbacks on these policy implications have been ranked as follows:

- **Connecting to major cities** – The broad connection to other cities can support a variety of passenger journeys, such as for leisure, work, and family purposes. Also, linking with major economic centres can enhance the job market and attract investment.
- **Linking to other public transit or transportation hubs** – The seamless connection between HSR and other forms of public transportation can stimulate passenger demand for public transit.
- **Offering special or discounted tickets** – Discounted tickets can increase passenger demand in highly competitive areas. Also, some passenger groups are then able to afford the service.
- **Connecting to business areas and attractions** – This supports demand from both investors and foreign travellers; as a result, it can stimulate the local market and the country's economy.
- **Increasing social value near HSR stations** – In some countries, the operating of HSR services has reduced urban agglomeration and social inequalities. In other words, there is a civilisation effect in city centres.
- **Offering reasonable ticket prices** – This is another important solution in reducing the gap in accessibility to HSR services among non-wealthy groups. HSR networks charge a premium for tickets in comparison to average national

earnings. Hence, HSR networks are only accessible to wealthy group, while the majority of people, including the young and elderly, cannot afford the services.

- **Extending early and late services** – The results from the thesis point out that HSR services have no influence on the growth of a country's economy or employment market. To support the expansion of the market, this thesis suggests that rearrangement of train schedules during the early morning and late evening be conducted to offer various options to passengers who live in suburban areas.
- **Expanding business areas near HSR stations** – The construction of business areas and office space near HSR stations improves employment rates because the HSR service offers convenience for employees.

8.4.2.1 Fare prices

One of the most serious issues is that individuals are unable to afford HSR fares. This is because certain HSR networks charge a premium for tickets in comparison to average national incomes. As a result, HSR networks are only accessible to the wealthy, while the majority of people cannot afford them. Indeed, the majority of train administrations give discounted tickets to youngsters and the elderly.

Several of them also provide special rates to visitors, such as the Shinkansen network, which recently introduced the Japan Rail Pass (JR Pass), which allows unlimited travel throughout Japan (JR Central, 2020). Nonetheless, there are no reductions or special rates for employees or other adult groups. This research proposes giving discounted HSR tickets to workers on weekdays. This will directly help individuals who commute to and from their homes and places of employment on a regular basis. These methods have the potential to have a long-term positive effect on a country's workforce and economy.

8.4.2.2 Train schedules

Train timetables are critical in meeting passenger demand. According to the finding in Chapter 7, HSR services have no effect on the growth of a country's economy or labour market. Despite the fact that services to commercial locations are provided and affordable fares are offered, workers may elect to go through alternative means of transportation. This is because train timetables are useless for all demographics, but particularly for those who reside in suburban regions. This study strongly advises that train operators monitor demand for travel at particular times of day. This is advantageous for those who want early and late running services.

8.4.2.3 Routes and distances

Indeed, several HSR routes are built with the clear purpose of connecting large cities, without any consideration for the consequences for neighboring medium- or small-sized communities. Additionally, operating distances have a significant effect on the effectiveness of HSR services. This research strongly advises that while developing new HSR networks, effective routes and distances be considered. As previously stated, HSR has been shown to be more effective than other modes of transportation over distances of 500-700 km. Thus, HSR lines of less than 500 km without an expansion plan should be avoided.

8.4.2.4 Location of HSR station and hubs

HSR networks have been intentionally built to boost local economies and national GDP numbers. As a result, several of the major HSR lines have successfully connected at least two economic zones. This is because HSR services may improve worker mobility and employment relocation, while also being appealing to employees commuting between their homes and offices. Additionally, the placement of stations is critical. This study strongly suggests that HSR stations and hubs be easily accessible and connected to other modes of public transit.

Additionally, considerations for supporting commercial districts, central business districts (CBDs), local markets, and tourist attractions must be made. Job possibilities may be increased by the development of business districts and office space near HSR stations. As has been demonstrated, HSR stations located near key business areas boost employment rates by providing a convenient service to employees (Rungskunroch *et al.,* 2020; Yao and Morikawa, 2005, Zhou *et al.,* 2018). Additionally, proximity to HSR stations has become a critical factor for employment searchers. These major regions have the potential to sustain future urban growth and population relocation. Effective design of such places has the potential to decrease urban agglomeration and social inequalities.

8.4.2.5 Intermodal transportation

HSR networks have been intentionally built to boost local economies and national GDP numbers. As a result, several of the major HSR lines have successfully connected at least two economic zones. This is because HSR services may improve worker mobility and employment relocation, while also appeal employees to commute between their homes and offices. Additionally, the placement of stations is critical. This study strongly suggests that HSR stations and hubs be easily accessible and be connected to other modes of public transit.

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8.4.3 Environmental impact

At present, numerous countries with HSRs have implemented practical initiatives to minimise energy consumption and increase the usage of green energy sources. In their first stages, HSR services must avoid utilising fossil fuels. Decarbonisation, the process of reducing and eventually eliminating CO_2 emissions from fossil fuels, is now widely recognised as a critical component of addressing climate change, and the transportation sector must play a role.

Regarding the aim of improving energy consumption and CO_2 emission in Chapter 6, the concept of 'net zero emission' should be broadly integrated across rail networks. The basic premise of net zero emission is to maintain a balance between carbon emissions and CO_2 in the atmosphere. The HSR sector must use sophisticated technology, such as carbon capture, storage, and trading, to release and remove CO_2

at equal rates. Also, local governments can participate by making net zero emission a requirement across HSR networks.

As an example, the United Kingdom government has already set a goal of reaching net zero emission by 2050; all diesel trains must be phased out of the system by 2040 as a first step toward this objective. In practice, effective public transportation design may be a 'net zero' facilitator. Effective transportation planning should take into account ticket prices, route options, and passenger preferences. It is critical to have a unified network that really facilitates passenger travels via many routes.

8.4.4 Technology and innovation

Technology and innovation, in conjunction with our suggested policies, can be used to build greener HSR systems. The combustion engine and components used in this process must be replaced in order to decrease CO_2 emissions. This thesis highly recommends that railway companies invest in their research and development sections to develop cleaner technology and innovation.

First, the DMU should be phased out and replaced with the EMU or vehicles based on renewable energy. Numerous forms of technology and improvements that mitigate environmental consequences have already been included in new car models. For instance, the Japanese 700 and N700 series Shinkansen trains gained additional weight savings with the use of the Insulated Gate Bipolar Transistor (IGBT) technology. The new HSR model is claimed to be less polluting than flying over the same distance (Hagiwara, 2008). The Korean KTX train, another example, is also labelled as an eco-friendly train, emitting 15% less carbon than passenger trains and 70% less than diesel trains (Lim and Yoo, 2014).

Second, while selecting materials for vehicles, recyclability and weight must be considered. One prominent material, carbon fibre reinforced polymer (CFRP), is a recyclable material containing robust and light properties. CFRP is suitable for use in automobile components such as bumpers, spoilers, and the bogie frames of railcars. Increased use of recyclable materials can help reduce energy consumption and CO_2 emissions associated with all phases of recycling, including dismantling, shredding, and cleaning, as well as trash in landfills. For example, in HSR vehicles, research indicates that the replacement of major components with CFRP materials results in a recycling rate of 73.1% of total vehicle mass (Kaewunruen *et al.,* 2019). Additionally, lightweight material can help reduce energy usage, which in turn helps reduce CO_2 emissions.

All of the suggestions above can be practically developed for both existing and upcoming HSR projects. The thesis strongly believes that the data gathered through benchmarking analysis can provide policy implications and evidence for long-term HSR development, supporting policymakers in formulating new policies for a more sustainable society.

8.5 Conclusion

In this era, HSR networks have grown massively around the world as they provide a service that is believed to ultimately bring benefits to society, especially in terms of socioeconomics. However, most HSR networks have been found to be inefficient and unsuccessful as a result of unexpected problems with internal and external issues such as a lack of operational profit and not being robust. These problems directly affect customers' behaviour when using HSR services. For this reason, the purpose of this thesis is to build a systems-based benchmarking framework for HSR in order to improve its efficiency in terms of life cycle cost, punctuality, productivity, risk and uncertainty, sustainability, and urbanisation.

To ensure that the framework developed is practically adopted on railway networks, five leading HSR networks, namely CR, JR Central, SNCF, Korail, and Renfe, have been chosen for benchmarking of their performance, resulting in a sustainable railway network. This research has involved collecting long-term data from rail authorities' reports, sustainability reports, the World Bank, and other reliable sources.

With a mix between analytical and objective datasets, the thesis applies both quantitative and qualitative analyse. Various mathematical models, statistical models, and novel computational-based programming methods have been integrated to evaluate the performance of the HSR networks in Chapters 3, 5, 6, and 7, in terms of quantitative analysis. Moreover, the thesis has adopted qualitative analysis to evaluate productivity and punctuality information in Chapter 4.

Table 8.1 shows an overview of the benchmarking framework as applied to the five HSR networks. The CR network has the highest overall score, followed by the Renfe, SNCF, JR Central, and Korail networks. It is worth discussing the interesting fact revealed by the framework that none of the selected HSR networks ranked highest for all pillars. The CR network performs well in operational cost (staff cost and demolition cost), and it has the lowest level of network risk. The Renfe network is notable for its low CO_2 emissions and low overall life cycle cost. The SNCF network consumes the least amount of energy while providing the greatest urbanisation benefit in terms of quality of life. The JR Central network has absolutely performed best in overall productivity. The Korail network performs best in productivity and punctuality, and it displays well in terms of sustainability and the urbanisation pillar in terms of employment. Korail has a high potential for long-term growth in order to achieve a sustainable goal.

In using the framework of this thesis, it can be practically adopted on all HSR networks. The model provides clear guidance on six pillars, covering fundamental safety, sustainability, and social impact frameworks. This allows any HSR authority to compare its own performance with that of other HSR networks, and hence, the authority can gradually develop its performance. Furthermore, upcoming networks can evaluate operating performance before officially launching their services.

According to comprehensively developed theories and long-term datasets, the benchmarking framework and models can be used as guidance to shape any rail network, leading to success and the meeting of sustainability goals. Furthermore, policy implications have led to proposals to improve the performance of HSR networks and guide them to success and to meet long-term goals.

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APPENDIX

APPENDIX A: EXPERT REVIEW ON THE IMPACT OF HSR ON SOCIETY

A1: Consent form

Dear Participant,

My name is Panrawee Rungskunroch. As you are an expert related to my research area, I invite you to participate in a research study entitled Benchmarking operation readiness for the High-speed rail (HSR) network. I am currently enrolled in the PhD in department of Civil Engineering at University of Birmingham, Birmingham United Kingdom and am in the process of writing my Doctoral Thesis. The purpose of the research is to develop systems-based benchmarking framework of HSR with enhancement its efficiency in term of operating cost, punctuality, resources usage, risk and uncertainty, sustainability and urbanization.

The enclosed questionnaire has been designed to collect information on the sustainability and urbanisation developments. Your participation in this research project is completely voluntary. You able to decline during the survey or leave blank any questions you don't wish to answer. The survey is stickly followed the General Data Protection Regulation (GDPR). There are no known risks to participation beyond those encountered in everyday life. Your responses will remain confidential and anonymous. Data from this research will be kept under lock and key and reported only as a collective combined total. No one other than the researchers will know your individual answers to this questionnaire.

If you agree to participate in this project, please answer the questions on the questionnaire as best you can. It should take approximately 5-10 minutes to complete. If you have any questions about this project, feel free to contact me via [redacted] Thank you for your assistance in this important endeavour.

Sincerely yours,

Panrawee Rungskunroch

[ ] I have read and understood the consent form; and I wish to continue the survey

A2: Personal Information

Years of experience: ______________________________

Positions: _______________________________________

Expertise: _______________________________________

(For example: policy development, environmental development, project management in railway or specific)

Country of experiences:

[ ] China

[ ] France

[ ] Japan

[ ] South Korea

[ ] Spain

[ ] Other *(please specify)*

A3: A discussion of evaluation of PCC's result

[ ] China

This study uses long-term data collection from the World Bank to evaluate social impacts from the High-speed rail (HSR) services. The research takes both k-nearest neighbour (KNN) and Pearson's correlation coefficient (PCC) methods and analyses through Python programming.

The CR has operated China's High-Speed rail network since 2014. The network has an operating distance of more than 35,000 km. The research measures 12 key factors of social impacts, including; quality of living, education and employment.

- The quality of living pillar - The impact of the high-speed rail on society towards residential, especially the elderly groups.
- The education pillar – The impact of the high-speed rail on society towards young generations, especially the educational benefits.
- The employment pillar – The impact of the high-speed rail on society towards adult generations, workers, GDP and country's economy.

The results show that the growth of CR's network substantially benefits the quality of living; whereas, the advantages of education and employment are lower. The research suggests that the affordable price to middle-class people should be adjusted as the main priorities. The CR service should apply the new strategies and promotions to reach more passengers, such as student discount, early tickets and return price.

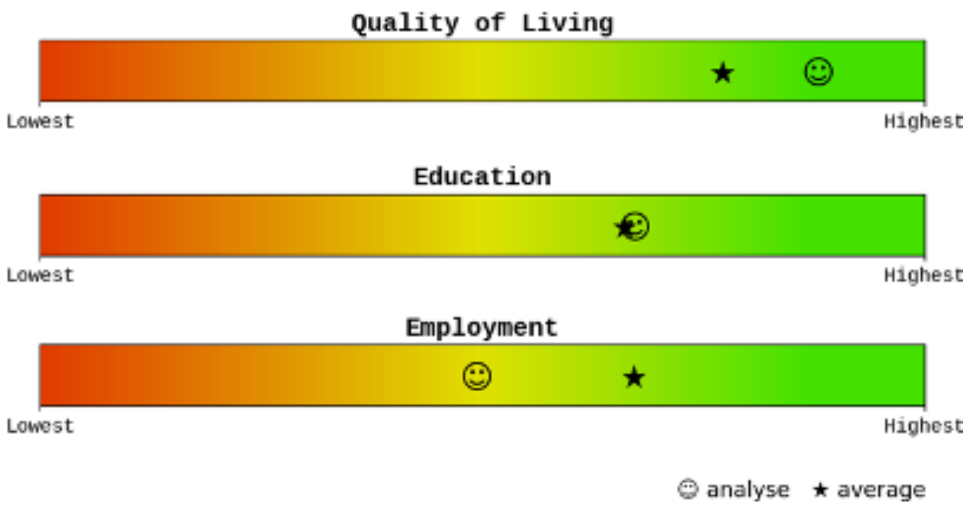

Figure B.1 An illustration of PCC's result of social impact on CR network

[ ] France

This study uses long-term data collection from the World Bank to evaluate social impacts from the High-speed rail (HSR) services. The research takes both k-nearest neighbour (KNN) and Pearson's correlation coefficient (PCC) methods and analyses through Python programming.

The French High-Speed rail network (TGV) has been operated by the Société nationale des chemins de fer français corporation since 1981. The network has operating distance more than 32,000 km. The research measures 12 key factors of social impacts, including; quality of living, education and employment.

• The quality of living pillar - The impact of the high-speed rail on society towards residential, especially the elderly groups.

• The education pillar – The impact of the high-speed rail on society towards young generations, especially the educational benefits.

• The employment pillar – The impact of the high-speed rail on society towards adult generations, workers, GDP and country's economy.

The results show that SNCF's network's growth has a powerful benefit with the quality of living; whereas, the advantages of employment and education show slightly lower than the living's quality. The HSR network can stimulate the job market and country's economy in both direct and indirect ways. Regarding the business area, the TGV services can also increase visibility and accessibility to customers caused by business obtains positive effects from high activities and productivities.

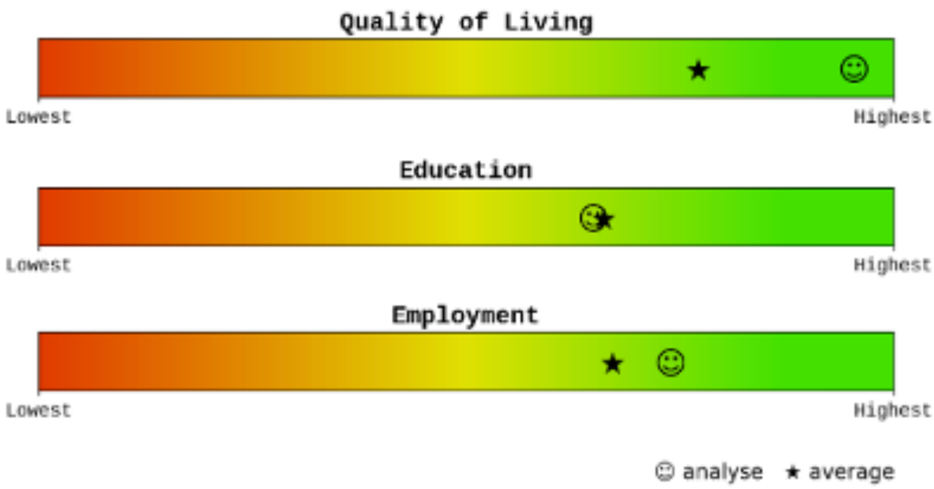

Figure B.2 An illustration of PCC's result of social impact on SNCF network

[ ] Japan

This study uses long-term data collection from the World Bank to evaluate social impacts from the High-speed rail (HSR) services. The research takes both k-nearest neighbour (KNN) and Pearson's correlation coefficient (PCC) methods and analyses through Python programming.

JR Central service has been operated by the since 1964. The network has an operating distance of more than 2,764.6 km. The research measures 12 key factors of social impacts, including; quality of living, education and employment.

• The quality of living pillar - The impact of the high-speed rail on society towards residential, especially the elderly groups.

• The education pillar – The impact of the high-speed rail on society towards young generations, especially the educational benefits.

• The employment pillar – The impact of the high-speed rail on society towards adult generations, workers, GDP and country's economy.The results show that the growth of the JR Central network has the highest benefit with education. Whereas the employment and quality of living pillars are shows at small impacts on society. The research finds that the network seems to impact the labour market at the beginning of the operational era, but its effect decreased slightly after the 20th century. The JR Central network shows low impacts in terms of Japanese's living quality. The research suggests increasing accessibility to the service by offering the reasonable price of train ticket.

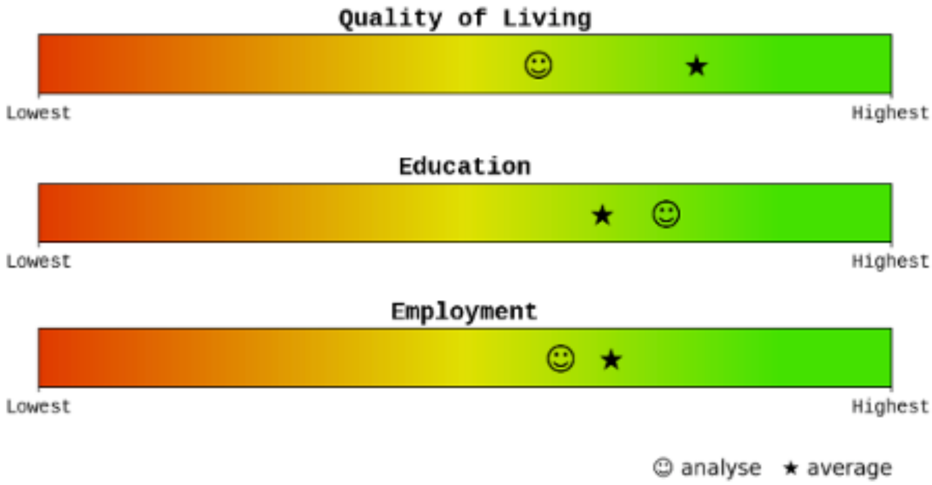

Figure B.3 An illustration of PCC's result of social impact on JR Central network

[ ] South Korea

This study uses long-term data collection from the World Bank to evaluate social impacts from the High-speed rail (HSR) services. The research takes both k-nearest neighbour (KNN) and Pearson's correlation coefficient (PCC) methods and analyses through Python programming.

The Korean Train Express (KTX) has operated by the South Korean's High-Speed rail network since 2004. The network has an operating distance of more than 1,603.2 km. The research measures 12 key factors of social impacts, including; quality of living, education and employment.

• The quality of living pillar - The impact of the high-speed rail on society towards residential, especially the elderly groups.

• The education pillar – The impact of the high-speed rail on society towards young generations, especially the educational benefits.

• The employment pillar – The impact of the high-speed rail on society towards adult generations, workers, GDP and country's economy.

The results show that the growth of Korail network has moderate benefits with the employment and quality of living; whereas, the advantages of education are lower. The research suggests that the affordable price to middle-class people should be adjusted as the main priorities. The Korail service should apply the new strategies and promotions to reach more passengers, such as student discount, early tickets and return price.

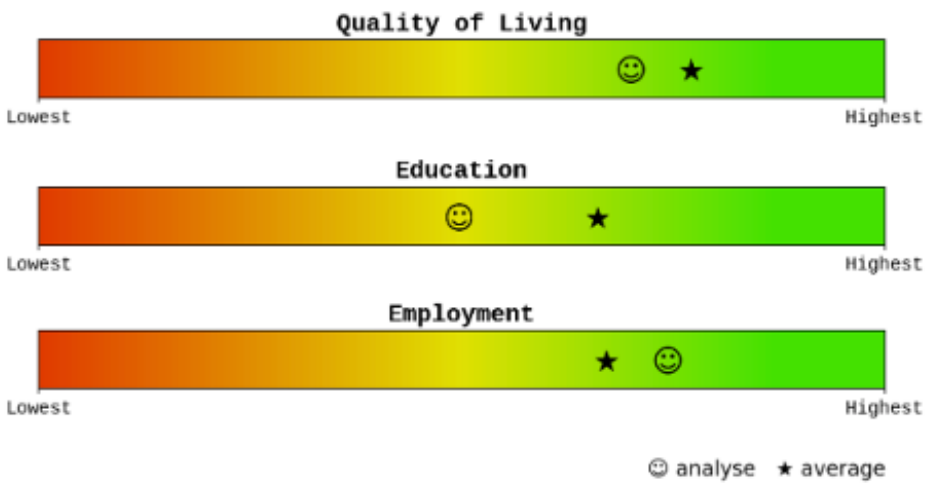

Figure B.4 An illustration of PCC's result of social impact on Korail network

[ ] Spain

This study uses long-term data collection from the World Bank to evaluate social impacts from the High-speed rail (HSR) services. The research takes both k-nearest neighbour (KNN) and Pearson's correlation coefficient (PCC) methods and analyses through Python programming.

Since 1992, the Renfe has operated the Spanish High-Speed rail network (AVE). And, the network has an operating distance of more than 3,240 km. The research measures 12 key factors of social impacts, including; quality of living, education and employment.

• The quality of living pillar - The impact of the high-speed rail on society towards residential, especially the elderly groups.

• The education pillar – The impact of the high-speed rail on society towards young generations, especially the educational benefits.

• The employment pillar – The impact of the high-speed rail on society towards adult generations, workers, GDP and country's economy.

The results show that the Renfe network's growth substantially benefits the quality of living; whereas, the advantages of employment and education show moderate. The research suggests enhancing jobs and education benefits by adapting the train schedule to support worker demands. It may stimulate the travel demand for people who live in suburban areas, requiring early and lately services.

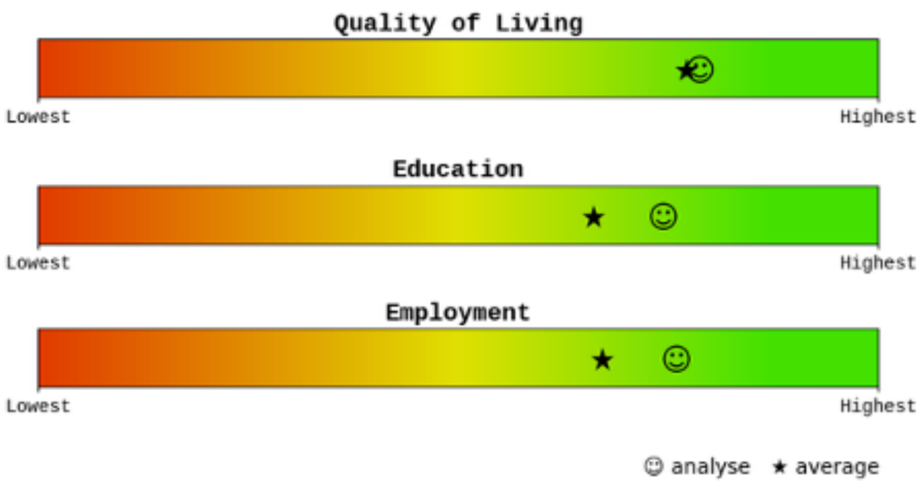

Figure B.5 An illustration of PCC's result of social impact on Renfe network

A4: Response to findings and policy implications

Please answer the following questions by choosing the most appropriate choice (Please note that 1 = Strongly disagree; 2 = disagree; 3 = normal; 4 = agree; 5 = strongly agree)

Questions	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
How do you agree with the statement in previous section?					
Offering reasonable prices compare to other transportations can reach more passenger					
Offering special tickets or promotion tickets (i.e., return ticket, student discount) can get more passenger					
Increasing particular schedule in early and late hours can support more passenger demand					
Connecting to the major cities is an essential point to the passenger using the high-speed rail services					
Connecting to the business areas are the most crucial point to the passenger using the high-speed rail services					

The location of high-speed rail nearby the business area can increase job opportunity
The location of high-speed rail station increases social values to the nearby business
Linking to other public transportation (i.e., airport, bus) or transportation hub can offer high social impacts

A5: Expert's feedbacks

Feedbacks for future development on the high-speed rail network

………………………………………………………………………………………………

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APPENDIX B: LCC AND NPV ANALYSIS

B1: CR network

Table B1. The LCC and NPV calculation of CR network

		Manufacturing	Maintenance	Manufacturing	Maintenance-Machine	Operation	Maintenance - Staff	Operation	Operation	Operation
#Year	Year	Construction cost	15% every 5 yrs.	Machine/Equip	15% every 5 yrs.	Operation-Staff	15% every 5 yrs.	Electricity cost	Rolling stock value	Rolling stock cost
2008	0	11,344.6874		5,951.8000	892.7700	1,236.4600	1,236.4600	544.3400	2,110,618.9477	2,110,618.9477
2009	1	12,025.3714		6,308.9080		1,310.6476		577.0004	2,237,256.0846	
2010	2	12,746.8937		5,952.8000		1,389.2865		611.6204	2,371,491.4497	
2011	3	13,511.7073		7,088.6890		1,472.6436		648.3176	2,513,780.9366	
2012	4	14,322.4097		5,953.8000		1,561.0023		687.2167	2,664,607.7928	
2013	5	15,181.7543		7,964.8510	1,194.7276	1,654.6624	248.1994	728.4497	2,824,484.2604	
2014	6	16,092.6596		5,954.8000		1,753.9421		772.1567	2,993,953.3160	
2015	7	17,058.2192		8,949.3066		1,859.1787		818.4861	3,173,590.5150	
2016	8	18,081.7123		5,955.8000		1,970.7294		867.5953	3,364,005.9459	
2017	9	19,166.6151		10,055.4409		2,088.9732		919.6510	3,565,846.3027	
2018	10	20,316.6120		5,956.8000	893.5200	2,214.3115	332.1467	974.8300	3,779,797.0808	
2019	11	21,535.6087		11,298.2934		2,347.1702		1,033.3198	4,006,584.9057	
2020	12	22,827.7452		11,976.1910		2,488.0004		1,095.3190	4,246,980.0000	
2021	13	24,197.4099		12,694.7624		2,637.2805		1,161.0382	4,501,798.8000	

2022	14	25,649.2545	5,953.8000		2,795.5173		1,230.7005	4,771,906.7280	
2023	15	27,188.2098	14,263.8351	2,139.5753	2,963.2483	444.4873	1,304.5425	5,058,221.1317	
2024	16	28,819.5024	5,954.8000		3,141.0432		1,382.8150	5,361,714.3996	
2025	17	30,548.6725	16,026.8451		3,329.5058		1,465.7839	5,683,417.2636	
2026	18	32,381.5928	5,955.8000		3,529.2762		1,553.7310	6,024,422.2994	
2027	19	34,324.4884	18,007.7631		3,741.0328		1,646.9548	6,385,887.6373	
2028	20	36,383.9577	5,956.8000	893.5200	3,965.4947	594.8242	1,745.7721	6,769,040.8956	
2029	21	38,566.9952	20,233.5226		4,203.4244		1,850.5185	7,175,183.3493	
2030	22	40,881.0149	5,957.8000		4,455.6299		1,961.5496	7,605,694.3503	
2031	23	43,333.8758	22,734.3860		4,722.9677		2,079.2425	8,062,036.0113	
2032	24	45,933.9083	24,098.4492		5,006.3457		2,203.9971	8,545,758.1720	
2033	25	48,689.9428	25,544.3561	3,831.6534	5,306.7265	796.0090	2,336.2369	9,058,503.6623	
2034	26	51,611.3394	5,954.8000		5,625.1301		2,476.4111	9,602,013.8820	
2035	27	54,708.0198	28,701.6386		5,962.6379		2,624.9958	10,178,134.7149	
2036	28	57,990.5010	5,955.8000		6,320.3961		2,782.4955	10,788,822.7978	
2037	29	61,469.9310	32,249.1611		6,699.6199		2,949.4453	11,436,152.1657	
2038	30	65,158.1269	5,956.8000	893.5200	7,101.5971	1,065.2396	3,126.4120	12,122,321.2956	
2039	31	69,067.6145	36,235.1574		7,527.6929		3,313.9967	12,849,660.5734	
2040	32	73,211.6714	5,957.8000		7,979.3545		3,512.8365	13,620,640.2078	
2041	33	77,604.3716	40,713.8229		8,458.1158		3,723.6067	14,437,878.6202	
2042	34	82,260.6339	5,958.8000		8,965.6027		3,947.0231	15,304,151.3375	
2043	35	87,196.2720	45,746.0514	6,861.9077	9,503.5389	1,425.5308	4,183.8445	16,222,400.4177	
2044	36	92,428.0483	48,490.8145		10,073.7512		4,434.8752	17,195,744.4428	17,195,744.4428
2045	37	97,973.7312	51,400.2633		10,678.1763		4,700.9677	18,227,489.1093	

2046	38	103,852.1551	5,955.8000		11,318.8669		4,983.0257	19,321,138.4559
2047	39	110,083.2844	57,753.3359		11,997.9989		5,282.0073	20,480,406.7633
2048	40	116,688.2814	5,956.8000	893.5200	12,717.8788	1,907.6818	5,598.9277	21,709,231.1690
2049	41	123,689.5783	64,891.6482		13,480.9515		5,934.8634	23,011,785.0392
2050	42	131,110.9530	5,957.8000		14,289.8086		6,290.9552	24,392,492.1415
2051	43	138,977.6102	72,912.2559		15,147.1971		6,668.4125	25,856,041.6700
2052	44	147,316.2668	5,958.8000		16,056.0290		7,068.5172	27,407,404.1702
2053	45	156,155.2428	81,924.2107	12,288.6316	17,019.3907	2,552.9086	7,492.6283	29,051,848.4204
2054	46	165,524.5574	5,959.8000		18,040.5541		7,942.1860	30,794,959.3257
2055	47	175,456.0308	92,050.0432		19,122.9874		8,418.7171	32,642,656.8852
2056	48	185,983.3927	97,573.0458		20,270.3666		8,923.8401	34,601,216.2983
2057	49	197,142.3962	103,427.4285		21,486.5886		9,459.2705	36,677,289.2762
2058	50	208,970.9400	5,956.8000	893.5200	22,775.7840	3,416.3676	10,026.8268	38,877,926.6328
2059	51	221,509.1964	116,211.0587		24,142.3310		10,628.4364	41,210,602.2308
2060	52	234,799.7482	5,957.8000		25,590.8709		11,266.1426	43,683,238.3646
2061	53	248,887.7331	130,574.7455		27,126.3231		11,942.1111	46,304,232.6665
2062	54	263,820.9971	5,958.8000		28,753.9025		12,658.6378	49,082,486.6265
2063	55	279,650.2569	146,713.7841	22,007.0676	30,479.1366	4,571.8705	13,418.1561	52,027,435.8241
2064	56	296,429.2723	5,959.8000		32,307.8848		14,223.2454	55,149,081.9735
2065	57	314,215.0286	164,847.6078		34,246.3579		15,076.6401	58,458,026.8919
2066	58	333,067.9304	5,960.8000		36,301.1394		15,981.2386	61,965,508.5054
2067	59	353,052.0062	185,222.7721		38,479.2078		16,940.1129	65,683,439.0158
2068	60	374,235.1265	196,336.1384	29,450.4208	40,787.9602	6,118.1940	17,956.5196	69,624,445.3567
2069	61	396,689.2341	208,116.3067		43,235.2378		19,033.9108	73,801,912.0781

2070	62	420,490.5882	5,957.8000		45,829.3521		20,175.9455	78,230,026.8028	
2071	63	445,720.0235	233,839.4822		48,579.1132		21,386.5022	82,923,828.4110	
2072	64	472,463.2249	5,958.8000		51,493.8600		22,669.6923	87,899,258.1156	
2073	65	500,811.0184	262,742.0422	39,411.3063	54,583.4916	8,187.5237	24,029.8739	93,173,213.6026	
2074	66	530,859.6795	5,959.8000		57,858.5011		25,471.6663	98,763,606.4187	
2075	67	562,711.2603	295,216.9587		61,330.0112		26,999.9663	104,689,422.8038	
2076	68	596,473.9359	5,960.8000		65,009.8119		28,619.9643	110,970,788.1721	
2077	69	632,262.3720	331,705.7748		68,910.4006		30,337.1621	117,629,035.4624	
2078	70	670,198.1143	5,961.8000	894.2700	73,045.0246	10,956.7537	32,157.3918	124,686,777.5901	
Sum		22,827.7452		123,439.9304	1,269,854.4351	43,854.1969	559,041.5891		19,306,363.3905

B2: JR Central network

Table B2. The LCC and NPV calculation of JR Central network

		Manufacturing	Maintenance	Manufacturing	Maintenance-Machine	Operation	Maintenance - Staff	Operation	Operation	Operation
#Year	Year	Construction cost	15% every 5 yrs	Machine/Equip	15% every 5 yrs	Operation-Staff	15% every 5 yrs	Electricity cost	Rolling stock value	Rolling stock cost
1964	0	838.7876	838.7876	11,979.4600	1,796.9190	430.0000	430.0000	1,188.8000	249,255.4262	249,255.4262
1965	1	889.1174		12,698.2276		455.8000		1,260.1280	264,210.7518	
1966	2	942.4644		13,460.1213		483.1480		1,335.7357	280,063.3969	
1967	3	999.0123		14,267.7285		512.1369		1,415.8798	296,867.2007	
1968	4	1,058.9530		15,123.7922		542.8651		1,500.8326	314,679.2327	
1969	5	1,122.4902	168.3735	16,031.2198	2,404.6830	575.4370	86.3155	1,590.8826	333,559.9867	
1970	6	1,189.8396		16,993.0930		609.9632		1,686.3355	353,573.5859	
1971	7	1,261.2300		18,012.6785		646.5610		1,787.5157	374,788.0011	
1972	8	1,336.9038		19,093.4393		685.3547		1,894.7666	397,275.2811	
1973	9	1,417.1181		20,239.0456		726.4760		2,008.4526	421,111.7980	
1974	10	1,502.1451	225.3218	21,453.3883	3,218.0083	770.0645	115.5097	2,128.9597	446,378.5059	
1975	11	1,592.2738		22,740.5916		816.2684		2,256.6973	473,161.2162	
1976	12	1,687.8103		24,105.0271		865.2445		2,392.0992	501,550.8892	
1977	13	1,789.0789		25,551.3288		917.1592		2,535.6251	531,643.9426	
1978	14	1,896.4236		27,084.4085		972.1887		2,687.7626	563,542.5791	
1979	15	2,010.2090	301.5314	28,709.4730	4,306.4210	1,030.5200	154.5780	2,849.0284	597,355.1339	
1980	16	2,130.8216		30,432.0414		1,092.3512		3,019.9701	633,196.4419	
1981	17	2,258.6709		32,257.9639		1,157.8923		3,201.1683	671,188.2284	

1982	18	2,394.1911		34,193.4417		1,227.3658		3,393.2384	711,459.5221	
1983	19	2,537.8426		36,245.0482		1,301.0078		3,596.8327	754,147.0934	
1984	20	2,690.1132	403.5170	38,419.7511	5,762.9627	1,379.0683	206.8602	3,812.6426	799,395.9190	
1985	21	2,851.5200		40,724.9362		1,461.8123		4,041.4012	847,359.6742	
1986	22	3,022.6111		43,168.4323		1,549.5211		4,283.8853	898,201.2546	
1987	23	3,203.9678		45,758.5383		1,642.4924		4,540.9184	952,093.3299	
1988	24	3,396.2059		48,504.0506		1,741.0419		4,813.3735	1,009,218.9297	
1989	25	3,599.9782	539.9967	51,414.2936	7,712.1440	1,845.5044	276.8257	5,102.1759	1,069,772.0655	
1990	26	3,815.9769		54,499.1512		1,956.2347		5,408.3065	1,133,958.3894	
1991	27	4,044.9356		57,769.1003		2,073.6088		5,732.8049	1,201,995.8928	
1992	28	4,287.6317		61,235.2463		2,198.0253		6,076.7731	1,274,115.6463	
1993	29	4,544.8896		64,909.3611		2,329.9068		6,441.3795	1,350,562.5851	
1994	30	4,817.5830	722.6374	68,803.9228	10,320.5884	2,469.7012	370.4552	6,827.8623	1,431,596.3402	
1995	31	5,106.6379		72,932.1581		2,617.8833		7,237.5340	1,517,492.1206	
1996	32	5,413.0362		77,308.0876		2,774.9563		7,671.7861	1,608,541.6479	
1997	33	5,737.8184		81,946.5729		2,941.4536		8,132.0933	1,705,054.1467	
1998	34	6,082.0875		86,863.3673		3,117.9409		8,620.0188	1,807,357.3956	
1999	35	6,447.0127	967.0519	92,075.1693	13,811.2754	3,305.0173	495.7526	9,137.2200	1,915,798.8393	
2000	36	6,833.8335		97,599.6794		3,503.3184		9,685.4532	2,030,746.7696	2,030,746.7696
2001	37	7,243.8635		103,455.6602		3,713.5175		10,266.5804	2,152,591.5758	
2002	38	7,678.4953		109,662.9998		3,936.3285		10,882.5752	2,281,747.0704	
2003	39	8,139.2050		116,242.7798		4,172.5082		11,535.5297	2,418,651.8946	
2004	40	8,627.5573	1,294.1336	123,217.3466	18,482.6020	4,422.8587	663.4288	12,227.6615	2,563,771.0083	
2005	41	9,145.2108		130,610.3874		4,688.2302		12,961.3212	2,717,597.2688	

2006	42	9,693.9234		138,447.0106		4,969.5240		13,739.0004	2,880,653.1049
2007	43	10,275.5588		146,753.8313		5,267.6955		14,563.3405	3,053,492.2912
2008	44	10,892.0924		155,559.0612		5,583.7572		15,437.1409	3,236,701.8287
2009	45	11,545.6179	1,731.8427	164,892.6048	24,733.8907	5,918.7827	887.8174	16,363.3694	3,430,903.9384
2010	46	12,238.3550		174,786.1611		6,273.9096		17,345.1715	3,636,758.1747
2011	47	12,972.6563		185,273.3308		6,650.3442		18,385.8818	3,854,963.6652
2012	48	13,751.0157		196,389.7306		7,049.3648		19,489.0347	4,086,261.4851
2013	49	14,576.0766		208,173.1145		7,472.3267		20,658.3768	4,331,437.1742
2014	50	15,450.6412	2,317.5962	220,663.5013	33,099.5252	7,920.6663	1,188.1000	21,897.8794	4,591,323.4046
2015	51	16,377.6797		233,903.3114		8,395.9063		23,211.7522	4,866,802.8089
2016	52	17,360.3405		247,937.5101		8,899.6607		24,604.4573	5,158,810.9774
2017	53	18,401.9609		262,813.7607		9,433.6403		26,080.7247	5,468,339.6361
2018	54	19,506.0785		278,582.5863		9,999.6588		27,645.5682	5,796,440.0142
2019	55	20,676.4432	3,101.4665	295,297.5415	44,294.6312	10,599.6383	1,589.9457	29,304.3023	6,144,226.4151
2020	56	21,917.0298		313,015.3940		11,235.6166		31,062.5604	6,512,880.0000
2021	57	23,232.0516		331,796.3177		11,909.7536		32,926.3141	6,903,652.8000
2022	58	24,625.9747		351,704.0967		12,624.3388		34,901.8929	7,317,871.9680
2023	59	26,103.5332		372,806.3425		13,381.7991		36,996.0065	7,756,944.2861
2024	60	27,669.7452	4,150.4618	395,174.7231	59,276.2085	14,184.7071	2,127.7061	39,215.7669	8,222,360.9432
2025	61	29,329.9299		418,885.2065		15,035.7895		41,568.7129	8,715,702.5998
2026	62	31,089.7257		444,018.3188		15,937.9369		44,062.8357	9,238,644.7558
2027	63	32,955.1093		470,659.4180		16,894.2131		46,706.6058	9,792,963.4412
2028	64	34,932.4158		498,898.9831		17,907.8659		49,509.0022	10,380,541.2477
2029	65	37,028.3608	5,554.2541	528,832.9220	79,324.9383	18,982.3378	2,847.3507	52,479.5423	11,003,373.7225

2030	66	39,250.0624		560,562.8974		20,121.2781		55,628.3148	11,663,576.1459	
2031	67	41,605.0662		594,196.6712		21,328.5548		58,966.0137	12,363,390.7146	
2032	68	44,101.3701		629,848.4715		22,608.2680		62,503.9745	13,105,194.1575	
2033	69	46,747.4523		667,639.3798		23,964.7641		66,254.2130	13,891,505.8069	
2034	70	49,552.2995	7,432.8449	707,697.7425	106,154.6614	25,402.6500	3,810.3975	70,229.4658	14,724,996.1554	
Sum		21,917.0298			414,699.4590	441,613.4829	15,251.0430	1,220,907.2291		2,280,002.1958

B3: Korail network

Table B3. The LCC and NPV calculation of Korail network

		Manufacturing	Maintenance	Manufacturing	Maintenance-Machine	Operation	Maintenance - Staff	Operation	Operation	Operation
#Year	Year	Construction cost	15% every 5 yrs	Machine/Equip	15% every 5 yrs	Operation-Staff	15% every 5 yrs	Electricity cost	Rolling stock value	Rolling stock cost
2004	0	9,118.5162		40,179.5700	6,026.9355	2,884.0000	2,884.0000	240.9600	1,238,051.2269	1,238,051.2269
2005	1	9,665.6312		42,590.3442		3,057.0400		255.4176	1,312,334.3005	
2006	2	10,245.5691		45,145.7649		3,240.4624		270.7427	1,391,074.3586	
2007	3	10,860.3032		47,854.5107		3,434.8901		286.9872	1,474,538.8201	
2008	4	11,511.9214		50,725.7814		3,640.9836		304.2064	1,563,011.1493	
2009	5	12,202.6367	1,830.3955	53,769.3283	8,065.3992	3,859.4426	578.9164	322.4588	1,656,791.8182	
2010	6	12,934.7949		56,995.4880		4,091.0091		341.8064	1,756,199.3273	
2011	7	13,710.8826		60,415.2172		4,336.4697		362.3147	1,861,571.2870	
2012	8	14,533.5355		64,040.1303		4,596.6578		384.0536	1,973,265.5642	
2013	9	15,405.5477		67,882.5381		4,872.4573		407.0968	2,091,661.4980	
2014	10	16,329.8805	2,449.4821	71,955.4904	10,793.3236	5,164.8048	774.7207	431.5227	2,217,161.1879	
2015	11	17,309.6734		76,272.8198		5,474.6930		457.4140	2,350,190.8592	
2016	12	18,348.2538		80,849.1890		5,803.1746		484.8589	2,491,202.3107	
2017	13	19,449.1490		85,700.1403		6,151.3651		513.9504	2,640,674.4494	
2018	14	20,616.0979		90,842.1488		6,520.4470		544.7874	2,799,114.9163	
2019	15	21,853.0638	3,277.9596	96,292.6777	14,443.9017	6,911.6738	1,036.7511	577.4747	2,967,061.8113	
2020	16	23,164.2476		102,070.2383		7,326.3743		612.1231	3,145,085.5200	
2021	17	24,554.1025		108,194.4526		7,765.9567		648.8505	3,333,790.6512	

2022	18	26,027.3487		114,686.1198		8,231.9141		687.7816	3,533,818.0903	
2023	19	27,588.9896		121,567.2870		8,725.8290		729.0485	3,745,847.1757	
2024	20	29,244.3289	4,386.6493	128,861.3242	19,329.1986	9,249.3787	1,387.4068	772.7914	3,970,598.0062	
2025	21	30,998.9887		136,593.0037		9,804.3414		819.1588	4,208,833.8866	
2026	22	32,858.9280		144,788.5839		10,392.6019		868.3084	4,461,363.9198	
2027	23	34,830.4637		153,475.8989		11,016.1580		920.4069	4,729,045.7550	
2028	24	36,920.2915		162,684.4528		11,677.1275		975.6313	5,012,788.5003	
2029	25	39,135.5090	5,870.3263	172,445.5200	25,866.8280	12,377.7552	1,856.6633	1,034.1692	5,313,555.8103	
2030	26	41,483.6395		182,792.2512		13,120.4205		1,096.2193	5,632,369.1589	
2031	27	43,972.6579		193,759.7863		13,907.6457		1,161.9925	5,970,311.3085	
2032	28	46,611.0174		205,385.3735		14,742.1044		1,231.7120	6,328,529.9870	
2033	29	49,407.6784		217,708.4959		15,626.6307		1,305.6147	6,708,241.7862	
2034	30	52,372.1391	7,855.8209	230,771.0056	34,615.6508	16,564.2285	2,484.6343	1,383.9516	7,110,736.2934	
2035	31	55,514.4675		244,617.2660		17,558.0823		1,466.9887	7,537,380.4710	
2036	32	58,845.3355		259,294.3019		18,611.5672		1,555.0081	7,989,623.2992	
2037	33	62,376.0557		274,851.9600		19,728.2612		1,648.3085	8,469,000.6972	
2038	34	66,118.6190		291,343.0776		20,911.9569		1,747.2071	8,977,140.7390	
2039	35	70,085.7361	10,512.8604	308,823.6623	46,323.5493	22,166.6743	3,325.0011	1,852.0395	9,515,769.1833	
2040	36	74,290.8803		327,353.0820		23,496.6748		1,963.1618	10,086,715.3343	10,086,715.3343
2041	37	78,748.3331		346,994.2670		24,906.4753		2,080.9516	10,691,918.2544	
2042	38	83,473.2331		367,813.9230		26,400.8638		2,205.8086	11,333,433.3497	
2043	39	88,481.6271		389,882.7584		27,984.9156		2,338.1572	12,013,439.3506	
2044	40	93,790.5247	14,068.5787	413,275.7239	61,991.3586	29,664.0105	4,449.6016	2,478.4466	12,734,245.7117	
2045	41	99,417.9562		438,072.2673		31,443.8512		2,627.1534	13,498,300.4544	

2046	42	105,383.0336		464,356.6033		33,330.4822		2,784.7826	14,308,198.4816
2047	43	111,706.0156		492,217.9995		35,330.3112		2,951.8695	15,166,690.3905
2048	44	118,408.3765		521,751.0795		37,450.1298		3,128.9817	16,076,691.8140
2049	45	125,512.8791	18,826.9319	553,056.1443	82,958.4216	39,697.1376	5,954.5706	3,316.7206	17,041,293.3228
2050	46	133,043.6519		586,239.5129		42,078.9659		3,515.7239	18,063,770.9222
2051	47	141,026.2710		621,413.8837		44,603.7038		3,726.6673	19,147,597.1775
2052	48	149,487.8472		658,698.7167		47,279.9261		3,950.2673	20,296,453.0082
2053	49	158,457.1181		698,220.6397		50,116.7216		4,187.2834	21,514,240.1886
2054	50	167,964.5452	25,194.6818	740,113.8781	111,017.0817	53,123.7249	7,968.5587	4,438.5204	22,805,094.6000
2055	51	178,042.4179		784,520.7108		56,311.1484		4,704.8316	24,173,400.2760
2056	52	188,724.9629		831,591.9534		59,689.8173		4,987.1215	25,623,804.2925
2057	53	200,048.4607		881,487.4706		63,271.2064		5,286.3488	27,161,232.5501
2058	54	212,051.3684		934,376.7189		67,067.4788		5,603.5297	28,790,906.5031
2059	55	224,774.4505	33,716.1676	990,439.3220	148,565.8983	71,091.5275	10,663.7291	5,939.7415	30,518,360.8933
2060	56	238,260.9175		1,049,865.6813		75,357.0191		6,296.1260	32,349,462.5469
2061	57	252,556.5725		1,112,857.6222		79,878.4403		6,673.8935	34,290,430.2997
2062	58	267,709.9669		1,179,629.0795		84,671.1467		7,074.3272	36,347,856.1177
2063	59	283,772.5649		1,250,406.8243		89,751.4155		7,498.7868	38,528,727.4847
2064	60	300,798.9188	45,119.8378	1,325,431.2338	198,814.6851	95,136.5004	14,270.4751	7,948.7140	40,840,451.1338
2065	61	318,846.8539		1,404,957.1078		100,844.6904		8,425.6368	43,290,878.2018
2066	62	337,977.6652		1,489,254.5343		106,895.3719		8,931.1750	45,888,330.8939
2067	63	358,256.3251		1,578,609.8063		113,309.0942		9,467.0455	48,641,630.7476
2068	64	379,751.7046		1,673,326.3947		120,107.6398		10,035.0683	51,560,128.5924
2069	65	402,536.8069	60,380.5210	1,773,725.9784	266,058.8968	127,314.0982	19,097.1147	10,637.1724	54,653,736.3080

2070	66	426,689.0153		1,880,149.5371		134,952.9441		11,275.4027	57,932,960.4864	
2071	67	452,290.3562		1,992,958.5093		143,050.1208		11,951.9269	61,408,938.1156	
2072	68	479,427.7776		2,112,536.0199		151,633.1280		12,669.0425	65,093,474.4026	
2073	69	508,193.4442		2,239,288.1811		160,731.1157		13,429.1850	68,999,082.8667	
2074	70	538,685.0509	80,802.7576	2,373,645.4719	356,046.8208	170,374.9826	25,556.2474	14,234.9361	73,139,027.8387	
Sum		23,164.2476			1,390,917.9496	2,961,891.3599	102,288.3910	247,467.8717		11,324,766.5612

B4: SNCF network

Table B4. The LCC and NPV calculation of SNCF network

		Manufacturing	Maintenance	Manufacturing	Maintenance-Machine	Operation	Maintenance - Staff	Operation	Operation	Operation
#Year	Year	Construction cost	15% every 5 yrs	Machine/Equip	15% every 5 yrs	Operation-Staff	15% every 5 yrs	Electricity cost	Rolling stock value	Rolling stock cost
1992	0	2,335.0256		22,314.1000	3,347.1150	1,019.8300	1,019.8300	92.6700	148,168.2785	148,168.2785
1993	1	2,475.1318		23,652.9460		1,081.0198		98.2302	157,058.3752	
1994	2	2,623.6397		25,072.1228		1,145.8810		104.1240	166,481.8777	
1995	3	2,781.0581		26,576.4501		1,214.6338		110.3715	176,470.7904	
1996	4	2,947.9216		28,171.0371		1,287.5119		116.9937	187,059.0378	
1997	5	3,124.7969	468.7195	29,861.2994	4,479.1949	1,364.7626	204.7144	124.0134	198,282.5801	
1998	6	3,312.2847		31,652.9773		1,446.6483		131.4542	210,179.5349	
1999	7	3,511.0218		33,552.1560		1,533.4472		139.3414	222,790.3070	
2000	8	3,721.6831		35,565.2853		1,625.4541		147.7019	236,157.7254	
2001	9	3,944.9841		37,699.2024		1,722.9813		156.5640	250,327.1889	
2002	10	4,181.6831	627.2525	39,961.1546	5,994.1732	1,826.3602	273.9540	165.9579	265,346.8203	
2003	11	4,432.5841		42,358.8239		1,935.9418		175.9153	281,267.6295	
2004	12	4,698.5391		44,900.3533		2,052.0983		186.4702	298,143.6873	
2005	13	4,980.4515		47,594.3745		2,175.2242		197.6585	316,032.3085	
2006	14	5,279.2786		50,450.0370		2,305.7377		209.5180	334,994.2470	
2007	15	5,596.0353	839.4053	53,477.0392	8,021.5559	2,444.0819	366.6123	222.0890	355,093.9018	
2008	16	5,931.7974		56,685.6615		2,590.7269		235.4144	376,399.5359	
2009	17	6,287.7052		60,086.8012		2,746.1705		249.5393	398,983.5081	

2010	18	6,664.9676		63,692.0093		2,910.9407		264.5116	422,922.5186	
2011	19	7,064.8656		67,513.5298		3,085.5971		280.3823	448,297.8697	
2012	20	7,488.7575	1,123.3136	71,564.3416	10,734.6512	3,270.7330	490.6099	297.2052	475,195.7419	
2013	21	7,938.0830		75,858.2021		3,466.9769		315.0376	503,707.4864	
2014	22	8,414.3680		80,409.6943		3,674.9956		333.9398	533,929.9356	
2015	23	8,919.2301		85,234.2759		3,895.4953		353.9762	565,965.7317	
2016	24	9,454.3839		90,348.3325		4,129.2250		375.2148	599,923.6756	
2017	25	10,021.6469	1,503.2470	95,769.2324	14,365.3849	4,376.9785	656.5468	397.7277	635,919.0961	
2018	26	10,622.9457		101,515.3864		4,639.5972		421.5913	674,074.2419	
2019	27	11,260.3224		107,606.3096		4,917.9731		446.8868	714,518.6964	
2020	28	11,935.9418		114,062.6881		5,213.0514		473.7000	757,389.8182	
2021	29	12,652.0983		120,906.4494		5,525.8345		502.1220	802,833.2073	
2022	30	13,411.2242	2,011.6836	128,160.8364	19,224.1255	5,857.3846	878.6077	532.2493	851,003.1997	
2023	31	14,215.8976		135,850.4866		6,208.8277		564.1843	902,063.3917	
2024	32	15,068.8515		144,001.5158		6,581.3573		598.0353	956,187.1952	
2025	33	15,972.9826		152,641.6067		6,976.2388		633.9175	1,013,558.4269	
2026	34	16,931.3615		161,800.1031		7,394.8131		671.9525	1,074,371.9326	
2027	35	17,947.2432	2,692.0865	171,508.1093	25,726.2164	7,838.5019	1,175.7753	712.2697	1,138,834.2485	
2028	36	19,024.0778		181,798.5958		8,308.8120		755.0058	1,207,164.3034	1,207,164.3034
2029	37	20,165.5225		192,706.5116		8,807.3407		800.3062	1,279,594.1616	
2030	38	21,375.4539		204,268.9023		9,335.7812		848.3246	1,356,369.8113	
2031	39	22,657.9811		216,525.0364		9,895.9280		899.2240	1,437,752.0000	
2032	40	24,017.4600	3,602.6190	229,516.5386	34,427.4808	10,489.6837	1,573.4526	953.1775	1,524,017.1200	
2033	41	25,458.5076		243,287.5309		11,119.0647		1,010.3681	1,615,458.1472	

2034	42	26,986.0180		257,884.7828		11,786.2086		1,070.9902	1,712,385.6360
2035	43	28,605.1791		273,357.8698		12,493.3812		1,135.2496	1,815,128.7742
2036	44	30,321.4898		289,759.3419		13,242.9840		1,203.3646	1,924,036.5006
2037	45	32,140.7792	4,821.1169	307,144.9025	46,071.7354	14,037.5631	2,105.6345	1,275.5665	2,039,478.6907
2038	46	34,069.2260		325,573.5966		14,879.8168		1,352.1005	2,161,847.4121
2039	47	36,113.3795		345,108.0124		15,772.6059		1,433.2265	2,291,558.2569
2040	48	38,280.1823		365,814.4932		16,718.9622		1,519.2201	2,429,051.7523
2041	49	40,576.9932		387,763.3627		17,722.0999		1,610.3733	2,574,794.8574
2042	50	43,011.6128	6,451.7419	411,029.1645	61,654.3747	18,785.4259	2,817.8139	1,706.9957	2,729,282.5488
2043	51	45,592.3096		435,690.9144		19,912.5515		1,809.4154	2,893,039.5018
2044	52	48,327.8482		461,832.3692		21,107.3046		1,917.9804	3,066,621.8719
2045	53	51,227.5191		489,542.3114		22,373.7429		2,033.0592	3,250,619.1842
2046	54	54,301.1702		518,914.8501		23,716.1674		2,155.0427	3,445,656.3352
2047	55	57,559.2404	8,633.8861	550,049.7411	82,507.4612	25,139.1375	3,770.8706	2,284.3453	3,652,395.7154
2048	56	61,012.7949		583,052.7255		26,647.4857		2,421.4060	3,871,539.4583
2049	57	64,673.5625		618,035.8891		28,246.3349		2,566.6904	4,103,831.8258
2050	58	68,553.9763		655,118.0424		29,941.1150		2,720.6918	4,350,061.7353
2051	59	72,667.2149		694,425.1250		31,737.5819		2,883.9333	4,611,065.4394
2052	60	77,027.2478	11,554.0872	736,090.6325	110,413.5949	33,641.8368	5,046.2755	3,056.9693	4,887,729.3658
2053	61	81,648.8826		780,256.0704		35,660.3470		3,240.3875	5,180,993.1278
2054	62	86,547.8156		827,071.4346		37,799.9678		3,434.8107	5,491,852.7154
2055	63	91,740.6845		876,695.7207		40,067.9659		3,640.8994	5,821,363.8784
2056	64	97,245.1256		929,297.4640		42,472.0438		3,859.3533	6,170,645.7111
2057	65	103,079.8331	15,461.9750	985,055.3118	147,758.2968	45,020.3664	6,753.0550	4,090.9145	6,540,884.4537

2058	66	109,264.6231		1,044,158.6305		47,721.5884		4,336.3694	6,933,337.5209	
2059	67	115,820.5005		1,106,808.1483		50,584.8837		4,596.5516	7,349,337.7722	
2060	68	122,769.7305		1,173,216.6372		53,619.9767		4,872.3447	7,790,298.0385	
2061	69	130,135.9144		1,243,609.6355		56,837.1754		5,164.6853	8,257,715.9208	
2062	70	137,944.0692	20,691.6104	1,318,226.2136	197,733.9320	60,247.4059	9,037.1109	5,474.5664	8,753,178.8761	
Sum		22,657.9811			772,459.2926	1,047,373.6704	36,170.8633	95,172.8406		1,355,332.5819

B5: Renfe network

Table B5. The LCC and NPV calculation of Renfe network

		Manufacturing	Maintenance	Manufacturing	Maintenance-Machine	Operation	Maintenance - Staff	Operation	Operation	Operation
#Year	Year	Construction cost	15% every 5 yrs	Machine/Equip	15% every 5 yrs	Operation-Staff	15% every 5 yrs	Electricity cost	Rolling stock value	Rolling stock cost
1981	0	3,070.5680		56,096.7400	8,414.5110	1,521.2190	1,521.2190	358.7200	250,679.7748	250,679.7748
1982	1	3,254.8042		59,462.5020		1,612.4921		380.2432	265,720.5613	
1983	2	3,450.0925		63,030.2521		1,709.2417		403.0578	281,663.7949	
1984	3	3,657.0980		66,812.0672		1,811.7962		427.2413	298,563.6226	
1985	4	3,876.5239		70,820.7913		1,920.5039		452.8757	316,477.4400	
1986	5	4,109.1153	616.3673	75,070.0388	11,260.5058	2,035.7342	305.3601	480.0483	335,466.0864	
1987	6	4,355.6622		79,574.2411		2,157.8782		508.8512	355,594.0516	
1988	7	4,617.0020		84,348.6955		2,287.3509		539.3822	376,929.6947	
1989	8	4,894.0221		89,409.6173		2,424.5920		571.7452	399,545.4764	
1990	9	5,187.6634		94,774.1943		2,570.0675		606.0499	423,518.2049	
1991	10	5,498.9232	824.8385	100,460.6460	15,069.0969	2,724.2715	408.6407	642.4129	448,929.2972	
1992	11	5,828.8586		106,488.2847		2,887.7278		680.9577	475,865.0551	
1993	12	6,178.5901		112,877.5818		3,060.9915		721.8151	504,416.9584	
1994	13	6,549.3055		119,650.2367		3,244.6510		765.1240	534,681.9759	
1995	14	6,942.2639		126,829.2509		3,439.3301		811.0315	566,762.8944	
1996	15	7,358.7997	1,103.8200	134,439.0060	20,165.8509	3,645.6899	546.8535	859.6934	600,768.6681	
1997	16	7,800.3277		142,505.3464		3,864.4312		911.2750	636,814.7882	
1998	17	8,268.3473		151,055.6671		4,096.2971		965.9515	675,023.6755	

1999	18	8,764.4482		160,119.0072		4,342.0750		1,023.9085	715,525.0960	
2000	19	9,290.3151		169,726.1476		4,602.5994		1,085.3431	758,456.6018	
2001	20	9,847.7340	1,477.1601	179,909.7164	26,986.4575	4,878.7554	731.8133	1,150.4636	803,963.9979	
2002	21	10,438.5980		190,704.2994		5,171.4807		1,219.4915	852,201.8377	
2003	22	11,064.9139		202,146.5574		5,481.7696		1,292.6609	903,333.9480	
2004	23	11,728.8087		214,275.3508		5,810.6758		1,370.2206	957,533.9849	
2005	24	12,432.5372		227,131.8719		6,159.3163		1,452.4338	1,014,986.0240	
2006	25	13,178.4895	1,976.7734	240,759.7842	36,113.9676	6,528.8753	979.3313	1,539.5799	1,075,885.1854	
2007	26	13,969.1988		255,205.3713		6,920.6078		1,631.9547	1,140,438.2965	
2008	27	14,807.3508		270,517.6935		7,335.8443		1,729.8719	1,208,864.5943	
2009	28	15,695.7918		56,097.7400		7,775.9949		1,833.6643	1,281,396.4700	
2010	29	16,637.5393		303,953.6805		8,242.5546		1,943.6841	1,358,280.2582	
2011	30	17,635.7917	2,645.3688	322,190.9013	48,328.6352	8,737.1079	1,310.5662	2,060.3052	1,439,777.0737	
2012	31	18,693.9392		341,522.3554		9,261.3344		2,183.9235	1,526,163.6981	
2013	32	19,815.5755		362,013.6967		9,817.0144		2,314.9589	1,617,733.5200	
2014	33	21,004.5101		383,734.5185		10,406.0353		2,453.8564	1,714,797.5312	
2015	34	22,264.7807		406,758.5896		11,030.3974		2,601.0878	1,817,685.3831	
2016	35	23,600.6675	3,540.1001	431,164.1050	64,674.6157	11,692.2213	1,753.8332	2,757.1531	1,926,746.5061	
2017	36	25,016.7076		457,033.9513		12,393.7545		2,922.5822	2,042,351.2964	2,042,351.2964
2018	37	26,517.7100		484,455.9883		13,137.3798		3,097.9372	2,164,892.3742	
2019	38	28,108.7726		513,523.3476		13,925.6226		3,283.8134	2,294,785.9167	
2020	39	29,795.2990		544,334.7485		14,761.1600		3,480.8422	2,432,473.0717	
2021	40	31,583.0169	4,737.4525	576,994.8334	86,549.2250	15,646.8296	2,347.0244	3,689.6927	2,578,421.4560	
2022	41	33,477.9979		611,614.5234		16,585.6393		3,911.0743	2,733,126.7433	

2023	42	35,486.6778		648,311.3948		17,580.7777		4,145.7388	2,897,114.3479
2024	43	37,615.8785		687,210.0785		18,635.6243		4,394.4831	3,070,941.2088
2025	44	39,872.8312		728,442.6832		19,753.7618		4,658.1521	3,255,197.6813
2026	45	42,265.2011	6,339.7802	772,149.2442	115,822.3866	20,938.9875	3,140.8481	4,937.6412	3,450,509.5422
2027	46	44,801.1131		818,478.1989		22,195.3268		5,233.8997	3,657,540.1147
2028	47	47,489.1799		867,586.8908		23,527.0464		5,547.9336	3,876,992.5216
2029	48	50,338.5307		919,642.1042		24,938.6692		5,880.8097	4,109,612.0729
2030	49	53,358.8426		974,820.6305		26,434.9893		6,233.6582	4,356,188.7973
2031	50	56,560.3731	8,484.0560	1,033,309.8683	154,996.4802	28,021.0887	4,203.1633	6,607.6777	4,617,560.1251
2032	51	59,953.9955		1,095,308.4604		29,702.3540		7,004.1384	4,894,613.7326
2033	52	63,551.2352		1,161,026.9680		31,484.4952		7,424.3867	5,188,290.5566
2034	53	67,364.3093		1,230,688.5861		33,373.5649		7,869.8499	5,499,587.9900
2035	54	71,406.1679		1,304,529.9013		35,375.9788		8,342.0409	5,829,563.2694
2036	55	75,690.5380	11,353.5807	1,382,801.6954	207,420.2543	37,498.5376	5,624.7806	8,842.5634	6,179,337.0655
2037	56	80,231.9703		56,098.7400		39,748.4498		9,373.1172	6,550,097.2895
2038	57	85,045.8885		1,553,715.9849		42,133.3568		9,935.5042	6,943,103.1268
2039	58	90,148.6418		1,646,938.9440		44,661.3582		10,531.6344	7,359,689.3144
2040	59	95,557.5603		1,745,755.2807		47,341.0397		11,163.5325	7,801,270.6733
2041	60	101,291.0139	15,193.6521	1,850,500.5975	277,575.0896	50,181.5021	7,527.2253	11,833.3445	8,269,346.9137
2042	61	107,368.4747		1,961,530.6333		53,192.3922		12,543.3451	8,765,507.7285
2043	62	113,810.5832		2,079,222.4713		56,383.9358		13,295.9458	9,291,438.1922
2044	63	120,639.2182		2,203,975.8196		59,766.9719		14,093.7026	9,848,924.4838
2045	64	127,877.5713		2,336,214.3688		63,352.9902		14,939.3247	10,439,859.9528
2046	65	135,550.2256	20,332.5338	2,476,387.2309	371,458.0846	67,154.1696	10,073.1254	15,835.6842	11,066,251.5500

2047	66	143,683.2391		2,624,970.4648		71,183.4198		16,785.8253	11,730,226.6430	
2048	67	152,304.2335		2,782,468.6927		75,454.4250		17,792.9748	12,434,040.2416	
2049	68	161,442.4875		2,949,416.8142		79,981.6905		18,860.5533	13,180,082.6560	
2050	69	171,129.0367		3,126,381.8231		84,780.5919		19,992.1865	13,970,887.6154	
2051	70	181,396.7789	27,209.5168	3,313,964.7325	497,094.7099	89,867.4274	13,480.1141	21,191.7177	14,809,140.8723	
Sum		15,695.7918			1,941,929.8710	1,562,304.2346	53,953.8987	368,408.3456		2,293,031.0712