Development of an Upgrade Selection Process for Railway Renewal Projects

by

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Abstract

Improving a railway system can play a significant role in economic growth. Currently, many railway systems need to be upgraded to meet the demand for rapidly increasing railway capability, environmental concerns and customer satisfaction, while there is a lack of the right models and tools required to support the early decision making stage of railway renewal projects.

In this thesis, the existing decision-making methods and support models and existing performance measurement frameworks in use in the railway industry are reviewed. A new railway selection upgrade process is proposed, which aims to support early stage decision-making in railway renewal projects by finding the most appropriate solutions to take forward for more detailed consideration. The railway selection upgrade process consists of modelling, which includes data collection and model set-up, and simulation, split into macroscopic assessment and microscopic simulation. A high-level feasibility analysis model is developed for the macro assessment in the simulation stage, to help engineers efficiently select the most promising upgrade options for further detailed consideration using microscopic simulation. This process provides a quick and efficient way to quantify evaluation functions, based on the 4Cs (capacity, carbon, customer satisfaction and cost) framework, to give a final suggestion on the most appropriate upgrade options.

Two case studies, based on the East Coast Main Lines and the Northern Ireland railway network, are presented in order to demonstrate the application and verify the feasibility of the high-level feasibility analysis model and the railway upgrade selection process. The results show the advantages of the process on efficiently finding appropriate and systematically selected solutions for railway upgrade projects.

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Glossary of Terms / List of Abbreviations

Term	**Explanation / Meaning / Definition**
4Cs	Capacity, Carbon, Customer satisfaction and Cost
AC	Alternating Current
AHP	Analytic Hierarchy Process
ANT	Antrim
BAM	Bellymena
BDR	Border
BFC	Belfast Central
BGS	Bangor
BMY	Ballymoney
CBA	Cost-Benefit Analysis
CBTC	Communications-Based Train Control
CMOOP	Constraint Multi-Objective Optimisation Problem
COL	Coleraine
CSP	Constraint Satisfaction Problem
DC	Direct Current
DEFRA	Department for Environment, Food and Rural Affairs
DEMU	Diesel-Electric Multiple Unit
DMU	Diesel Multiple Unit
ECML	East Coast Main Line
EMU	Electric Multiple Unit
GB	Great Britain (England, Scotland and Wales)
GRIP	Governance for Railway Investment Projects
GVS	(Belfast) Great Victoria Street
HFAM	High-level Feasibility Analysis Model
IEA	International Energy Agency
KPI	Key Performance Indicator
LDY	Londonderry
LIS	Lisburn
LRH	Larne Harbour
M&S	Modelling and Simulation

Term	Explanation / Meaning / Definition
MCDM	Multi-Criteria Decision-Making
MOOP	Multi-Objective Optimisation Problem
MTS	Multi-Train Simulator
NIRN	Northern Ireland Railway Network
NR	Network Rail
NRPS	National Rail Passenger Survey
NRY	Newry
ORR	Office of Rail and Road
PiXC	Passengers in excess of capacity’
POR	Portadown
PPM	Public Performance Measure
PRH	Portrush
RUSP	Railway upgrade selection Process
STS	Single-Train Simulator
SWOT	Strengths, Weaknesses, Opportunities and Threats
TCRP	Transit Capacity and Quality of Service Manual
UIC	International Union of Railways
UK	United Kingdom (Great Britain and Northern Ireland)
WebTAG	Web-based Transport Analysis Guidance
WHA	Whiteabbey
WHD	Whitehead
YKG	Yorkgate

Chapter 1 Introduction

1.1 Introduction to railway systems in UK

1.1.1 Overview on current situation

The railway plays a significant role in economic growth, both nationally and globally [1-4]. The railway system is an efficient transport model for long distance travel, for transporting both people and goods, and also for shorter urban commuter journeys, since it is fast, safe, high capacity, customer and environmentally friendly [5-7]. As indicated in the figures presented in *Transport Statistics Great Britain 2016* [8], trains use less than 2% of the total transport energy use to carry around 10% of the passenger-km and around 12% of the freight tonnes-km, whereas cars carry about 65% passenger-km and emit 58% of total transport CO_2 emissions. In addition, National Rail passenger journeys (including all passenger services in Great Britain) have increased by 57% since 2005/06. Railway transport can be the solution to issues raised by rapidly increasing demand for travel, increasingly energy intensive lifestyles and a tendency to choose faster travel [9].

The railway system in the United Kingdom is the oldest in the world, at nearly 200 years old [10]. Nowadays it is one of the busiest railway networks, running more train services than most countries in Europe, with nearly 20% more train services than France, and 60% more than Italy [11]. Since 2010, the number of passenger journeys has grown rapidly and continuously, reaching 1.69 billion in 2015/16 (1.25 billion in 2010/11), as shown in statistical reports by the ORR (Office of Rail and Road) [12, 13]. The pressure on railway services from the demand for railway capacity is therefore increasing significantly, which leads to overcrowding at peak times [14]. Furthermore, due to the limited availability of funds and limited space for new infrastructure [15, 16], an efficient option is to improve an existing railway network to meet the rapidly increasing demand for railway capacity.

1.1.2 Overview on the direction of future development

In the coming decades, cities will be increasing in number, size and geographical spread. The global urban population is rapidly increasing, which means the demand for high capacity and fast rail transport between or inside cities is also rapidly increasing. The growing pace of urbanisation will add stress to the demand for city systems and infrastructure; a safe and more reliable rail transport will be required to meet this demand. More frequent and intensive extreme weather, as a result of climate change, may make transportation infrastructure design, operation and maintenance more difficult, which will also give rise to concerns about the environment. Meanwhile, constraints on available energy and resources may limit economic growth. As a low carbon mode of transport, rail has great potential to meet environmental and resource issues. New advanced technologies may lead to smarter, faster, safe, integrated and intermodal transport solutions. The trends described here will have significant impacts on the direction of future development in the rail industry [17-19].

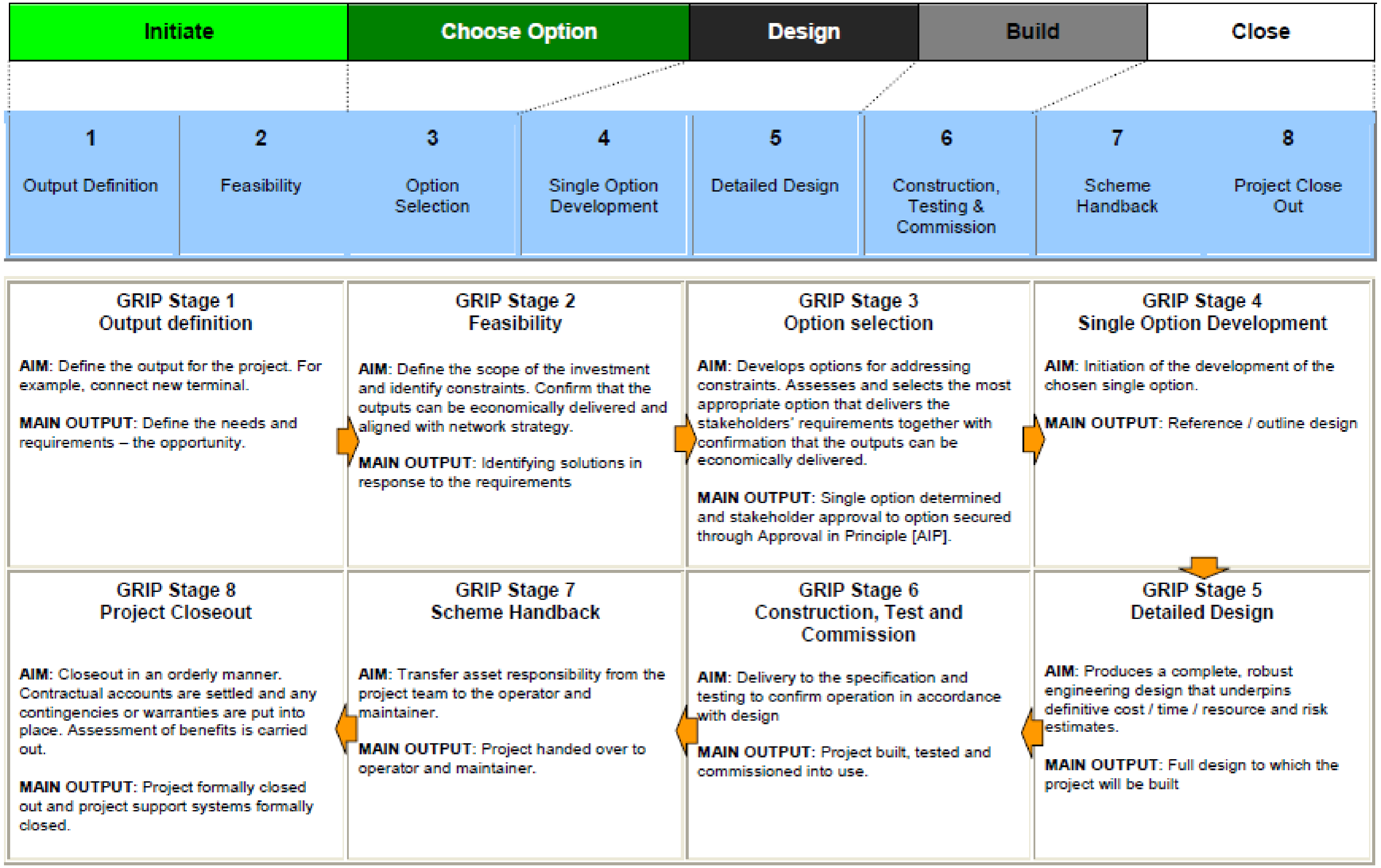
In order to promote the competitiveness of the rail industry and adapt to trends, capacity, carbon, customer satisfaction and cost (4Cs) have been proposed as strategic objectives by the UK Department for Transport [20]. The optimisation of the 4C targets, which essentially means expanding capacity, reducing carbon emissions, improving cost efficiency and better meeting customer satisfaction, has been used in the GB rail industry as a key strategy in the improvement of the railway [21]. As discussed before, the challenges of future development of the rail industry mainly encompass high capacity demand, being an environmentally-friendly transport mode, limited resources and the tendency towards faster, smarter and safe travel, which could be addressed in the 4Cs strategic objectives. (Details of the 4Cs framework are presented in Chapter 2.3.) A range of research aimed at improvement of each target has been published, for example [22-25], but few of these studies consider the railway as a complete system (which is further discussed in Chapter 2.3.5).

1.2 Decision-making in systems engineering

Systems engineering plays a significant role in developing complex engineering systems (especially railway renewal projects), the core of which is utilising systems thinking principles to form a structured process. Systems thinking refers to considering the interaction between parts of a whole system, rather than concentrating just on the parts. Systems engineering is an interdisciplinary approach, which encompasses (1) the initial definition of system requirements and relating these requirements to specific design criteria to ensure the effectiveness of early decision-making in the design process; (2) addressing all phases, including system design and development, production and construction, verification, deployment, operation, maintenance and support, disposal, etc. over the life-cycle of an engineering system;(3) ensuring that all system objectives are addressed in an effective and efficient way in the process of the system design and development. [26, 27]

As a systems engineering model, Network Rail introduced Governance for Railway Investment Projects (GRIP) to support and guide project managers on investment projects through their lifecycle, as shown in Figure 1-1. GRIP describes how to manage and control railway system upgrade projects, which has proven its ability to help steer upgrade projects from requirements through to delivery [28]. GRIP divides a project into 8 stages from initial definitions, options selection, design and test to project support system closed, including the aims and main outputs of each stage. However, the success of a project depends on appropriate options being explored in the early stages [29-31] (e.g. the 3rd stage in GRIP, option selection). As shown in Figure 1-2 [29], by the time of decision making, the project has only spent around 15% of its budget while over 80% (as estimated by Atkins) of its cost has been committed. Even though the cost incurred in the early stages is low, cost influence on the whole project is quite high. A lack of thought in the decision making in the early stages of a project will result in inevitable changes in the later stages, which could result in unexpected cost and time overruns. In Elliott's research [32], the later the changes occurred, the greater the unexpected influence has on a complex project. For example, for the modernisation of the Great Western railway network [33, 34], the original budget was £2.1bn in 2013, but the final cost has now overrun to £5.6bn with 18 months of delay due to inadequate planning, such as underestimating the number of bridges for replacement or alteration to make space for overhead lines, and lack of research on the location of some new structures. If engineers had been able to make the right decisions on appropriate solutions at the early stages, the overspend could have been reduced, though the original estimate could have been higher. Similarly, in Netherlands, the government decided to build a freight rail link which would be the only solution to connect Rotterdam Harbour and the Ruhr Area; due to underestimating the capacity of the existing rail network and the costs of new infrastructure (higher than the benefits), alternative solutions were evaluated only at a very late stage which led to unexpected cost overruns [31]. It can be seen that the problem of cost and time overruns is a common phenomenon for large or mega railway renewal projects. [35]

From past experiences of projects which have overrun in terms of cost or time, it can be seen that the main reason for the overruns was inadequate consideration and appraisal at the early stage. In many instances, due to a lack of well-defined requirements from the beginning, the common approach followed has been to 'deliver it now and fix it later'. In all fields of engineering, the solutions commonly become too technically focussed at a low-level too quickly without consideration of a large number of alternatives, which may result in missing potential alternatives as there seems to be little likelihood of proving their feasibility [36]. In order to avoid this situation, it is better to consider many alternatives than to overlook one that might be preferred. Due to the complexity of railway systems, it is difficult to consider all the interactions between various railway system components at the early stages in a railway renewal project. (A review of railway systems architecture is demonstrated in Chapter 2.1.) McNulty’s report [29] indicates that there is a lack of effective and efficient decision-making support models and tools applied in the early stages, which could allow a large number of possible alternatives to be taken into account, and simultaneously the railways should be considered as a complete system. Over recent decades, many decision-making methods have been proposed to choose solutions from numerous alternatives based on the decision-makers’ preferences, the most popular of which applied to rail projects are analytic hierarchy process (AHP) [37-39], cost-benefit analysis [31, 40] and analytic network process (ANP) [41, 42]. Most of these decision making methods stay at a very high level and can only focus on assessing a limited number of alternatives, rather than a large number of upgrade options. A review of complex decision-making is demonstrated in Chapter 3.



GRIP Stage 1
Output definition

AIM: Define the output for the project. For example, connect new terminal.

MAIN OUTPUT: Define the needs and requirements – the opportunity.

GRIP Stage 2
Feasibility

AIM: Define the scope of the investment and identify constraints. Confirm that the outputs can be economically delivered and aligned with network strategy.

MAIN OUTPUT: Identifying solutions in response to the requirements

GRIP Stage 3
Option selection

AIM: Develops options for addressing constraints. Assesses and selects the most appropriate option that delivers the stakeholders' requirements together with confirmation that the outputs can be economically delivered.

MAIN OUTPUT: Single option determined and stakeholder approval to option secured through Approval in Principle [AIP].

GRIP Stage 4
Single Option Development

AIM: Initiation of the development of the chosen single option.

MAIN OUTPUT: Reference / outline design

GRIP Stage 5
Detailed Design

AIM: Produces a complete, robust engineering design that underpins definitive cost / time / resource and risk estimates.

MAIN OUTPUT: Full design to which the project will be built

GRIP Stage 6
Construction, Test and Commission

AIM: Delivery to the specification and testing to confirm operation in accordance with design

MAIN OUTPUT: Project built, tested and commissioned into use.

GRIP Stage 7
Scheme Handback

AIM: Transfer asset responsibility from the project team to the operator and maintainer.

MAIN OUTPUT: Project handed over to operator and maintainer.

GRIP Stage 8
Project Closeout

AIM: Closeout in an orderly manner. Contractual accounts are settled and any contingencies or warranties are put into place. Assessment of benefits is carried out.

MAIN OUTPUT: Project formally closed out and project support systems formally closed.

Figure 1-1: Guide to Governance for Railway Investment Projects (GRIP) [28]

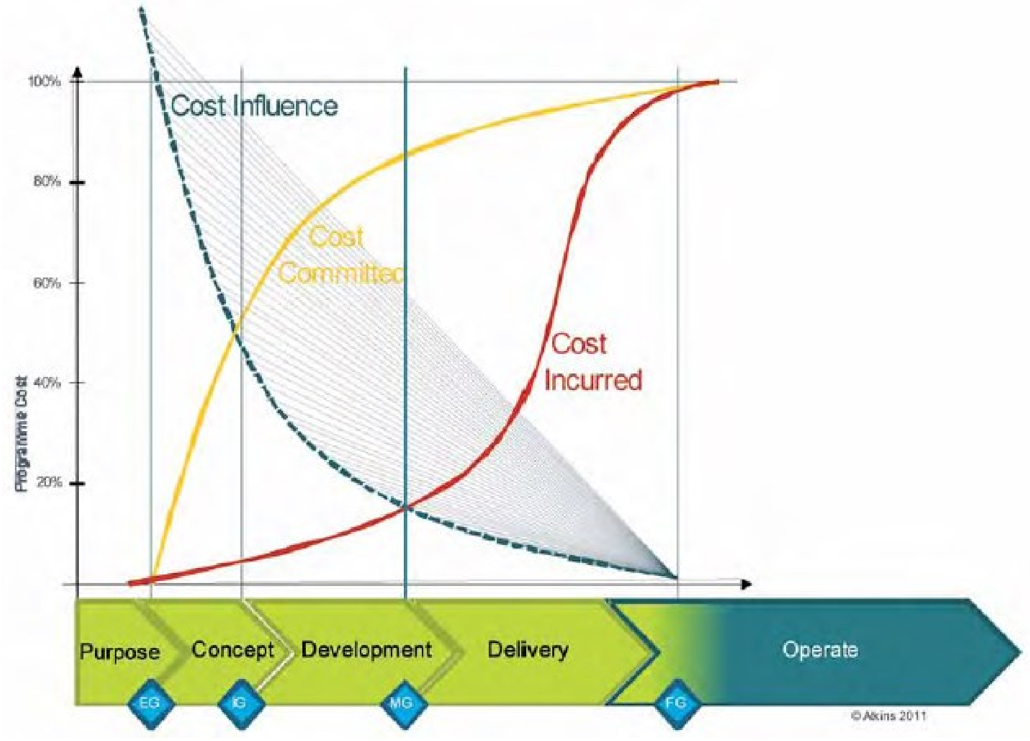


Figure 1-2: Cost influence, cost committed and cost incurred relationship curve against project phases [29]

1.3 General research problem statement

This thesis focuses on the research problem of how to find appropriate solutions for railway renewal projects.

- A railway renewal project refers to complex engineering projects that aim to alter railway system components (infrastructure, rolling stock or operation) to improve the performance (capacity, energy efficiency, reliability, safety, etc.) of the existing railway system with old conditions to meet requirements.
- The appropriate solutions refer to those upgrade scenarios that could meet requirements and have better performance.

- Upgrade category refers to the type of upgrade, e.g., adding wagons, lengthening platforms, improving signalling system.
- Upgrade option refers to the specific upgrade, e.g., increasing the number of carriages per trainset from 3 to 4, improving signalling system from 3-aspect signalling to 4-aspect signalling.
- Upgrade scenario refers to a combination of upgrade options in one or more categories, e.g., increasing the number of carriages per trainset from 3 to 4 meanwhile lengthening 20m platforms, improving signalling system from 3-aspect signalling to 4-aspect signalling meanwhile increasing line speed from 60 mph to 90 mph.

The scope of this research only includes the existing railway system running in a normal and safe manner, including infrastructure, rolling stock, operation and timetable. It is appropriate not to consider safety as part of the solution identification process, as all solution would be in line with existing safety standards, and therefore be considered to be safe. However, at a later date further works could be focused or compare solutions in terms on construction and operational safety risks. The railway system models considered in this thesis mainly include urban railway systems and mainline railway systems, while some scenarios similar to metro system are also discussed in Chapter 6. The solutions to the research problem identified in this research are high-level, the specific implementation of which in the real-world is not taken into account. For example, with limited investment, improving a signalling system from 3-aspect to a 4-aspect signalling system is the most appropriate solution for a rail system, while the precise technical details are outside the scope of this research.

1.4 Aims & objectives

The aim of this research is to develop a support process and model for early-stage decision-making of a railway renewal project to find the most appropriate solutions that can meet high-level requirements. It is called the Railway Upgrade Selection Process (RUSP). This aims to help to: (1) reduce the number of design changes in the later stages of a railway renewal project; (2) provide evidence to project sponsors and regulators that a wide range of design scenarios have been considered; (3) make certain that all relevant data has been collected prior to going ahead with a detailed design decision.

The objectives of the research presented in this thesis are as follows:

- In order to find appropriate solutions for railway renewal projects, this thesis targets the development of a railway upgrade selection process (RUSP) to support decision making in the early stages.
- For an existing railway system, in order to be able to develop appropriate solutions to address high-level requirements, this thesis targets the collection of sufficient data and information that could represent a particular line with qualitative characterisation, including existing problems or bottlenecks, current conditions and requirements. In order to comprehensively evaluate a railway system, this research targets using 4Cs as performance measurements.
- An efficient combination of macroscopic and microscopic modelling could potentially benefit the project planning process. In order to evaluate every possibility, this research aims to develop a high-level feasibility analysis model (HFAM) to assist decision makers to remove infeasible options and identify candidate solutions with a straight-forward and quick evaluation of a large number of upgrade options for further

detailed consideration using microscopic modelling. The candidate solutions are further evaluated in microscopic modelling to determine the appropriate solutions, which could be a combination of upgrade options.

- In order to verify the feasibility of the high-level feasibility model and the railway upgrade selection process, this thesis presents two case studies.

1.5 Thesis structure

The structure of the thesis is set out as follows:

- Chapter 1 is a general introduction to the background and research motivation (including an overview of the current situation, the direction of future development of the railway system in the UK, existing problems or bottlenecks when improving the railway system and the introduction to systems engineering), aims and objectives and thesis structure.
- Chapter 2 provides an introduction to railway system architecture, including infrastructure, rolling stock and operation. A review of modelling and simulation is also taken into consideration in this chapter, including the importance of M&S, category thereof (macro and micro simulation), and commonly-used simulators. This chapter also reviews a wide range of railway system performance measurements, mainly surrounding 4Cs, including the different definitions and measurements. The knowledge presented in this chapter will support the new methods for the decision-making process, including the methodology (Chapter 4) and case study (Chapter 5 and Chapter 6).
- Chapter 3 provides a review of established decision-making processes, definitions and methods thereof. This chapter discusses how to define the existing problem into an academic research problem and relevant researches and methods. The knowledge

presented in this chapter aims to support the modelling phase (in Chapter 4) and propose that the existing decision-making methods still have some drawbacks to solve this specific research problem.

- Chapter 4 presents a method to solve the research problem set out in Chapter 1.3, which is the railway upgrade selection process. This chapter details the structure of the RUSP, which consists of three stages: data collection and system analysis, candidate solution identification (including details of the high-level feasibility analysis model) and evaluation and optimisation (micro simulation).
- Chapter 5 demonstrates the development process of the high-level feasibility analysis model, which is part of the simulation stage of the RUSP. An initial version of the HFAM was proposed at the beginning of the design process of the HFAM. A case study based on the East Coast main line is presented to verify the feasibility of the initial version. Based on the outcomes of the initial version and its verification, an updated final version of the HFAM has been proposed and is verified based on the Northern Ireland railway network case study.
- Chapter 6 details the application of the RUSP on the Northern Ireland railway network, including the results of the HFAM gained in Chapter 5 and the simulation results of candidate scenarios in OpenTrack.
- Chapter 7 draws a conclusion on major contributions, limitations and further work of the research demonstrated in this thesis.

Chapter 2 Background

This chapter gives an overview of the British railway architecture, including infrastructure, rolling stock and operations. Thus, there are various alternatives in each component associated with railway renewal projects. Due to the complexity of a railway system, modelling and simulation (M&S) plays an important role in testing solutions before implementation in real life. Therefore, an overview of M&S and widely-used software tools is given in this chapter. The evaluation of the performance of a railway system depends on the choice of performance indicators and measurements. As introduced in Chapter 1.1.2, the 4Cs framework is the key strategy for railway system optimisation, thus the fundamental knowledge of 4Cs is also presented in this chapter.

2.1 Railway systems architecture

Railway transport is a means of conveyance of passengers and goods on wheeled vehicles running on tracks, which is comprised of different systems, such as urban railway systems, high-speed railway systems, and metro railway systems. Generally, a railway system consists of three essential components: infrastructure, rolling stock and operations. Rolling stock can be running in the network, based on infrastructure support and operation control. The relationship between these three key components is presented in Figure 2-1.

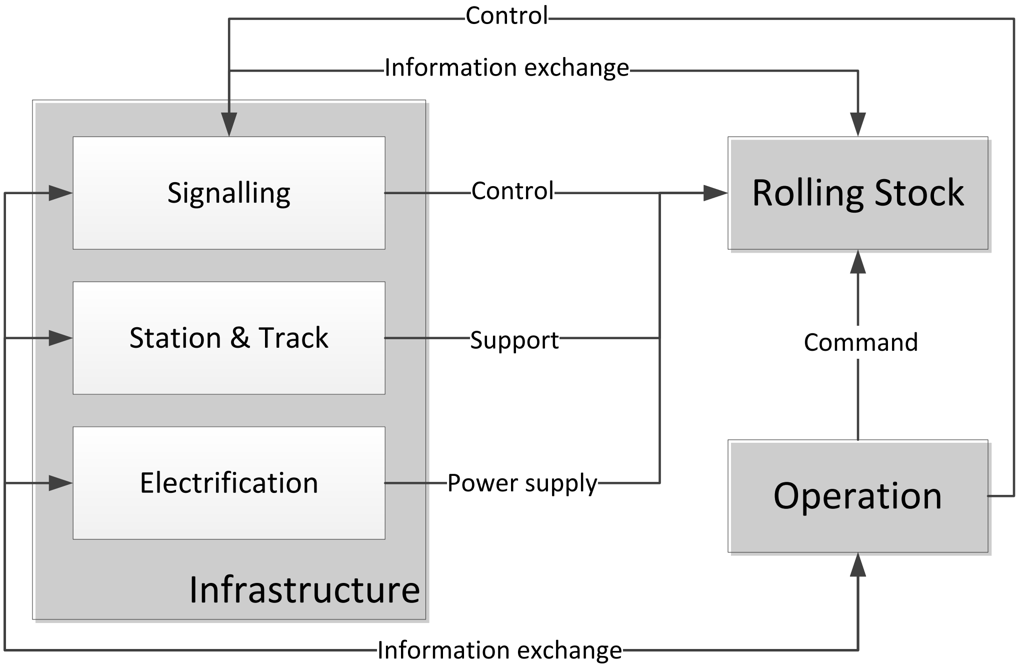


Figure 2-1: Relationship between infrastructure, rolling stock and operation in an electrifiedrailway system [43]

2.1.1 Infrastructure

Infrastructure is the fundamental base for a railway system. The choice of route (where the tracks are laid) is usually largely dictated by traffic demands and existing physical constraints (such as ground conditions, water levels, existing building foundations, cost), while in some instances alternatives such as bridges and tunnels can be taken into consideration to reduce operation costs and allow higher speeds.

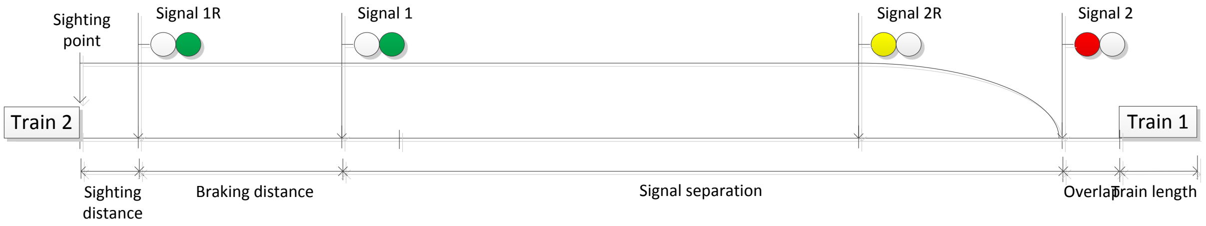
- Track

Track guides hard steel flanged wheels to keep rolling stock on the track without active steering, which traditionally consists of two parallel rails set using timber or concrete sleepers to maintain a standard gauge, supported by track ballast. There are also other structures, such as ballastless track, ladder track or continuous longitudinally supported track. No matter whether it is complicated layouts at terminal stations or a simple single-track rail with passing loops, all railways require turnouts (known as switches or points) at a railway junction to direct trains from one track to another and crossings to allow trains to cross other tracks. Any assembly of points and crossings is called a layout. Due to passing trains, weather and day/night conditions, track maintenance is essential to ensure trains run safely and efficiently. [43]

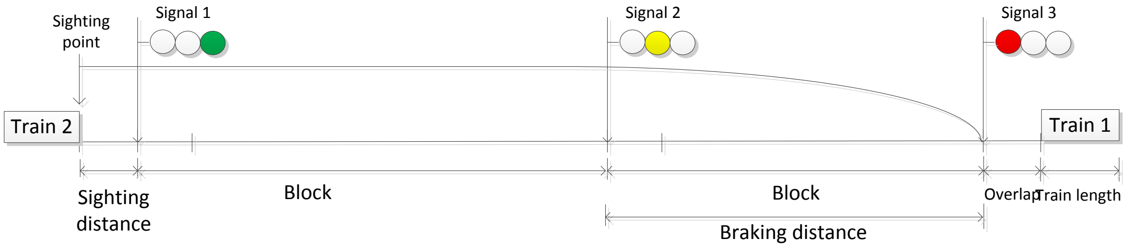
The most common rail lines are single-track, double-track, triple track or quadruple track. Single track is usually found on lower traffic lines or branch lines, where trains share the same track when running in both directions. In order to create more capacity on single-track sections, passing loops are required to allow trains travelling in both directions to pass each other, when more than one train is running on the same single-track sections. Single track is relatively cheap to build but takes less capacity. Double-track lines allow trains to run on one track for each direction, which can take more capacity, allow higher speed trains, and have lower operation risks, compared with single-track lines. Lines with more than two tracks allow more trains with different velocities to run parallel and share infrastructure in stations and junctions.

- Signalling

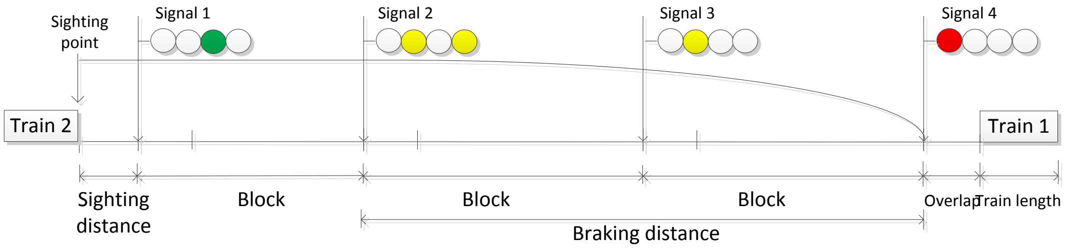
Signalling systems are used to control and maintain trains running in a safe manner with a headway distance as pre-planned, to prevent conflict movements and to ensure that points are locked in the correct positions. Due to the low friction between wheels and rails, a long braking distance is essential to prevent collision when trains are running at high speed. In order to avoid collision, trains are not allowed to occupy the same track section at the same time, known as blocks. Most blocks are fixed, but not all. Fixed blocks are controlled using fixed signals, which are placed at the beginning of each block. The signalling is a means of showing whether blocks are clear or not, which is detected by track circuits or other means such as axle counters. The train is given permission to proceed only if the signal is ‘green’.



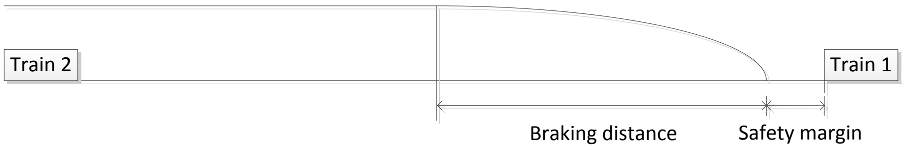
2-aspect signalling



3-aspect signalling



4-aspect signalling



Moving block signalling

Figure 2-2: Different signalling systems and headway

The modern signalling system can encompass fixed block signalling (such as 2-aspect signalling, 3-aspect signalling, 4-aspect signalling) and moving block signalling, as shown in Figure 2-2. The headway is the minimum time or distance interval that can be run between trains, which consists of the braking distance, sighting allowance, overlap and train length. The more aspects a signalling system has, the shorter a headway can be. One of the disadvantages of fixed block signalling is that a longer stopping distance is required to allow fast trains to run safely, so a longer block is required, thus reducing the line capacity. If the train location can be defined precisely, moving block signalling can be introduced to increase the line capacity. Radio-based communications-based train control (CBTC) systems are sometimes deployed to use moving block principles. [43-46]

- Station

A railway station enables passengers to embark and disembark and allow efficient and reliable access and interchange. When designing or improving a station, numerous facilities need to be taken into consideration, such as ticket halls, car parking, access for the disabled, access for emergency services, interchange facilities, passageways, staircases, escalators, footbridges, level crossings, and platforms, which are related to customer satisfaction in rail transport. Station platforms play a crucial role as part of the infrastructure of any railway systems, which should provide sufficient spaces for passengers to wait, board and get off trains. The location of entrances and exits to platforms is also important to keep dwell time to a minimum (the time a train spends at a scheduled stop). Meanwhile, the width and curve of a platform should be carefully considered to ensure passenger safety in crowded conditions. The length of a platform also needs to be taken into account to match the length of rolling stock. [43]

- Electrification

The railway electrification system is a power supply for trains (excluding DMUs), which results in lower operation costs than running diesel locomotives but requires large capital investment for construction. With a power supply, trains are allowed to run under a continuous conductor along the track. There are two forms of power supply: mainlines and tram systems usually have an overhead line suspended from poles or towers along the track, whereas metro systems usually use a ground third rail. The two most common electrification systems for mainline railways are the 25 kV 50 Hz AC (alternating current) single phase system and the 750 V DC (direct current) system. Metro and light railways also use these systems, but often adopt lower voltages. High voltage AC systems require cheaper fixed equipment but more expensive locomotives; in contrast, medium voltage DC systems require cheaper locomotives but more extensive and expensive lineside equipment. [43, 47, 48]

2.1.2 Rolling stock

Railway rolling stock runs on hard wheels along the track. A wide range of rolling stock is used for different railway systems, such as passenger vehicles, freight vehicles, multiple units, trams, and maintenance trolleys. Motive power for the train is provided by a separate locomotive or individual motors built in each carriage, known as multiple units. Multiple units are more energy-efficient, have easier acceleration, shorter turnaround times and lighter axle loads than locomotive-hauled trains, but they are noisier, more difficult to maintain or replace when they fail, and have less flexibility to be split or joined. [43]

- Traction type

The first locomotive using steam motive power was developed in Great Britain in 1804, but steam was gradually superseded by diesel and electric traction. The power of electric traction comes from an overhead line or third rail, while the power of diesel traction comes from diesel engines. Most rolling stock running on railway systems in Great Britain are either locomotives or multiple units, which can be classified by their traction types, including diesel locomotives and diesel multiple units (DMU) or electric locomotives and electric multiple units (EMU). Electro-diesel locomotives or diesel-electric multiple units (DEMU) can run as electric locomotives or EMU on electrified sections and as diesel-electric locomotives or DEMU on electrified sections, which have a diesel engine to drive a generator producing electricity for traction motors.

- Passenger/ freight trains

Passenger trains carry passengers between stations while freight trains haul goods between freight depots or individual plants. Passenger trains often run on long-distance intercity railway systems, daily commuter railway systems, or local urban transit railway systems. In order to meet the requirements of different railway systems, the performance of passenger trains varies, such as operation speed, specialised vehicles (dining cars or sleeping cars), stops and service frequency. Generally, long-distance railways (inter-city railways) require higher speeds and lower station frequency, while short-distance railways (daily commuter railways and urban transit railways) require higher station and service frequency. Some freight trains share tracks with passenger trains, whereas others run on specialised freight railway systems between ports and various factories carrying standard containers. The railway has proven its advantages in terms of cost and energy efficiency for moving freight, especially over long distances. Approaching 100 million tons of freight a year is transported on the railway in the UK. [49]

2.1.3 Operations

Railway operation is through a system of control to ensure that the railway system runs in a safe and efficient manner; nowadays this is usually achieved by electronic and computerised control systems.

- Timetabling

Timetabling is the process of planning a feasible schedule for each train path based on the available infrastructure and rolling stock. A railway timetable should coordinate the train paths for optimum use of the infrastructure, ensure sufficient train separation and avoid traffic conflicts, provide traffic information to passengers, and support traffic control, rolling stock usage and crew scheduling. In passenger operation, a pre-defined timetable is currently essential since it is not feasible to coordinate on-demand trains whilst ensuring safe operation when traffic is busy. In freight operation, due to changing demands from shippers, extra freight trains are allowed to replace pre-defined on-demand paths through computer-based timetabling. An extra train has to be scheduled as accurately as a regular train, but on a dynamic basis. [50]

In the UK, timetable generation starts with the train operators submitting their service bids for track access to the infrastructure manager (i.e. Network Rail). The infrastructure manager then solves the operational conflicts and develops a draft timetable. After that, a negotiation between the infrastructure manager and train operators will be undertaken to modify the draft timetable and solve further operational differences. The final timetable is published 6 months before implementation to allow Network Rail to allocate spare capacity and operators to sell tickets. [51]

Train services are usually run based on a pre-defined conflict free timetable in daily operation. However, in reality, for various different reasons (such as human behaviour, infrastructure failure, and weather) disturbances occur, and one or more trains may be delayed. In this scenario, the control centre must reschedule train services using methods such as re-timing, re-order, re-route or cancellation to help reduce the influence of delays and recover from the timetable disturbance. [52]

- Maintenance

Every railway system relies upon proper maintenance of infrastructure (including stations, track, signalling, and electrification) and rolling stock to ensure that efficient, reliable and safe operation is sustained. All components of maintenance and maintenance costs need to be taken into consideration in the early planning stages. Both short-term and long-term maintenance need to be carried out. Railway depots are set up to maintain rolling stock, thus the location and design of depots is important. For instance, due to main line railway operation patterns, depots are usually required to be close to termini for passenger trains or to the origin or destination points for freight trains. [43]

2.2 Modelling & Simulation

A model is an external and explicit representation of a system as seen by the people who wish to use it to understand, manage or control the real-world system, which is built through extracting the critical characteristics and the factors from a real-world problem [53]. A simulation is used to imitate the action of a physical system by means other than that actually employed by the system [54]. Modelling and simulation (M&S) is normally used to support the early stages of a railway renewal project in order to verify the feasibility of technical decision making, save major resources and time, increase the quality of solutions, and investigate safety issues before implementation. Generally, the higher degree of details there is in the modelling, the more useful the result of the modelling will be to the decision maker.

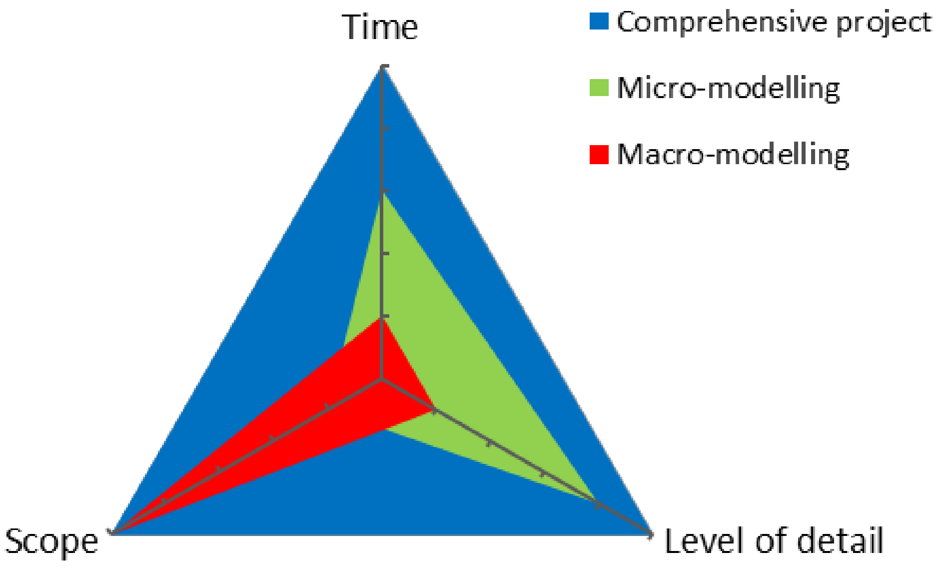


Figure 2-3: Relationship between micro and macro modelling and complex projects

M&S can be divided into two categories: macroscopic and microscopic. The function of macroscopic and microscopic modelling for complex projects is shown in Figure 2-3, which demonstrates 3 key indicators of a comprehensive project (as the blue triangle), including long time, large scope and high level of details. Macroscopic modelling can efficiently provide an overview but less detail (as the red triangle), while microscopic models are closer representations of real-world systems. However, microscopic simulations (as the green triangle) can be technically challenging to perform, although they can give the fine scale details that are often required as part of project planning. It is common to use either macroscopic or microscopic simulation to support decision making in real-life problems. As discussed in Chapter 1.2, at the outset of a railway renewal project, promising upgrade options and innovations could potentially be missed without a systematic exhaustive consideration of all possible options. However, it would be prohibitively time consuming to perform detailed simulation of every upgrade option and combination thereof (e.g. double-tracking a single-track section, replacing point machines, upgrading the control system). It is also a challenge to collect all possible upgrade options for a railway upgrade project. Therefore, an efficient combination of macroscopic and microscopic modelling could potentially benefit complex engineering projects.

The application of M&S encompasses running time and headway calculation, capacity calculation, conflict detection and timetable design, signalling system depiction, energy consumption calculation, operational simulation and train driving simulation, etc. In general, macroscopic modelling, which is an abstract view of a system, is usually preferred for long-term planning tasks [50]. Typical applications in the rail industry include VIRIATO [55], which aims to assess timetable robustness and support strategic timetable planning. Microscopic modelling is concerned with more details such as track information (including speed limits, gradient, radius, etc.), the signalling system (including signals, block sections, etc.), rolling stock (including vehicle types, mass, power, traction, capacity, maximum speed, etc.) and some operational information (including timetable, routes, alternative platforms, etc.). Commonly used microscopic rail simulators are RailSys [56] and OpenTrack [57]. The examples of simulators presented in the following sections aim to support the case studies in Chapter 5 and Chapter 6.

2.2.1 Single-Train Simulator & Multi-Train Simulator

Both the Single Train Simulator [58] and Multi-Train Simulator [59, 60] are microscopic simulation software, developed in MATLAB at the University of Birmingham. The STS aims to evaluate the kinematic vehicle model to provide the mechanical power delivered at the wheels. The input data of the STS mainly involves vehicle models (including resistance characteristics based on the Davis equation, traction, mass, maximum speed, etc.) and route information (including station stops, gradient profile, and speed limit profile). The STS is capable of providing a variety of train graphs and the data thereof, including the altitude profile graph, velocity profile graph, running diagram, traction, resistance and acceleration curve, acceleration vs. distance graph and traction/braking power graph, as shown in Figure 2-4, and the results of energy consumption at the wheel.

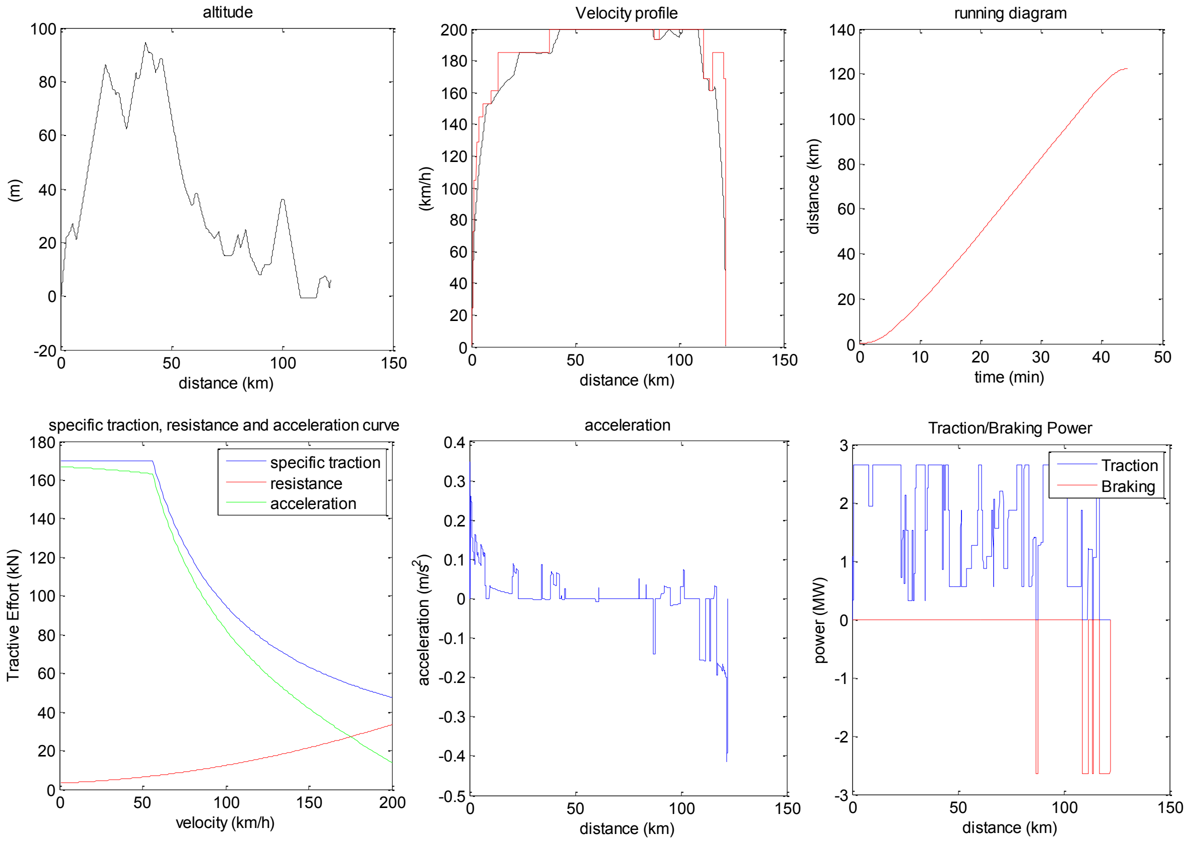


Figure 2-4: Train graphs in STS

Due to a lack of interaction analysis between two consequent running trains in the STS, the MTS adds a signalling system to the system based on the STS. The MTS also can analyse the impact on the mechanical power of the second vehicle when the first vehicle is delayed. The input and output data of the MTS is similar to that of the STS. These two simulators are user-friendly, but only focus on an evaluation of the energy consumption of train movements and they lack operation simulation (such as timetabling, traffic management).

2.2.2 OpenTrack

OpenTrack is a well-established, integrated commercial simulator, which was originally developed in the mid-1990s at the Swiss Federal Institute of Technology's Institute for Transportation Planning and Systems. OpenTrack allows the modelling of different types of railway systems (such as intercity rail, commuter rail, metro and high speed rail) and supports numerous tasks (such as capacity analysis of lines and stations, running time calculation, timetable construction, signalling system design, energy consumption calculation).

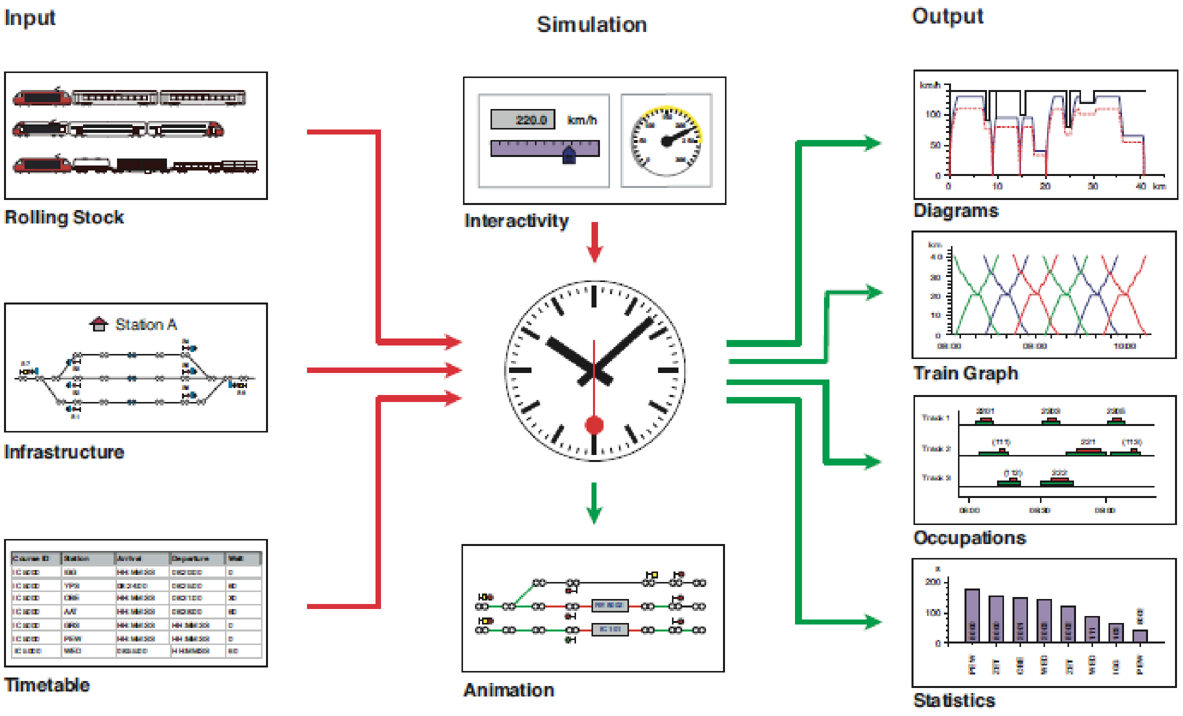


Figure 2-5: Main elements in OpenTrack [57]

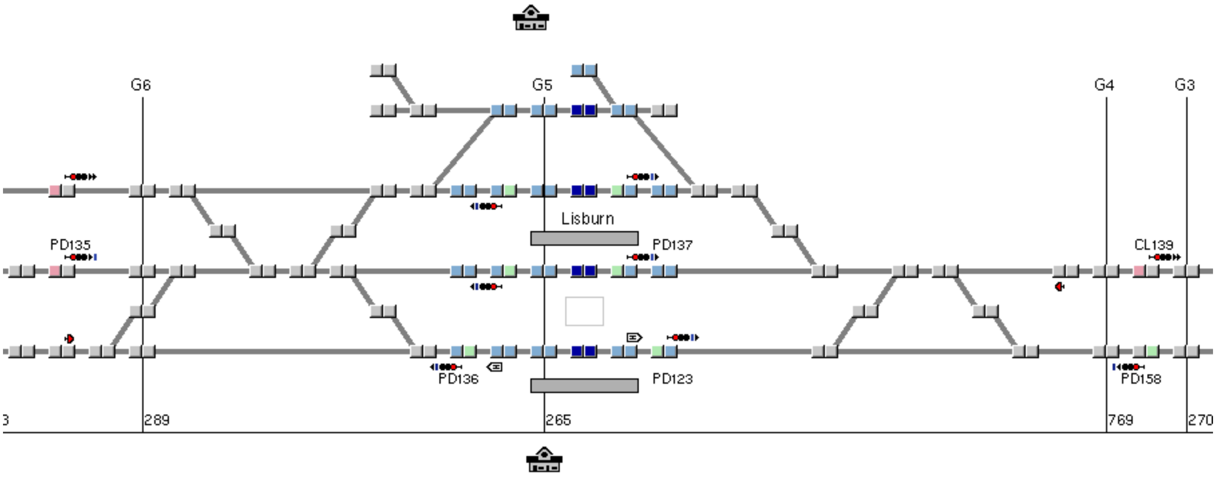


Figure 2-6: An example model in OpenTrack

The elements of input and output included in the OpenTrack are demonstrated in Figure 2-5. The input data involve infrastructure, rolling stock and timetable, as shown on the left of Figure 2-5. A railway network is described in double vertex graphs, as shown in Figure 2-6, which can be easily edited. Each vertex represents a change which has happened in the infrastructure (such as gradient changes, speed limit changes, signals or junction location), and each edge (connecting two adjacent vertex) contains the data of the infrastructure (such as length, gradient, speed limit for different train categories). The characteristics of locomotives and trainsets (such as tractive effort/speed diagrams, length, load, number of carriages per trainset) and timetable (such as arrival and departure times, dwell time) are organised in a database. During the simulation, animation of the train movement is provided, which is under the constraints of the signalling system and timetable. The output is in the form of diagrams, train graphs, occupation diagrams and a statistics log file, as shown on the right of Figure 2-5. [57, 61]

2.3 Railway performance

The European railway system is facing the challenge of accommodating the rapid growth of transport demand, whilst simultaneously improving train punctuality and safety and saving energy. More specifically, to improve a railway system, is to improve the performance of a railway system. Performance measurement, commonly applied in industry or business, is the process of providing objectives and quantitative indicators of various aspects with respect to the performance of a system [62, 63]. The aims can be summarised in Behn's research [64]: (1) evaluate how well a system performs, (2) control subordinates doing the right thing, (3) allocate budget, (4) motivate staff, stakeholders and citizens, (5) promote the organisation, (6) celebrate success, (7) learn strength and weaknesses, and (8) improve performance. In general, performance measurement has been widely used in the rail industry and is crucial for railway planning and management.

Numerous researches of performance measurement framework development have been proposed to provide a more comprehensive view of a railway system. For instance, Onatere et al. [65] aims to collect and standardise the performance of urban transport services in Nigeria to support decision makers, who categorised KPIs into safety, security, environment, finance, traffic management and customer satisfaction, and listed most of the measurement units of each KPI. Lu et al. [66] proposed a railway performance measurement framework to support European railway improvements for timetabling, real time traffic management, operational management and driver advisory systems, using accommodation, journey time, connectivity, punctuality, resilience, passenger comfort, energy and resource usage and listed system properties as influencing factors, categorised into strategic and tactical factors, such as rolling stock, infrastructure, traffic management, human factors. Due to the complexity of railway systems, the definitions of KPIs vary depending on different objectives, the level of details, and relevant systems. For example, Gonzalez-Gil et al. [67] provided a hierarchical list of KPIs for optimising energy consumption of urban rail systems, including traction power supply, vehicle traction, regenerative braking, vehicle auxiliaries, waste heat recovery, depots, stations and infrastructure. Compared with two researches for the entire railway system, Gonzalez-Gil et al. [67] put more emphasis on energy performance indicators and the selection and definition of KPIs is more specific. Therefore, the challenges are what related KPIs need to be used, how to integrate data, and how to present and interpret them.

As introduced in Chapter 1.1.2, the UK Department for Transport proposed a 4C strategic framework for further railway systems development. The 4C framework, including expanding capacity, reducing carbon emissions, improving cost efficiency and better meeting customer satisfaction, represents four trends of railway system improvement, which can also cover most KPIs listed in the researches previously mentioned. For instance, in Lu et al.'s and Onatere et al.'s researches, the customer satisfaction indicator comprises those KPIs such as journey time, connectivity, punctuality, resilience, passenger comfort, and safety, the capacity indicator comprises traffic management and resource usage, the carbon indicator comprises environment and energy, and the cost indicator comprises finance. Therefore, as the basis of railway system improvement, the definitions, measurements and improvements of each 4C target are presented in the following chapters.

2.3.1 Capacity

Commonly, when improving a railway system, the first consideration is to increase capacity. A large number of researches have been undertaken to improve railway capacity, and numerous railway components have a significant influence on capacity [68]. However, different stakeholders have various views on railway capacity. For instance, customers focus on more on satisfying peak values (number of trains) and shorter journey times, while infrastructure planners put more emphasis on guaranteeing profitable utilisation of the infrastructure [69]. Therefore, capacity is defined in different ways by the different requirements of various stakeholders. The International Union of Railways (UIC) [69] provided the definition of capacity as “the total number of possible paths in a defined time window”. E. Kozan [70] defined “the capacity of a single line is the total number of standard train paths that can be accommodated across a critical section in a given time period”. M. Abril [68] proposed that capacity is “the maximum number of trains that would be able to operate on a given railway infrastructure, during a specific time interval, given the operational conditions”.

In practice, railway capacity is often associated with the capability of infrastructure to accommodate train traffic. Therefore, the most widely used measurements of existing railway capacity can generally be categorised into two different areas: traffic volume capability and infrastructure utilisation. The most common definition of railway capacity is traffic volume capability, addressed by UIC leaflet 405. The infrastructure utilisation is addressed by UIC leaflet 406, which is usually used to identify bottlenecks and for planning new or upgrading existing infrastructure.

2.3.1.1 UIC 405 method

UIC 405 was proposed by the International Union of Railways in 1983 to determine the line capacity [71]. Although this method has been superseded, it still provides a basic, direct and theoretical assessment of capacity in terms of the number of trains per given time period. UIC 405 can be expressed in function (2-1).

$$L = \frac{T}{t_{fm} + t_r + t_{zu}} \left({}^{trains}/_{reference\ period} \right) \tag{2-1}$$

where:

- L is capacity of a line section;
- T is the reference period;
- t_{fm} is the average duration of minimum train headway time;
- t_r is an extra time margin;
- t_{zu} is additional time.

- Minimum headway time (t_{fm})

The average duration of minimum train headway time is the minimum possible time between two consequent trains that the signalling system will permit. The headway time is the time to clear the headway distance, which consists of braking distance, sighting distance, overlap distance and train length, as shown in Figure 2-7.

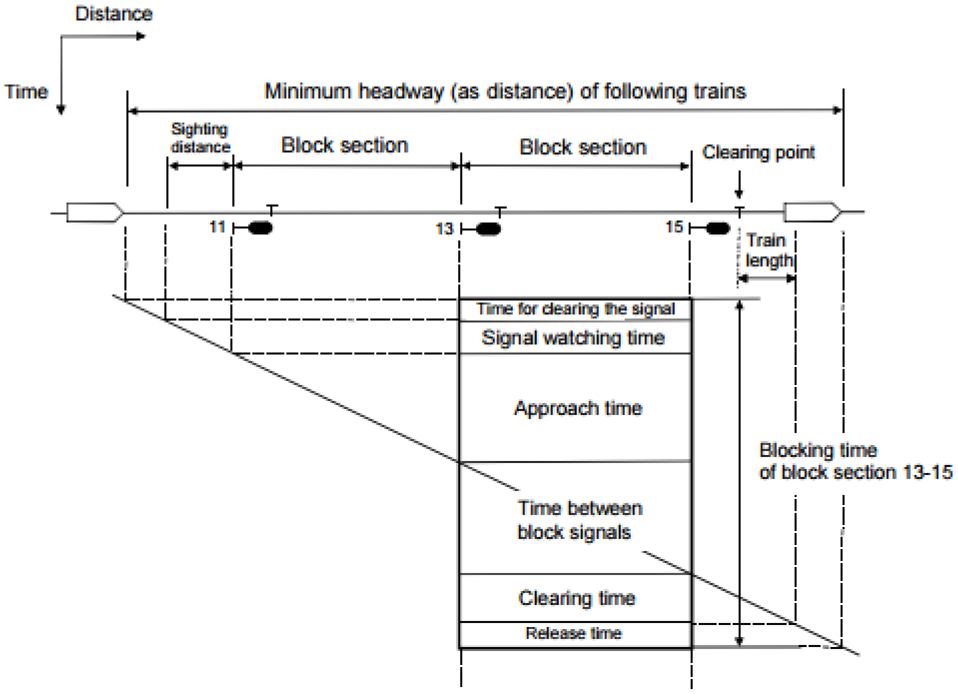


Figure 2-7: Blocking time of a block section [50]

Figure 2-2: different signalling systems, presented in Chapter 2.1.1, also illustrates what the headway time for each signalling system consists of. For a 2-aspect signalling system, the headway time can be calculated by Equation (2-2); for an n-aspect signalling system (n≥3), the headway time can be calculated by Equation (2-3); and for a moving block signalling system, the headway time can be calculated by Equation (2-4).

$$HD_t = BD_t + SS_t + SD_t + OL_t + TL_t$$

(2-2)

$$HD_t = [\frac{n-1}{n-2}]BD_t + SD_t + OL_t + TL_t$$

(2-3)

$$HD_t = BD_t + SD_t + OL_t + TL_t$$

(2-4)

where:

- HD_t is the headway time, second;
- BD_t is the time to clear braking distance, second;
- SS_t is the time to clear signal separation (only for a 2-aspect signalling system), second;
- SD_t is the time to clear sighting distance, second;
- OL_t is the time to clear overlap length, second;
- TL_t is the time to clear train length, second;
- n is the number of aspects (only for $n \geq 3$);

- Extra time margin (t_r)

The extra time margin is a "breathing space" added after each minimum train headway time to reduce the risk of delay occurrence, which varies depending on the maximum permission occupation. The value of the extra time margin is suggested based on experiments carried out by certain railways, stated in UIC leaflet 405. If the maximum permissible occupation of the determinant sector of line is 60%, the extra time margin will be $t_r = 0.67 \times t_{fm}$. If the maximum permissible occupation of the determinant sector of line is 75%, the extra time margin will be $t_r = 0.33 \times t_{fm}$.

- Additional time (t_{zu})

The additional time is another “double insurance” time allowed after each train headway time to achieve an acceptable quality of service over the whole line section, which varies depending on the number of sectors of line, $t_{zu} = a \times 0.25$, where a is the number of sectors of line.

2.3.1.2 UIC 406 method

Defining railway capacity as traffic volume capability (addressed by UIC 405) is easily measurable and understandable, but cannot reflect quality of service. Therefore, infrastructure utilisation has been proposed to define railway capacity, which is addressed by UIC leaflet 406 [72]. This method is applied on existing timetables to evaluate infrastructure capacity using a compression method, which can be summarised into four steps: [72, 73]

- Defining target railway system

This step puts emphasis on defining the infrastructure and timetable boundaries, with consideration of corridors, lines, interlockings, and areas excluded in the defined railway system.

- Defining sections for evaluation

This step aims at determining line sections, which are split from the whole railway line when any infrastructure (such as signalling system, number of tracks in the line section) or timetable (such as beginning or ending services, different number of trains, train mixture) varies. This criterion is usually applied on a double-track line, rather than a single-track line. Landex [74] proposed that, for a single-track line, a split in a line section is not suggested when a passenger loop appears, in order to enable a consistent capacity statement. If UIC 406 is strictly applied, the railway line should be divided at every passing loop or crossing station, which may result in the theoretical capacity being much higher than the actual capacity.

- Calculating occupancy time

Occupancy time is the time to compress all train paths together with minimum theoretical headway time in a line section train graph which reflects a real timetable, as shown in Figure 2-8. It is highly recommended to define a time period longer than two hours. Train paths which enter the line section before the beginning or after the end of the defined time period are not included, as shown in the left figure of Figure 2-8. Through the compression method, all train paths are pushed close to each other but without overlap, as shown in the right figure of Figure 2-8.

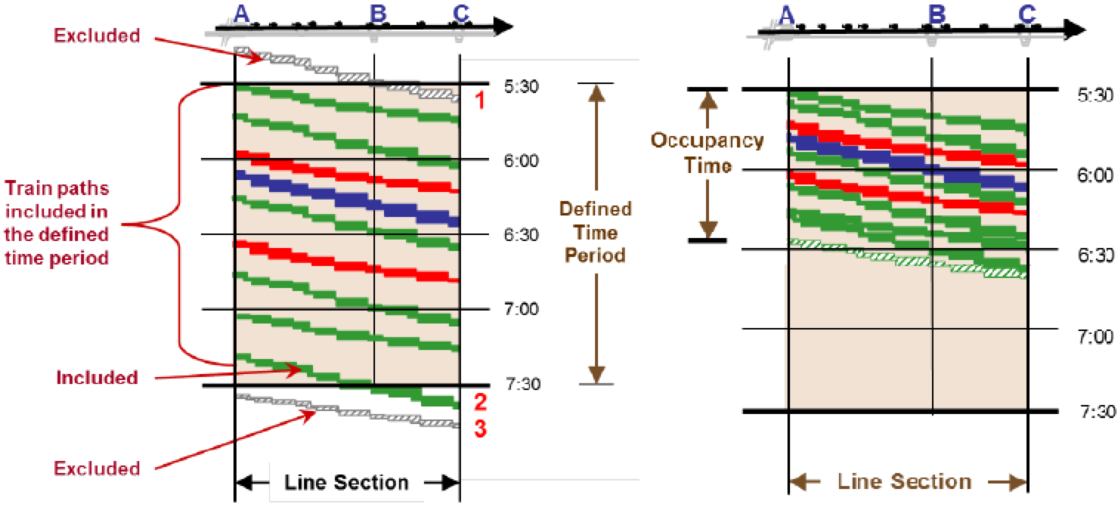


Figure 2-8: Compression method on a double track line section (before (L) and after (R))[72]

- Evaluating capacity consumption

Based on the characteristics of line sections defined above, capacity consumption can be calculated by Function (2-5), where additional time includes any time (e.g., buffer time) added to ensure quality of operation and the defined time period is recommended to be longer than two hours.

$$Capacity\ consumption\ [\%] = \frac{Occupancy\ Time + Additional\ Times}{Defined\ Time\ Period} \times 100 \tag{2-5}$$

The line section with the highest capacity consumption is the bottleneck of the whole railway line.

2.3.2 Carbon

As evidenced by the data in the *Railway Handbook 2015* by the IEA (International Energy Agency) and the UIC (International Union of Railways) [75], rail is only responsible for 1.3% of energy use in Europe in 2012, lower than 72.2% for road, 12.7% for shipping and 12.4% for aviation, whereas the rail share of transport activity is 8.7% in total (including 7.6% passenger (PKM) and 10.6% freight (TKM)), compared with 69.6% for road, 15.9% for shipping and 5.8% for aviation. In general, rail transport is more energy efficient and environmentally friendly than other modes of transport. Even through rail is already a low carbon mode of transport, it is still essential to keep reducing carbon emissions and considering environmental issues, such as climate change, sustainable energy sources [76, 77]. The key method of reducing carbon emissions is improving propulsion systems and using more energy-efficient modes [78]. Statistics reported by the ORR [79] indicate that CO_2 emissions per railway passenger kilometre have declined by 23.9% since 2005-06, while CO_2 emissions per freight tonne kilometre are up 20.1% since 2005-06. CO_2 emissions are converted from traction energy consumption, which is the total traction electricity (kWh) and diesel usage consumption (litres) from actual and estimated data for both passenger and freight trains, using standard conversion factors (in kgCO_2 per kWh or in kgCO_2 per litre) published every year by the Department for Environment, Food and Rural Affairs (DEFRA) [80].

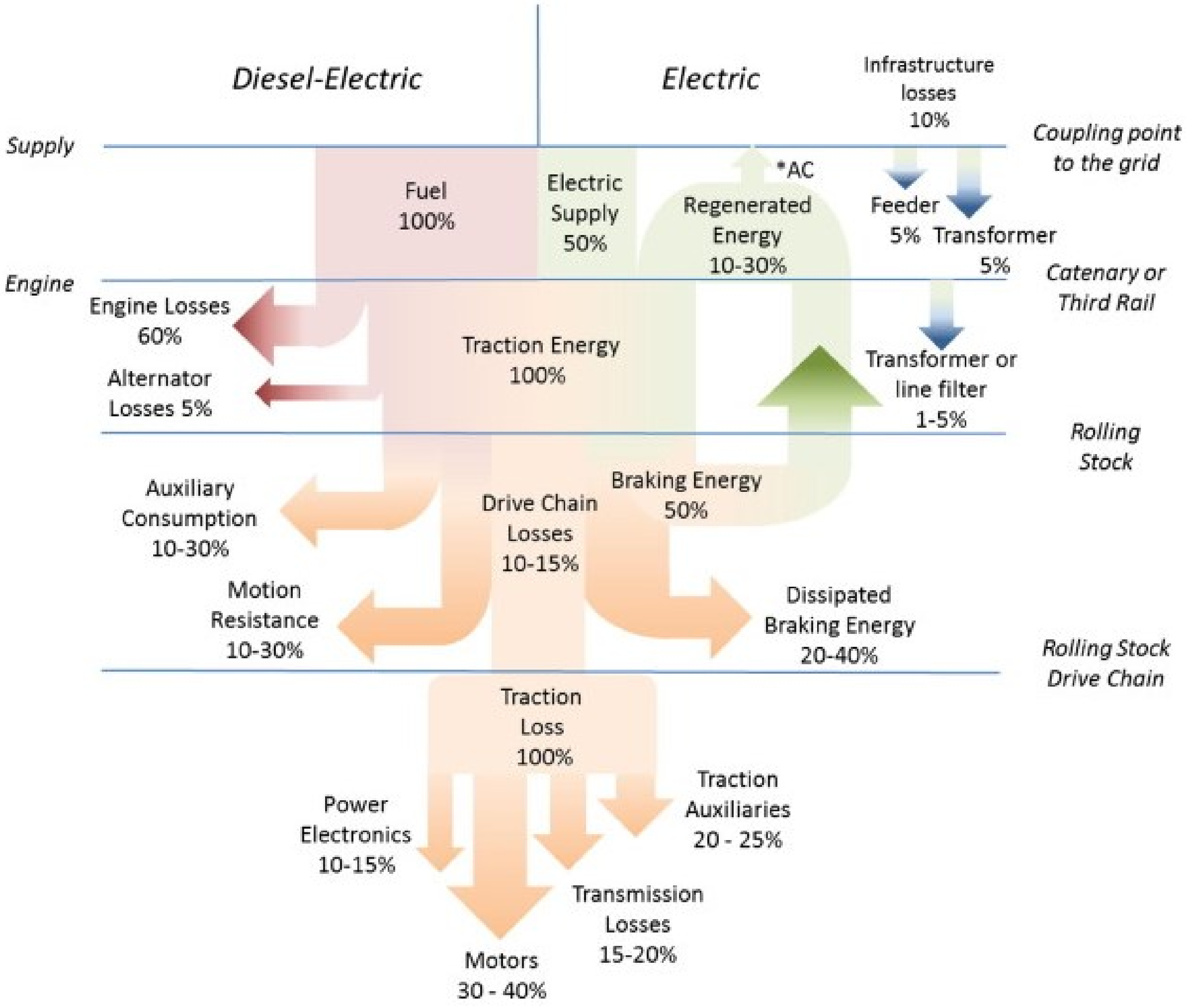


Figure 2-9: Traction energy flow for diesel-electric and electric vehicles [81]

However, traction energy consumption is more straightforward and easily estimated than CO_2 emissions when assessing a railway system. Traction energy flow for diesel-electric and electric vehicles is demonstrated in Figure 2-9, where the given percentage may vary depending on different vehicles and railway systems. The major energy consumed within a railway system is used to power the trains, which accounts for up to 80% of the total energy consumption from the power supply. In diesel-electric traction the engine has significant losses, and in electric traction there are conversion losses between the national grid and catenary. Meanwhile, some power is used for the auxiliary functions, sometimes known as 'hotel' power, such as heating, air conditioning, lighting, to improve the comfort of passengers [81].

2.3.2.1 Measurements of energy consumption

As the energy losses and 'hotel' power would ideally be considered as a fixed portion of the total energy consumption, the energy consumption usually considered is generated by train movement. Generally, the energy consumed per train per journey is expressed in terms of kWh. The methods used to solve the dynamic movement equations have been listed in earlier researches, [58-60, 81, 82]. These equations are used to evaluate the energy consumption of the vehicle at the wheels, which is also the basis of the STS and the MTS, mentioned in Chapter 2.2.1.

Train motion is governed by Lomonossoff's equation, which is based on Newton's Second Law, and can be expressed in Equation (2-6):

$$M_E \times \frac{d^2 s}{dt^2} = F_T - R - F_\alpha \tag{2-6}$$

where:

- M_E is the effective mass of the vehicle ($M_E = M(1+\lambda)$, M is the mass of the vehicle, λ is a constant of rotary allowance).

- $\frac{d^2s}{dt^2}$ is the acceleration.
- F_T is the traction force.
- R is the vehicle resistance.
- F_α is the force due to the gradient.

The vehicle resistance R can be described by the Davis Equation (2-7).

$$R = A + B\frac{ds}{dt} + C(\frac{ds}{dt})^2$$

(2-7)

where:

- A, B, C are vehicle specific coefficients related to the static resistance, rolling resistance and aerodynamic resistance respectively.
- $\frac{ds}{dt}$ is the velocity of the vehicle.

The power (*P*) of the train can be computed by Equation (2-8), and the energy consumption (*E*) of the train at the wheel can be computed by Equation (2-9).

$$P = F \times \frac{ds}{dt}$$

(2-8)

$$E = \int_0^t P \times dt$$

(2-9)

The equations listed here are the basis principle of the STS and the MTS to describe the physics of train movement, mentioned in Chapter 2.2.1.

2.3.3 Customer satisfaction

The needs and aspirations of the customer should be kept at the forefront when planning, constructing, maintaining, or improving any railway system. The passengers' basic needs are comfortable travel and safe arrival on time, and the freight customer needs safe and on time delivery of their goods [43]. Transport Focus collects the opinions of more than 50,000 passengers each year to publish the National Rail Passenger Survey (NRPS), which provides a wide view of customer satisfaction with rail travel. According to the statistical reports by Transport Focus [83], a wide range of performance indicators are listed in the report, including journey planning, ticket service, station layout, punctuality, reliability, crowding, etc.

Some performance indicators are listed here, which are widely used to measure customer satisfaction.

- Journey time

Passengers usually prefer faster travel, in other words, a shorter journey time. Journey time is the actual train time consumed to complete the journey without connections with other services, which may vary from the planned time in the timetable depending on different traffic and driving conditions [66].

- Reliability/ Punctuality

Since passengers rely on the railway for travel, either for business or leisure purposes, the punctuality of a railway system is the biggest overall driver of satisfaction, as shown in the

NRPS. The public performance measure (PPM) is proposed by Network Rail, which combines the reliability and punctuality figures as the industrial standard performance measurement. The PPM shows the percentage of trains arriving at the terminating station within 5 minutes for commuter services and within 10 minutes for long distance services [84].

- Resilience

Resilience refers to how quickly a system can recover its functionality from pressure, perturbations, or unpredictable changes, which is based on the stability, robustness and recoverability of the timetable [85]. A method has been proposed in Lu et al.'s research [66] to measure resilience through the maximum total delay, the time to recover and the delay area (calculated as the area under the system delay versus time curve).

- Passenger comfort

Passenger comfort can be measured through temperature and humidity, train vibration, noise, the number of jerks, crowding, etc. For instance, Zhang [86] developed an evaluation method for temperature and humidity, train vibration and rate of train vertical acceleration change. A standard measurement of crowding has been proposed by the Department of Transport [87], known as 'Passengers in excess of capacity' (PiXC), which shows the number of standard class passengers in excess of capacity at the critical load point. Meanwhile, Mohd Mahudin et al. [88] described another method to capture the dimensionality of rail passenger crowding with consideration of psychological factors.

- Safety

Safety can be measured through the accident rate, including human errors rate, equipment failure rate, mortality rate, etc. [89]. For instance, an appropriate safety measure is the fatal accident rate (including injury and fatality), addressed in Elms' research [90].

2.3.4 Cost

When making decisions on a railway project, it is crucial to have economic appraisals to support consideration of alternatives, in order to balance the cost and benefit of a project. However, it is difficult to measure the cost precisely, since a large number of factors associated with the cost need to be taken into account. The cost of a railway project can be categorised into investment cost, planning or design cost, construction cost, operation cost, maintenance cost, etc.

The life-cycle cost is commonly used to measure complex mega-projects. Life-cycle cost consists of cost for planning, design, construction, operation, maintenance, and renewal until abandonment. Numerous researches have been published to develop cost analysis models. For example, Chen [91] proposed a whole life-cycle cost model for urban rail transit, considering planning and design cost, construction cost, operation and maintenance cost and scrap value. Rong [92] proposed a similar life-cycle cost analysis for urban rail transit vehicles, covering purchase cost, operation cost, maintenance cost and salvage cost. Gattuso [93] also developed a tool to support rail planners to estimate investment and operation costs.

In addition to various cost analysis models, some statistic reports of average cost for different rail sectors have been published to support cost estimation for railway projects, [94, 95] even though sometimes the actual figures from the cost analysis models or from practical projects may vary from the figures in these statistic reports.

2.3.5 Discussion

The 4Cs framework is a comprehensive railway performance framework, which can cover most indicators. Compared with the examples mentioned above, most KPIs listed in previous researches can be covered by the 4Cs. For example, in Lu's research [66], accommodation and resource usage can be covered in capacity; journey time, connectivity, punctuality, resilience and passenger comfort can be covered in customer satisfaction; energy can be covered in carbon; however, the consideration of cost is missing.

In addition, a wide range of new technologies have been implemented to improve the railway system based on one or two 'C' targets at the same time. For instance, Bocharnikov's research [23] and Ning's research [59] put emphasis on optimisation of energy consumption and delay cost through controlling train movements. In D'Ariano's research [22], a new concept of flexible timetable is developed to improve punctuality without decreasing capacity. However, there is a lack of studies to consider the railway as a complete system, such as improving the performance of the 4Cs simultaneously in a railway system. There is also a lack of researches which collect and list all these improvement alternatives.

2.4 Summary

This chapter gives a review of what a railway system is (Chapter 2.1 Railway systems architecture), the tools that can be used to simulate a railway system (Chapter 2.2 Modelling & Simulation), and how to appraise a railway system (Chapter 2.3 Railway performance). A railway system is a complex system associated with various disciplines, which consists of infrastructure, rolling stock and operation. In order to verify the feasibility of technical decision making and save time and cost, M&S is usually carried out to support decision-making in a rail project before implementation. M&S can be categorised into macroscopic and microscopic modelling, depending on different requirements. The 4Cs framework provides a comprehensive view of a railway system, including capacity, carbon, customer satisfaction and cost. The knowledge presented in this chapter will support the methodology and case study development presented later in this thesis.

Chapter 3 Review of decision-making for railway renewal projects

Based on the introduction of decision-making in systems engineering, this chapter presents reviews of decision making for railway renewal projects, including a generic complex decision-making process, definitions of various decision-making problems, and widely-used related decision-making methods.

3.1 Complex decision-making process

Decision-making is the cognitive process resulting in logically choosing solutions from available alternatives based on the decision-makers' preferences, which has been widely applied in many areas, such as business organisation, education, crisis management, supply chains, and medicine [96]. Due to the complexity, uncertainty, multi-objectives, and often different perspectives (in group decision-making) of the decision-makers' preferences, it is difficult to make systematic rational decisions when the outcome is important, such as high investment or high risks [97]. In order to make better decisions for different decision-making problems, decision-making processes have been proposed in numerous ways. The generic decision-making process can be generalised into 7 steps [54, 97-100], shown in Figure 3-1.

- Identifying a problem includes specifying the decision situation, understanding aims or objectives, and having recognised the need for a decision.
- Gathering information and data includes current conditions, presence of bottlenecks and possible causes, constraints and criteria, etc.
- Developing alternatives means generating ideas (such as brainstorming, consultants can be employed to assist with this step) to list all the possible solutions.

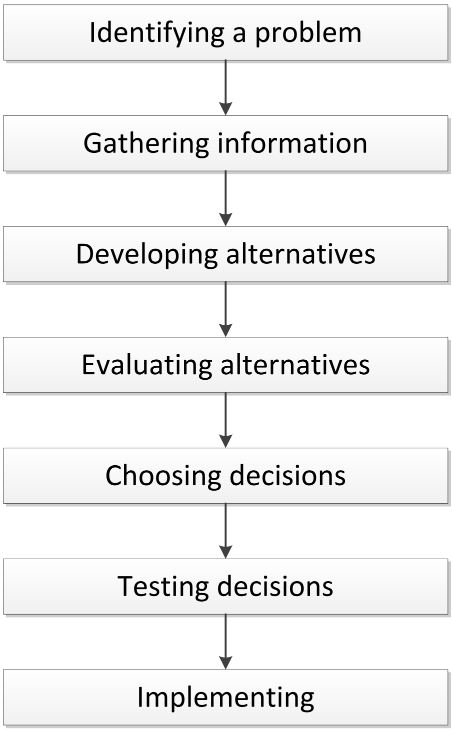


Figure 3-1: The decision-making process steps [97-100]

- Evaluating alternatives aims to help to seek the best or the most appropriate solutions to the problem. A number of decision-making methods have been proposed to evaluate alternatives against different criteria or objectives (initiated in the first two steps) depending on different needs of specific decision-making problems.
- Choosing appropriate decisions is based on the results of alternatives evaluation. According to the aims, objectives and constraints initiated in the first two steps, one alternative, or even a combination of alternatives, can be selected as the solution of decision-making problem.
- Testing decisions aims to verify the feasibility of decisions under the range of possible circumstances that might happen in the implementation step.
- Implementing is carrying out the decision, monitoring the performance to make sure the decision is effective to the problem, and reviewing.

As discussed in Chapter 2.2, the modelling and simulation plays an important role in the early stages of a railway renewal project. In the preliminary decision-making it is usual to put emphasis on considering the first 5 steps of the decision-making process, which can be divided into three phases based on the M&S approach, as shown in Figure 3-2.

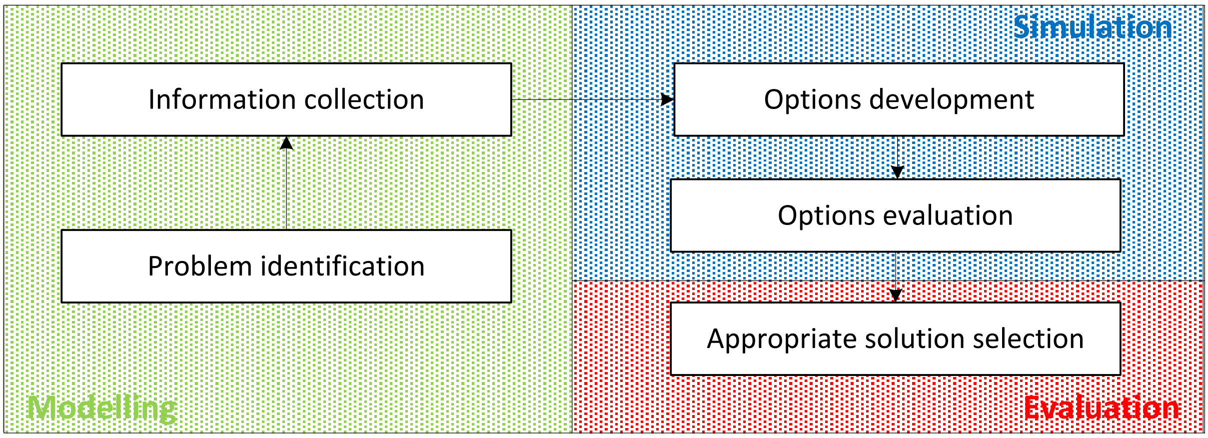


Figure 3-2: Framework of the decision-making process in the early stages of a project

- Modelling includes problem identification and information collection, which aims to build models with quantitative characterisation to represent a selected specific physical or abstract railway system in real life, as a basis for the simulation and evaluation phases.
- Simulation includes options development and evaluation, which refers to evaluating possible options under the operation of the model developed in the first phase over time.
- Evaluation refers to comparing the results in the second phase and making the appropriate decision based on the aims and constraints developed in the first phase.

These three phases can cover most of the decision-making process in railway renewal project planning. The main contribution of this research is developed in the simulation phase.

3.2 Decision-making problem identification

If a decision-making problem is associated with the analysis of a finite number of alternatives described in terms of several evaluated criteria, this problem is called a multi-criteria decision-making (MCDM) problem [101]. Three key terms involved in MCDM problems are [101, 102]:

- Alternatives, which represent the different choices of action available to the decision-maker.
- Multiple criteria, which usually represent the different dimensions from which the alternatives can be viewed, and which may conflict with each other.
- Decision weights, which usually represent the importance of the criteria. Sometimes, due to incommensurable units of different criteria, the assignment of weights may be controversial.

A MCDM problem can be easily expressed in a matrix format, as shown in Function (3-1) [101]. Element a_{ij} indicates the performance of alternative A_i under evaluation in terms of decision criteria C_j (where $i = 1, 2, 3, \cdots, m$ and $j = 1, 2, 3, \cdots, n$). The assignment of decision weights for decision criteria may be required, denoted as w_j (for $j = 1, 2, 3, \cdots, n$).

$$
\begin{array}{ccccc}
 & C_1 & C_2 & \cdots & C_n \\
 & (w_1 & w_2 & \cdots & w_n) \\
A_1 & a_{11} & a_{12} & \cdots & a_{1n} \\
A_2 & a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
A_m & a_{m1} & a_{m2} & \cdots & a_{mn}
\end{array}
\tag{3-1}
$$

There are different purposes of a MCDM problem; if it is simply trying to find a solution that can meet all the requirements, it falls into a constraint satisfaction problem (CSP); whereas if it is trying to make an optimal decision, it falls into a multi-objective optimisation problem (MOOP). Generally, optimisation has a longer decision-making process than constraint satisfaction, since optimisation needs additional more careful trade-offs across different criteria. In some instances, the decision weights for decision criteria are assigned based on imprecise, uncertain and subjective human judgements or experience.

A CSP is concerned with a set of variables with a finite domain and a set of constraints or limitations. The aim is an assignment of values to some or all variables that can satisfy all the constraints [103]. A CSP can be expressed in a triple, as shown in Function (3-2).

$$\begin{aligned} &(X, D, C) \\ where\ X &= a\ finite\ set\ of\ variables\ \{X_1, X_2, \cdots, X_n\} \\ D &= a\ finite\ set\ of\ domains\ \{D_1, D_2, \cdots, D_n\} \\ C &= a\ \ finite\ set\ of\ constraints\ \{C_1, C_2, \cdots, C_n\} \end{aligned} \tag{3-2}$$

An optimisation problem is defined as the search for a minimum or a maximum for a function, which usually called an objective function. Similarly, a MOOP has more than one objective function to be minimised or maximised simultaneously. A MOOP can be expressed as Function (3-3) [104, 105].

$$\begin{gathered} Minimise/\,maximise\ \ f_i(x) \quad i \geq 2 \\ subject\ to\ \ x \in D \end{gathered} \tag{3-3}$$

D is a decision variable space, which is typically defined by some constraint functions.

Sometimes, when solving a real-world optimisation problem, the variables of the objective functions to be optimised are constrained to be searched for the solution in a specific defined area; such a problem is also called a constrained multi-objective optimisation problem (CMOOP).

3.2.1 Research problem classification

Based on the overview of the research problem and the MCDM problems presented above, this research problem of how to find appropriate solutions from a large number of upgrade options for railway renewal projects to meet high-level requirements can firstly be defined as a MCDM problem, since a major part of this research problem involves the analysis of a number of rail upgrade options measured in terms of several key performance indicators (KPIs).

Then, if this research only aims to find appropriate solutions that can meet high-level requirements (e.g. saving 10% on energy consumption, improving 10% on capacity), it can be further defined as a CSP. However, the result of a CSP may be a few solutions rather than a single unique solution. Alternatively, if this research aims to find the most appropriate solution, it can be further defined as a CMOOP, since in a railway renewal project, at first a solution should meet all the high-level requirements, and furthermore an ideal optimal solution should perfect the performance of a railway system, for example, simultaneously maximising capacity, minimising energy consumption, and maximising cost-benefit. However, the units of different KPIs are incommensurable, which leads to difficultly in defining an objective function, and particularly in the assignment of weights for KPIs.

In brief, due to considering the applications in the real world, this research problem is a MCDM problem. As the applications in are real, this problem could probably be preferred as a CSP, while as pure research, this problem could be preferred as a CMOOP. With the assistance of the method developed to solve this research problem, the final results are expected to list all appropriate solutions and give suggestions as to the most appropriate solutions depending on different railway systems.

3.3 Decision-making methods

Over recent decades, numerical MCDM methods have been proposed [106, 107], such as analytic hierarchy process (AHP), cost-benefit analysis [31, 40] and the analytic network process (ANP). Each of the methods uses numerical techniques to help decision makers choose from a number of alternatives. The best decision-making method depends on the problem specification. Here, with the aim of solving this research problem, some commonly-used MCDM methods and problem-specific MCDM support models are discussed. MCDM techniques are widely-applied to a range of multi-criteria problems, rather than only for railway renewal projects. Problem-specific MCDM support models are proposed to solve MCDM problems in the rail industry, some of which are similar to this research problem of finding appropriate solutions for railway renewal project. These MCDM methods and models aim to support evaluating alternatives (Step 5 in the generic complex decision-making process presented in Figure 3-1 in Chapter 3.1). There are three steps which are commonly-used in any decision-making technique involving numerical analysis of alternatives [101].

1) Determine the relevant criteria and alternatives.
2) Assign numerical values to the relative importance of the criteria and to the impact of the alternatives on these criteria.

3) Process the numerical values assigned in the last step to determine a ranking of each alternative.

3.3.1 Commonly-used decision-making methods

In a MCDM problem, optimising a system that involves improving one outcome at the expense of reducing another requires the assignment of weighting values to the outcome criteria. The problem of how best to define weighting values in a trade-off analysis of different performance indicators is open to different interpretations. Various MCDM methods have been proposed and applied in group decision making to define numerical weights or priorities; the most commonly used in project planning in the railway industry is the analytic hierarchy process (AHP), proposed by Thomas L. Saaty [108]. The steps of the AHP can be summarised as: [101, 108, 109]

1) Decompose a decision-making problem into several hierarchies, including decision goal, decision criteria, and alternatives.
2) Make a series of judgements on pairwise comparisons between alternatives against individual decision criteria, and criteria against goal, based on the pre-defined AHP fundamental scale.
3) Transfer the weights (assigned in each pairwise comparison) to a matrix and calculate the matrix's principal right eigenvector, which represents the performance of each alternative in terms of criteria.
4) Check the consistency of the judgements and make a final decision.

The AHP is usually applied to solve selection problems in the railway industry via judgements by experts, such as infrastructure project selection, new route selection, manufacturer selection, [38-40, 110]. The AHP is easily applied, stable and flexible for a

MCDM problem, which provides a rich picture of how the criteria function at a lower level and goals at a higher level. Furthermore, this method can also easily evaluate the problem from different perspectives based on different stakeholders' judgement [106, 107]. However, due to the complex and time-consuming computation in pairwise comparisons, the AHP cannot deal with a problem with a large number of alternatives.

The analytic network process (ANP) [41, 42] is proposed as an extension of the AHP. The AHP structures a problem as a hierarchy with the natural cognitive process while the ANP structures a problem into a network. Due to the interdependence in the system's elements and individual criteria of the same hierarchical level, the interactions among elements and criteria are considered in the ANP. The outline steps of the ANP are similar to the AHP, which also makes pairwise comparisons to measure the weights of alternatives. Longo et al. [111] proposed the application of the AHP and ANP to support decision-making of railway infrastructure projects. It was found that the ANP represents a better preference structure of decision makers than the AHP but is more complex to carry out, thus it is more time-consuming when measuring a large number of alternatives.

Cost-benefit analysis (CBA) is another decision-making method, which plays a significant role in the early-stage evaluation of rail projects in many western countries. The CBA provides an estimation of all the benefits (pros) and costs (cons) of a project, which quantifies in monetary terms the value of all consequences. Generally, there are two major applications of the CBA: ex-ante CBA and ex-post CBA. Ex-ante CBA is commonly used in the rail industry, which is conducted while a project is under consideration, before it is started or implemented. Ex-post CBA is conducted at the end of a project to review and learn from it. The steps of CBA can be summarised as: [112-114]

1) List alternative projects and stakeholders and select measurements and measurement indicators.
2) Predict outcome of cost and benefit over the life of the project and convert them into the same currency.
3) Discount costs and benefits to obtain present value (the value of the income stream) and calculate the net present value (the value of the differences of the present value of cash outflows and cash inflows) of each alternative.
4) Sensitivity analysis on the uncertainty or risk in CBA parameters and make a decision.

The CBA is usually applied either to verify the feasibility of an investment decision or to appraise and compare projects [40, 112, 115]. Theoretically, in a new rail infrastructure project, the costs consist of investment, maintenance and operational costs while the benefits are travel time savings and increased consumers. The CBA can simplify complex business level decisions and provide a straightforward way to compare projects. Compared to MCDM methods (such as AHP), CBA is more value-free due to having no weights assignment on criteria. Nevertheless, the major disadvantage of CBA is inaccuracy due to the estimations of costs and benefits. In addition, several components (such as environmental performance, reliability or safety of a railway system) that could affect cost and benefit are either not addressed at all or are scarcely accounted for in CBA [112]. Thus the CBA for railway renewal projects has some flaws since not every rail-related performance indicators can be evaluated as a cost or benefit.

A combination of AHP and CBA has been proposed in many researches to give more informed decision support for rail infrastructure project appraisal. Longo et al. [110] proposed a hierarchical structure to assess railway infrastructure based on the AHP. Furthermore, Baric et al. [40] combined the AHP with the strengths, weaknesses, opportunities and threats (SWOT) analysis and the CBA to select appropriate railway line reconstruction solutions via assessing criteria (technical solutions, traffic safety, economic indicators, and environmental indicators) from 4 alternatives for Croatia's railway system. Ambrasaite et al. [115] also proposed a decision support system, involving a combination of the CBA and the AHP for 3 different transport infrastructure project appraisals. The CBA was introduced to evaluate economic criteria (net present value, internal rate of return, benefit-cost ratio), while the AHP was applied to evaluated strategic criteria (business development, location of companies and logistics centres, effect on tourism and effect on landscape), which cannot be evaluated in the CBA as a monetary term. Based on these two researches, as a high level analysis, it gives a rational combination of different decision-making methods and convincing suggestions for solving selection problems.

However, with respect to this type of railway renewal project, there is still a lack of argument as to why the 3 or 4 alternatives analysed in these two researches have been chosen from a large number of possible alternatives. Therefore, once the number of alternatives and criteria becomes large in a railway renewal project, it is difficult to use these decision-making methods for evaluation, since it is time consuming to make a pairwise comparison and difficult to maintain consistency in judgement. Meanwhile, having a large number of alternatives amplifies the impact of inconsistent pairwise comparisons.

Another weakness of traditional decision-making methods is that it is difficult to represent a human’s judgement as specific numbers. To address this issue, the concept of fuzzy set theory can be introduced as an alternative in decision-making methods to quantify the imprecision, uncertainty and subjective human reasoning involved in real world decision-making problems. Fuzzy set theory is a better way to transfer linguistic variables to fuzzy numbers under ambiguous assessments [116], such as trapezoidal fuzzy numbers or triangular fuzzy numbers, which are a real number is based on specific membership functions to represent a set of possible values whose own weight is between 0 and 1. For example, a fuzzy extended AHP method was proposed in Chan et al.'s [37] and Huang et al.'s [39] researches to select global suppliers and government sponsored projects. Similarly, Perrone [117] also introduced a fuzzy multiple criteria decision model to evaluate advanced manufacturing systems. All these researches used fuzzy extended decision-making methods to tackle the linguistic assessments of customers' feelings or experts' judgement.

3.3.2 Problem-specific decision-making support models

Since these decision-making methods cannot fit the transportation project appraisal problem perfectly, due to some real world applications, some researches started to develop unique decision-making support models.

- Transportation decision-making support models

Web-based Transport Analysis Guidance (WebTAG) [118], proposed by the Department for Transport, is the guidance and toolkit used for transport appraisal, which aims to provide the information and knowledge on the key components of the transport appraisal process for business case development and supporting investment decisions. WebTAG consists of software tools and guidance on transport modelling and appraisal methods, including cost-benefit analysis, economic impacts, environmental impacts, social and distributional impacts, demand modelling, assignment modelling, forecasting, etc., which are used for highways and public transport projects. WebTAG provides a widely-applied well-structured process for transport project appraisals and widely covers the concerns of the government or investors.

However, since WebTAG is designed from the government and investors' point of view, and is applied to all transport projects, the detailed methods for evaluating specific transport models (such as how to evaluate the capacity of a commuter railway system) are not gathered in WebTAG.

- Railway decision-making support models

The Transit Capacity and Quality of Service Manual [119], proposed by the Transportation Research Board, is a guide to transit capacity and quality of service issues, including influence factors and measurements. Compared with WebTAG, the manual provides detailed knowledge and information, which consists of background, statistics, figures and measurements for different public transportation, including buses, rail and ferry, as well as transport stops, stations and terminals. In the Rail Transit Capacity section, the manual provides rail-specific capacity definitions, details of how train control and signalling and train operations relate to capacity, a methodology for evaluating capacity and its potential applications, and some examples for different railway systems. A spreadsheet tool based on the methodology detailed in the rail capacity section is also offered to support rail system capacity evaluation. This manual is mainly designed from the engineers’ or planners’ point of view and only focuses on capacity analysis, without consideration of other factors, such as economics or energy.

In order to support railway companies or agencies to find an optimal allocation of their capital investment for capacity planning, Lai et al. [120] proposed a comprehensive decision support framework for strategic railway capacity planning. This framework consists of three independent tools: alternatives generator, investment selection model, and impact analysis module. The alternative generator was developed to evaluate the current condition of the railway system and then generate the possible alternatives with capacity increases and construction costs. Through optimisation of the total cost (composed of the net cost of the infrastructure upgrade and flow cost of running trains), the investment selection model determines the investment options. Finally, the impact analysis module integrates the net cost, delay cost and benefit of the investment options into an impact and benefit table and then ranks them to find the optimal solutions. This framework has been applied on North American class 1 railroad to determine the optimal investment plan successfully. This research gives a reasonable process to generate alternatives, takes capacity and cost into account simultaneously and provides qualitative and quantitative results to support investor decisions.

A recent study undertaken by the University of Birmingham and Transport Research Laboratory for the Department of Transport [121, 122] has shown that it is possible to evaluate a large number of upgrade options quickly at a high level. A capacity dependencies matrix was developed, which decomposes the railway system into the individual components, including elements of railway infrastructure, vehicle fleet and operations, to evaluate the impact of changes to their status on capacity. According to current and expected improved conditions, and using predefined look-up tables developed by a group of experts in railway capacity, the overall impact scores of each individual component are calculated automatically. The impact factors in the pre-defined look-up tables have been validated based on a case study of the line between Reading and London Waterloo, which analysed the capacity results (UIC 406) from the RailSys simulator. This model evaluates the feasibility of the proposed changes in terms of context, cost and technical difficulty in combination with the capacity assessment. The outcome demonstrated how changing different railway system attributes from their existing condition by different levels affects capacity. As mentioned above, a common issue which often occurs in railway renewal projects is that already-recognised solutions are chosen too quickly without consideration of the full range of possible options. To address this issue, the capacity dependencies matrix developed in this research has proven its advantage over commonly used decision making methods in the simultaneous evaluation of numerous alternatives. Furthermore, this method provides a more comprehensive evaluation by taking into consideration the feasibility and sensitivity of each alternative, rather than only capacity performance indicators.

These three rail decision-making support models have demonstrated their advantages in capacity planning. However, the choice of criteria for rail improvement appraisal should be more than just capacity, since the capacity analysis in the TRB model is only appropriate for metro-type systems: homogeneous traffic with simple networks. In addition, the capacity dependencies matrix developed by UoB/TRL only evaluates individual alternative without taking the combination of alternatives into account. Furthermore, the weighting values between different performance indicators in the pre-defined look-up tables are based on group discussion rather than using any structured process. A wide range of impacts for rail improvement appraisal are coved in WebTAG, but without detailed information (such as capacity definitions and measurements presented in the Transit Capacity and Quality of Service Manual). Therefore, it is necessary to expand these capacity planning decision-making support models to create a more comprehensive railway renewal decision-making support model. In addition, these models only support evaluation of upgrade options individually, whereas a railway renewal project usually takes a combination of upgrade options to achieve the most efficient outcome. The combination of different upgrade options cannot be evaluated by the sum of their individual scores due to interdependencies between different components. Moreover, the weighting values between different performance indicators were defined by an expert group discussion; their justification and adjustment could be strengthened by following a systematic process [110].

3.4 Summary

In this chapter, the background of complex decision making is reviewed, including typical decision-making processes, a definition of MCDM problems, and details of commonly-used and problem-specific decision making methods. The research problem, which is how to find appropriate solutions from a large number of upgrade options for railway renewal projects, can be defined as a MCDM problem. However, to date few researches have put emphasis on developing a system approach to generating solutions for railway renewal projects. Based on the discussion covered in Chapter 3.3, it can be seen that the current methods available for decision making do not fully resolve this problem.

Chapter 4 The railway upgrade selection process

As discussed in Chapter 3, the research problem of finding the most appropriate solution from a large number of upgrade options for a railway renewal projects is a MCDM problem, while the current decision-making method or decision-making support models are not ideal. Therefore, to aid decision making in railway renewal project planning, a railway upgrade selection process (RUSP) is proposed, based on the knowledge in Chapter 2 and Chapter 3.

The major challenges of this research problem are:

- Collecting a large number of upgrade options: As discussed in Chapter 3.3, in upgrade planning there is often not a robust process to generate alternatives covering all reasonable options. A railway renewal project may put emphasis on the improvement of infrastructure, rolling stock, timetables or operation and each category has numerous upgrade options, as mentioned in Chapter 2.1, rather than focussing on the whole railway system.
- Time-consuming to carry out micro-simulation: As discussed in Chapter 2.2, due to the complexity of a railway system, it is time-consuming to model and simulate every upgrade scenario (including the combination of upgrade options) at the microscopic level.
- Multiple objectives: The performance aims of a railway system are various, as introduced in Chapter 2.3, thus a railway renewal project may well have more than one objective. It is essential to choose appropriate performance indicators (or objectives) for railway renewal projects so that the best trade-offs can be made.

This chapter presents the structure of the RUSP in detail, which consists of three stages: (1) modelling, which collects information and data and builds the railway model on the basis of the railway characteristics; (2) simulation, which simulates the upgrade scenarios and provides the results of the performance of the 4Cs of the railway model; and (3) evaluation, which determines the appropriate solutions. Through the mathematic model of the research problem, it can be shown that the number of all possible upgrade scenarios is very high. Therefore, this RUSP combines macro and micro simulation at the simulation stage. The macro assessment, a high-level feasibility analysis model, aims to make a quick and high-level decision to remove infeasible and lower potential upgrade options, thus reducing the number of upgrade scenarios in the micro simulation.

4.1 Mathematical model

The problem of how to find appropriate solutions for a railway upgrade project can be defined as a MCDM problem. The appropriate solutions refer to those upgrade scenarios which could meet requirements and potentially have better performance. The methodology developed in this research is based on MCDM processes and methods.

The problem can be transferred to the following mathematical model, which indicates how to find an appropriate solution from a large number of upgrade scenarios (U_i) under the criteria of the performance of the 4Cs meanwhile satisfying the constraints of the 4Cs targets.

Suppose that there are n upgrades categories ($uc = 1, 2, 3, \ldots, n$) and the nth upgrade category has i_n options. Since upgrade scenarios (U_i) consist of a combination of upgrade options, if all upgrade categories are independent, the total number of upgrade scenarios (U_i) is

$$N_{total} = (i_1 + 1)(i_2 + 1) \cdots (i_n + 1) - 1 = \left(\prod_{k=1}^{n} (i_k + 1) \right) - 1$$

(4-1)

When calculating the total number of upgrade scenarios, in each upgrade category there are $i_n + 1$ options, since the one additional option is not selecting this upgrade category. Thus one upgrade scenario needs to be subtracted.

It would not be possible to evaluate all of the N_{total} upgrade scenarios in a micro simulator, since if we suppose that there are 40 upgrade categories ($n = 40$) and each upgrade only has 2 options ($i_n \equiv 2$), the result is that the total number of upgrade scenarios has $3^{40} - 1$ options ($N_{total} = 3^{40} - 1$). Therefore, the aim of the RUSP is to develop a quick and efficient process to find a small group of appropriate upgrade solutions for more detailed investigation.

Element a_{ip}, a_{ib}, a_{is}, a_{io} indicates the performance of upgrade scenario U_i under evaluation in terms of the decision criteria and the 4Cs performance, C_p, C_b, C_s, C_o (where $i = 1, 2, 3, \cdots, N_{total}$). The assignment of decision weights for decision criteria may be required, denoted as w_p, w_b, w_s, w_o. Therefore, this research problem can be easily expressed in a matrix format, as shown in Function (4-2).

$$\begin{array}{ccccc}
 & C_p & C_b & C_s & C_o \\
 & (w_p & w_b & w_s & w_o) \\
U_1 & a_{1p} & a_{1b} & a_{1s} & a_{1o} \\
U_2 & a_{2p} & a_{2b} & a_{2s} & a_{2o} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
U_{N_{total}} & a_{N_{total}p} & a_{N_{total}b} & a_{N_{total}s} & a_{N_{total}o}
\end{array}$$

(4-2)

where:

- C_p, C_b, C_s, C_o are the performance results of the capacity, carbon, customer satisfaction, and cost, which may be a matrix as well when there is more than one evaluation criterion for a particular 'C'.
- w_p, w_b, w_s, w_o are the weights of the capacity, carbon, customer satisfaction, and cost.
- U_i is the ith upgrade scenario.

The element a_{ip}, a_{ib}, a_{is}, a_{io} can be calculated using the performance measurement functions, as shown in Function (4-3).

$$a_{ip} = f_p(U_i) \quad i \in [1, N_{total}]$$

$$a_{ib} = f_b(U_i) \quad i \in [1, N_{total}]$$

$$a_{is} = f_s(U_i) \quad i \in [1, N_{total}]$$

$$a_{io} = f_o(U_i) \quad i \in [1, N_{total}]$$

(4-3)

where:

- f_p, f_b, f_s, f_o are the evaluation functions of the capacity, carbon, customer satisfaction, and cost performance.

Usually in a railway upgrade project, the 4Cs targets can be set according to the requirements at an early stage. The constraints are set also depending on the definition of each C target. For instance, if capacity is defined as capacity volume (trains per hour), the capacity after improvements should be higher than the corresponding constraints. Similarly, if capacity is defined as infrastructure utilisation, the capacity usage after improvements should be lower than the constraint. Those upgrade scenarios that can fully satisfy the constraints are appropriate solutions. If in some instances that it is not possible to meet the targets, the 4Cs targets need to be reconsidered. Therefore, the constraints can be written as follows:

$$\begin{aligned} subject\ to\ f_p(U_i) &\leq CC_p \quad for\ i = 1, \cdots, N_{total} \\ f_b(U_i) &\leq CC_b \quad for\ i = 1, \cdots, N_{total} \\ f_s(U_i) &\leq CC_s \quad for\ i = 1, \cdots, N_{total} \\ f_o(U_i) &\leq CC_o \quad for\ i = 1, \cdots, N_{total} \end{aligned} \tag{4-4}$$

Where $CC_P,\ CC_b,\ CC_s,\ CC_o$ are constraints of the 4Cs targets which must be satisfied.

Those upgrade scenarios that satisfy the constraints can be optimised in the case of defining an objective function. The ranking of the appropriate solutions could depend on the optimisation of the 4Cs targets. The optimisation of the 4Cs targets means maximising or minimising the 4Cs targets, which also depends on the definition of the 4Cs. The optimisation can be formulated as

$$\begin{aligned} &min\ (f_p(U_i), f_b(U_i), f_s(U_i), f_o(U_i)) \\ &\text{s.t. } i \in [1, N_{total}] \end{aligned} \tag{4-5}$$

The RUSP aims to solve this mathematical model. A process is proposed before micro-level to identify candidate solutions for micro-simulation. The aim of this process is to remove infeasible and less favourable upgrades category (reduce the number of upgrade category (uc)) thus reducing the number of upgrade scenarios (U_i) which will be evaluated in micro simulation. The upgrades with most potential selected from the process are identified as candidate solutions. For example, if it is supposed that, through the process, the number of upgrade category is reduced to 3 ($uc = 3$) and each upgrade still has only 1 option ($i_n \equiv 1$), the number of potential upgrade scenarios will be reduced to $2^4 - 1 = 15$. It is more efficient to evaluate these 15 upgrade scenarios rather than evaluating every upgrade scenario in the micro simulation. Those upgrade scenarios (U_i) that can satisfy equation (4-4) are appropriate solutions, while those upgrade scenarios (U_i) that can satisfy both equation (4-4) and equation (4-5) are the optimal solutions for the railway upgrade project.

4.2 The structure of the railway upgrade selection process

The RUSP aims to find the most appropriate solutions to support early stage decision-making in railway renewal projects. Based on the framework of the decision-making process in the early stages of a project shown in Figure 3-2 and described in Chapter 3.1, the RUSP has three main stages, which are demonstrated in a flow chart in Figure 4-1.

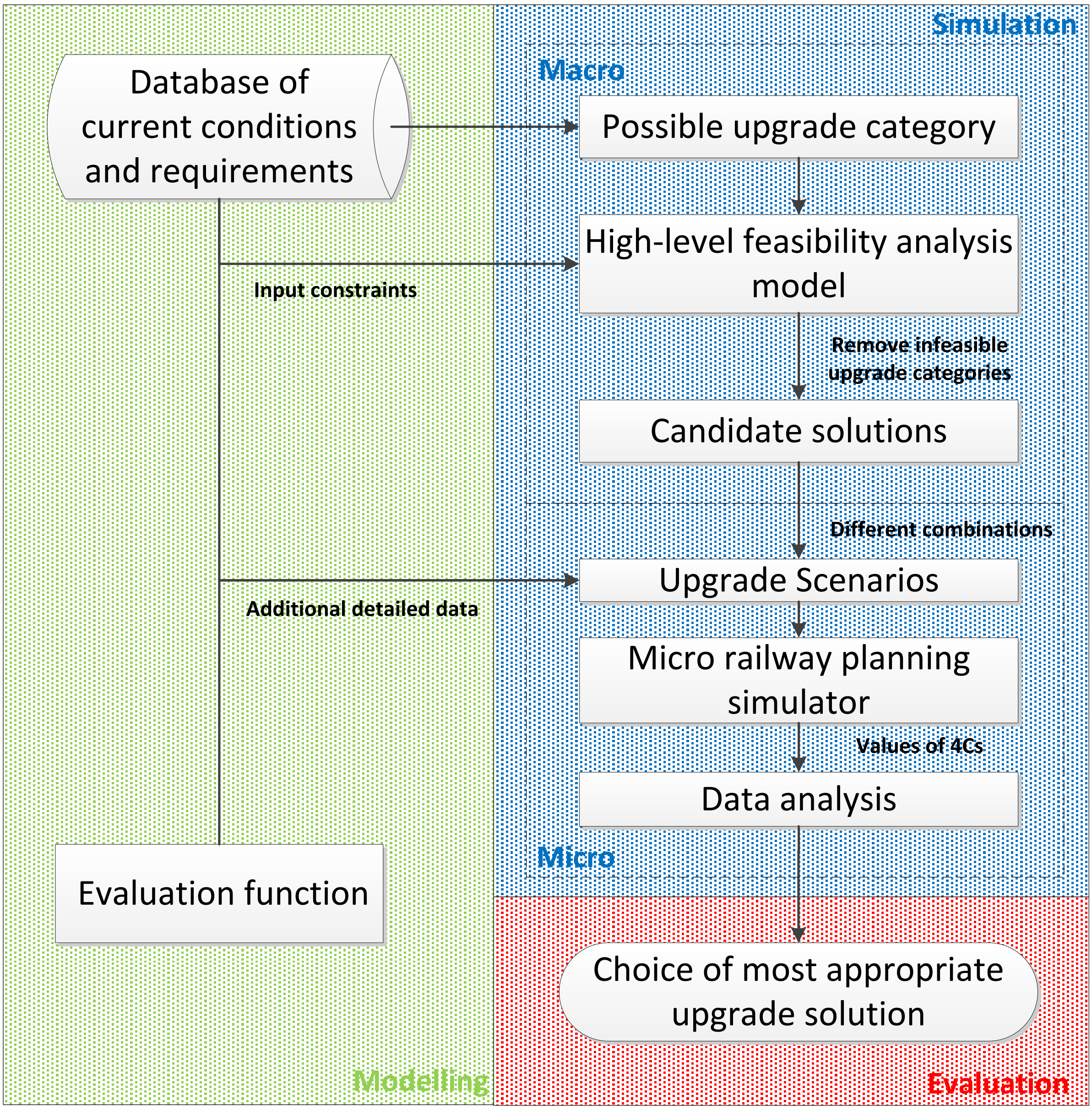


Figure 4-1: Framework of the railway upgrade selection process

1) Modelling: In order to ensure the following stages of the RUSP are well-supported, model set-up based on the problem description is proposed in this stage, including data collection of a particular line, information collection and general system analysis of finding out bottlenecks and weaknesses.

2) Simulation: A combination of macro assessment and micro simulation is proposed in this stage. For macro assessment (the process of options development in Figure 3-2), a high-level feasibility analysis model (HFAM) is introduced. It evaluates a large number of possible upgrade options individually to determine the candidate solution at a high-level in a quick and effective way to reduce workload for micro-level analysis. Micro-simulation (the process of options evaluation in Figure 3-2) evaluates candidate upgrade scenarios consisting of a combination of the candidate solutions.
3) Evaluation: According to the requirements in modelling, the results of the micro simulation, and the specific circumstances, this stage quantifies the evaluation functions to give a final suggestion on the most appropriate solution to be used as an upgrade.

The advantages of the RUSP are that:

- It can give a systematic view while improving a railway system.
- It gathers knowledge in one place and is standardised.
- It saves time by evaluating a large number of upgrade options at the same time and reduces the risk of missing potential upgrade options.
- It has a structured process and can give qualitative and quantitative results to support decision making on finding the most appropriate solutions.
- It builds a traceable link between the system level requirements and technical specifications.
- It can be modified and applied on various railway systems with different characteristics.

The following sections present the details of each stage of the RUSP.

4.2.1 Modelling

In order to be able to find appropriate solutions to address a set of requirements for an upgrade, it is necessary to bring together a large number of data sets, as a ‘rich picture’, that describes a particular line. The data collection and the model set-up in this modelling stage aim to support the following simulation (including the macro assessment and the micro simulation) and the evaluation stages.

For a user of the RUSP, it is a prerequisite to have the information about the practical situation regarding the existing problems, bottlenecks or weaknesses of the railway system (e.g. frequently delayed due to signalling failures, frequent service cancellation on single-track sections due to lack of passing loops) before modelling. For the macro level of the simulation stage, the data collection includes current asset data (e.g. type, condition, age, constraints, signalling system, rolling stock type), which relates to the system component categories in the model in the macro assessment (introduced in the following section A of Chapter 4.2.2.1). Additional requirements from investors, e.g. increasing capacity, saving energy consumption, are required to support the weights assignment in the macro assessment. For the micro level of the simulation stage, the data collection includes topology (e.g. layout, gradients, speed limits, location of signalling), rolling stock (e.g. types, mass, traction, acceleration and braking rate), and operation aspects (e.g. timetable). These data assist to build the railway system model in simulators.

The information from investors will also be required in the final evaluation stage to identify selection criteria (e.g. capacity performance improvement, energy performance improvement) as well as any constraints (e.g. cost, land availability).

In order to maintain consistency in the next two stages, the RUSP should be applied on the train path line sections divided as specified by UIC leaflet 406, which measures the railway capacity as infrastructure utilisation (the details have been presented in Chapter 2.3.1.2).

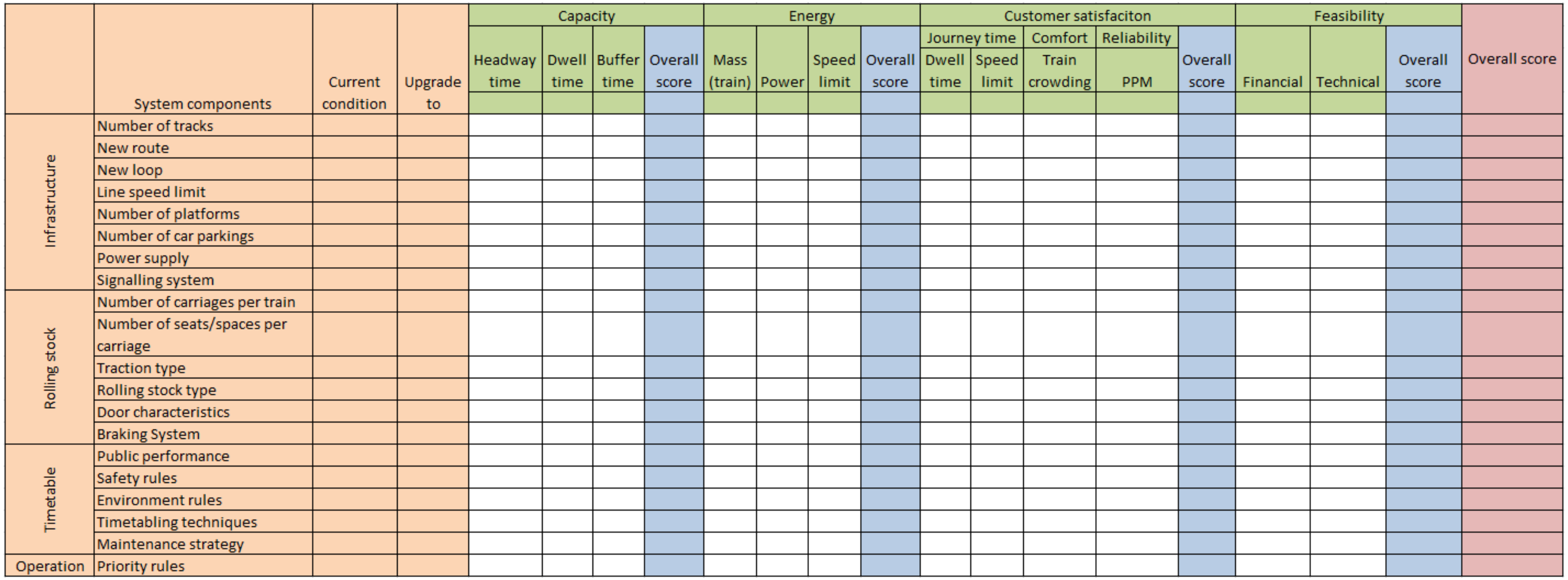
4.2.2 Simulation

4.2.2.1 Macro assessment

This section has been previously published in C. Xindi, G. L. Nicholson, and C. Roberts, "Development of a high-level feasibility analysis model for the selection of railway upgrade options," in *2016 IEEE International Conference on Intelligent Rail Transportation (ICIRT)*, 2016, pp. 231-235. Where the work has been previously published, it is shown in the thesis in italic.

A high-level feasibility analysis model (HFAM) has been developed to help engineers efficiently select the most promising upgrade options for further detailed consideration using microscopic modelling. The HFAM evaluates the impact on the 4Cs targets of changes to the capability status of a wide range of aspects of the railway system. The HFAM, as the macroscopic model in this process, gathers a broad set of potential upgrade options and is used to evaluate these options in an efficient manner to remove infeasible upgrade options and identify candidate solutions for more detailed consideration. This process will avoid time wasting in microscopic simulation, while systematically giving adequate consideration to a comprehensive range of potential upgrade options. As mentioned before, it is time-consuming to evaluate every upgrade scenario in microscopic modelling. The aim of this stage (as macro assessment) is to allow the efficient identification of candidate upgrade options for the next stage (micro simulation). Examples of some elements of the HFAM are given in Figure 4-2 and a full version of the HFAM is given in Figure 4-3.

The structure of the HFAM is designed to be compatible with both macroscopic and microscopic simulation requirements. The HFAM consists of three parts: a system component list, key performance indicators (KPIs) and KPI function elements, and assignment of weighting values and impact scores. The details of these three parts are presented in the following sections, which have been labelled in Figure 4-3.



				Capacity				Energy				Customer satisfaciton					Feasibility			Overall score
												Journey time		Comfort	Reliability					
	System components	Current condition	Upgrade to	Headway time	Dwell time	Buffer time	Overall score	Mass (train)	Power	Speed limit	Overall score	Dwell time	Speed limit	Train crowding	PPM	Overall score	Financial	Technical	Overall score	
Infrastructure	Number of tracks																			
	New route																			
	New loop																			
	Line speed limit																			
	Number of platforms																			
	Number of car parkings																			
	Power supply																			
	Signalling system																			
Rolling stock	Number of carriages per train																			
	Number of seats/spaces per carriage																			
	Traction type																			
	Rolling stock type																			
	Door characteristics																			
	Braking System																			
Timetable	Public performance																			
	Safety rules																			
	Environment rules																			
	Timetabling techniques																			
	Maintenance strategy																			
Operation	Priority rules																			

Figure 4-2: Example of the high-level feasibility analysis model

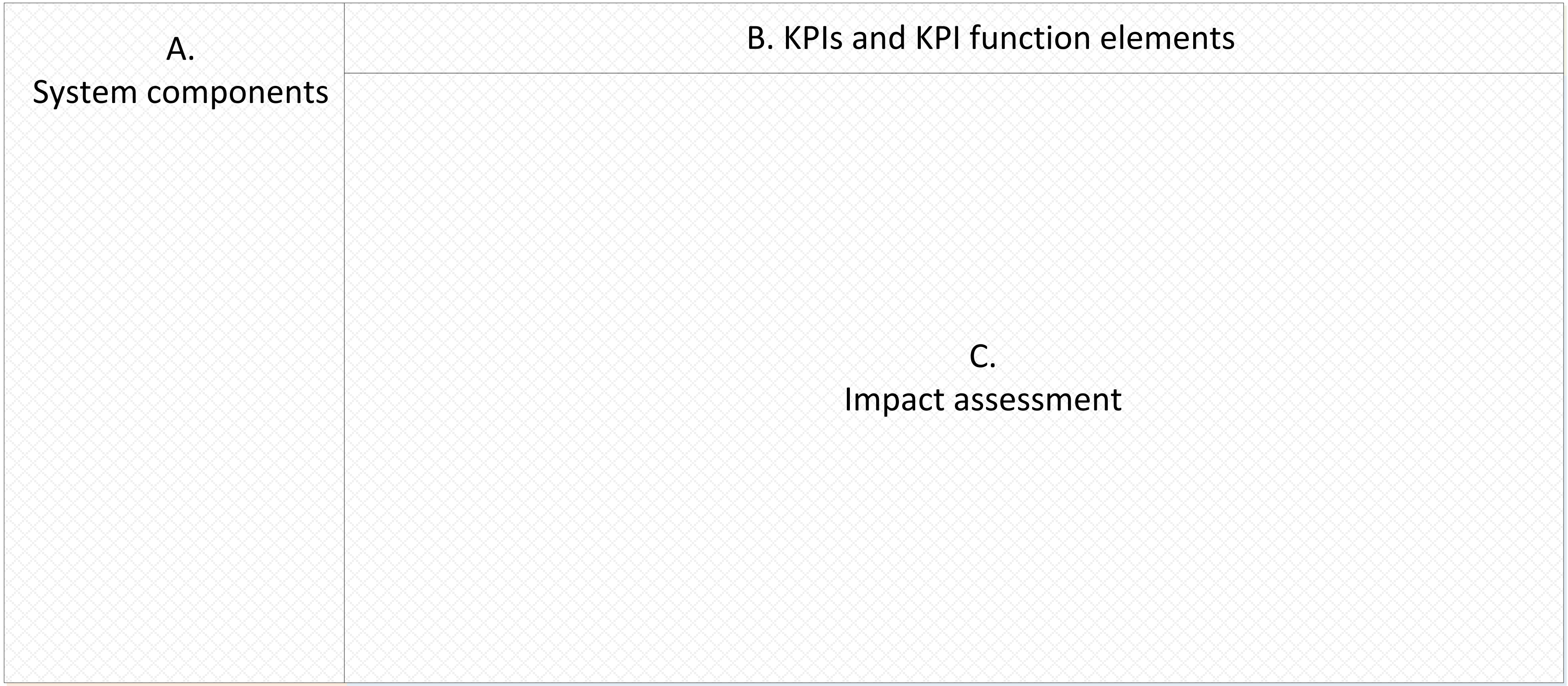


Figure 4-3: Full version of the high-level feasibility analysis model

A. System components

The HFAM is organised in a matrix structure (see Figure 4-3); the rows contain the system component list, consisting of 40 options categorised as infrastructure, rolling stock, timetable and operations, which were selected and summarised from 23 Network Rail Route Utilisation Strategies (RUS) reports [123-145] and reports from some other rail projects [121, 122]. These RUS reports are focused on analysing existing capacity, infrastructure condition, operations and forecasting future demand to give corresponding suggestions to meet current and future demand. The reports cover 17 sections of the GB railway and 5 different categories for potential upgrades (including electrification, stations, passenger rolling stock, and alternative solutions). The system component list of the HFAM aims to cover all main potential upgrade options. In order to evaluate using the HFAM, the impact of changes in the system components on the KPIs, the current conditions and expected upgrade conditions should be taken into consideration.

The potential impact and limitations of these 40 upgrade options are listed below. The cost feasibility and technical feasibility of most upgrade options really depends on individual practical situations of the specific network (including existing conditions and requirements). As mentioned in Chapter 1.3, the specific implementation of every upgrade option in the real-world is not within the scope of this research, thus only an overview of each upgrade option is given here, based on the knowledge in Chapter 2.1.

1) Infrastructure

- Number of tracks

The number of tracks has a significant impact on railway line capacity. Nevertheless, adding more tracks to a line only increases the actual capacity if the existing line capacity has reached or is approaching its maximum utilisation; in other words, if it is difficult to put more trains into the timetable. Meanwhile, adding more tracks is extremely expensive and has high technical difficulty, probably limited by land space.

- Line speed

Line speed affects capacity, journey time and energy consumption at the same time. As indicated in Woodland's research [146], Figure 4-4 illustrates that, no matter what the signalling system is, the optimum line speed for maximising capacity is around 55 mph to maximise capacity. Headway, as defined in Figure 4-4 is in terms of trains per hour, which is the theoretical maximum throughput of trains that the system allows whereby the following train is not affected by the train ahead [146]. If line speed is increased or decreased from this optimum speed, then capacity will be lost.

Furthermore, when improving line speed, improving the signalling system and track conditions also need to be taken into consideration to ensure the safety of the operation. Hence, the cost of improving the line speed limit is relatively high.

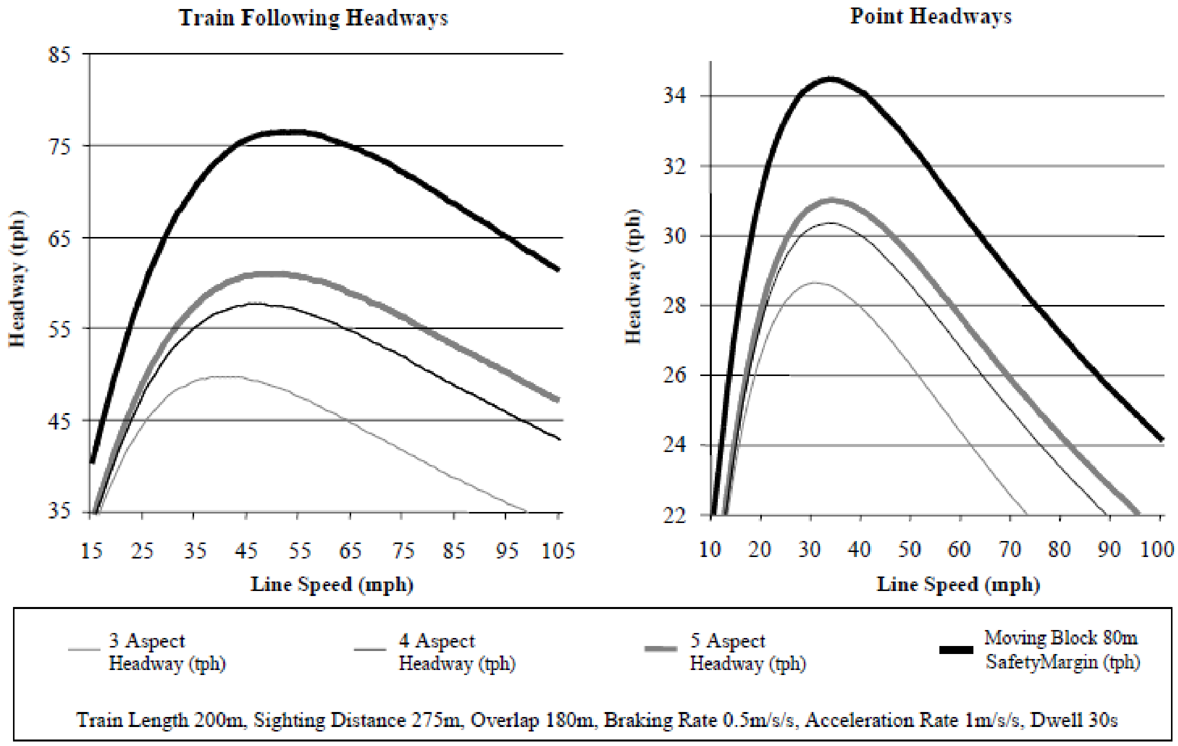


Figure 4-4: Theoretical relationship between line speed and headway [146]

- Signalling system

Commonly used signalling systems include 2-aspect, 3-aspect, 4-aspect, 5-aspect, and moving block [44, 45]. Figure 4-4 shows how different signalling systems and line speeds influence headway [146]; therefore the signalling system has a significant influence on capacity. When improving the signalling system, a general trend to increase the rolling stock performance is required. Thus higher speed trains are allowed, which can improve journey time.

- Track horizontal curvature

A sharp curve may restrict the operational speed, which may affect the headway time and, thus, the line capacity. As demonstrated in [121], curve radius is in proportion to the square of line speed (see Figure 4-5). However, 55 mph is the optimum line speed, unless existing curvature warrants a speed limit below 55 mph, when improving the horizontal curvature could improve the capacity.

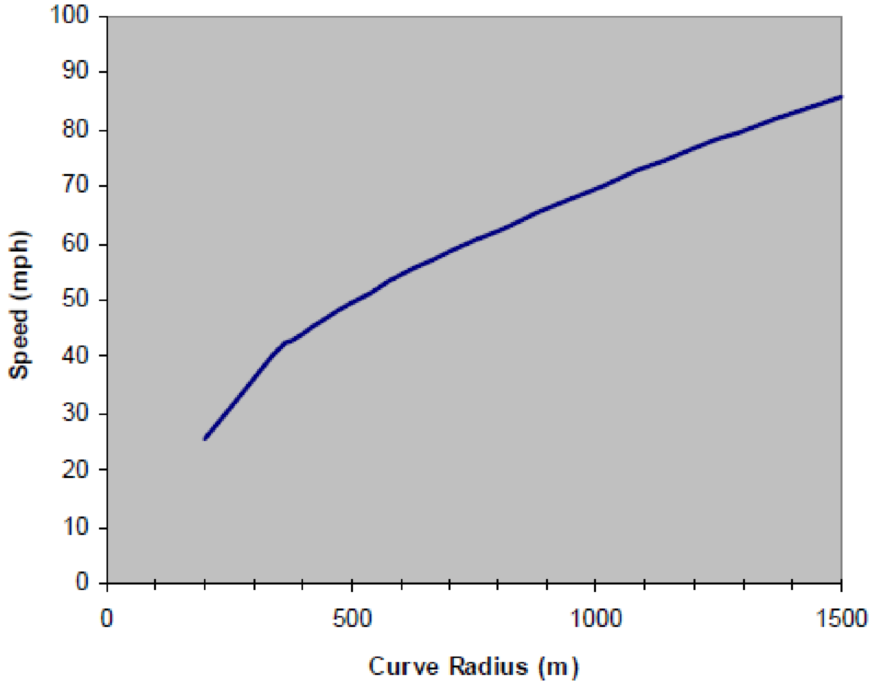


Figure 4-5: Impact of curve radius improvement on speed [121]

- Track gradient

A steep uphill gradient track could reduce the train speed and thus the line capacity, which is likely to happen more to freight trains than to passenger trains. Nevertheless, in metro systems, vertical alignment optimisation [147] at stations can improve energy efficiency. The optimisation of track vertical alignment attempts to adjust the track gradient around the platform and put a station at the top of a parabolic curve in order to help the train come to a stop at the platform without using any braking or traction.

- New route

If the existing railway system is nearly at the maximum capacity, another efficient option, other than adding tracks, is building a new route. Although building a new route has a huge positive impact on capacity and journey time, the limitations are high cost and lack of land. Due to route duplication, some routes have been closed or are now only used by freight trains. If this type of route is reopened for service trains, the cost will be reduced massively compared to new construction.

- New or remove tunnel/bridge

This upgrade option is usually linked with building a new route and is only relevant for some specific situations. Of course, this option is extremely expensive and has many technical difficulties.

- Loop conditions

For single-track sections in a railway system, due to the high cost of adding tracks where there is not a high enough demand for capacity, adding a new loop is a more cost-efficient alternative. Likewise, extending the existing loop is another much cheaper option. [148]

- Number of platforms

The number of platforms impacts on line capacity as it affects the headway. Similar to adding tracks, adding more platforms at stations only increases the actual capacity if the existing line has reached or is approaching its maximum utilisation.

- Length of platforms

Extending the length of a platform, which is usually linked with increasing the number of carriages per train, would reduce the dwell time. It also could improve customer satisfaction through reducing crowding when waiting, boarding and getting off trains.

- Number of car parking / Provision of step free access between platforms / Station passenger seating / Station ticket hall / Station passenger handling facilities / Layout in station area / Station interchange facilities

These 7 upgrade options can improve customer satisfaction on the experience of using rail transportation and they also encourage people to use rail transportation, thus reducing traffic congestion and contributing to a green environment by reducing carbon emissions. Some options (e.g. improving the layout in the station area and interchange facilities) could also improve the connectivity by reducing the interchange time. Other options (e.g. improving passenger handling facilities) can improve capacity by reducing dwell time. However, it is unlikely that these options can reflect their significance in the HFAM, however, they can inspire the decision maker in specific cases.

- Junction characteristics

Improving junction characteristics has positive impact on capacity (only when the speed limit is lower than 55 mph) and journey time by easing the speed limit. This upgrade needs to be co-ordinated with signalling adjustment.

- Switches characteristics

Point machine renewal would reduce failure rate and switching time, thus improving reliability. Meanwhile, increasing or reducing the complexity with the number of switches also has an impact on line speed and reliability. The cost and technical feasibility depends on practical situations.

- Power supply

Improving power supply will have low impact on capacity and energy consumption, and is relevant only when power supply capability is limited. Usually, when more trains are added to the railway system, the power supply should be improved. Furthermore, substation spacing optimisation [149] has been applied on some railway systems to stabilise the power supply system and reduce power transmission loss for saving energy consumption. The feasibility of cost and techniques depends on practical situations.

- Level crossings characteristics

Using level crossings enables people to cross the railway safely, while a transport risk still exists, caused by rail level crossing [150, 151]. Renewing level crossings would reduce the failure rate, thus improving reliability and safety. It also could impact capacity, since the time that people used for crossing restricts to trains. A safer alternative is to replace a level crossing with a footbridge or bridge, although, of course, the cost and technical difficulty of a footbridge or bridge is higher than a level crossing renewal.

- Freight paths

Shifting freight from road to rail could contribute to a green environment by reducing carbon emissions, and it could also reduce logistics costs [152, 153]. If the rail network is a mixed traffic railway where both passenger and freight traffic operate on the same lines, increasing the proportion of freight traffic running will decrease capacity.

2) Rolling stock

- Number of carriages per train

Increasing the number of carriages per trainset would increase the total number of passenger seats and the number of passengers, thus increasing passenger capacity, but it will increase headway time and dwell time as well. This upgrade can also reduce crowding problems, but only if the existing trains are often fully loaded. However, since adding more carriages would increase the mass of the train and also change power and traction, it has a negative impact on the energy consumption per journey. When adding more carriages, there can also be a requirement to extend the length of platforms.

- Number of seats/spaces per carriage

Similarly, increasing the seats or spaces per carriage would increase passenger capacity and energy consumption and release the crowding problem, but not as much as adding more carriages. Since this upgrade does not lengthen the trains, it is not necessary to lengthen the platform and it would not affect headway time.

- Rolling stock type

Due to varying rolling stock with different characteristics, according to the different requirements of a railway system, changing the type of rolling stock may have both a positive and negative impact on capacity, energy consumption and journey time. For example, if an old railway system is electrified, replacing DMU rolling stock with EMU can improve energy efficiency.

- Train speed

Improving train scheduled speed increases energy consumption, but can improve capacity and journey time, although only when the maximum train speed is lower than the line speed and the optimum line speed.

- Door characteristics

Improving door characteristics includes changing the number of doors, the width, opening and closing speed, operation technology, etc., which can reduce dwell time, thus improving capacity, journey time and connectivity.

- Mass of train

Replacing rolling stock with lighter vehicles would benefit energy consumption; furthermore, brake wear is reduced, thus reducing track maintenance costs. The cost and the technical difficulty depend on the practical situation.

- Braking system/ Acceleration system

Improving the braking rate and acceleration rate may reduce headway time, thus improving capacity and journey time, especially for frequently-stop journey. Meanwhile, there also may be a large impact on energy consumption.

- Train speed heterogeneity

When a train follows another train which is travelling at a different speed (heterogeneous), the headway time is increased compared to homogeneous traffic (see Figure 4-6) [154]. Thus, by running all trains at the same speed with the same stopping patterns (homogeneous), capacity can be improved by shortening the headway time.

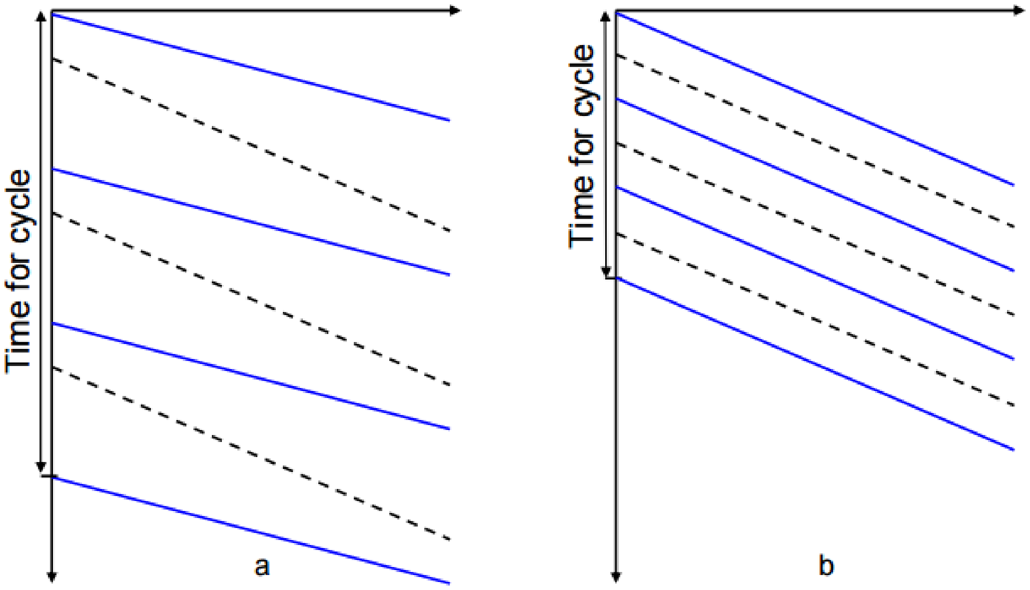


Figure 4-6: Heterogeneous (a) and homogeneous (b) timetable [154]

- Heterogeneity of braking rate/ Heterogeneity of acceleration rate

Similar to improving train speed heterogeneity, improving heterogeneity of the braking rate and acceleration rate could improve capacity..

3) Timetable

- Buffer time

The need to meet some key performance indicator targets (e.g. punctuality, reliability, resilience) may lead to increased buffer time, thus reducing capacity. Meanwhile, increasing buffer time would improve customer satisfaction through improving reliability.

- Safety rules

Improving certain safety requirements may increase headway time and thus has a negative impact on capacity and journey time. The cost and technical difficulty depends on specific safety requirements.

- Environmental protection rules

Rules may prevent freight trains from operating during night-time due to noise disturbance, which leads these freight trains being run during the day-time, thus reducing capacity. [155]

- Station stops

As mentioned before, homogenous stopping patterns, as in practical metro operation, can improve capacity. Station stops can also influence journey time and energy consumption.

- Timetabling techniques

Improving timetabling techniques may increase reliability through improving the robustness and resilience of the timetable.

4) Operation

- Priority rules

Changing the priorities of train services represents changing the order of trains running during disturbed situations. It could have either a positive or negative impact on capacity, journey time, and reliability.

- Driving techniques

Improving driving techniques can benefit energy consumption. For example, some researches about train trajectory optimisation have been proposed to apply an automatic train control system or a driver guidance system which suggests to drivers that they should obey an optimised driving speed curve during operation [59, 156]. This technique can benefit energy consumption with minimal influence on journey time and capacity.

B. KPIs and KPI function elements

Many processes and researches associated with railway system improvement focus on specific individual targets in terms of a single or a limited number of upgrade options [40], for example, improving robustness through improved timetabling. With a wide range of factors taken into consideration, the HFAM is inspired by systems thinking to give a comprehensive view of the actual impact for the entire railway system. Therefore, the HFAM also aims to cover the major categories of performance indicators that are considered in a railway upgrade project.

The impact of system upgrades is evaluated using four KPIs, which are defined based on the 4Cs framework. Each KPI is associated with several function elements, which are derived from the decomposition of the KPI. The principle for defining the KPI function elements is such that they are straightforwardly understood and estimated, and has primary and direct impact on their KPIs.

Definitions of the KPI function elements are given in Table 4-1, which are based on the reviews of railway performance in Chapter 2.3 and railway decision making support tools mentioned in Chapter 3.3.2. *The assignment of the KPI function elements' weighting values depends on their relative influence on the relevant KPI (e.g. altering minimum headway time typically has a larger effect on capacity than altering buffer time). The KPI function element weighting values have been determined based on the relative influence of the functions on their KPI.* In other words, the basic rule of weighting assignment is that, if the value of each capacity function element is changed in the same amount, how much change occurs on the capacity defines the category weightings. *The capacity function elements and weightings are based on the capacity calculation outlined in UIC leaflet 405*, mentioned in Chapter 2.3.1.1 *and the energy consumption function elements are based on the calculation of energy* *consumption at the wheel, mentioned in* Chapter 2.3.2.1. *The weightings of the capacity, and energy consumption KPIs' function elements should remain fixed; for the customer satisfaction and feasibility function elements, suggested weightings are provided below. The assignment of KPI weighting values depends on their overall importance to the goals of a railway upgrade project. These weighting values are presented in Table 4-1, which are recommended values and could be adjusted by the HFAM user.*

- Capacity KPI

Capacity is defined here as traffic volume capability, addressed by the method outlined in UIC leaflet 405 [71]. The weightings are defined based on the size of the impact on the KPIs of changes to the KPI function elements. Based on the definitions and functions of capacity assessment, mentioned in Chapter 2.3.1.1, the minimum headway time, dwell time and buffer time have a main and direct influence on the capacity assessment, leading to their inclusion as capacity KPI function elements. Due to the fact that the size of the minimum headway time is typically larger than buffer time, the weightings of the headway time is M and the buffer time is L. Furthermore, passenger capacity per train should also be taken into consideration, the impact of which is more straightforwardly reflected in the capacity. If the passenger capacity is doubled, the capacity will be doubled as well. Therefore, the weighting of passenger capacity is H.

- Carbon KPI

The carbon KPI is assessed in terms of energy consumption per journey at the wheel by services [58], instead of carbon emissions, since most upgrade options have a more direct influence on energy consumption and it is easier to estimate. Based on the functions about energy consumption assessment, mentioned in Chapter 2.3.2, 8 carbon KPI function elements are defined, as the total mass of the train, the total mass of fully-loaded passengers, the maximum power, traction and train speed, the line speed limits and the number of stops. Similar to the weighting assignment of the capacity function elements, doubling the train mass, traction, or power, the energy consumption will be doubled in theory as well, so the weightings of train mass, traction, power is H.

- Customer satisfaction KPI

To improve customer satisfaction, many factors have an influence, as mentioned in Chapter 2.3.3; here, for the macroscopic level evaluation, three major factors are used to represent customer satisfaction: journey time, comfort and reliability. Due to not every customer satisfaction function element having theoretical measurements, the weighting assignment needs to be based on experience and on the choice of KPI function elements.

- Feasibility KPI

The cost of an upgrade determines if it is feasible or not. Meanwhile, the technical feasibility also needs to be taken into account. Therefore, in this macro assessment, the feasibility KPI is used and includes financial feasibility and technical feasibility.

Table 4-1: Definitions of KPI function elements

<table>
<tr><th>KPI</th><th colspan="2">KPI function elements</th><th>Weighting value</th><th>Definitions</th></tr>
<tr><td rowspan="4">Capacity</td><td colspan="2">Minimum line headway time</td><td>M</td><td>The minimum time interval on a section of line between two consequent running trains to keep the system operating safely.</td></tr>
<tr><td colspan="2">Dwell time</td><td>M</td><td>The total elapsed time from the time that a train stops in a station until its departure.</td></tr>
<tr><td colspan="2">Buffer time</td><td>L</td><td>An extra time that is added between train paths to the minimum line headway to avoid the transmission of small delays.</td></tr>
<tr><td colspan="2">Passenger capacity</td><td>H</td><td>The total number of passengers when fully seated.</td></tr>
<tr><td rowspan="8">Carbon</td><td colspan="2">Mass (train)</td><td>H</td><td>The total mass of a train including the locomotive and carriages.</td></tr>
<tr><td colspan="2">Mass (passenger)</td><td>L</td><td>The total mass of passengers on a fully loaded passenger train.</td></tr>
<tr><td colspan="2">Power</td><td>H</td><td>The maximum power of a train.</td></tr>
<tr><td colspan="2">Traction</td><td>H</td><td>The maximum traction capability of a train.</td></tr>
<tr><td colspan="2">Maximum cruising speed</td><td>M</td><td>The maximum train speed capability.</td></tr>
<tr><td colspan="2">Speed limit</td><td>M</td><td>The speed limit of junction, stations.</td></tr>
<tr><td colspan="2">Gradient</td><td>L</td><td>The average gradient of track.</td></tr>
<tr><td colspan="2">Number of station stops</td><td>M</td><td>The total number of station stops in a line section.</td></tr>
<tr><td>Customer satisfaction</td><td>Journey time</td><td>Dwell time</td><td>M</td><td>The total elapsed time from the time that a train stops in a station until its departure.</td></tr>
</table>

		Number of station stops	M	The total number of station stops in a line section.
		Maximum cruising speed	M	The maximum train speed capability.
		Speed limit	L	The speed limit of line sections.
	Comfort	Train crowding	L	The number of standard class passengers that are in excess of capacity at the critical load point. (PiXC)
		Connectivity	M	The passenger interchanging time between two services at a given interchange.
	Reliability	PPM	M	The percentage of trains arriving within 5 minutes for commuter services and within 10 minutes for long distance services.
Feasibility	Financial		M	The capital investment cost of an upgrade option.
	Technical		M	The technical difficulty and complexity of implementation of an upgrade option.

C. Impact assessment

Each KPI and KPI function element has a weighting value associated with it. The HFAM process results in calculating an impact score for each system component for every KPI function element. Inspired by fuzzy extended decision making methods, the weighting values and impact scores are defined using categorised levels, for example H (high level positive impact), M (medium level positive impact), L (low level positive impact) and –H (high level negative impact), -M (medium level negative impact), -L (low level negative impact). The number of categorised levels depends on how the decision maker wishes to evaluate the upgrade options. It is suggested that the categorised levels should be kept simple, since the fewer the number of categorised levels, the easier it is to define and estimate the weighting values and impact score. The assignment of impact score is based on the HFAM user's industrial experience.

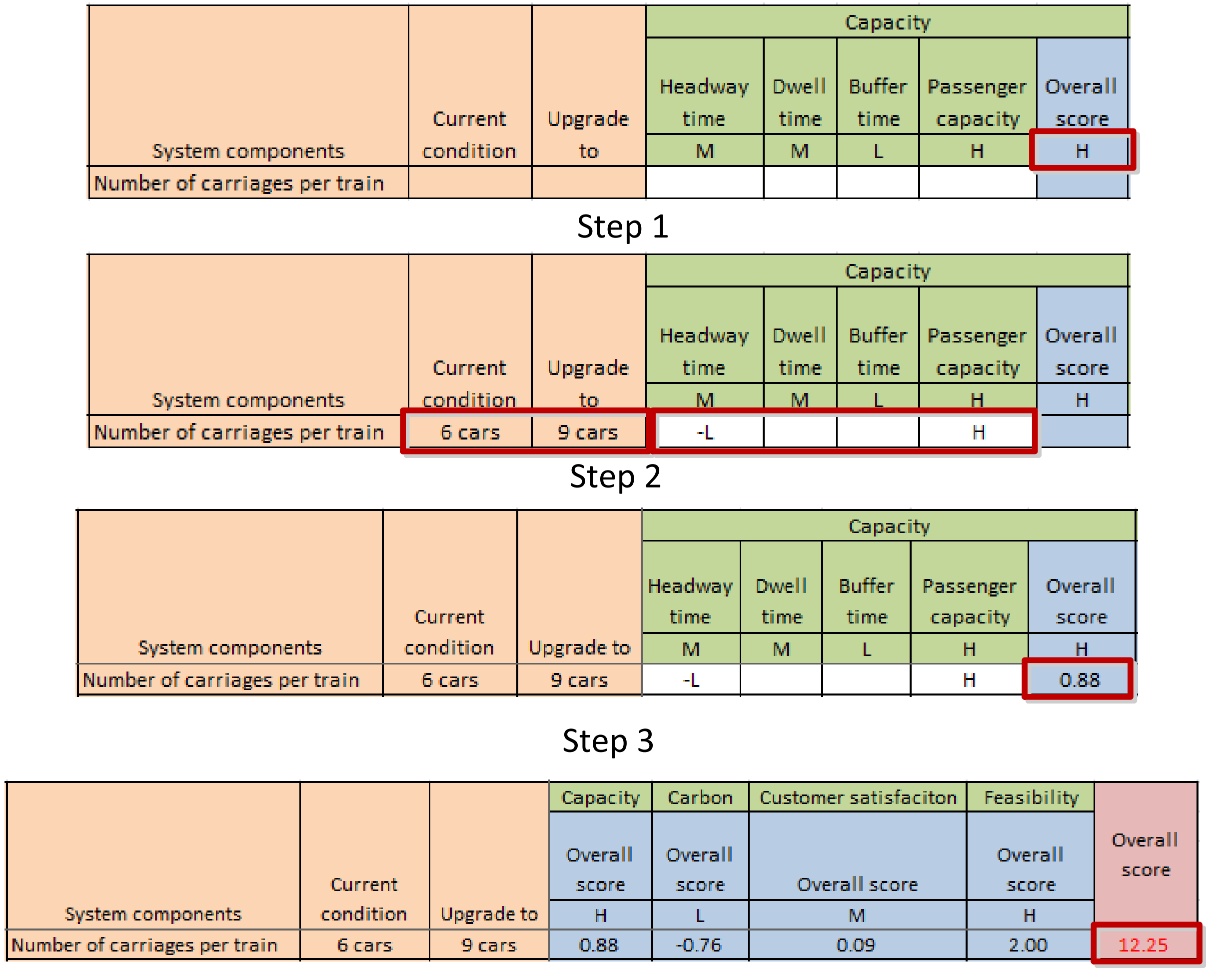
The HFAM procedure is as follows:

1. *Determine and assign KPI weighting values (meanwhile adjust KPI function elements' weighting values if needed).*
2. *Confirm current condition and proposed upgrade condition of each system component and assign impact levels (L, M or H) for each system component on each KPI function element.*
3. *Calculate the impact score for each KPI, which is the normalised weighted sum of the products of the KPI's function elements impact score.*

4. *Calculate the final overall impact scores for each system component, which is the weighted sum of the products of capacity KPI's, carbon KPI's and customer satisfaction KPI's impact scores, then multiplied by the feasibility impact score.*

Once the first two steps have taken place, the two steps of calculation (steps 3 – 4) are automatically completed within the matrix model. The arithmetic calculation underlying this process uses integer values corresponding to the categorised levels. For instance, if there are 3 categorised levels, H is equivalent to 3, M to 2, L to 1, and –H is equivalent to -3, -M to -2, -L to -1; the calculation outlined in steps 3 and 4 results in overall numerical impact scores for each system component, which are used to rank the options. The individual and overall impact scores may be negative (except for feasibility scores) in cases where alteration of the system component value results in a negative influence (e.g. longer minimum headway times caused by stricter safety rules). The assignment of feasibility differs from the other 3 'C' targets, which can only be positive. It means low cost and technical difficulty indicate high feasibility, and high cost and technical difficulty indicate low feasibility, thus it has no negative impact.

An example (see Figure 4-7) of how the impact assessment works is presented here.



			Capacity				
System components	Current condition	Upgrade to	Headway time	Dwell time	Buffer time	Passenger capacity	Overall score
			M	M	L	H	H
Number of carriages per train							

Step 1

			Capacity				
System components	Current condition	Upgrade to	Headway time	Dwell time	Buffer time	Passenger capacity	Overall score
			M	M	L	H	H
Number of carriages per train	6 cars	9 cars	-L			H	

Step 2

			Capacity				
System components	Current condition	Upgrade to	Headway time	Dwell time	Buffer time	Passenger capacity	Overall score
			M	M	L	H	H
Number of carriages per train	6 cars	9 cars	-L			H	0.88

Step 3

			Capacity	Carbon	Customer satisfaciton	Feasibility	
System components	Current condition	Upgrade to	Overall score	Overall score	Overall score	Overall score	Overall score
			H	L	M	H	
Number of carriages per train	6 cars	9 cars	0.88	-0.76	0.09	2.00	12.25

Step 4

Figure 4-7: Example of impact assessment process in the HFAM

The HFAM produced with 4 steps has been described before, which corresponds to the 4 steps in Figure 4-7.

- Step 1 aims to define KPI weight values, tagged in a red box. The upgrade chosen here is adding more carriages for an urban railway system, and the KPI weighting value are pre-defined as H (high level positive impact) on capacity, L (low level positive impact) on carbon (which would probably be adjusted to H for a metro system), M (medium level positive impact) on customer satisfaction, and H (high level positive impact) on feasibility.

- In Step 2, the current condition and expected upgrade condition of the system component need to be confirmed and the impact levels of the KPI function elements need to be assigned, tagged in the red box. Improving the number of carriages per train from 6 cars to 9 cars would increase headway time due to lengthening the trains (low level negative impact on headway time) and increase passengers per train (high level positive impact on passenger capacity).
- Step 3 and Step 4 are automatically completed once the first two steps have finished. As mentioned before, L, M and H are equivalent to 1, 2, and 3. The capacity overall score can be calculated as $\frac{M\times(-L)+H\times H}{M+M+L+H}=\frac{2\times(-1)+3\times 3}{8}=0.88$. The same procedure is applied on other KPIs. The final overall score can be calculated as $(H\times 0.88+L\times(-0.76)+M\times 0.09)\times(H\times 2)=(3\times 0.88+1\times(-0.76)+2\times 0.09)\times(3\times 2)=12.25$.

In theory, the range of each KPI overall score is -3 to 3, while the final overall score depends on the assignment of the weightings of each KPI. Based on the results of case studies, presented in Chapter 5, the final overall score is around 10, which equates to a high score.

A system component with a high overall impact score means it has high potential as an upgrade solution. The output of the macroscopic evaluation process, namely, a set of ranked candidate upgrade solutions, along with their macroscopically evaluated scores, forms the input to the next step in the process, the microscopic evaluation of candidate solutions.

4.2.2.2 Micro simulation

In the macro assessment, infeasible and inefficient upgrade options have been removed meanwhile candidate solutions have been identified. In the HFAM, since all upgrade options are evaluated individually and subjectively, those potential upgrade scenarios consisting of the combination of the candidate solutions will be verified in a micro simulator and data analysis software to provide an objective quantitative analysis and results on the most appropriate solutions.

As mentioned in Chapter 2.2, M&S plays an important role in supporting decision making and has been widely used in the rail industry to imitate real-world railway system operations comprehensively by using a microscopic model (including rolling stock, infrastructure, signalling, timetable, etc.). The choice of microscopic simulator in this stage depends on the requirements of the railway renewal projects. Here, based on the detailed data collected in the modelling stage, the output of OpenTrack can assist the evaluation of capacity, energy consumption and journey time; therefore, it has been chosen to support the third stage of the RUSP.

As mentioned in the mathematical model (Chapter 4.1), the 4Cs targets are four optimisation objectives of upgrade scenarios, which will be evaluated in OpenTrack and then compared to find the most appropriate solutions satisfying the constraints of the 4Cs targets. The definition of the most appropriate solutions for each practical railway renewal project will depend on its specific characteristics. The definitions and measurements of 4Cs targets in this micro simulation stage of the RUSP are commonly used and applied in the industry.

- Capacity objective function

Since capacity utilisation helps make recommendations for robust timetabling, in the case of keeping the same timetable after applying the upgrade scenario, the improvement to capacity cannot be reflected in the traffic volume capacity. Thus the capacity objective function in this stage is defined as infrastructure utilisation, addressed by the method outlined in UIC leaflet 406 [72-74]. As mentioned in Chapter 2.3.1.2, in UIC leaflet 406, the timetable compression method is applied on an existing timetable to compress all train paths in a line section together, according to their timetable orders, with minimum theoretical headway to calculate infrastructure occupancy. Since OpenTrack can only provide train graphs, an extended program based on MATLAB has been built to compress the train graphs from OpenTrack for calculating capacity consumption in UIC leaflet 406. The principle of the program in MATLAB is based on Function (2-5). If the upgrade scenario is applied with adjusting the timetable, the capacity at this stage can be defined as the traffic volume (UIC leaflet 405), which is more straightforward than the infrastructure utilisation.

- Carbon objective function

Since there is a relation between carbon emissions and energy consumption, as mentioned in Chapter 2.3.2, the carbon objective function is measured in terms of energy consumption at the wheel by services (kWh/seat-km) [157, 158]. OpenTrack can provide the log file for energy consumption at wheel used in the distance covered.

- Customer satisfaction objective function

As the customer satisfaction objective function is measured in terms of journey time [66], the practical consumed train time is used rather than the planned time in the timetable, which can also be provided by OpenTrack.

- Cost objective function

The cost objective function is measured in terms of the total investment cost [93-95].

Since the capacity objective function is measured in terms of capacity consumption, improving capacity utilisation for a particular service specification means the capacity consumption is reduced. Therefore, the optimisation of the 4Cs targets at this stage means minimising capacity consumption, energy consumption, journey time and investment cost. The most appropriate solutions should satisfy the constraints of the 4Cs and have better performance.

4.2.3 Evaluation

Due to incommensurable units of 4Cs' results from the simulation stage, it is difficult to agree on the definition of an objective function to find the most optimised solutions. At this stage, it is recommended to list all appropriate solutions, the quantitative values for each KPI of which have satisfied the constraints, and make a final decision depending on the specific circumstances. For instance, urban railway systems may emphasise capacity optimisation, whereas metro railway systems may need to consider energy consumption, since there may not be sufficient space to improve capacity due to high density and the same stopping patterns.

4.3 Summary

This chapter demonstrates the structure of the railway upgrade selection process, which aims to support early stage decision-making to find the most appropriate solutions for railway renewal projects. At the beginning of this chapter, a mathematical model derived from this research problem is proposed. In order to reduce the number of upgrade scenarios, the high-level feasibility analysis model (as a macro assessment) has been introduced to quickly identify candidate solutions at a high-level. Those potential upgrade scenarios, which consist of a combination of these candidate solutions, are evaluated in a microscopic simulator (OpenTrack). The final results give the most appropriate solutions, which satisfy the constraints of the 4Cs and have better performance.

Chapter 5 presents the design process of the high-level feasibility analysis model. Impact assessment methods are compared based on the East Coast main line and the Northern Ireland railway network. The feasibility of the HFAM is also verified. Chapter 6 presents the application of the whole railway upgrade selection process based on the Northern Ireland railway network.

Chapter 5 Design of the high-level feasibility analysis model

As mentioned in Chapter 4 at macro assessment, the high-level feasibility analysis model (HFAM) has been proposed in the macro-simulation stage of the RUSP, in order to identify candidate solutions in an efficient way for micro simulation. With the support of the HFAM, the process of decision making before microscopic simulation can be simplified while reducing the chance of missing potential alternatives. The HFAM, based on a matrix, aims to evaluate the impact on the 4Cs targets of changes to the expected capability status of a wide range of aspects of the existing railway system. The detailed structure of the HFAM has been presented in Chapter 4.2.2.1.

This chapter demonstrates the design and verification process of the HFAM. The impact assessment method mentioned in Section C of Chapter 4.2.2.1 is the final developed version. The HFAM process and how the impact assessment methods are developed, compared and verified is presented. Verification is based on case studies using the East Coast Main Line (ECML) and the Northern Ireland Railway Network (NIRN).

5.1 Preliminary design of the high-level feasibility analysis model

Based on the motivations and previous approaches to support early decision-making for railway renewal projects, it was necessary to develop a well-adapted macro model that can store knowledge, collate information and give systematically comprehensive consideration to the entire railway system. A previous study [121, 122], mentioned in Chapter 3.3.2, has shown the ability of a matrix of capacity interdependencies for capacity assessment, with the aim of evaluating the impact on capacity of changes to individual components of a railway system, using pre-defined look-up tables. The evaluation of capacity alone should be extended to give a more comprehensive analysis for a railway renewal project. The HFAM aims to evaluate the impact of a large number of upgrade options on the 4Cs, rather than capacity alone. The impact assessment used in the HFAM uses categorised levels, inspired by fuzzy extended decision making methods, which is a simplified numerical scheme.

The preliminary verification of the HFAM is based on the East Coast Main Line (ECML) mainly in the Single Train Simulator (STS) [58], a well-established microscopic railway modelling tool.

5.1.1 Introduction to the case study based on the East Coast main line

The ECML is one of the busiest, fastest (with most lines rated for 125 mph operation) and well-developed railway lines in Britain, comprising 393 miles long route linking London to Edinburgh via major cities in the south and north east (e.g., Peterborough, Doncaster, Newcastle), as shown in geographical format in Figure 5-1. It is electrified along the whole route (with 25 kV AC overhead lines), and it carries long distance regional commuter services, local passenger services and heavy tonnage freight traffic. [123, 159]

A case study using the ECML section from Kings Cross to Newcastle via Peterborough is used to verify the feasibility of the HFAM with the initial version impact assessment using categorised levels by comparing the results from the HFAM with those from simulation. Two scenarios are presented that demonstrate the impact result comparisons of several upgrade options on energy consumption (carbon), journey time (customer satisfaction) and capacity on two types of journey: one is a long journey without stops, and the other is a frequent stops journey, as listed in Table 5-1. The overall score of energy consumption, journey time and capacity in the HFAM on both of long journey without stop and frequent stops is compared to simulation results, to verify the feasibility of this approach.

Figure 5-1: East coast main line geographic scope [123]

Table 5-1: Information of two scenarios from Kings Cross to Peterborough

	Length	**No. of stations**	**Rolling stock**
Scenario 1	122 km	0	IC 125 (DMU), including 2 cars of Class 43 (80 t weight) and 8 cars of Mark 3 Coach (40 t weight), maximum speed is 200 km/h, 80 seats per carriage.
Scenario 2	122 km	25	IC 125 (DMU), including 2 cars of Class 43 (80 t weight) and 8 cars of Mark 3 Coach (40 t weight), maximum speed is 200 km/h, 80 seats per carriage. (Dwell time at each station is 200 seconds.)

The STS can provide values for energy consumption at the wheel and journey time, while the results for capacity come from the Multi-Train Headway Simulator (MTHS). The MTHS is developed by the author to evaluate the theoretical capacity volume, based on a Multi-Train Simulator (MTS) [59, 60] introduced in Chapter 2.2.1. Capacity defined here is in terms of trains per hour, which is the theoretical maximum throughput of trains that the system allows without any influence between two continuously running trains. Energy consumption is measured the total energy consumption at wheel with fully loaded passengers per journey and journey time is also measured per journey. The original results of two scenarios are set out in Table 5-2. Due to frequently stops and dwell time, the journey time of Scenario 2 is much longer than that of Scenario 1. The changes after the upgrades is applied, presented as percentages in Table 5-6, Table 5-7, and Table 5-8, are compared with the original 3Cs' results in Table 5-2.

Table 5-2: 3Cs' results of two scenarios in original conditions

	Capacity	**Energy consumption**	**Journey time**
Scenario 1	17.7 trains per hour	1187 kW·h	2658 seconds
Scenario 2	17.7 trains per hour	1982 kW·h	8588 seconds

5.1.2 Preliminary verification of the high-level feasibility analysis model

The case study aims to preliminarily verify the HFAM through comparing the results from the HFAM and the STS to find if the results match. Several upgrade options have been applied on the ECML.

5.1.2.1 Upgrade descriptions

Several upgrade options have been chosen to verify the feasibility of HFAM, which could have either positive or negative effects on the railway system. The evaluation of these upgrade options in the simulators is in ideal conditions, where feasibility is not assessed. Details of these upgrade options are set out below:

- Increased line speed limit to 200 km/h: It only is applied on the line sections where the train cannot reach its maximum speed capability due to the line speed limit. Since most sections of this railway has the speed limit of 200 km/h, it would not have large impact on energy consumption, while due to different stopping patterns, the impacts on the journey time is varied.
- Replacing rolling stock to Class 220 or Class 150: Class 220 (Voyager) is a class of diesel-electric multiple-unit trains (DEMU). Class 220 is more powerful and energy efficient and has better braking and acceleration characteristics. Class 150 is also a class of DMU trains, with a lower maximum speed (120 km/h) and lower traction requirements. For scenario 2, due to the fact that the maximum cruising speed does not reach speed limits, using Class 150 can save energy consumption without sacrificing journey time.
- Changing the number of carriages per train: A reduction from 8 cars to 6 cars per trainset and an increasing from 8 cars to 12 cars per trainset are carried out, which

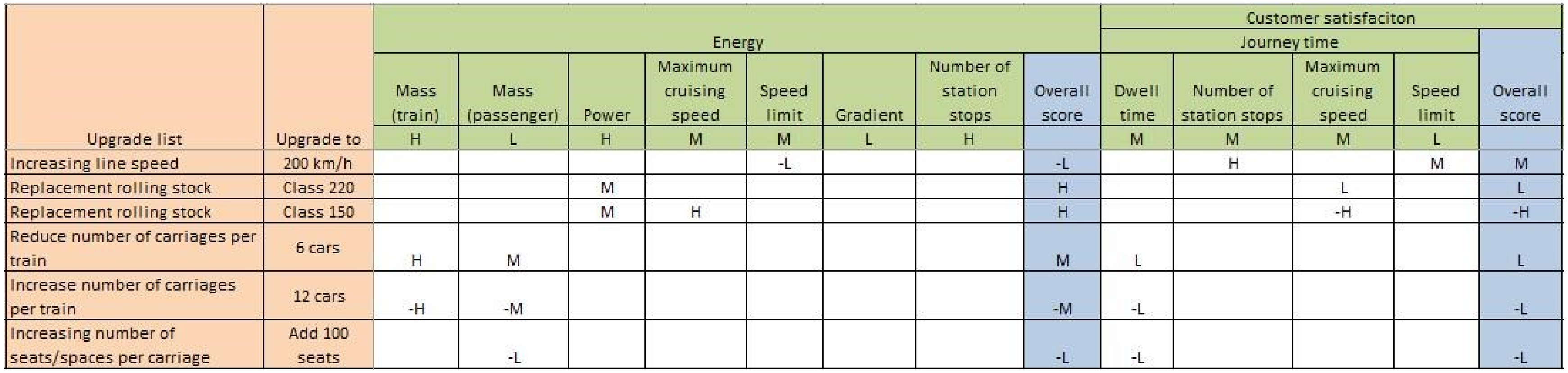
would have a high impact on the train mass, and also have low impact on dwell time for non-stop journey but medium impact on overall dwell time for frequent stop journey.

- Increasing the number of seats per train: In the original conditions, every train has 8 cars of Mark 3 Coach with 80 seats, thus 640 seats per trainset in total. Here the impact of adding 100 seats per trainset (increasing to 740 seats per trainset in total) is carried out. This upgrade option would have a medium impact on the train mass, and low impact on dwell time.
- Signalling system: The original signalling system of the ECML is 4-aspect signalling system. Changing the signalling system to a 3-aspect signalling system and a moving block signalling system is carried out, which would have a high impact on headway time.

5.1.2.2 Results of preliminary verification

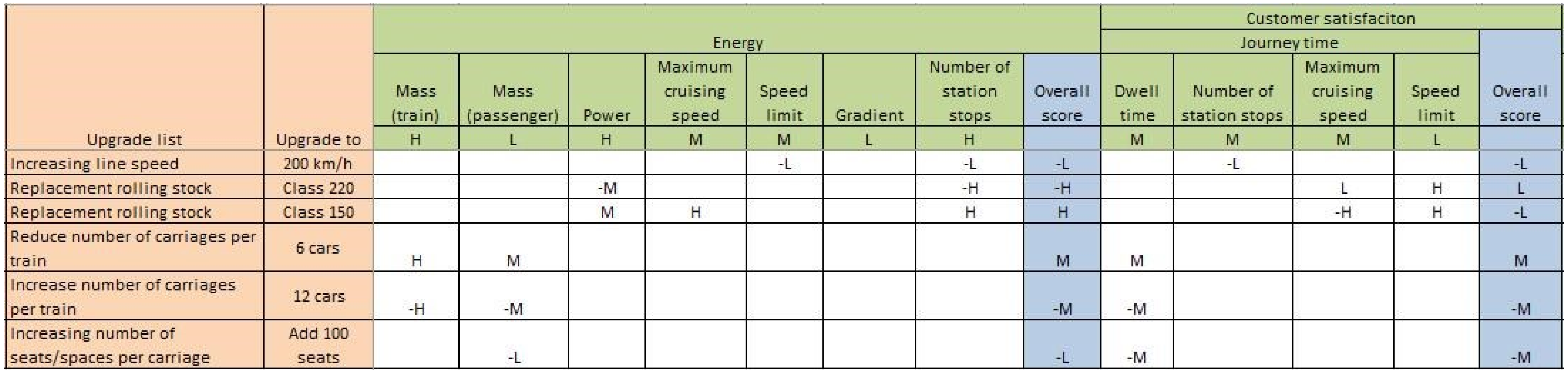
The details of upgrade options assessment are listed in Table 5-3, Table 5-4, and Table 5-5. In the initial impact assessment, the overall score is calculated as the average weighted sum of the products of the KPI’s function element impact score and presented as a categorised level. The impact scores presented in the tables below are assigned by the author, including H (high level positive impact), M (medium level positive impact), L (low level positive impact) and –H (high level negative impact), -M (medium level negative impact), -L (low level negative impact). Based on the initial assessment, all the overall scores are presented as a category level.

Table 5-3: The HFAM results of energy and journey time on Scenario 1



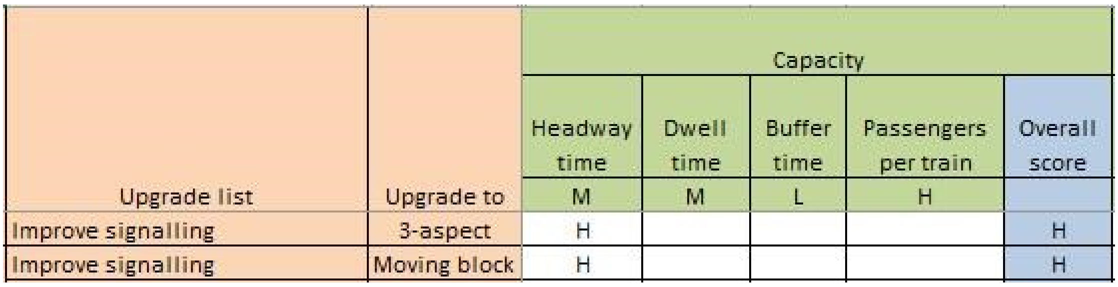
		Energy								Customer satisfaciton				
										Journey time				
		Mass (train)	Mass (passenger)	Power	Maximum cruising speed	Speed limit	Gradient	Number of station stops	Overall score	Dwell time	Number of station stops	Maximum cruising speed	Speed limit	Overall score
Upgrade list	Upgrade to	H	L	H	M	M	L	H		M	M	M	L	
Increasing line speed	200 km/h					-L			-L		H		M	M
Replacement rolling stock	Class 220			M					H			L		L
Replacement rolling stock	Class 150			M	H				H			-H		-H
Reduce number of carriages per train	6 cars	H	M						M	L				L
Increase number of carriages per train	12 cars	-H	-M						-M	-L				-L
Increasing number of seats/spaces per carriage	Add 100 seats		-L						-L	-L				-L

Table 5-4: The HFAM results of energy and journey time on Scenario 2



		Energy								Customer satisfaciton				
										Journey time				
		Mass (train)	Mass (passenger)	Power	Maximum cruising speed	Speed limit	Gradient	Number of station stops	Overall score	Dwell time	Number of station stops	Maximum cruising speed	Speed limit	Overall score
Upgrade list	Upgrade to	H	L	H	M	M	L	H		M	M	M	L	
Increasing line speed	200 km/h					-L		-L	-L		-L			-L
Replacement rolling stock	Class 220			-M				-H	-H			L	H	L
Replacement rolling stock	Class 150			M	H			H	H			-H	H	-L
Reduce number of carriages per train	6 cars	H	M						M	M				M
Increase number of carriages per train	12 cars	-H	-M						-M	-M				-M
Increasing number of seats/spaces per carriage	Add 100 seats		-L						-L	-M				-M

Table 5-5: The HFAM results of capacity on Scenario 1/2



		Capacity				
		Headway time	Dwell time	Buffer time	Passengers per train	Overall score
Upgrade list	Upgrade to	M	M	L	H	
Improve signalling	3-aspect	H				H
Improve signalling	Moving block	H				H

The comparison results of the two scenarios are listed in Table 5-6, Table 5-7, and Table 5-8. The HFAM results come from the overall scores presented in the Table 5-3, Table 5-4, and Table 5-5. The STS provides the results of energy consumption and journey time and the MTHS provides the results of capacity. The percentages are represented the comparisons between the original conditions (Table 5-2) and the conditions with upgrade options applied (Chapter 5.1.2.1) of two scenarios. Negative percentage results in the tables mean that the upgrade option has a negative influence when optimising energy consumption and journey time, and the values for energy consumption and journey time have increased. Likewise, a positive percentage result in the tables means that the upgrade option saves energy consumption and journey time and that the values for energy consumption and journey time have decreased.

If the improvement percentage for energy consumption, journey time and capacity is defined as lower than 3% it belongs to Low level impact, 3% -7% belongs to Medium level impact, larger than 7% belongs to High level impact. In the table below, the HFAM results in green represent the HFAM results match the STS results, while the HFAM results in red represent the HFAM results do not match the STS results. It can be seen that more than 70% of results match.

Table 5-6: Impact results comparisons of scenario 1

Scenario 1	**Energy consumption**		**Journey time**	
Upgrade option list	**STS results**	**HFAM results**	**STS results**	**HFAM results**
Improve line speed	-1.7%	-L	4.6%	M
Replace rolling stock to Class 220 (Max. speed 200 km/h)	9.2%	H	2.9%	L
Replace rolling stock to Class 150 (Max. speed 120 km/h)	65.6%	H	-46%	-H
Reduce to 6 cars per trainset	2%	M	1.8%	L
Increase to 12 cars per trainset	-3.2%	-M	-4.2%	-L
Increase 100 seats per trainset	-0.6%	-L	0	-L

Table 5-7: Impact results comparisons of scenario 2

Scenario 2	**Energy consumption**		**Journey time**	
Upgrade option list	**STS results**	**HFAM results**	**STS results**	**HFAM results**
Improve line speed	0	-L	0	-L
Replace rolling stock to Class 220 (Max. speed 200 km/h)	-10.2%	-H	10.2%	L
Replace rolling stock to Class 150 (Max. speed 120 km/h)	47.9%	H	-0.2%	-L
Reduce to 6 cars per trainset	5.3%	M	5.8%	M
Increase to 12 cars per trainset	-7.5%	-M	-9.6%	-M
Increase 100 seats per trainset	-1.8%	-L	0	-M

Table 5-8: Capacity impact results comparisons of two scenarios

Improving signalling system		**3-aspect signalling**	**Moving block signalling**
Scenario 1	**Capacity**	13.3 trains per hour	21.4 trains per hour
	MTHS results	-33%	60.9%

	HFAM results	-H	H
Scenario 2	**Capacity**	13.3 trains per hour	21.4 trains per hour
	MTHS results	-33%	60.9%
	HFAM results	-H	H

5.1.3 Discussion

Based on the comparison results, it can be shown that the initial version impact assessment using the categorised level applied in the HFAM is potentially a feasible method to estimate the upgrade option impact. In addition, it can be seen that the same upgrade option can show different levels of improvement under different conditions, whereas the HFAM can still be applied. For example, replacing existing rolling stock with new rolling stock that has an increased maximum speed capability for a nonstop journey is a good alternative for reducing journey time, while it is a less attractive choice for a frequently stopping service pattern, since the trains may not be able to reach cruising speed between two pairs of stations. Moreover, as a macro model to make a high-level decision, using the HFAM takes less time than the simulators in evaluating every upgrade option.

However, the initial version impact assessment needs to be improved.

- The fact that the results of the HFAM does not 100% match the results of the STS (falling into next category level) is mainly due to the definitions used to categorise the percentage results from the simulators into categorised levels, since the percentage results for improvement of different 'C's should have a different impact. For example, the value of an 8% improvement on energy consumption can be regarded as a high impact, while the value of an 8% improvement on capacity volume is only regarded as a medium or low impact.

- Another reason for the discrepancy is that using an average to define the addition and subtraction of the categorised level could reduce the overall score of the impact of an upgrade option with one H term and many L terms. For example, the overall score of one upgrade option consists of one H term and four L terms, and the result will be $\frac{3+1+1+1+1}{5} = 1.2$, which belongs to M. While the overall score of another upgrade option consists of only one H term, and the result will be $\frac{3+0+0+0+0}{1} = 3$, which belongs to H. It is obvious that the first upgrade option should have a higher positive impact than the second, but this cannot be reflected in the impact scores when these two upgrade options are compared in this initial version HFAM. This also leads to the result that the final overall impact score has many M and L terms, but few H terms.
- Furthermore, it is difficult to choose the expected number of candidate solutions according to the rank of the final overall impact score using a categorised level, since the final impact score of all the upgrade options only falls into these predefined 3 categorised levels (i.e., H, M or L). For example, if there should be 10 categorised levels in order to identify 4 candidate solutions out of 40 upgrade options, this could lead to difficultly in assigning weights in the HFAM.

To overcome these drawbacks, a final version impact assessment has been developed based on using a combination of categorised level and numerical values. In addition, another investigation of 20 experienced industrial practitioners was undertaken to further verify and improve the HFAM feasibility, which will be presented in Chapter 5.2.

5.2 Further development of the high-level feasibility analysis model

The preliminary verification, which is presented above, demonstrates that the concept of using categorised levels is feasible but that it has some drawbacks due to the arithmetic calculation used. This final version has been presented in Section C in Chapter 4.2.2.1, including the example demonstrated in Figure 4-7. Based on the preliminary verification, a comprehensive investigation into the overall feasibility of the HFAM, based on a case study of the Northern Ireland Railway network (NIRN) was conducted.

5.2.1 Introduction to the case study based on Northern Ireland railway network

This section has been previously published in C. Xindi, G. L. Nicholson, and C. Roberts, "Development of a high-level feasibility analysis model for the selection of railway upgrade options," in *2016 IEEE International Conference on Intelligent Rail Transportation (ICIRT)*, 2016, pp. 231-235. Where the work has been previously published, it is shown in the thesis in italic.

The NIRN runs at close to full capacity at peak times. The NIRN consists of approximately 300 km of track with 54 stations in total. A major challenge is that the NIRN has 55% single track lines, lacking in passing loops to allow more capacity. The major rolling stock for passenger services is the DMU Class 3000 with a maximum speed of 90 mph. For this case study, the NIRN has been simplified into the model shown in Figure 5-2. The signalling system on the single-track sections is 2-aspect with a 50 mph speed limit and on the double-track sections it is 3-aspect with a 70 mph speed limit.

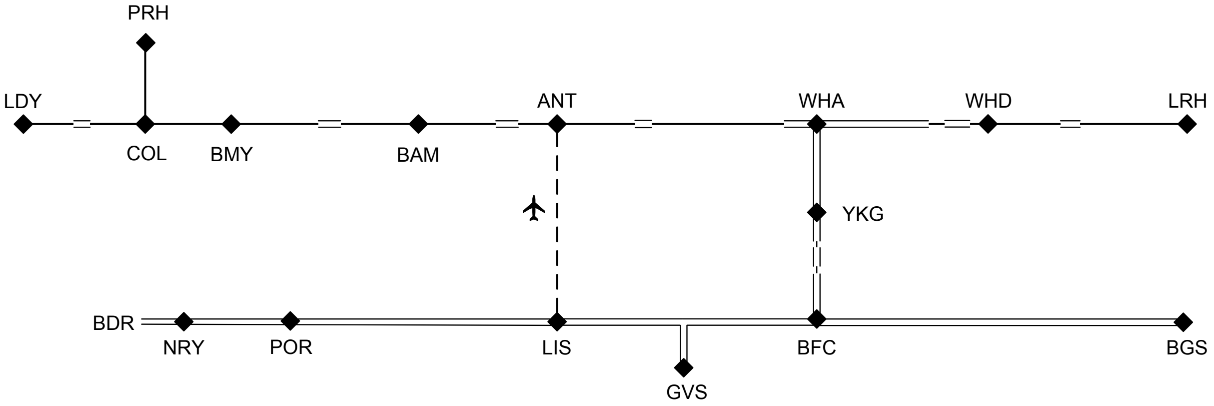


Figure 5-2: Simplified NIRN map for the investigation

In order to verify the HFAM feasibility on different railway systems, a group of 20 experienced railway industry professionals assessed the HFAM. They were divided into 5 groups, each considering a limited section of the NIRN;

- *2 groups examined the single-track sections from Londonderry (LDY) / Portrush (PRH) to Whiteabbey (WHA) running 1 train/hour.*
- *1 group reviewed the half single-track running 1.5 trains/hour and half double-track section running 3.5 trains/hour from Larne (LRH) to Belfast Central (BFC).*
- *2 groups reviewed the double-track sections from Newry (NRY) to Great Victoria Street (GVS) running 2 trains/hour and from Bangor (BGS) to Great Victoria Street (GVS) running 5.5 trains/hour.*

Each group analysed the current condition of the railway system, made decisions on the top 3 most appropriate upgrade options based on group discussion around their own professional judgment. They then performed the decision making process to select the top 3 most appropriate upgrade options using the HFAM. Finally, they compared the results of their *decisions with and without the HFAM support and gave feedback and suggestions on the experience of using the HFAM.*

5.2.2 Further verification of the high-level feasibility analysis model

5.2.2.1 The final version impact assessment

Based on the disadvantages of the initial version impact assessment, this final version impact assessment using a combination of categorised levels and numerical values has been proposed. The categorised level is still regarded as having corresponding numerical values for the purposes of performing arithmetic calculations. While the calculation of each KPI score and final overall score is displayed in numerical form. Of course, the calculation of this final version impact assessment in the HFAM is also automatically completed once the weighting values and impact level are assigned. Furthermore, a high level of financial and technical feasibility is a necessary condition for the implementation of an upgrade option that has positive influence on the 3Cs. Another improvement is that the final impact overall score of each upgrade option is calculated as the weighted sum of the products of capacity, carbon and customer satisfaction KPI impact scores and then multiplied by the feasibility impact score, rather than the weighted sum of these 4 KPI's impact scores. This improvement can clearly distinguish potential options and inappropriate options. When multiplied the feasibility impact score, the positive overall impact score of 3Cs will be amplified, so does the negative overall impact score of 3Cs.

Therefore, in the final version impact assessment, the advantage of having categorised levels is retained (easy and quick assignment of weights in the HFAM), while the impact of the upgrade options can be straightforwardly ranked from high to low according to the overall numerical score.

5.2.2.2 Results of the further verification investigation

The group discussion results are:

- The top 3 most appropriate solutions for single-track sections are doubling tracks, extending passing loops and adding passing loops.
- The top 3 most appropriate solutions for double-track sections are upgrading the signalling system, improving speed limits, and replacing the DMU rolling stock with EMU.

The upgrade option list that the expert group need to evaluate is the same as that presented in Section A in Chapter 4.2.2.1 (shown in Figure 4-3). The results of the HFAM with the final version impact assessment are displayed in Table 5-9 and Table 5-10. The details of the HFAM results are attached in Appendix A Tables 1-8, where the assignment of the impact scores are based on the expert group discussion. It can be seen that the results of the top 5 most appropriate solutions from the HFAM with the final version impact assessment can cover most of the group decisions on both the single-track and double-track sections.

It took 4 hours for the industrial experts to discuss and generate the results, while with the HFAM support it only took 2 hours to find the results. Based on these 20 industrial experts' feedback, the following can be concluded:

- The HFAM is feasible since it can provide support to find potential solutions. (20 out of 20)
- The HFAM is faster than the group discussion. (16 out of 20)

- The HFAM covers more options than the group discussion. (15 out of 20)
- The HFAM gives quantitative results. (14 out of 20)
- The HFAM is easy to use. (13 out of 20)
- The HFAM is well-structured. (11 out 20)

The number of experts agreeing with each statement is given in parentheses.

Table 5-9: Results of the HFAM with the final version impact assessment on single-track sections

System components	Current condition	Upgrade to	Capacity	Energy	Customer satisfaction	Feasibility	Overall score
			Overall score	Overall score	Overall score	Overall score	
			H	L	M	H	
Number of tracks	single	double	0.88	0.00	0.55	1.00	11.15
New loop			0.88	0.00	0.00	2.00	15.75
Loop condition		extend	0.63	0.00	0.00	3.00	16.88
Signalling system			1.00	0.00	0.18	1.00	10.09
Number of carriages per trainset	6 cars	9 cars	0.88	-0.76	0.09	2.00	12.25

Table 5-10: Results of the HFAM with the final version impact assessment on double-track sections

System components	Current condition	Upgrade to	Capacity	Energy	Customer satisfaction	Feasibility	Overall score
			Overall score	Overall score	Overall score	Overall score	
			H	L	M	H	
Number of tracks	2	3	0.63	0.00	0.18	1.00	6.72
Line speed limit			-0.25	-0.24	0.18	2.00	-3.73
Signalling system	3-aspect	4-aspect	1.00	0.00	0.00	1.00	9.00
Number of carriages per train	6 cars	9 cars	0.88	-0.76	0.09	2.00	12.25
Rolling stock type	DMU	EMU	0.00	1.06	0.18	2.00	8.53
Timetabling techniques			0.00	0.00	0.36	3.00	6.55

5.2.3 Discussion

Table 5-11: Comparison results for the NIRN single-track sections

Group Discussion Results	HFAM Results
Doubling tracks	Doubling tracks (4th)
Extending passing loops	Extending passing loops (1st)
Adding passing loops	Adding passing loops (2nd)
	Increasing the number of carriages per trainset from 6 cars to 9 cars (3rd)

Table 5-12: Comparison results for the NIRN double-track sections

Group Discussion Results	HFAM Results
Upgrading the signalling system	Upgrading the signalling system (2nd)
Improving speed limits	
Replacing the DMU rolling stock with EMU	Replacing the DMU rolling stock with EMU (3rd)
	Increasing the number of carriages per trainset from 6 cars to 9 cars (1st)

Based on the comparison results presented in Table 5-11 and Table 5-12, most group discussion results have been covered in the HFAM results. The following findings can be concluded:

- Based on the result of the HFAM, improving the number of carriages per trainset from 6 cars to 9 cars is a high potential upgrade option for both single-track and double-track sections, since it has significant improvement on carrying capacity straightforwardly and medium feasibility on both of finance and technical difficulty. However, the group discussion missed this option since they mainly underestimate the feasibility of the upgrade options.

- Doubling track for the single-track sections is one of the group discussion results, which can give good performance improvement, but is expensive and technically difficult, so it's ranked 4th in the HFAM results.
- Improving the line speed limit was included in the results of the top 3 most appropriate solutions for double-track sections in the group discussion, whereas it has a negative impact overall score in the HFAM, since this option increases headway time due to longer braking distances and also increases energy consumption. It can be seen that even with experts with professional experience, it is still easy to follow the traditional thinking in the group discussion and miss some potentially good improvements.

Furthermore, with the support of the HFAM, some further potential upgrade options that were missed by the experts in the group discussion process were taken into consideration, although they fell outside the top 3 potential solutions in the NIRN case. For example, increasing car parking in the central stations could encourage people to use public transportation.

Based on the results and discussion of the case study, it is proposed that the HFAM is feasible and effective in supporting decision making in the early stages of a rail upgrade project. It was shown that using the HFAM was faster than the group discussion. It can give quantitative results, and also ensure a wide range of upgrade options is taken into consideration.

5.3 Summary

This chapter demonstrates the design process of the high-level feasibility analysis model. The final version HFAM has been identified and applied in the RUSP at last.

The preliminary design is based on an East Coast main line case study and the verification compares the results from the simulators and the HFAM, which has illustrated that using categorised levels for weights assignment is feasible and the HFAM is quicker than simulators for making a high-level decision, although the initial version impact assessment has some limitations. The final version impact assessment has been developed based on the initial version, which uses numerical values to rank overall impact scores of upgrade options to overcome the initial version's drawbacks. The verification of the final version impact assessment has been carried out based on the industry expert group investigation on the Northern Ireland railway network. According to the results comparison from group discussions and the HFAM, the HFAM is feasible, faster than unstructured group discussions and can reduce the risk of missing potential upgrade options. It is found that the feasibility of using categorised levels is verified in the East Coast main line case study and the arithmetic calculation of categorised level is improved and verified in the Northern Ireland network railway case study.

Chapter 6 presents the application of the railway upgrade selection process based on a case study of the Northern Ireland railway network.

Chapter 6 Application of the railway upgrade selection process

The structure and details of the railway upgrade selection process (RUSP) are presented in Chapter 4, consisting of three stages: modelling, simulation and evaluation. As part of the simulation stage, the high-level feasibility analysis matrix (HFAM) is verified in Chapter 5, meanwhile through the application of HFAM, candidate solutions of a simplified case study based on the Northern Ireland railway network (NIRN) have been identified. This chapter demonstrates the application of the entire RUSP based on the NIRN case study. This chapter emphasises the demonstration of the process, thus the final results may vary from the projects in reality due to the fact that the estimation data for costs used in this case study is not entirely from the NIRN.

6.1 Introduction to the Northern Ireland railway network

The NIRN, operated by NI Railways (a subsidiary of Translink), is 305 km (191 miles) long with 54 stations and in 2014-15 it carried 13.4 million passenger journeys and 416.5 million passenger kilometres (increased 28.8% and 35.8% from 2010) [160]. The major rolling stock for passenger services is the DMU Class 3000 and Class 4000. The NI Railway also owns Class 201, Diesel locomotives, and is investigating the use of Class 222, DEMU, which requires modification of the NIRN to operate. Regular passenger services are operated along the following routes (only major stations are listed), as shown in Figure 6-1.

- Belfast to Dublin, via Belfast Central, Belfast Great Victoria Street, Lisburn, Portadown.
- Belfast to Bangor, via Belfast Great Victoria Street, Belfast Central, Holywood.
- Belfast to Larne, via Belfast Great Victoria Street, Belfast Central, Carrickfergus.

- Belfast to Londonderry, via Belfast Great Victoria Street, Belfast Central, Antrim, Ballymena, Coleraine.
- Coleraine to Portrush.
- Lisburn to Antrim has been suspended since 1978, although it is planned to re-open this line for airport services. This route is still maintained by NI Railways for occasional training operations.

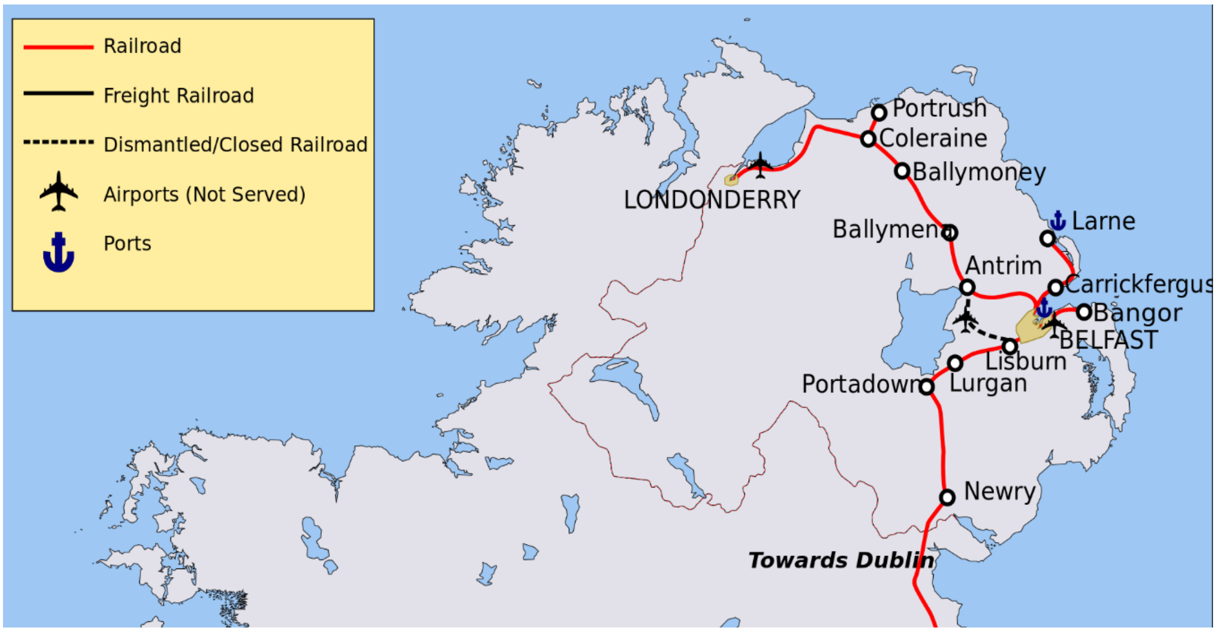


Figure 6-1: Northern Ireland railway network

The development of the NIRN is regarded as one of the key component of future economic growth in Northern Ireland [161]. The routes operated by NI Railways for Belfast Central station and Belfast Great Victoria Street station are extremely busy, since nearly all lines pass these two stations. The challenges are to meet the demands for increased capacity, solve the problem of full capacity at peak times and encourage people to choose public transport to release road congestion. Another bottleneck of the NIRN is that 55% is single track line lack of passing loops, which leads to limitations in both the service frequency and speed, and it is inevitable that services will have to be cancelled once failures or delays occur. In addition, the suggestion of linking Belfast International Airport to the NIRN has been considered for many years, but reopening the suspended line (Lisburn to Antrim) would require a great deal of refurbishment.

6.2 The application of the railway upgrade selection process

In the case study presented in this chapter, the RUSP is applied to find most appropriate solutions for a NIRN renewal project. It is used to support early stage decision making in the renewal project. Based on the introduction of the NIRN current conditions, this renewal project mainly focuses on improving capacity. The remainder of the section demonstrate the whole RUSP in its three stages: modelling, simulation and evaluation.

6.2.1 Modelling

The NIRN (see Figure 6-2) has been set up into a model. The lines from Whiteabbey to Londonderry/Portrush and from Whitehead to Larne are single-track sections with some passing loops, while the rest of the NIRN is double-track sections. The single-track sections are equipped with 2-aspect signalling, while the double-track sections are equipped with 3-aspect signalling. The whole network is divided into 4 main lines, for which brief details of current conditions have been listed in Table 6-1.

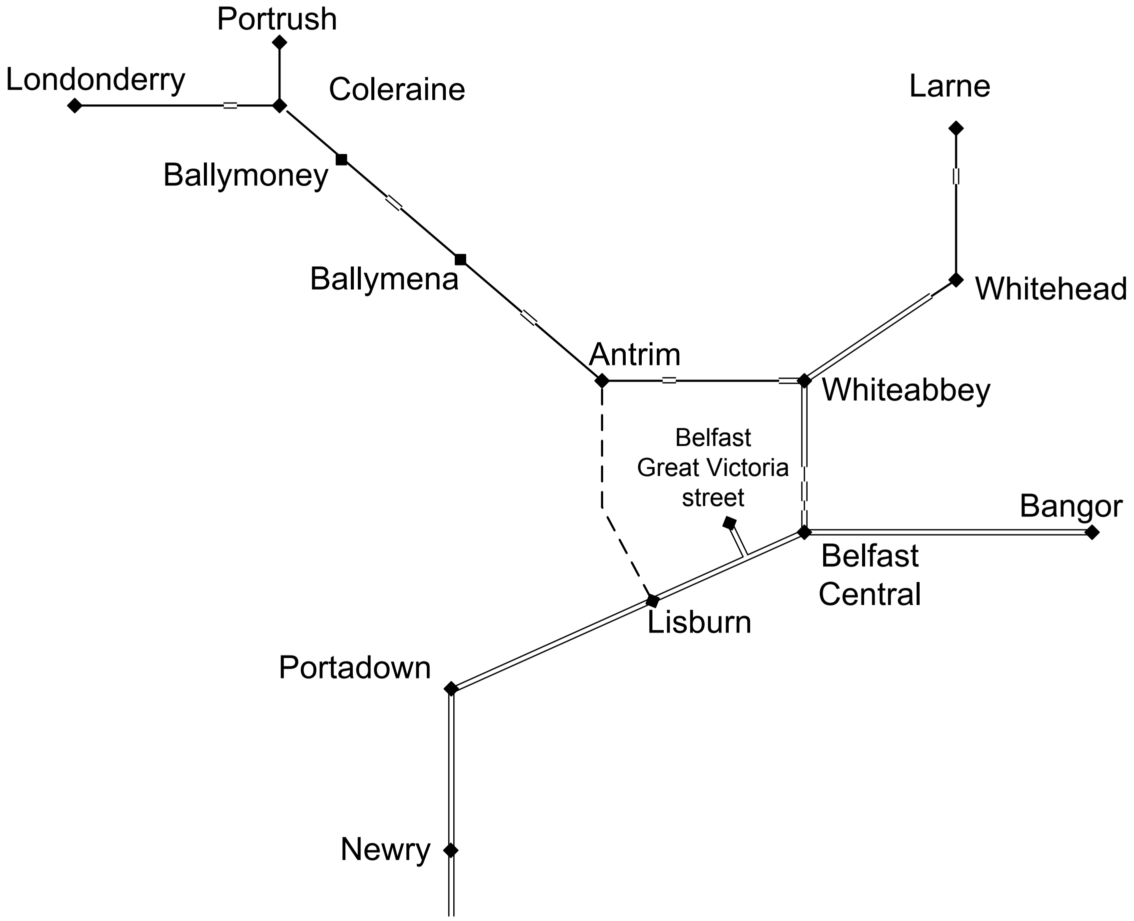


Figure 6-2: Northern Ireland railway network simulation area

Due to full-used capacity at peak time, this research puts emphasis on analysis of peak time in the morning section (6 a.m. to 10 a.m.), running a timetable which includes 86 services in total and is based on the 2015 timetable. Two main passenger rolling stock are diesel-electric locomotives Class 201 (3 cars) with 200 seats (max speed limit 100 mph) running mainly on the double track sections (and is not allowed to run on some specific single track sections), and DMU Class 3000 (3 cars) with 200 seats (max speed limit 90 mph) running on both the single track sections and the double track sections.

Table 6-1: Current condition of 4 main lines

Main Line	Total length	No. of Stations	Condition
Belfast Great Victoria Street – Newry	69.2 km	15	Double-track, 3-aspect signalling, speed limit 90 mph for Class 201, 90 mph for Class3000
Belfast Great Victoria – Bangor	22.3 km	14	Double-track, 3-aspect signalling, speed limit 70 mph for Class201, 70 mph for Class3000
Belfast Central – Larne	41.5 km	15	Double-track until Whitehead with 3-aspect signalling; Single-track until Larne with 2-aspect signalling, one passenger loop, speed limit 70 mph for Class3000
Belfast Central – Londonderry/Portrush	154.6 km/ 110.1 km	12/12	Double-track until Whiteabbey with 3-aspect signalling, speed limit 70 mph for Class 201, 70 mph for Class3000; Single-track until end with 2-aspect signalling, four passenger loops, speed limit 70 mph for Class 201, 70 mph for Class 3000

Generally, it is difficult to compare upgrade options on different lines. For example, it is difficult to compare the performance and allocate investment on doubling track on the Belfast Central – Londonderry/Portrush section and upgrading signalling systems on Belfast Great Victoria Street – Newry section in one NIRN renewal project, since they are not on the same line and have different services. In this case study, the RUSP is applied on two main lines of the NIRN to see what solutions can be selected under the same amount of investment, which could support the decision maker to allocate investment on the same network.

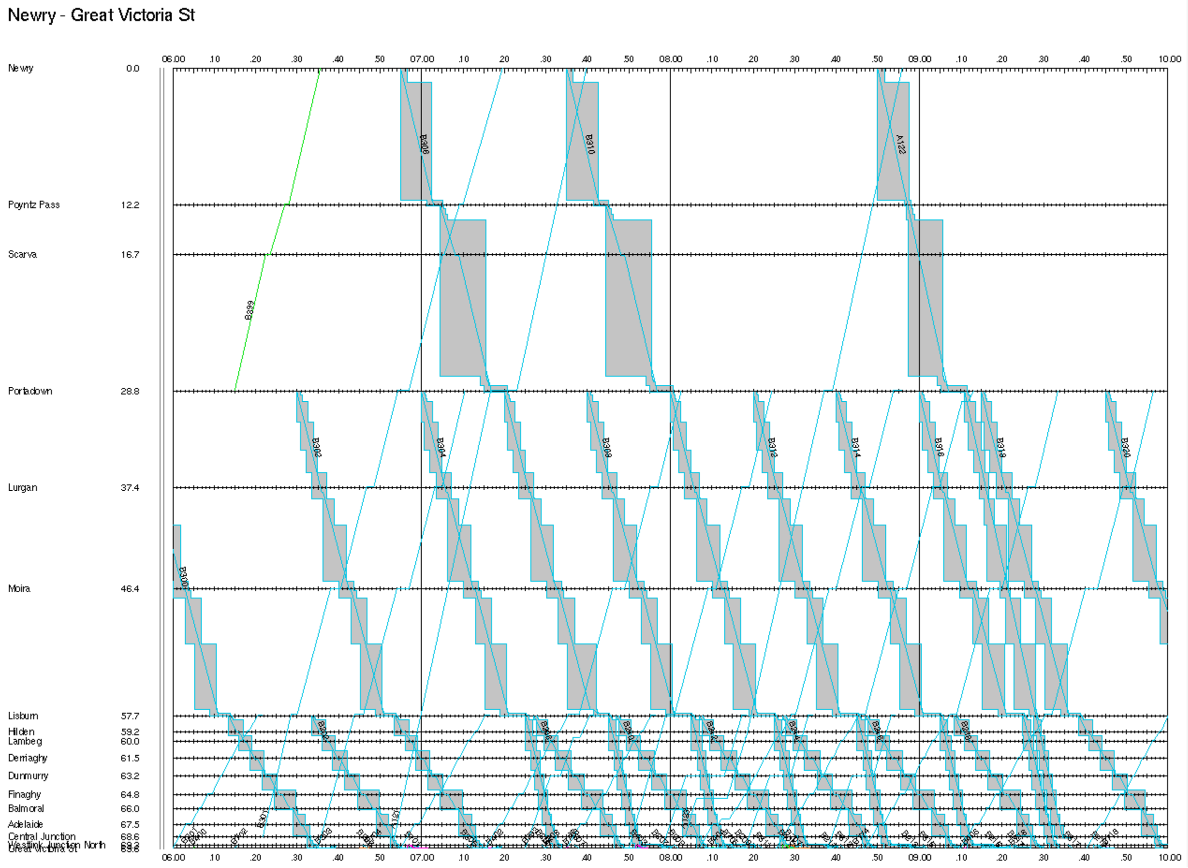


Figure 6-3: Newry to Belfast Great Victoria Street train graph

Main Line A is from Newry to Belfast Great Victoria Street, the train graph for which is demonstrated in Figure 6-3. The entire line is double track with 3-aspect signalling and a 90 mph speed limit. As seen from the train graph, trains running on this line have the same stopping patterns and a high frequency of stops and services, which is similar to a metro system model or a well-developed urban railway system model.

Main Line B is from Londonderry to Belfast Central, the train graph for which is demonstrated in Figure 6-4. The major sections of this line are single track with 2-aspect signalling and a 70 mph speed limit. This line is similar to an urban transit railway system that cannot meet capacity demands.

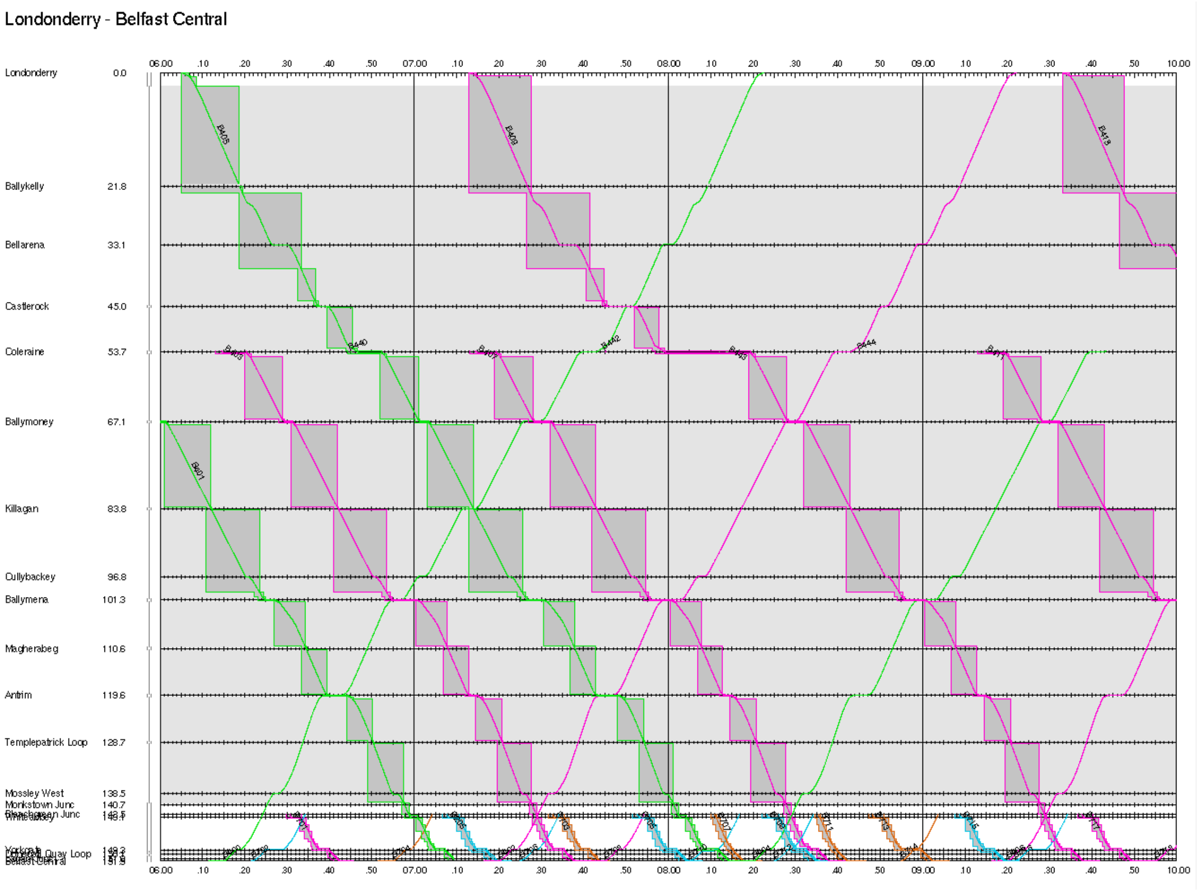


Figure 6-4: Londonderry to Belfast Central train graph

6.2.2 Simulation

In this stage, the HFAM is applied to these two main lines to identify the candidate upgrade solutions. Candidate scenarios, consisting of these candidate solutions, are evaluated in OpenTrack.

6.2.2.1 Macro assessment

The details of the HFAM are described in Chapter 4.2.2.1, and the verification of the HFAM is presented in Chapter 5. Two case studies have been undertaken to support the verification, one of which is simplified from the NIRN (in Chapter 5.2). The process of how the HFAM is applied is not duplicated here.

The results of candidate solution identification for the two main lines mainly refer to the results of the HFAM feasibility investigation (see Table 5-9 and Table 5-10), which was undertaken by a group of experienced railway industry professionals, but the results were slightly modified depending on the current conditions of the NIRN and the typical characteristics of the two main lines. The customer satisfaction performance of the NIRN is quite high, so the requirement on the weight value for the customer satisfaction KPI has been changed to L. For Main Line A, Newry to Great Victoria Street, the weight value for the carbon KPI could be considered to be M.

The results of the HFAM for both main lines are presented in Table 6-2 and Table 6-3. It can be found that, for Main Line A (Newry to Great Victoria Street), the top 3 candidate solutions are upgrading the signalling system from 3-aspect signalling to 4-aspect signalling, replacing rolling stock from DMU to EMU, and increasing the number of carriages per trainset from 3 to 6, since reducing the mass of train can be realised by changing the rolling stock. For Main Line B (Londonderry to Belfast Central), the top 3 candidate solutions are adding a new passing loop, extending the existing passing loop and increasing the speed limit from 60 mph to 80 mph.

Table 6-2: Results of the HFAM for Main Line A (Newry to Great Victoria Street)

System components	Current condition	Upgrade to	Capacity	Energy	Customer satisfaction	Feasibility	Overall score
			Overall score	Overall score	Overall score	Overall score	
			H	M	L	H	
Number of tracks	2	3	0.63	0.00	0.18	1.00	6.17
Signalling system	3-aspect	4-aspect	1.00	0.00	0.00	1.00	9.00
Rolling stock type	DMU	EMU	0.88	-0.35	0.45	2.00	14.24
Number of carriages per train	3 cars	6 cars	0.00	0.71	0.00	2.00	8.47

Table 6-3: Results of the HFAM for Main Line B (Londonderry to Belfast Central)

System components	Current condition	Upgrade to	Capacity	Energy	Customer satisfaction	Feasibility	Overall score
			Overall score	Overall score	Overall score	Overall score	
			H	L	L	H	
Number of tracks	1	2	0.88	0.00	0.55	1.00	9.51
New loop			0.88	0.00	0.55	1.50	14.27
Loop condition		extend	0.63	0.00	0.55	2.00	14.52
Number of carriages per train	3 cars	6 cars	0.63	-0.24	0.55	1.00	6.56
Line speed limit	60 mph	80 mph	0.88	-0.76	0.55	1.00	7.22

6.2.2.2 Micro simulation

With the assistance of the HFAM, the number of upgrade categories can be reduced from 44 (mentioned in Section A in Chapter 4.2.2.1) to 3 candidate solutions. In this phase, the microscopic simulation of candidate scenarios is undertaken to evaluate the 4Cs performance of the NIRN in OpenTrack. The definitions and measurement of 4Cs performance in this phase are presented in Chapter 2.3 and Chapter 4.2.2.2.

At first, it is essential to evaluate and present the 4Cs performance for both of the main lines in original conditions.

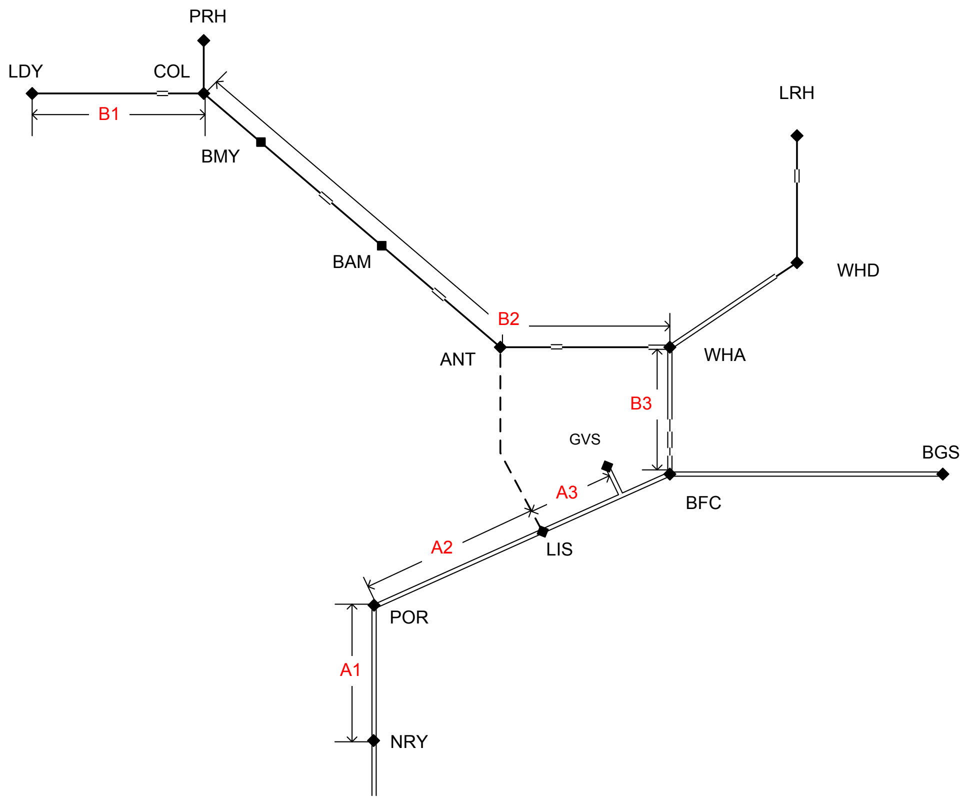


Figure 6-5: Line sections of Main Lines A and B

An entire model of the NIRN has been built in OpenTrack. Since UIC 406 is applied as the capacity performance measurement, according to the criterion of defining line sections described in the UIC leaflet 406 (presented in Chapter 2.3.1.2), both of the main lines can be divided into 3 line sections, as shown in Figure 6-5.

As mentioned in Chapter 2.2.2, OpenTrack can provide train graphs for specific corridors and log files for energy consumption in distance, journey time, etc. Therefore, the results for energy consumption and journey time come from the OpenTrack simulator directly, while the results for capacity utilisation come from further evaluation of the train graph (from OpenTrack), which is built in MATLAB. The train running in the model built in OpenTrack is on the basis of keeping train running as fast as possible. If the journey time is reduced, the trains will arrive at the station earlier than the timetable, but will still be despatched on time.

The details of each main line are listed separately in Table 6-4 and Table 6-5, including the 4Cs performance in original conditions. Since Line Sections A1, A2, A3 and B3 are double-track sections, the capacity utilisation of each line section has two results, which represent the two running directions. The energy consumption and the journey time of Line Section A3 is categorised into two types: fast train (which only stops at major stations) and slow train (which stops at every station).

Table 6-4: Original conditions of Main Line A

Line Sections	**Distance (km)**	**No. of stations**	**Capacity (%)**		**Energy consumption (kw·h/seat·km)**	**Journey time (seconds)**
			Down	**Up**		
A1: NRY - POR	28.8	4	14.78	21.34	0.041	1314
A2: POR - LIS	28.9	4	36.98	35.14	0.037	1369
A3: LIS - CLJ	10.8	8	54.03	66.25	0.032/0.13	416/1200

Table 6-5: Original conditions of Main Line B

Line Sections	**Distance (km)**	**No. of stations**	**Capacity (%)**		**Energy consumption (kw·h/seat·km)**	**Journey time (seconds)**
			Down	**Up**		
B1: LDY - COL	53.7	4	49.15		0.029	2522
B2: COL – MTJ	87.0	6	83.76		0.026	4303
B3: MTJ - BFC	10.3	2	33.92	19.94	0.028	719

Figure 6-6 and Figure 6-7 demonstrate the busiest line section (which has the highest capacity utilisation) of each main line, which is also the bottleneck line section of each main line.

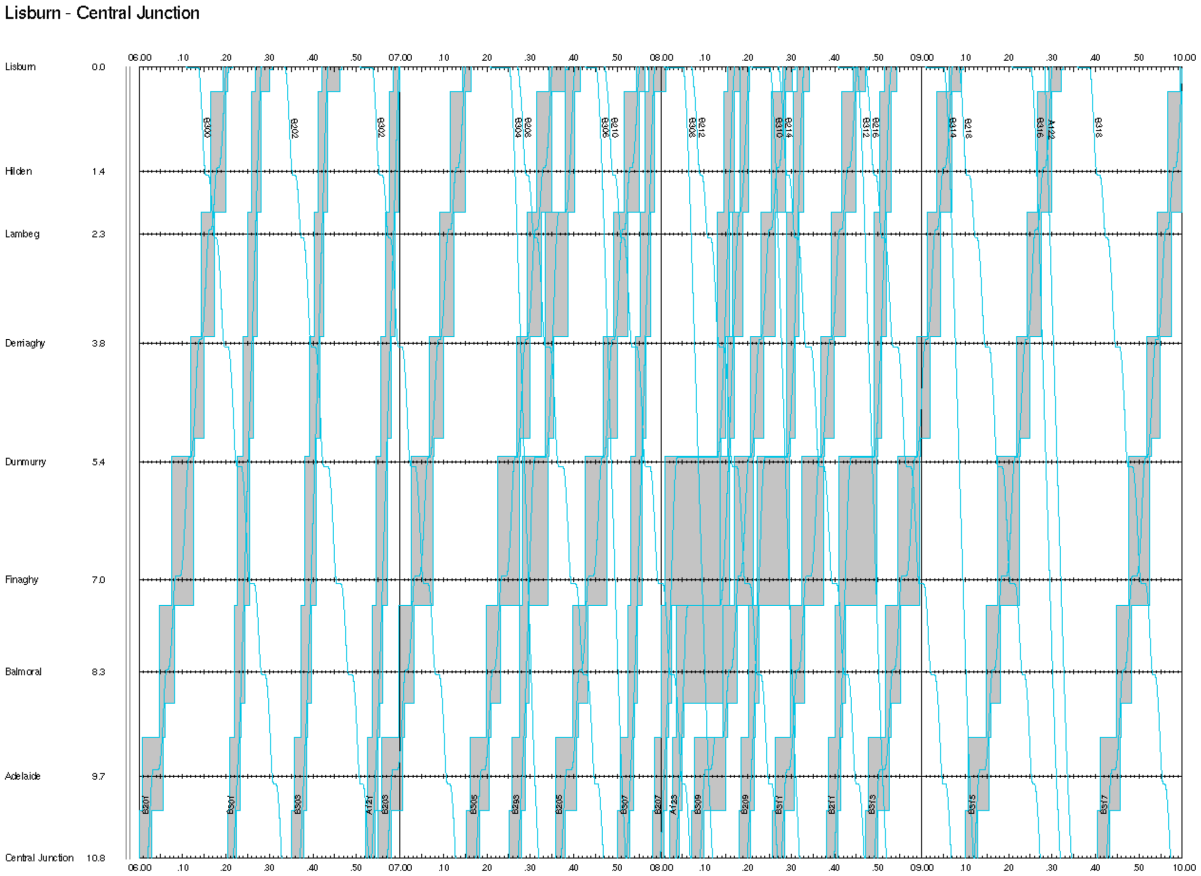


Figure 6-6: Train graph of Line Section A3 (Down)

Line Section A3 from Lisburn to Central Junction is the busiest section of Main Line A. During peak hours, the capacity utilisation of Line Section A3 is 66.25% running from Central Junction to Lisburn. From Figure 6-6, it is found that this line is extremely busy during the period from 7:30 a.m. to 9:00 a.m. since many train paths are close to each other. The energy consumption of a fast train on Line Section A3 is 0.045 kw·h/seat·km, while the energy consumption of a slow train is 0.13 kw·h/seat·km, which is higher than that Line Sections A1 and A2 due to frequent stops over a short distance. The journey times of a fast train and a slow train on Line Section A3 are 416 seconds and 1606 seconds, respectively.

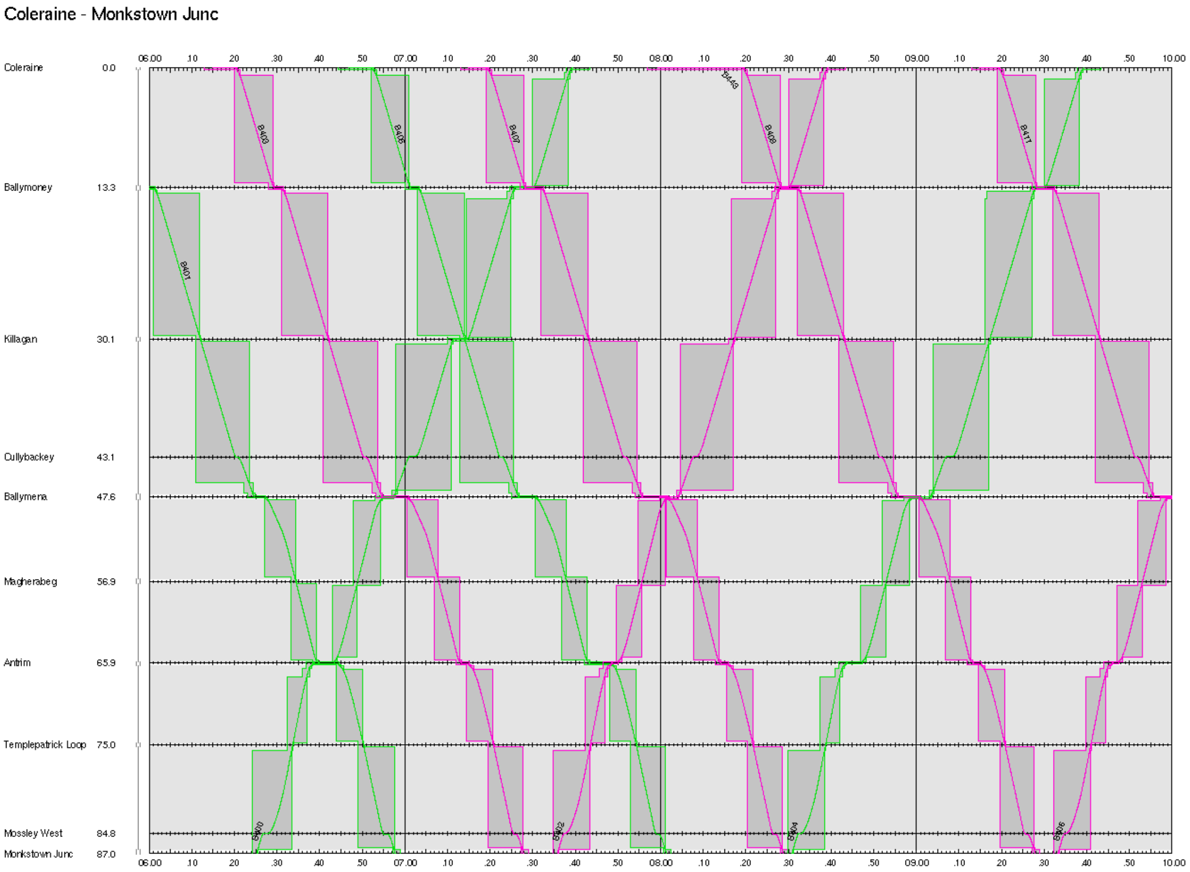


Figure 6-7: Train graph of Line Section B2

Line Section B2 from Lisburn to Central Junction is the busiest section of Main Line B, as shown in Figure 6-7. In the figure, the red line represents the trains starting/ending at LDY while the green line represents the trains starting/ending at PRH. Since Line Section B2 is a single-track section and the capacity utilisation of Line Section B2 is 83.75%, from Figure 6-7, it can be seen that it is difficult to add any train paths into this line section. (In practice, adding more train paths can still be carried out. Here the conclusion is drawn only based on the results of UIC 406, the disadvantage of which on the single-track application has been addressed in Landex's research [74] and discussed in Chapter 2.3.1.2.) The energy consumption on Line Section B2 is 0.022 kw·h/seat·km and the journey time on Line Section B2 is 4219 seconds.

Therefore, in order to improve these two main lines, this case study mainly focuses on finding solutions for the bottleneck sections, Line Sections A3 and B2.

Upgrade scenarios consist of a combination of candidate solutions from the macro assessment stage, the details of which are listed in Table 6-6 and Table 6-7. All the upgrade scenarios were carried out by modifying the model in the OpenTrack simulator.

For Line Section A3, upgrade scenarios comprise three candidate solutions and their combinations, which are replacing rolling stock, upgrading the signalling system and increasing the number of carriages per train. Class 80 is old classic Electric locomotive, which is only allowed 70 mph line speed limit running in the NIRN.

Table 6-6: Upgrade scenarios for Line Section A3

Upgrade Scenario No.	**Line Section No.**	**Details**
UA1	A3	Replace rolling stock type from Class 201 to Class 80
UA2	A3	Upgrade signalling from 3-aspect to 4-aspect
UA3	A3	Increase from 3 cars per trainset to 6 cars
UA13	A3	Replace rolling stock type from Class 201 to Class 80 Increase from 3 cars per trainset to 6 cars
UA12	A3	Replace rolling stock type from Class 201 to Class 80

		Upgrade signalling from 3-aspects to 4-aspects
UA23	A3	Upgrade signalling from 3-aspects to 4-aspects Increase from 3 cars per trainset to 6 cars
UA123	A3	Replace rolling stock type from Class 201 to Class 80 Upgrade signalling from 3-aspects to 4-aspects Increase from 3 cars per trainset to 6 cars

For Line Section B2, upgrade scenarios comprise three candidate solutions and their combinations, which are doubling track, increasing line speed limits and increasing the number of carriages per train.

Table 6-7: Upgrade scenarios for Line Section B2

Upgrade Scenario No.	**Line Section No.**	**Details**
UB1	B2	New loop at Cullybackey with 800 m in length
UB2	B2	Extend Temlepatrick loop and Killagan loop from 1 km to 4 km
UB3	B2	Increase speed limit from 60 mph to 80 mph
UB4	B2	Increase from 3 cars per trainset to 6 cars
UB5	B2	Doubling track
UB35	B2	Doubling track Increase speed limit from 60 mph to 80 mph
UB45	B2	Doubling track Increase from 3 cars per trainset to 6 cars
UB34	B2	Increase speed limit from 60 mph to 80 mph Increase from 3 cars per trainset to 6 cars
UB345	B2	Doubling track Increase speed limit from 60 mph to 80 mph Increase from 3 cars per trainset to 6 cars

The data for cost is estimated based on the statistical data in the *Little Black Book* in 2004-2005 [94]. The construction cost for signalling is 300-650 £'000s/single track km, for electrification it is 200-400 £'000s/single track km, for telecoms it is 50-150 £'000s/single track km and for permanent way (track) upgrade it is 100-900 £'000s/single track km. The purchase cost for a locomotive is 1000 £'000s/locomotive and for a carriage it is 100

£'000s/car. The construction cost for each upgrade scenario consists of various components, listed in Table 6-8. For instance, when doubling track the cost for new permanent track, new signalling and updating communication systems needs to be taken into account. The given figures are meant to be demonstrative and will vary depending on specific projects.

Table 6-8: Construction cost of upgrade scenarios

Upgrade scenario No.	**Signalling (£'000s/single track km)**		**Telecoms (£'000s/single track km)**		**Permanent way (£'000s/single track km)**		**Rolling stock (£'000s/locomotive) (£'000s/car)**		**Cost (million)**
	Renew	**New**	**Renew**	**New**	**Renew**	**New**	**Locomotive**	**Carriage**	
	300	650	50	150	100	900	1000	100	
UA1							9		9
UA2	10.8		10.8						3.78
UA3								54	5.4
UA13							9	54	14.4
UA12	10.8		10.8				9		12.78
UA23	10.8		10.8					54	9.18
UA123	10.8		10.8				9	54	18.18
UB1		0.8		0.8		0.8			1.36
UB2		3		3		3			5.1
UB3					87				8.7
UB4								27	2.7
UB5		87		87		87			147.9
UB35		87		87	87	87			156.6
UB45		87		87		87		27	150.6
UB34					87			27	11.4
UB345		87		87	87	87		27	159.3

All of the 16 upgrade scenarios are evaluated in the OpenTrack simulator, and the results of the 4Cs performance for each upgrade scenario are listed in Table 6-11 and Table 6-12.

Table 6-9: Results of 4Cs performance of upgrade scenarios on Line Section A3

Upgrade Scenario No.	**Capacity (%)**	**Energy consumption (kw·h/seat·km)**	**Journey time (second)**	**Cost (million)**
Original	66.5	0.13	1200	N/A
UA1	66.25	0.042	1200	9
UA2	65.74	0.13	1168	3.78
UA3	66.30	0.066	1190	5.4
UA13	66.33	0.024	1445	14.4
UA12	65.74	0.042	1168	12.78
UA23	66.02	0.066	1120	9.18
UA123	65.87	0.024	1440	18.18

Table 6-10: Results of 4Cs performance of upgrade scenarios on Line Section B2

Upgrade Scenario No.	**Capacity (%)**	**Energy consumption (kw·h/seat·km)**	**Journey time (second)**	**Cost (million)**
Original	83.76	0.26	4303	N/A
UB1	83.76	0.026	4303	1.36
UB2	83.76	0.026	4303	5.1
UB3	82.2	0.033	4176	8.7
UB4	84.63	0.021	4380	2.7
UB5	52.01	0.026	4303	147.9
UB35	51.66	0.033	4176	156.6
UB45	52.01	0.021	4380	150.6
UB34	83.41	0.029	4208	11.4
UB345	51.18	0.029	4208	159.3

6.2.3 Evaluation

Comparing the results of the upgrade scenarios (in Table 6-9 and Table 6-10) with the original data (in Table 6-4 and Table 6-5), the figures for capacity, energy consumption and journey time in Table 6-11 and Table 6-12, presented in terms of percentage, demonstrate how these upgrade options improve the railway system. The positive percentages represent positive influence on capacity, energy consumption and journey time, which means reducing capacity utilisation, reducing energy consumption and shortening journey time; similarly, the negative percentages represent negative influence. In the case of keeping the same timetable after upgrade, since the measurement of capacity performance in the micro-simulation level adopts infrastructure utilisation, UIC 406, improving capacity means reducing infrastructure utilisation, in other words, allowing more space for new train paths.

Table 6-11: Comparison results of 4Cs performance on Line Section A3 in percentages

Upgrade Scenario No.	Capacity	Energy consumption	Journey time	Cost (million)
UA1	0	67.69%	0	9
UA2	0.51%	0	2.67%	3.78
UA3	-0.05%	49.23%	0.83%	5.4
UA13	-0.08%	81.54%	-20.42%	14.4
UA12	0.51%	67.69%	2.67%	12.78
UA23	0.23%	49.23%	6.67%	9.18
UA123	0.38%	81.54%	-20.00%	18.18

Table 6-12: Comparison results of 4Cs performance on Line Section B2 in percentages

Upgrade Scenario No.	Capacity	Energy consumption	Journey time	Cost (million)
UB1	0	0	0	1.36
UB2	0	0	0	5.1
UB3	1.56%	-26.92%	2.94%	8.7
UB4	-0.87%	19.23%	-1.79%	2.7
UB5	31.75%	0	0	147.9

UB35	32.10%	-26.92%	2.94%	156.6
UB45	31.75%	19.23%	-1.81%	150.6
UB34	0.35%	-11.54%	2.21%	11.4
UB345	32.58%	-11.54%	2.21%	159.3

Due to incommensurable units of the 4Cs' results, it is difficult to define weight values for the 4Cs targets, and thus it is difficult to define the objective function, the final results only provide a suggestion of the most appropriate solutions, rather than the optimal solutions.

- Individual upgrade options

For the Line Section A3, three candidate solutions are identified in the HFAM. The upgrade scenario UA1, replacing the rolling stock from Class 201 to Class 80, has a significant positive impact (67.69%) on the energy consumption. As shown in Figure 6-8 (speed vs. distance), the blue line is Class 201 and the brown line is Class 80, which has a lower vehicle maximum speed. In the case of keeping the same journey time, even though Class 80 is an old electric locomotive, it consumes less energy for a frequent-stop journey than Class 201.

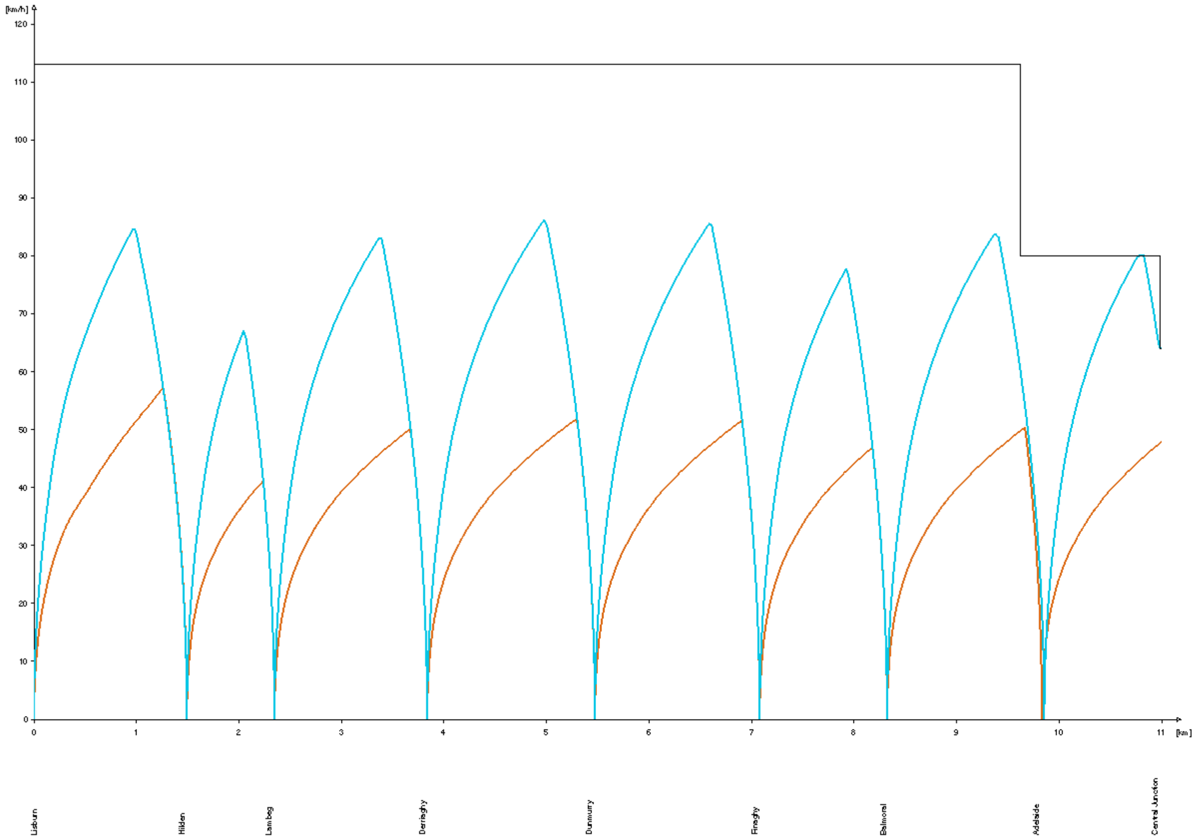


Figure 6-8: Class 201 vs. Class 80 on Line Section A3

The upgrade scenario UA2, upgrading signalling from 3-aspects to 4-aspects, does not have much improvement on capacity. If upgrading signalling without improving the line speed, the time for clearing each block in a train path cannot be reduced, thus the infrastructure utilisation cannot be improved. In addition, due to the frequent stops, improving line speed cannot give much support for capacity improvement; in some instances, it may reduce the capacity volume. The upgrade scenario UA3, increasing from 3 cars per trainset to 6 cars, also has a positive impact on energy efficiency, due to increasing the passenger seats per journey. In fact, the UA3 also should also have a positive impact on capacity volume, but this cannot be reflected through UIC 406. If the priority is improving capacity in terms of carrying capacity, the UA3 is the most appropriate solution. Since almost all the trains running on Line

Section A3 are operated in the same pattern, this model can be regarded as a metro system. If the priority is saving energy consumption for a metro system, from the figures presented in the tables, UA1 replacing rolling stock is a potential solution. Where capacity and energy consumption are considered at the same time, UA3 increasing the number of cars per train set is better than UA1.

For the Line Section B2, five candidate solutions are identified in the HFAM. Due to the limitations of UIC 406 for single-track section analysis (mentioned in Chapter 2.3.1.2), in the case of keeping the same timetable, the advantages of UB1 and UB2 (building a new loop and extending an existing loop) cannot be reflected in the results of the infrastructure utilisation. Thus in order to demonstrate the RUSP, the top 3-5 candidate solutions are chosen to compose upgrade scenarios for Line Section B2. The upgrade scenario UB3, increasing line speed from 60 mph to 80 mph, has a positive impact on capacity and journey time but takes more energy consumption. As discussed before, the upgrade scenario UB4, increasing from 3 cars per trainset to 6 cars, should have a positive impact on both capacity and energy consumption. The upgrade scenario UB5, doubling track, has a significant positive impact on capacity but is extremely expensive. Since the Line Section B2 is an old single-track railway system, the most appropriate solution is UB5 doubling track in the case of unlimited funding. Otherwise, UB4 increasing the number of cars per trainset is more cost-effective than UB5.

- Unlimited funding

If only the results of capacity, energy consumption and journey time are considered, for Line Section A3, the upgrade scenario UA23 (a combination of upgrading signalling and increasing the number of cars per trainset) is the most appropriate solution. Although Class 80 is more energy-efficient on a frequent-stop journey, it does not have enough traction to take 6 carriages, thus increasing the journey time. For the Line Section B2, both UB45 (a combination of doubling track and increasing the number of cars per trainset) and UB345 (a combination of doubling track, improving line speed and increasing the number of cars per trainset) are the most potential solutions. Both of these upgrade scenarios have a great impact on capacity, but UB45 would increase journey time and UB345 would increase energy consumption.

- Limited funding

If it is supposed that the capital investment of the NIRN is under £12 million. If only applied on Line Section A3, the upgrade scenario UA23 (a combination of upgrading signalling and increasing the number of cars per trainset) is the most appropriate solution. If only applied on Line Section B2, the UB34 (a combination of increasing line speed and increasing the number of cars per trainset) is the most appropriate solution.

In the case where both Main Lines A and B are considered, a combination of UA3 and UB4 could be an appropriate solution. The problem of how to allocate the capital investment for both main lines would require further evaluation and forecasting of traffic demand.

6.3 Summary

In this chapter, the application of the railway upgrade selection process based on a Northern Ireland railway network renewal project is demonstrated. Firstly, the research models of two main lines are simplified in the modelling stage of the RUSP, based on an overview of the current conditions and the challenges facing the NIRN. In the simulation state of the RUSP, through the HFAM, the candidate solutions for each main line are identified. Then the micro-simulation (OpenTrack) provides the results of the 4Cs performance of 16 upgrade scenarios, which are composed of a combination of candidate solutions. Finally, according to the results from the simulation stages, the most appropriate solutions are discussed and recommended under different cases in the evaluation stage of the RUSP. It is found that this decision-making support process can successfully provide suggestions with qualitative and quantitative results as to the most appropriate solutions for complex railway renewal projects in an effective and efficient way. Some data in this case study is meant to be demonstrative of how the RUSP goes through this process, and will vary depending on specific projects. The details in the micro simulation need to be further developed in the future.

Chapter 7 Conclusion & future work

7.1 General summary

The contents of this thesis can be divided into two parts:

- Part one encompasses the first three chapters, which present the background and literature review to support this research. Chapter 1 introduces the current situation of the railway system in GB and the direction of future development, which indicates that, although the railway is already a very mature industry, the challenge it is now facing is how to innovate and adopt new technologies to existing railway systems. Rather than building a new railway system, upgrading the existing railway systems will incur less cost and can also solve problems, such as full capacity, limited space for new infrastructures, environmental issues. In such complex railway renewal projects, the early-stage decision-making plays a significant role in the identification of the most appropriate solutions. Chapter 2 gives the background of railway system architecture, M&S and performance measurements and framework. Chapter 3 reviews decision-making applied in the rail industry, including different decision-making processes, identification and methods. The discussion also indicates that there is a lack of processes and models to generate solutions to support decision-making at the early stages.
- Part two of this thesis describes the railway upgrade selection process, which is developed to support early-stage decision-making, and its verification and application. Chapter 4 presents the structure of the railway upgrade selection process, which can be divided into three stages: modelling, simulation and evaluation. The RUSP combines

macro and micro modelling to provide an effective and efficient way for railway renewal projects to find the most appropriate solutions from a large number of alternatives. Chapter 5 puts emphasis on the application and verification of the high-level feasibility analysis model, which is the core of the RUSP. Two case studies have been carried out to verify the feasibility of the HFAM, one of which is based on the ECML to compare the results from the HFAM and the STS, and the other is through an investigation with a group of experienced railway industry professionals based on the NIRN. Chapter 6 demonstrates the process of how the RUSP is applied to renew the NIRN. It is found that most appropriate solutions can be identified under the support of quantitative results, reducing the risk of missing potential upgrade options, and the RUSP can be widely applied to different railway systems.

7.2 Findings and contributions

The major findings and contributions are concluded as follows:

7.2.1 The railway upgrade selection process

Since there are few researches on developing tools and models to support early-stage decision-making in rail appraisal projects, the railway upgrade selection process is developed in this thesis to efficiently and effectively find the most appropriate solutions for railway renewal projects. The structure of the RUSP is presented in Chapter 4 and its application based on the NIRN is presented in Chapter 6. The RUSP consists of three stages: modelling, simulation and evaluation. In the modelling stage, the main tasks are to collect data, clarify requirements, analyse the system to find out the bottlenecks, and build a research model. In the simulation stage, a combination of macro assessment and micro simulation is proposed to evaluate a large number of alternatives and simultaneously save time. In the evaluation stage, based on the results from the simulation stage and pre-defined circumstances from the modelling stage, the final suggestions of the most appropriate solutions can be made to support decision-making. Based on the process and the results depicted in Chapter 6, the major findings and contributions of the RUSP can be concluded, and compared with the challenges in this research listed in the beginning of Chapter 4, as follows.

- In complex engineering projects, it is common that solutions are identified too quickly without considering a large number of alternatives, which may result in missing potential alternatives. In the RUSP, 40 upgrade categories have been taken into account, which cover most possibilities in infrastructure, rolling stock, timetabling and operation. The details of these alternatives and their interactions are concluded in Chapter 4.2.2.1.
- Due to the complexity of a railway system, it is time-consuming to evaluate every upgrade scenario (which consists of different combinations of upgrade options) at a microscopic detail. In the simulation stage of the RUSP, a method that combines the advantages of macro modelling and micro simulation has been proposed, which uses macro assessment first to efficiently remove infeasible alternatives and identify candidate upgrade solutions, and then uses micro simulation to provide more fine scale details to support final decision-making.
- Through the application of the RUSP on the NIRN renewal case study, described in Chapter 6, it was found that the RUSP can be widely-applied to various railway systems and different purposes can be considered simultaneously, according to the specific characteristics of a railway system, the choice of KPIs and the assignment of their weights. In other words, the RUSP can be used to solve both multi-criteria problems and multi-objective problems.

7.2.2 The high-level feasibility analysis model

As the macro level in the RUSP, the HFAM has proven its ability to evaluate numerous alternatives and to quickly remove infeasible upgrade categorises and identifying candidate upgrade solutions. The details of the HFAM are described in Chapter 4.2.2.1 and its application and verification are demonstrated in Chapter 5. Numerous upgrade categories are gathered in the HFAM, which are individually evaluated under the 4Cs performance measurement framework. Through the ranking of the overall impact scores of each upgrade options, those alternatives with higher impact scores are defined as candidate upgrade solutions. In Chapter 5, based on the comparison results with existing simulators in the ECML case study and the feedback from experienced railway industry professionals in the NIRN investigation, the HFAM has been verified and improved. The major findings and contributions are concluded as follows:

- The HFAM collects most upgrade categorises for the infrastructure, rolling stock, timetable and operations, which compose a railway system. As the KPIs in the model, the 4Cs framework covers most trends of railway system improvement. Through effective, fast and automatic assessment, candidate upgrade solutions are easily identified. Since the HFAM gathers knowledge and data and provides a structured process, it is capable of giving an efficient, comprehensive and systematic evaluation of the railway system.
- The assignment of impact assessment for KPI weights and system component impact scores in the HFAM adopts categorised levels rather than specific numerical values, which is inspired by fuzzy extended decision making methods. This assessment provides an effective and efficient way to evaluate upgrade categorises individually, whilst avoiding the need to use numerical values for assignment.

- By modifying the system components and the KPI weight assignments, the HFAM can be applied to various railway systems and different purposes.
- Based on a comparison of the results from the HFAM and the published simulators on the ECML case study, it is recognised that the HFAM can be validated. Furthermore, based on the feedback from the experienced railway industry professionals in the NIRN case study, it is found that the HFAM is feasible.

7.3 Future work

7.3.1 Further development of the high-level feasibility analysis model

It is recognised that the HFAM itself is not at a fully mature stage of development and there is a need to refine and validate the system components and the impact assessment.

- The collection of upgrade categorises in the HFAM can be refined and standardised in order to be a widely-applied rail upgrade options database for railway renewal projects. For example, the system components could be further sub-divided to provide more possibilities for upgrade, such as automatic or manual driving for signalling, location of station exits, seating vs. standing space in carriages and more detailed guidance for the weighting assignment.
- In order to keep impact assessment simple and quick, the weighting values and impact scores are assigned using categorised levels, which is inspired by fuzzy extended decision making methods. It may also be interesting to consider and compare other decision making methods for weights assignment to give results more accurately and quickly, such as the ratio method, swing method, trade-off methods, AHP.

- The HFAM can provide an effective and efficient way to evaluate upgrade categorises individually. It may also be interesting to consider the interactions between the upgrade categories when assessing them individually in the HFAM.

7.3.2 Further development of the railway upgrade selection process on practical application

Due to lack of available data, some studies are omitted from the application of the RUSP on the NIRN case study.

- Journey time is not the only KPI in customer satisfaction performance measurement, and similarly investment cost is not the only KPI in cost performance measurement. In order to be close to the practical application, the analysis of customer satisfaction and cost in the micro-simulation stage needs further investigation, for example, considering life-cycle costs in the cost target, the reliability of the railway system in the customer satisfaction target.
- The RUSP currently can only give some support figures when considering the investment allocation in a simplified railway system. A future development to the RUSP of the investment allocation within any type of actual railway systems would require more study.
- In this thesis, the RUSP gives the suggestion of the most appropriate solutions for railway renewal projects, which is usually a combination of some of the available upgrades. The work to identify the optimal sequence of the solutions is worth more study from a practical application standpoint, such as the study of implementation schedules, the study of optimising implementation orders to save time and cost.

7.3.3 Further validation and verification

The study of the RUSP covered in this thesis is based on theoretical simulation, which provides useful information to find the most appropriate solution for railway renewal projects. Validation and verification remains as the further work. For example, applying the RUSP to those existing successful or not very successful railway renewal projects, and then comparing the results of the RUSP with the solutions that have been implemented to see if the RUSP is effective and efficient.

References

[1] J. Myszczyszyn, "Use of econometric modelling to evaluate the impact of the railways on economic growth of German reich (1879–1913)," *Actual Problems of Economics,* vol. 181, pp. 475-484, 2016.

[2] P. Caruana-Galizia and J. Martí-Henneberg, "European regional railways and real income, 1870-1910: A preliminary report," *Scandinavian Economic History Review,* vol. 61, pp. 167-196, 2013.

[3] F. Jin and J. Wang, "Railway network expansion and spatial accessibility analysis in China: 1906-2000," *Acta Geographica Sinica,* vol. 59, pp. 293-302, 2004.

[4] Department for Transport, "2010 to 2015 government policy: rail network," 2015.

[5] E. D. Kreutzberger, "Distance and time in intermodal goods transport networks in Europe: A generic approach," *Transportation Research Part A: Policy and Practice,* vol. 42, pp. 973-993, 2008.

[6] A. A. Assad, "Models for rail transportation," *Transportation Research Part A: General,* vol. 14, pp. 205-220, 1980.

[7] W. X. Li and S. Yin, "Analysis on cost of urban rail transit," *Jiaotong Yunshu Xitong Gongcheng Yu Xinxi/Journal of Transportation Systems Engineering and Information Technology,* vol. 12, pp. 9-14, 2012.

[8] Department for Transport, "Transport Statistics Great Britain 2016," 2016.

[9] R. A. Smith, "Railways: How they may contribute to a sustainable future," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* vol. 217, pp. 243-248, 2003.

[10] J. Holland, *The Times History of Britain's Railways: From 1603 to the Present Day*: HarperCollins Publishers Limited, 2015.

[11] Network Rail. (2010). *Nine out of ten trains arrive on time during January*. Available: http://www.networkrailmediacentre.co.uk/news/nine-out-of-ten-trains-arrive-on-time-during-january#downloads

[12] N. Nair, "Passenger Rail Usage 2015-16 Q4 Statistical Release," Office of Rail and Road26 May 2016 2016.

[13] N. Nair, "Passenger Rail Usage 2014-15 Quarter 3 Statistical Release," Office of Rail and Road5 March 2015 2015.

[14] M. Wardman and G. Whelan, "Twenty years of rail crowding valuation studies: Evidence and lessons from British experience," *Transport Reviews,* vol. 31, pp. 379-398, 2011.

[15] BBC. (2015, 25 June 2015). *Network Rail upgrade delayed by government*. Available: http://www.bbc.co.uk/news/business-33270586

[16] Network Rail, "Report from Sir Peter Hendy to the Secretary of State for Transport on the replanning of Network Rail's Investment Programme," 2015.

[17] A. Igwe, "The transport challenge in the sustainability of megacities," in *WIT Transactions on the Built Environment*, 2006, pp. 23-32.

[18] D. Pojani and D. Stead, "Sustainable urban transport in the developing world: Beyond megacities," *Sustainability (Switzerland),* vol. 7, pp. 7784-7805, 2015.

[19] W. Liu, H. Lund, and B. V. Mathiesen, "Modelling the transport system in China and evaluating the current strategies towards the sustainable transport development," *Energy Policy,* vol. 58, pp. 347-357, 2013.

[20] Department for Transport, "Delivering a sustainable railway: White paper CM 7176," 2007.

[21] Transport Research Laboratory, "The Second Rail Industry Research Strategy," 2011.

[22] A. D’Ariano, D. Pacciarelli, and M. Pranzo, "Assessment of flexible timetables in real-time traffic management of a railway bottleneck," *Transportation Research Part C: Emerging Technologies,* vol. 16, pp. 232-245, 4// 2008.

[23] Y. V. Bocharnikov, A. M. Tobias, C. Roberts, S. Hillmansen, and C. J. Goodman, "Optimal driving strategy for traction energy saving on DC suburban railways," *IET Electric Power Applications,* vol. 1, pp. 675-682, 2007.

[24] M. Brons and P. Rietveld, "Improving the quality of the door-to-door rail journey: A customer-oriented approach," *Built Environment,* vol. 35, pp. 122-135, 2009.

[25] F. P. García Márquez, R. W. Lewis, A. M. Tobias, and C. Roberts, "Life cycle costs for railway condition monitoring," *Transportation Research Part E: Logistics and Transportation Review,* vol. 44, pp. 1175-1187, 11// 2008.

[26] B. S. Blanchard and W. J. Fabrycky, *Systems engineering and analysis*: Pearson Prentice Hall, 2006.

[27] C. Dickerson and D. N. Mavris, *Architecture and Principles of Systems Engineering*: Taylor & Francis, 2009.

[28] R. Ollerenshaw and P. Murphy, "Assessing safety impact of process change," in *Rail Human Factors Around the World: Impacts on and of People for Successful Rail Operations*, 2012, pp. 579-593.

[29] S. R. McNulty, "Realising the Potential of GB Rail: Final Report of the Rail Value for Money Study : Detailed Report," Department for Transport 9781848641242, 2011.

[30] H. Priemus and B. van Wee, *International Handbook on Mega-Projects*: Edward Elgar Publishing, 2013.

[31] H. Priemus, B. Flyvbjerg, and B. van Wee, *Decision-making on Mega-projects: Cost-benefit Analysis, Planning and Innovation*: Edward Elgar, 2008.

[32] B. J. Elliott, "Benefits of adopting systems engineering approaches in rail projects," Ph.D. Ph.D., School of Civil Engineering, University of Birmingham, 2014.

[33] BBC. (2016). *Great Western rail modernisation costs rocket, says NAO*. Available: http://www.bbc.co.uk/news/business-37914853

[34] NAO, "Modernising the Great Western railway," Department for Transport and Network Rail2016.

[35] P. E. D. Love, J. Zhou, D. J. Edwards, Z. Irani, and C.-P. Sing, "Off the rails: The cost performance of infrastructure rail projects," *Transportation Research Part A: Policy and Practice,* vol. 99, pp. 14-29, 5// 2017.

[36] R. C. Dorf, *The Technology Management Handbook*: Taylor & Francis, 1998.

[37] F. T. S. Chan and N. Kumar, "Global supplier development considering risk factors using fuzzy extended AHP-based approach," *Omega,* vol. 35, pp. 417-431, 8// 2007.

[38] S. Dhir, M. V. Marinov, and D. Worsley, "Application of the analytic hierarchy process to identify the most suitable manufacturer of rail vehicles for High Speed 2," *Case Studies on Transport Policy,* vol. 3, pp. 431-448, 12// 2015.

[39] C.-C. Huang, P.-Y. Chu, and Y.-H. Chiang, "A fuzzy AHP application in government-sponsored R&D project selection," *Omega,* vol. 36, pp. 1038-1052, 12// 2008.

[40] D. Baric, D. Curepic, and Z. Radacic, "Implementation of relevant methods in assessing traffic-technological projects," *Promet-Traffic & Transportation,* vol. 19, pp. 329-336, 2007.

[41] D. Macura, B. Bošković, N. Bojović, and M. Milenković, "A model for prioritization of rail infrastructure projects using ANP," *International Journal of Transport Economics,* vol. 38, pp. 285-309, 2011.

[42] C. Zhu, Z. Wang, and X. Shan, "Evaluation of urban rail network based on analytic network process," in *ICTE 2011 - Proceedings of the 3rd International Conference on Transportation Engineering*, 2011, pp. 31-36.

[43] C. F. Bonnett, *Practical Railway Engineering*: Imperial College Press, 2005.

[44] O. S. Nock, *Railway Signalling*: A & C Black, 1993.

[45] C. Bailey and I. o. R. S. Engineers, *European Railway Signalling*: A & C Black, 1995.

[46] G. Theeg, E. Anders, and S. V. Vlasenko, *Railway Signalling & Interlocking: International Compendium*: Eurailpress, 2009.

[47] F. Schmid and C. J. Goodman, "Overview of electric railway systems," in *IET Conference Publications*, 2014.

[48] M. Chymera and C. J. Goodman, "Overview of electric railway systems and the calculation of train performance," in *IET Seminar Digest*, 2012, pp. 1-18.

[49] F. Amusan, "Freight Rail Usage 2016-17 Q1 Statistical Release," Office of Rail and Road23 November 2016 2016.

[50] I. A. Hansen and J. Pachl, *Railway Timetable & Traffic: Analysis - Modelling - Simulation*: Eurailpress, 2008.

[51] T. K. Ho, C. W. Tsang, K. H. Ip, and K. S. Kwan, "Train service timetabling in railway open markets by particle swarm optimisation," *Expert Systems with Applications,* vol. 39, pp. 861-868, 1// 2012.

[52] J. Törnquist, "Railway traffic disturbance management—An experimental analysis of disturbance complexity, management objectives and limitations in planning horizon," *Transportation Research Part A: Policy and Practice,* vol. 41, pp. 249-266, 3// 2007.

[53] M. Pidd, *Tools for Thinking: Modelling in Management Science*: Wiley, 2009.

[54] D. Jennings and S. Wattam, *Decision Making: An Integrated Approach*: Financial Times Pitman Pub., 1998.

[55] F. Barber, M. Abrill, M. A. Salido, L. P. Ingolotti, P. Tormos, and A. Lova, "Survey of antomated systems for railway management," 2007.

[56] J. P. Bendfeldt, U. Mohr, and L. Müller, "RailSys, a system to plan future railway needs," in *Advances in Transport* vol. 7, ed, 2000, pp. 249-255.

[57] A. Nash and D. Huerlimann, "Railroad simulation using OpenTrack," in *Advances in Transport* vol. 15, ed, 2004, pp. 45-54.

[58] S. Hillmansen and C. Roberts, "Energy storage devices in hybrid railway vehicles: A kinematic analysis," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* vol. 221, pp. 135-143, 2007.

[59] N. Zhao, C. Roberts, S. Hillmansen, and G. Nicholson, "A Multiple Train Trajectory Optimization to Minimize Energy Consumption and Delay," *IEEE Transactions on Intelligent Transportation Systems,* vol. 16, pp. 2363-2372, 2015.

[60] N. Zhao, C. Roberts, and S. Hillmansen, "The application of an enhanced Brute Force Algorithm to minimise energy costs and train delays for differing railway train control systems," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* November 28, 2012 2012.

[61] T. Schlechte, R. Borndörfer, B. Erol, T. Graffagnino, and E. Swarat, "Micro–macro transformation of railway networks," *Journal of Rail Transport Planning & Management,* vol. 1, pp. 38-48, 11// 2011.

[62] T. H. Poister, *Measuring Performance in Public and Nonprofit Organizations*: Wiley, 2008.

[63] M. Franco-Santos and M. Bourne, "An examination of the literature relating to issues affecting how companies manage through measures," *Production Planning and Control,* vol. 16, pp. 114-124, 2005.

[64] R. D. Behn, "Why Measure Performance? Different Purposes Require Different Measures," *Public Administration Review,* vol. 63, pp. 586-606, 2003.

[65] J. O. Onatere, C. Nwagboso, and P. Georgakis, "Performance indicators for rail transport system in Nigeria," in *T and DI Congress 2014: Planes, Trains, and Automobiles - Proceedings of the 2nd Transportation and Development Institute Congress*, 2014, pp. 753-764.

[66] G. L. N. M. Lu, F. Schmid, L. Dai, L. Chen, C. Roberts, "A Framework of the Evalution of the Performance of Railway Networks," *The International Journal of Railway Technology,* vol. 2, 2013.

[67] A. González-Gil, R. Palacin, and P. Batty, "Optimal energy management of urban rail systems: Key performance indicators," *Energy Conversion and Management,* vol. 90, pp. 282-291, 2014.

[68] M. Abril, F. Barber, L. Ingolotti, M. A. Salido, P. Tormos, and A. Lova, "An assessment of railway capacity," *Transportation Research Part E: Logistics and Transportation Review,* vol. 44, pp. 774-806, 2008.

[69] International Union of Railways, "UIC Code 406 (1st edition)," 2004.

[70] E. Kozan and R. Burdett, "A railway capacity determination model and rail access charging methodologies," *Transportation Planning and Technology,* vol. 28, pp. 27-45, 2005.

[71] International Union of Railways, "UIC Code 405," 1983.

[72] International Union of Railways, "UIC Code 406," 2012.

[73] T. Lindner, "Applicability of the analytical UIC Code 406 compression method for evaluating line and station capacity," *Journal of Rail Transport Planning & Management,* vol. 1, pp. 49-57, 11// 2011.

[74] A. Landex, "Evaluation of Railway Networks with Single Track Operation Using the UIC 406 Capacity Method," *Networks & Spatial Economics,* vol. 9, pp. 7-23, Mar 2009.

[75] International Energy Agency and International Union of Railways, "Railway Handbook 2015 - Energy Consumption and CO_2 Emissions," International Energy Agency & International Union of Railways2015.

[76] Department for Transport, "Creating Growth, Cutting Carbon - Making Sustainable Local Transport Happen," 2011.

[77] HM Goverment, "The Carbon Plan: Delivering our low carbon future," 2011.

[78] European Commission, "White Paper: Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system," 2011.

[79] C. Casanovas, "Rail infrastructure, assets and environmental 2015-16 Annual Statistical Release," Office of Rail and Road27 October 2016 2016.

[80] Department for Environment, Food & Rural Affairs, "2011 Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors," 2011.

[81] H. Douglas, C. Roberts, S. Hillmansen, and F. Schmid, "An assessment of available measures to reduce traction energy use in railway networks," *Energy Conversion and Management,* vol. 106, pp. 1149-1165, 12// 2015.

[82] Z. Tian, S. Hillmansen, C. Roberts, P. Weston, N. Zhao, L. Chen, *et al.*, "Energy evaluation of the power network of a DC railway system with regenerating trains," *IET Electrical Systems in Transportation,* vol. 6, pp. 41-49, 2016.

[83] T. Focus, "Franchising: what passengers want," 23 November 2016 2016.

[84] N. Best, B. Hyland, and S. Waters, "UK railway system reliability - modelling the future - a case study," in *22nd Annual International Symposium of the International Council on Systems Engineering, INCOSE 2012 and the 8th Biennial European Systems Engineering Conference 2012, EuSEC 2012*, 2012, pp. 945-962.

[85] R. M. P. Goverde, "Punctuality of Railway Operations and Timetable Stability Analysis," PhD, Netherlands TRAIL Research School for Transport, Infrastructure and Logistics, Delft University of Technology, Netherlands, 2005.

[86] X. W. Zhang, H. H. Dong, L. M. Jia, X. P. Ma, and Y. C. He, "Research on the passenger comfort evaluation system of urban rail transit," in *Proceedings of the 2015 27th Chinese Control and Decision Conference, CCDC 2015*, 2015, pp. 3389-3392.

[87] Department for Transport, "Rail passenger numbers and crowding statistics: notes and definitions," Department of Transport.

[88] N. D. Mohd Mahudin, T. Cox, and A. Griffiths, "Measuring rail passenger crowding: Scale development and psychometric properties," *Transportation Research Part F: Traffic Psychology and Behaviour,* vol. 15, pp. 38-51, 1// 2012.

[89] N. Dulac, "A Framework for Dynamic Safety and Risk Management Modeling in Complex Engineering Systems," PhD, Department of Aeronautical and Astronautical Engineering, Massachusetts Institute of Technology, 2007.

[90] D. Elms, "Rail safety," *Reliability Engineering & System Safety,* vol. 74, pp. 291-297, 12// 2001.

[91] J. J. Chen, F. Chen, Q. H. Liang, and G. F. Gao, "Whole life-cycle cost analysis of urban rail transit," *Jiaotong Yunshu Gongcheng Xuebao/Journal of Traffic and Transportation Engineering,* vol. 10, pp. 82-87, 2010.

[92] Y. Rong, X. Zhang, Baiyun, L. Liu, Y. Chen, and Y. Sun, "Life cycle cost analysis of urban rail transit vehicle," in *Proceedings - 2016 8th International Conference on Measuring Technology and Mechatronics Automation, ICMTMA 2016*, 2016, pp. 375-378.

[93] D. Gattuso and A. Restuccia, "A Tool for Railway Transport Cost Evaluation," *Procedia - Social and Behavioral Sciences,* vol. 111, pp. 549-558, 2/5/ 2014.

[94] A. FRANKLIN, *Railways Little Black Book - Construction Cost Data Guide 2004*: FRAKLIN ANDREWS Construction Economists, 2004.

[95] J. P. Baumgartner, *Prices and Costs in the Railway Sector*: Institut des transports et de planification, 2001.

[96] R. Gr]nig and R. Kühn, *Successful Decision-making: A Systematic Approach to Complex Problems*: Springer, 2005.

[97] R. T. Clemen, *Making Hard Decisions: An Introduction to Decision Analysis*: Duxbury Press, 1996.

[98] J. Adair, *Effective Decision Making: The Essential Guide to Thinking for Management Success*: Pan Macmillan, 2009.

[99] H. Noorani, *Rational Decision-Making*: Xlibris US, 2010.

[100] B. M. Roth and J. D. Mullen, *Decision Making: Its Logic and Practice*: Rowman & Littlefield Publishers, Incorporated, 2002.

[101] E. Triantaphyllou, *Multi-criteria Decision Making Methods: A Comparative Study*: Springer US, 2000.

[102] Y. P. Pavlov, *Decision Control, Management, and Support in Adaptive and Complex Systems: Quantitative Models: Quantitative Models*: Information Science Reference, 2013.

[103] E. Tsang, *Foundations of Constraint Satisfaction*: Academic Press, 1993.

[104] Y. Collette and P. Siarry, *Multiobjective Optimization: Principles and Case Studies*: Springer Berlin Heidelberg, 2013.

[105] K. Deb, *Multi-Objective Optimization Using Evolutionary Algorithms*: Wiley, 2001.

[106] M. Velasquea and P. T. Hester, "An analysis of Multi-Criteria Decision Making Methods," *International Journal of Operations Research,* vol. 10, pp. 56-66, 2013.

[107] G. Kabir, R. Sadiq, and S. Tesfamariam, "A review of multi-criteria decision-making methods for infrastructure management," *Structure and Infrastructure Engineering,* vol. 10, pp. 1176-1210, 2014/09/02 2014.

[108] T. L. Saaty, *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*: RWS Publications, 1994.

[109] T. L. Saaty, "How to make a decision: The analytic hierarchy process," *European Journal of Operational Research,* vol. 48, pp. 9-26, 9/5/ 1990.

[110] G. M. Giovanni Longo, Elio Padoano, "Using Simulation to Assess Infrastructure Performance in Multicriteria Evaluation of Railway Projects," presented at the 2nd International Conference on Road and Rail Infrastructure, Dubrovnik, Croatia, 2012.

[111] G. Longo, E. Padaono, P. Rosato, and S. Strami, "Considerations on the Application of AHP/ANP Mthodologies to Decisions Concerning a Railway Infrastrucutre," *Proceedings of the International Symposium on the Analytic Hierarchy Process,* 2009.

[112] B. Van Wee, "Rail Infrastructure: Challenges for Cost-Benefit Analysis and Other ex ante Evaluations," *Transportation Planning and Technology,* vol. 30, pp. 31-48, 2007.

[113] A. E. Boardman, D. H. Greenberg, A. R. Vining, and D. L. Weimer, *Cost-benefit Analysis: Concepts and Practice*: Pearson/Prentice Hall, 2006.

[114] R. J. Brent, *Applied Cost-benefit Analysis*: E. Elgar Pub., 1996.

[115] I. Ambrasaite, M. B. Barfod, and K. B. Salling, "MCDA and Risk Analysis in Transport Infrastructure Appraisals: the Rail Baltica Case," *Procedia - Social and Behavioral Sciences,* vol. 20, pp. 944-953, 2011/01/01 2011.

[116] L. A. Zadeh, "The concept of a linguistic variable and its application to approximate reasoning—I," *Information Sciences,* vol. 8, pp. 199-249, 1975/01/01 1975.

[117] G. Perrone, "Fuzzy multiple criteria decision model for the evaluation of AMS," *Computer Integrated Manufacturing Systems,* vol. 7, pp. 228-239, 1994/11/01 1994.

[118] Department for Transport, "Transport analysis guidance: WebTAG," 2013.

[119] Transportation Research Board, "Transit Capacity and Quality of Service Manual, Third Edition," 2014.

[120] Y. Lai and C. P. L. Barkan, "Comprehensive Decision Support Framework for Strategic Railway Capacity Planning," *Journal of Transportation Engineering,* vol. 137, pp. 738-749, 2011.

[121] F. S. C Roberts, P Connor, V Ramdas, J sharpe, "A new railway system capacity model," 2010.

[122] C. R. V Ramdas, J Sharpe, L Chen, "Client Project Report: Rail Capability Trade-Offs Phase II Report," 2011.

[123] Network Rail, "East Coast Main Line Route Utilisation Strategy," 2008.

[124] Network Rail, "Network Route Utilisation Strategy: Scenarios & Long Distance Forecasts," 2009.

[125] Network Rail, "West Coast Main Line Route Utilisation Strategy," 2011.

[126] Network Rail, "Great Westren Route Utilisation Strategy," 2010.

[127] Network Rail, "West Midlands and Chiltern Route Utilisation Strategy," 2011.

[128] Network Rail, "East Midlands Route Utilisation Strategy," 2010.

[129] Network Rail, "Kent Route Utilisation Strategy," 2010.

[130] Network Rail, "Cross London Route Utilisation Strategy," 2006.

[131] Network Rail, "South West Main Line Route Utilisation Strategy," 2006.

[132] Network Rail, "Scotland Route Utilisation Strategy," 2007.

[133] Network Rail, "North West Route Utilisation Strategy," 2007.

[134] Network Rail, "Greater Anglia Route Utilisation Strategy," 2007.

[135] Network Rail, "South London Route Utilisation Strategy," 2008.

[136] Network Rail, "Lancashire and Cumbria Route Utilisation Strategy," 2008.

[137] Network Rail, "Wales Route Utilisation Strategy," 2008.

[138] Network Rail, "Merseyside Route Utilisation Strategy," 2009.

[139] Network Rail, "Yorkshire and Humber Route Utilisation Strategy," 2009.

[140] Network Rail, "Sussex Route Utilisation Strategy," 2010.

[141] Network Rail, "Freight Route Utilisation Strategy," 2007.

[142] Network Rail, "Network RUS: Alternative Solutions," 2013.

[143] Network Rail, "Network RUS: Staions," 2011.

[144] Network Rail, "Network RUS: Passenger Rolling Stock," 2011.

[145] Network Rail, "Network RUS: Electrification," 2009.

[146] D. Woodland, "Optimisation of automatic train protection systems," University of Sheffield, 2005.

[147] T. Xin, C. Roberts, J. He, S. Hillmansen, N. Zhao, L. Chen*, et al.*, "Railway vertical alignment optimisation at stations to minimise energy," in *17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, 2014, pp. 2119-2124.

[148] O. Lindfeldt, "From single to double track: Effects of alternative extension measures," in *WIT Transactions on the Built Environment*, 2012, pp. 313-324.

[149] T. A. Kneschke, "Simple Method for Determination of Substation Spacing for AC and DC Electrification Systems," *IEEE Transactions on Industry Applications,* vol. IA-22, pp. 763-780, 1986.

[150] P. M. Salmon, G. J. M. Read, N. A. Stanton, and M. G. Lenné, "The crash at Kerang: Investigating systemic and psychological factors leading to unintentional non-compliance at rail level crossings," *Accident Analysis & Prevention,* vol. 50, pp. 1278-1288, 1// 2013.

[151] P. M. Salmon, M. G. Lenné, G. J. M. Read, C. M. Mulvihill, M. Cornelissen, G. H. Walker*, et al.*, "More than meets the eye: Using cognitive work analysis to identify design requirements for future rail level crossing systems," *Applied Ergonomics,* vol. 53, Part B, pp. 312-322, 3// 2016.

[152] G. Li, "Approach for evaluating the effectiveness of rail freight transport in reducing logistics costs and carbon dioxide (CO2) emissions," *Quarterly Report of RTRI (Railway Technical Research Institute) (Japan),* vol. 52, pp. 76-80, 2011.

[153] A. Ballis and J. Golias, "Comparative evaluation of existing and innovative rail-road freight transport terminals," *Transportation Research Part A: Policy and Practice,* vol. 36, pp. 593-611, 2002.

[154] A. Landex, A. H. Kaas, B. Schittenhelm, and J. Schneider-Tilli, "Evaluation of railway capacity," in *Proceedings of Trafficdays*, ed, 2006.

[155] G. Parker, "Modelling the real-time performance of noise barriers for the night time operation of a rail-freight terminal," in *20th International Congress on Acoustics 2010, ICA 2010 - Incorporating Proceedings of the 2010 Annual Conference of the Australian Acoustical Society*, 2010, pp. 2249-2254.

[156] S. Lu, S. Hillmansen, T. K. Ho, and C. Roberts, "Single-Train Trajectory Optimization," *IEEE Transactions on Intelligent Transportation Systems,* vol. 14, pp. 743-750, 2013.

[157] Network Rail, "Comparing environmental impact of conventional and high speed rail."

[158] A. GARCIA, "High speed, energy consumption and emissions," International Union of Railways 2010.

[159] NetworkRail, "London North Easterm Route Sectional Appendix Module LN1," 2006-2014.

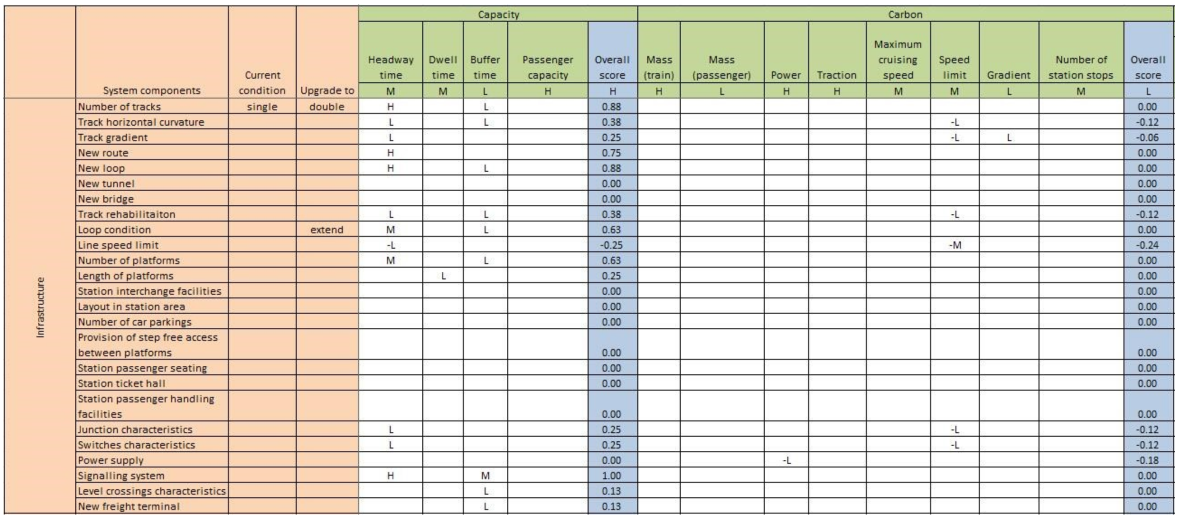
[160] Translink, "Northern Ireland Transport Statistics 2014-15," 2014-15.

[161] Translink, "The Translink Corporate Plan 2015/16 -2017/18 & Business Plan 2015/16," 2015.

Appendix A

The HFAM results from industry expert group investigation on the Northern Ireland railway network for the single-track and double-track sections are attached below.

Table 1: NIRN results of the HFAM on single-track sections (Part 1)



				Capacity					Carbon								
	System components	Current condition	Upgrade to	Headway time	Dwell time	Buffer time	Passenger capacity	Overall score	Mass (train)	Mass (passenger)	Power	Traction	Maximum cruising speed	Speed limit	Gradient	Number of station stops	Overall score
				M	M	L	H	H	H	L	H	H	M	M	L	M	L
Infrastructure	Number of tracks	single	double	H		L		0.88									0.00
	Track horizontal curvature			L		L		0.38						-L			-0.12
	Track gradient			L				0.25						-L	L		-0.06
	New route			H				0.75									0.00
	New loop			H		L		0.88									0.00
	New tunnel							0.00									0.00
	New bridge							0.00									0.00
	Track rehabilitaiton			L		L		0.38						-L			-0.12
	Loop condition		extend	M		L		0.63									0.00
	Line speed limit			-L				-0.25						-M			-0.24
	Number of platforms			M		L		0.63									0.00
	Length of platforms				L			0.25									0.00
	Station interchange facilities							0.00									0.00
	Layout in station area							0.00									0.00
	Number of car parkings							0.00									0.00
	Provision of step free access between platforms							0.00									0.00
	Station passenger seating							0.00									0.00
	Station ticket hall							0.00									0.00
	Station passenger handling facilities							0.00									0.00
	Junction characteristics			L				0.25						-L			-0.12
	Switches characteristics			L				0.25						-L			-0.12
	Power supply							0.00			-L						-0.18
	Signalling system			H		M		1.00									0.00
	Level crossings characteristics					L		0.13									0.00
	New freight terminal					L		0.13									0.00

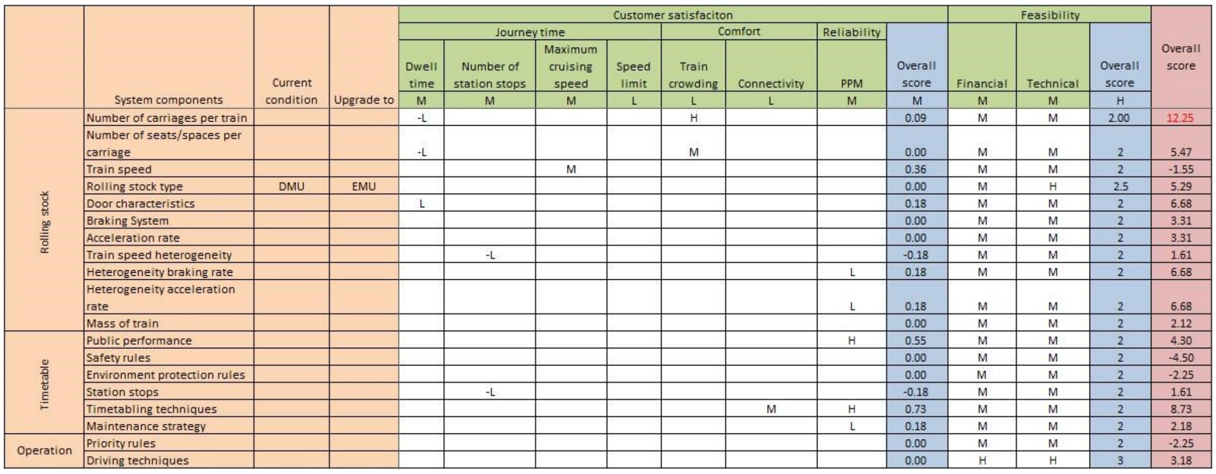
Table 2: NIRN results of the HFAM on single-track sections (Part 2)

				Customer satisfaciton								Feasibility			Overall score
				Journey time				Comfort		Reliability					
	System components	Current condition	Upgrade to	Dwell time	Number of station stops	Maximum cruising speed	Speed limit	Train crowding	Connectivity	PPM	Overall score	Financial	Technical	Overall score	
				M	M	M	L	L	L	M	M	M	M	H	
Infrastructure	Number of tracks	single	double							H	0.55	L	L	1.00	11.15
	Track horizontal curvature						L				0.09	L	L	1.00	3.57
	Track gradient						L				0.09	M	M	2.00	5.24
	New route										0.00	L	L	1.00	6.75
	New loop										0.00	M	M	2.00	15.75
	New tunnel										0.00	L	L	1.00	0.00
	New bridge										0.00	L	L	1.00	0.00
	Track rehabilitaiton						L			L	0.27	M	M	2.00	9.32
	Loop condition		extend								0.00	H	H	3.00	16.88
	Line speed limit						M				0.18	M	M	2.00	-3.73
	Number of platforms										0.00	L	L	1.00	5.63
	Length of platforms										0.00	M	M	2.00	4.50
	Station interchange facilities								H		0.27	M	M	2.00	3.27
	Layout in station area								L		0.09	M	M	2.00	1.09
	Number of car parkings										0.00	M	M	2.00	0.00
	Provision of step free access between platforms								L		0.09	M	M	2.00	1.09
	Station passenger seating										0.00	M	M	2.00	0.00
	Station ticket hall										0.00	M	M	2.00	0.00
	Station passenger handling facilities								L		0.09	M	M	2.00	1.09
	Junction characteristics						L				0.09	L	L	1.00	2.44
	Switches characteristics						L				0.09	L	L	1.00	2.44
	Power supply										0.00	L	L	1.00	-0.53
	Signalling system									L	0.18	L	L	1.00	10.09
	Level crossings characteristics										0.00	L	L	1.00	1.13
	New freight terminal										0.00	L	L	1.00	1.13

Table 3: NIRN results of the HFAM on single-track sections (Part 3)

				Capacity					Carbon								
	System components	Current condition	Upgrade to	Headway time	Dwell time	Buffer time	Passenger capacity	Overall score	Mass (train)	Mass (passenger)	Power	Traction	Maximum cruising speed	Speed limit	Gradient	Number of station stops	Overall score
				M	M	L	H	H	H	L	H	H	M	M	L	M	L
Rolling stock	Number of carriages per train				-L		H	0.88	-M	-L	-L	-L					-0.76
	Number of seats/spaces per carriage				-L		M	0.50	-L	-L	-L	-L					-0.59
	Train speed			-L				-0.25					-M				-0.24
	Rolling stock type	DMU	EMU					0.00			M	M					0.71
	Door characteristics				L			0.25									0.00
	Braking System					L		0.13				L					0.18
	Acceleration rate					L		0.13				L					0.18
	Train speed heterogeneity			L				0.25								-L	-0.12
	Heterogeneity braking rate			L				0.25									0.00
	Heterogeneity acceleration rate			L				0.25									0.00
	Mass of train							0.00	M								0.35
Timetable	Public performance					-L		-0.13									0.00
	Safety rules			-L				-0.25									0.00
	Environment protection rules					-L		-0.13									0.00
	Station stops			L				0.25								-L	-0.12
	Timetabling techniques							0.00									0.00
	Maintenance strategy							0.00									0.00
Operation	Priority rules					-L		-0.13									0.00
	Driving techniques							0.00					H				0.35

Table 4: NIRN results of the HFAM on single-track sections (Part 4)



				Customer satisfaciton								Feasibility			Overall score
				Journey time				Comfort		Reliability					
	System components	Current condition	Upgrade to	Dwell time	Number of station stops	Maximum cruising speed	Speed limit	Train crowding	Connectivity	PPM	Overall score	Financial	Technical	Overall score	
				M	M	M	L	L	L	M	M	M	M	H	
Rolling stock	Number of carriages per train			-L				H			0.09	M	M	2.00	12.25
	Number of seats/spaces per carriage			-L				M			0.00	M	M	2	5.47
	Train speed					M					0.36	M	M	2	-1.55
	Rolling stock type	DMU	EMU								0.00	M	H	2.5	5.29
	Door characteristics			L							0.18	M	M	2	6.68
	Braking System										0.00	M	M	2	3.31
	Acceleration rate										0.00	M	M	2	3.31
	Train speed heterogeneity				-L						-0.18	M	M	2	1.61
	Heterogeneity braking rate									L	0.18	M	M	2	6.68
	Heterogeneity acceleration rate									L	0.18	M	M	2	6.68
	Mass of train										0.00	M	M	2	2.12
Timetable	Public performance									H	0.55	M	M	2	4.30
	Safety rules										0.00	M	M	2	-4.50
	Environment protection rules										0.00	M	M	2	-2.25
	Station stops				-L						-0.18	M	M	2	1.61
	Timetabling techniques								M	H	0.73	M	M	2	8.73
	Maintenance strategy									L	0.18	M	M	2	2.18
Operation	Priority rules										0.00	M	M	2	-2.25
	Driving techniques										0.00	H	H	3	3.18

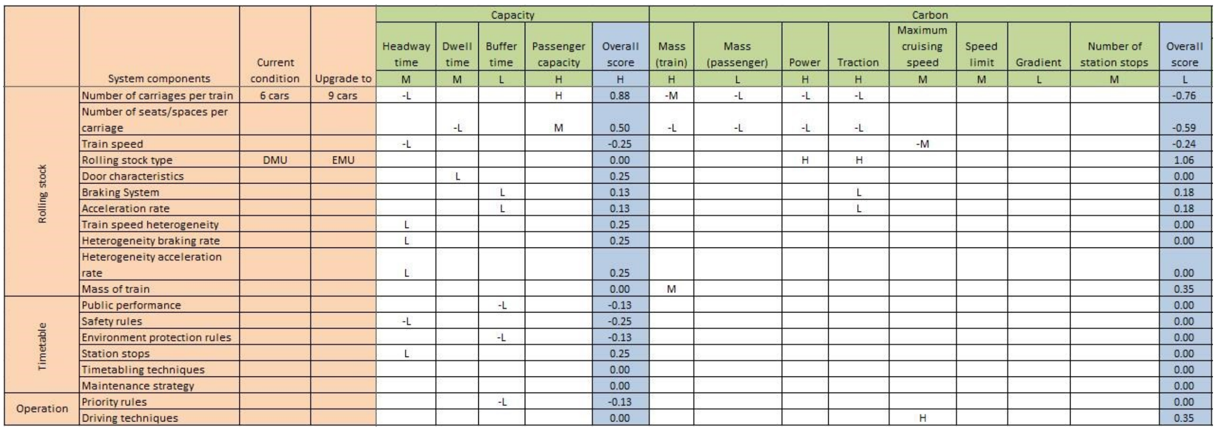
Table 5: NIRN results of the HFAM on double-track sections (Part 1)

				Capacity					Carbon								
		Current		Headway time	Dwell time	Buffer time	Passenger capacity	Overall score	Mass (train)	Mass (passenger)	Power	Traction	Maximum cruising speed	Speed limit	Gradient	Number of station stops	Overall score
	System components	condition	Upgrade to	M	M	L	H	H	H	L	H	H	M	M	L	M	L
Infrastructure	Number of tracks	double	third	M		L		0.63									0.00
	Track horizontal curvature			L		L		0.38						-L			-0.12
	Track gradient			L				0.25						-L	L		-0.06
	New route							0.00									0.00
	New loop							0.00									0.00
	New tunnel							0.00									0.00
	New bridge							0.00									0.00
	Track rehabilitaiton					L		0.13									0.00
	Loop condition		extend					0.00									0.00
	Line speed limit			-L				-0.25						-M			-0.24
	Number of platforms					L		0.13									0.00
	Length of platforms				L			0.25									0.00
	Station interchange facilities							0.00									0.00
	Layout in station area							0.00									0.00
	Number of car parkings							0.00									0.00
	Provision of step free access between platforms							0.00									0.00
	Station passenger seating							0.00									0.00
	Station ticket hall							0.00									0.00
	Station passenger handling facilities							0.00									0.00
	Junction characteristics			L				0.25						-L			-0.12
	Switches characteristics			L				0.25						-L			-0.12
	Power supply							0.00			-L						-0.18
	Signalling system	3-aspect	4-aspect	H		M		1.00									0.00
	Level crossings characteristics					L		0.13									0.00
	New freight terminal					L		0.13									0.00
	Number of carriages per train	6 cars	9 cars	-L			H	0.88	-M	-L	-L	-L					-0.76

Table 6: NIRN results of the HFAM on double-track sections (Part 2)

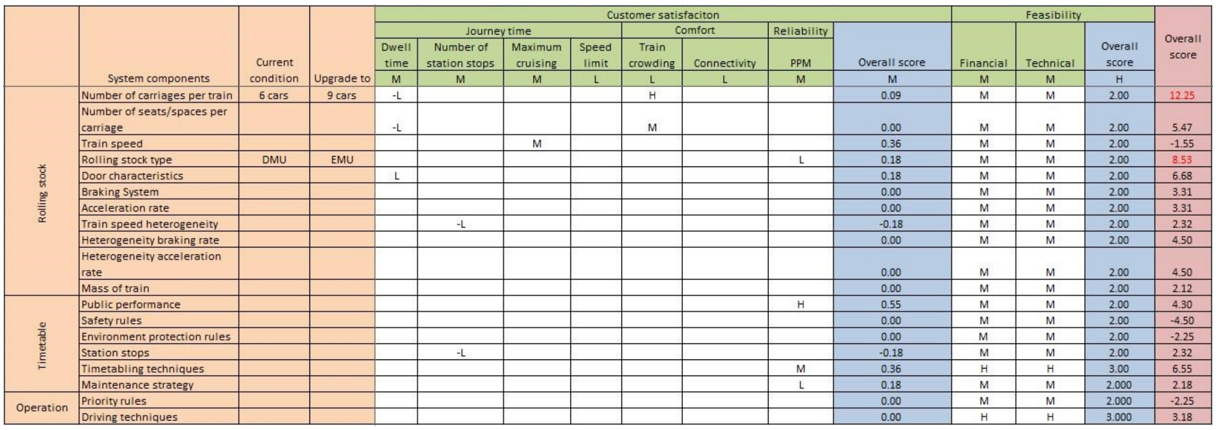
				Customer satisfaciton								Feasibility			Overall score
				Journey time				Comfort		Reliability					
		Current		Dwell time	Number of station stops	Maximum cruising	Speed limit	Train crowding	Connectivity	PPM	Overall score	Financial	Technical	Overall score	
	System components	condition	Upgrade to	M	M	M	L	L	L	M	M	M	M	H	
Infrastructure	Number of tracks	double	third							L	0.18	L	L	1.00	6.72
	Track horizontal curvature						L				0.09	L	L	1.00	3.57
	Track gradient						L				0.09	M	M	2.00	5.24
	New route										0.00	L	L	1.00	0.00
	New loop										0.00	L	L	1.00	0.00
	New tunnel										0.00	L	L	1.00	0.00
	New bridge										0.00	L	L	1.00	0.00
	Track rehabilitaiton									L	0.18	M	M	2.00	4.43
	Loop condition		extend								0.00	M	M	2.00	0.00
	Line speed limit						M				0.18	M	M	2.00	-3.73
	Number of platforms										0.00	L	L	1.00	1.13
	Length of platforms										0.00	M	M	2.00	4.50
	Station interchange facilities								H		0.27	M	M	2.00	3.27
	Layout in station area								L		0.09	M	M	2.00	1.09
	Number of car parkings										0.00			0.00	0.00
	Provision of step free access between platforms								L		0.09	M	M	2.00	1.09
	Station passenger seating										0.00	M	M	2.00	0.00
	Station ticket hall										0.00	M	M	2.00	0.00
	Station passenger handling facilities								L		0.09	M	M	2.00	1.09
	Junction characteristics						L				0.09	L	L	1.00	2.44
	Switches characteristics						L				0.09	L	L	1.00	2.44
	Power supply										0.00	L	L	1.00	-0.53
	Signalling system	3-aspect	4-aspect								0.00	L	L	1.00	9.00
	Level crossings characteristics										0.00	L	L	1.00	1.13
	New freight terminal										0.00	L	L	1.00	1.13

Table 7: NIRN results of the HFAM on double-track sections (Part 3)



				Capacity					Carbon								
	System components	Current condition	Upgrade to	Headway time	Dwell time	Buffer time	Passenger capacity	Overall score	Mass (train)	Mass (passenger)	Power	Traction	Maximum cruising speed	Speed limit	Gradient	Number of station stops	Overall score
				M	M	L	H	H	H	L	H	H	M	M	L	M	L
Rolling stock	Number of carriages per train	6 cars	9 cars	-L			H	0.88	-M	-L	-L	-L					-0.76
	Number of seats/spaces per carriage				-L		M	0.50	-L	-L	-L	-L					-0.59
	Train speed			-L				-0.25					-M				-0.24
	Rolling stock type	DMU	EMU					0.00			H	H					1.06
	Door characteristics				L			0.25									0.00
	Braking System					L		0.13				L					0.18
	Acceleration rate					L		0.13				L					0.18
	Train speed heterogeneity			L				0.25									0.00
	Heterogeneity braking rate			L				0.25									0.00
	Heterogeneity acceleration rate			L				0.25									0.00
	Mass of train							0.00	M								0.35
Timetable	Public performance					-L		-0.13									0.00
	Safety rules			-L				-0.25									0.00
	Environment protection rules					-L		-0.13									0.00
	Station stops			L				0.25									0.00
	Timetabling techniques							0.00									0.00
	Maintenance strategy							0.00									0.00
Operation	Priority rules					-L		-0.13									0.00
	Driving techniques							0.00					H				0.35

Table 8: NIRN results of the HFAM on double-track sections (Part 4)



				Customer satisfaciton								Feasibility			Overall score
				Journey time				Comfort		Reliability					
	System components	Current condition	Upgrade to	Dwell time	Number of station stops	Maximum cruising	Speed limit	Train crowding	Connectivity	PPM	Overall score	Financial	Technical	Overall score	
				M	M	M	L	L	L	M	M	M	M	H	
Rolling stock	Number of carriages per train	6 cars	9 cars	-L				H			0.09	M	M	2.00	12.25
	Number of seats/spaces per carriage			-L				M			0.00	M	M	2.00	5.47
	Train speed					M					0.36	M	M	2.00	-1.55
	Rolling stock type	DMU	EMU							L	0.18	M	M	2.00	8.53
	Door characteristics			L							0.18	M	M	2.00	6.68
	Braking System										0.00	M	M	2.00	3.31
	Acceleration rate										0.00	M	M	2.00	3.31
	Train speed heterogeneity				-L						-0.18	M	M	2.00	2.32
	Heterogeneity braking rate										0.00	M	M	2.00	4.50
	Heterogeneity acceleration rate										0.00	M	M	2.00	4.50
	Mass of train										0.00	M	M	2.00	2.12
Timetable	Public performance									H	0.55	M	M	2.00	4.30
	Safety rules										0.00	M	M	2.00	-4.50
	Environment protection rules										0.00	M	M	2.00	-2.25
	Station stops				-L						-0.18	M	M	2.00	2.32
	Timetabling techniques									M	0.36	H	H	3.00	6.55
	Maintenance strategy									L	0.18	M	M	2.000	2.18
Operation	Priority rules										0.00	M	M	2.000	-2.25
	Driving techniques										0.00	H	H	3.000	3.18