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Optimising the Economic Feasibility of High-Speed Maglev Systems: A Simulation-Based Approach for Variable and Parameter Analysis

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ABSTRACT

This study introduces an advanced software platform and process for the quantitative national economic evaluation of high-speed maglev systems, overcoming limitations of traditional methods through parameter variation experiments and automated solution search. Utilising the adapted German standardised evaluation, this research demonstrates how integrated modelling, evaluation and optimisation software can deeply analyse the impact of various variables and parameters on economic outcomes. By employing an optimisation algorithm, the software not only determines critical evaluation parameters to ensure benefits exceed costs but also deduces optimised model variables. The macroeconomic benefit-cost ratio guides the optimal design concept, with the research finding a critical value for ensuring economic feasibility. The proposed solution achieves a 22% improvement in this ratio (1.106 vs. 0.909) compared to the existing Hefei-Wuhu route, highlighting its potential for large-scale maglev implementation. Future development directions include integration with micro-simulation systems, support for random behaviour, sensitivity analysis, data-driven machine learning and enhanced user interface design for broader applicability. The findings underscore the software's capability to provide robust, data-driven insights for economic feasibility studies of high-speed maglev systems, presenting a significant step forward in infrastructure project evaluation.

KEYWORDS

standardised evaluation; high-speed maglev; modal variable; evaluation parameter; optimisation; economic feasibility; critical value.

1. INTRODUCTION

The standardised evaluation method [1] has been enacted as a mandatory standard procedure for investment in infrastructure construction for urban and regional public transport projects in Germany. The method has also been employed for the assessment of the high-speed maglev line connecting the airport to the main railway station in Munich [2]. Taking into account the operational experience of the high-speed magnetic levitation demonstration line in Shanghai, an adapted standardised evaluation was carried out for the Hefei-Wuhu high-speed maglev line in Anhui Province [3]. Based on the data conditions and assumptions given in the evaluation, in comparison with a normal high-speed rail system, the operation of high-speed maglev in Hefei-Wuhu cannot guarantee that the national economic benefits outweigh the costs, whereas an extension to Guangde (in Anhui Province) is able to reach a balance and achieve profitability. The results of this study prove the applicability of the adapted German standardised evaluation method to high-speed maglev. However, there are also the following shortcomings:

1) The influence of each parameter and variable on the evaluation results cannot be represented.

2) It is unable to automatically search for the optimal solution within the solution space. Moreover, improving different design alternatives requires manual adjustments by the designer, and the advancement of design alternatives heavily relies on the designer's experience.
3) There is a lack of a software platform to conduct parameter and variable analysis as well as solution optimisation.

This paper aims to address these shortcomings by establishing a software platform and process for conducting quantitative national economic evaluation, focusing on variable and parameter analysis and optimisation algorithm development.

The main content of the seven chapters of the paper is as follows. Chapter 1 introduces the research background and content. A literature review of the present research is presented in Chapter 2. The research methods and the workflow of the process are presented in Chapter 3. Chapter 4 provides the modelling and simulation of transport systems based on AnyLogic. In Chapter 5, the influence of model variables and parameters on the evaluation is analysed. Chapter 6 describes the design of the optimisation algorithm and the results of optimisation. Finally, Chapter 7 presents the conclusion of this research and prospects for follow-up research.

2. Literature review

High-speed maglev trains represent a potential future in high-speed transportation, offering faster travel times, smoother rides and potentially lower environmental impact compared to conventional high-speed rail. However, their high upfront construction costs raise concerns about their economic viability.

Cost-benefit analysis (CBA) is a traditional approach that measures economic viability by comparing projected costs with expected benefits. [3–6] have analysed the cost-benefit aspects of maglev systems, including construction, operation and maintenance costs, against the economic benefits, such as reduced travel time, increased connectivity and potential for regional economic growth.

Multi-criteria decision analysis (MCDA) incorporates qualitative factors like environmental impact, noise pollution and social equity alongside economic metrics [7]. Assigning weights to different criteria can be subjective and lead to biased results. Selecting appropriate criteria also requires careful consideration. Studies like [8–9] illustrate the approach with lifecycle analysis (LCA) to consider the impacts of the maglev system throughout the entire life cycle. Real options analysis (ROA) acknowledges the inherent uncertainties in large infrastructure projects and allows for flexibility in decision-making. It evaluates the value of waiting and adapting to changing circumstances [10–11].

Emerging methodologies include agent-based modelling that simulates the interactions of individual agents (e.g., passengers, operators) within the maglev system to understand its dynamic behaviour and potential economic impacts [12]. While recent years have seen successful applications of big data analytics, data-driven approaches and machine learning in transportation planning and operations, a mature method for integrating economic evaluation and operational simulation for high-speed maglev systems is still lacking. This gap stems from two key challenges: limited software platforms and data availability.

Traditional evaluation methods often rely on manually set schemes with a limited ability to fully represent the influence of various parameters and variables on the evaluation results. This limitation, coupled with the inability to automatically search for the optimal solution within the solution space and the necessity for manual adjustments by designers, underscores the need for a more advanced approach. The reliance on designer experience for the advancement of design alternatives further highlights the need for a systematic and automated evaluation method. The lack of a software platform to conduct comprehensive parameter and variable analysis, as well as solution optimisation, represents a significant gap in the existing research and practice.

This paper introduces an integrated modelling, evaluation and optimisation software specifically designed for the economic evaluation of high-speed maglev lines. This approach enables a more detailed and dynamic analysis of the impacts of various model variables and evaluation parameters. By employing an optimisation algorithm, the research moves beyond the static comparisons of pre-defined alternatives, allowing for the automated search of an optimal solution within a broader solution space. This method not only identifies the optimised model variables but also calculates the critical value of evaluation parameters, ensuring that the benefits of a project exceed its costs.

3. Research methods

Existing analytical methodologies are predicated on structured calculations, suitable for given traffic models and parameters. To examine the influence of various model variables and parameters on evaluation results, and to discover optimal configurations, it is necessary to develop a unified software platform for simulation, evaluation, analysis and optimisation. Currently, a multitude of generic simulation modelling tools are available [13–15], providing a robust underlying logic and offering users flexible, customisable interfaces.

This study will utilise AnyLogic as a simulation modelling tool [16]. It facilitates modelling using multiple methods such as intelligent-agent-based modeling, discrete-event simulation, and system dynamics, making it easier to validate, communicate and comprehend different design propositions. It offers a clear insight into complex systems, providing observation, analysis and decision-making tools for dynamic processes. Unlike spreadsheet or solver-based analysis, simulation allows the behaviours of the system to be observed at any level of detail and can offer a visual user interface, delivering algorithmic support for user analysis and optimisation.

The data prepared for modelling, analysis and optimisation are categorised into two distinct groups: "Model Variables" and "Evaluation Parameters". Model variables represent the transport model data utilised in specific evaluation projects, encompassing rail infrastructure, vehicles and operational concepts. Their values must be determined based on the specific information of each studied transport system. Evaluation parameters, on the other hand, are parameters employed in the evaluation process that are independent of specific projects. This category includes both universal parameters, such as the conversion factor for monetary evaluation of saved travel time, which can be applied to the evaluation of all projects, as well as project-specific parameters, such as the carbon dioxide emissions per unit energy consumption of maglev trains, specifically relevant to the evaluation of maglev-related projects.

The presented approach will at first complete the simulation of train operations in AnyLogic and national economic evaluations, establishing the model variables and the parameters used for evaluation. It will then analyse the impacts of the model variables and evaluation parameters for system planning and train operations. The optimal design alternatives including the operational mileage and train formation under the objective of maximising the benefit-cost-ratio will be determined. Eventually, the study will deduce the critical values needed for reaching the economic feasibility, to ensure that the benefits of the invested project outweigh the costs. The research methods and process of this project are shown in *Figure 1*.

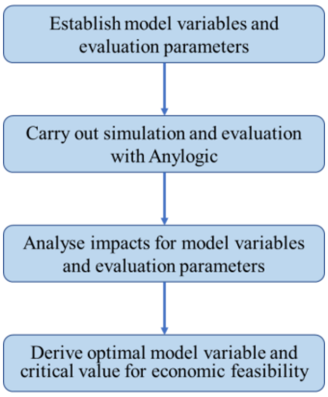


Figure 1 – Research methods and processes

4. Modelling and simulation of transport projects based on AnyLogic

4.1 Data preparation and parameter settings

The project utilises the data from the "Standardised evaluation of Hefei-Wuhu-Guangde high-speed maglev train project" [3] to establish the initial model variables and evaluation parameters. Subsequently, AnyLogic is employed to perform the standardised evaluation and conduct the corresponding analysis and optimisation. To validate the software's accuracy, the evaluation results obtained using AnyLogic must match those calculated through spreadsheets in [3] for the Hefei-Wuhu high-speed maglev project. Both approaches utilise the same database and fundamental assumptions, which will not be discussed in detail in this paper. For analysing and optimising model variables and evaluation parameters, it is essential to define the range of changes based on benchmark-setting parameters. Chapters 4 and 5 will introduce the setting and analysis of the value range for different model variables and evaluation parameters.

Model variables of transport systems need to be set for each subsystem, including infrastructure, vehicles and operations. Values should be provided for both with-case scenarios (high-speed maglev system) and without-case scenarios (high-speed wheel-rail system).

1) Infrastructure: According to the plan of infrastructure, the first step is to determine the relevant geographic information system (GIS) data required for the modelling of stations, routes and other related information used for AnyLogic simulation. The train operating mileage will also be calculated automatically through the GIS module.
2) Vehicles: The train formation and the number of seats per carriage will be provided. Those variables will be set separately for with-case and without-case scenarios.
3) Operations: The daily unidirectional passenger count for with-case and without-case scenarios will be prepared, based on transport plan or statistical data. Meanwhile, the number of train services, the required number of trains, the crew number, the crew size and train schedules will be provided.

In this paper, for without-case scenarios (high-speed wheel-rail system), the data on infrastructure, vehicles and operations can be obtained from existing lines and operating programs. These data are used as inputs in the simulation software PULSim [17] to simulate the required travel time and energy consumption. From these simulation results, further variable values for evaluation are derived and input into AnyLogic. In this project, the simulation results are input as a fixed value in AnyLogic, the integration between PULSim and AnyLogic has not been implemented yet. In future developments, the ability to integrate railway simulation with standardised evaluation and optimisation will be implemented directly within PULSim.

However, modelling with-case scenarios presents a challenge due to the absence of operational data for the 600 km/h maglev system currently under development. Therefore, simulation software cannot be validated based on realistic data. In such cases, this paper adopts the same infrastructure layout as the high-speed wheel-rail system within AnyLogic using GIS data. Design parameters specific to the maglev train, such as the number of carriages and average passenger count per carriage, are treated as variables to analyse their impact on evaluation results and determine optimal settings. Other maglev system parameters are taken from the existing Shanghai Maglev demonstration line [18]. An example to calculate the energy consumption and the resulting emissions is presented in 4.3.

In this study, model variables are determined either through simulation software PULSim or by consulting relevant literature. Economic evaluation and parameter optimisation are achieved through Java classes written in AnyLogic. Future development aims to integrate the simulation software and the evaluation model within AnyLogic, leveraging the shared Java programming language for seamless integration.

Similar to the settings of model variables, the evaluation parameters are also specified for infrastructure, vehicles and operations, respectively, based on with-case and without-case scenarios.

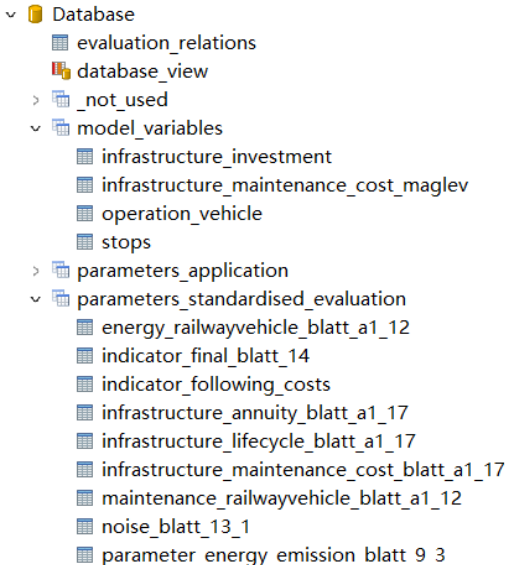
1) Infrastructure: The investment and construction costs per kilometre for each infrastructure subsystem need to be provided. This allows for the calculation of total investments under with-case and without-case scenarios based on the operational mileage planned in the operation concepts. The service life of each subsystem will also be determined, from which the maintenance cost rate for each subsystem can be set.
2) Vehicle: It is necessary to define the service life, price of train carriages and maintenance cost rate of the vehicles. Energy consumption rates for with-case and without-case scenarios should also be established for the vehicles.
3) Operations: Parameters that need to be set include the unit price of energy, the average annual salary of drivers and crews, carbon dioxide and other waste emission amounts per unit of energy consumption along with their conversion rates, the conversion rate of saved passenger travel time, and the rates for noise and casualties.

4.2 National economic evaluation based on AnyLogic

To compare the with-case and without-case scenarios, this study uses the existing Hefei-Wuhu line of the Shangqiu-Hefei-Hangzhou [19] high-speed rail as the without-case scenario. Firstly, all existing rail tracks in Hefei and Wuhu are imported into the GIS software, SAGA GIS [20]. The software is used to view and edit the track sections and their attributes. Based on this, the GIS data is then imported into AnyLogic to establish a model of the rail infrastructure, with the setting up of stations and routes.

Upon completion of the route and station settings in AnyLogic, the process of modelling for national economic evaluation will be commenced. The model used for evaluating a transportation project can be set up by inputting data into AnyLogic's database. These data are then read, calculated and evaluated by the evaluation program. Specific model variables and evaluation parameters used for analysis and optimisation will be presented separately in the evaluation module, in which the parameters and variables are dynamically modified and adjusted to observe data trends and derive optimised values. In 4.2, the data structure used for the evaluation will be described. The result of using AnyLogic for the standardised evaluation is presented in 4.3.

The foundational data for national economic evaluation is stored in the AnyLogic database, organised into individual tables and related table groups (refer to *Figure 2*). Model variables are summarised in the “model_variables” table group, while evaluation parameters are summarised in the “parameter_standardised_evaluation” table group.

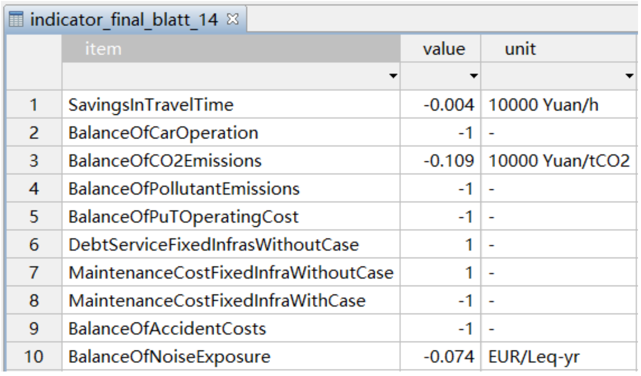


- Database
  - evaluation_relations
  - database_view
  - _not_used
  - model_variables
    - infrastructure_investment
    - infrastructure_maintenance_cost_maglev
    - operation_vehicle
    - stops
  - parameters_application
  - parameters_standardised_evaluation
    - energy_railwayvehicle_blatt_a1_12
    - indicator_final_blatt_14
    - indicator_following_costs
    - infrastructure_annuity_blatt_a1_17
    - infrastructure_lifecycle_blatt_a1_17
    - infrastructure_maintenance_cost_blatt_a1_17
    - maintenance_railwayvehicle_blatt_a1_12
    - noise_blatt_13_1
    - parameter_energy_emission_blatt_9_3

Figure 2 – Overview of standardised evaluation databases

The table group “model_variables” includes the project-specific information. Users can define the required items for evaluation, according to the evaluation objectives and availability of the data. As described in 4.1, the unit costs of infrastructure investment, the procurement and maintenance costs for vehicles, and the related value for calculating operational costs are defined in this table group. For example, the energy consumption for with-case and without-case is defined as 90.07 W/person • km and 74 W/person • km in the table “operation_vehicle”, which will be used for calculating energy consumption and the resulting CO_2 emissions.

Evaluation parameters used in German standardised evaluation are exactly defined in the table group “parameter_standardised_evaluation”. In this context, the table “indicator_final_blatt_14” (*Figure 3*) is derived from the “Blatt 14” in German standardised evaluation parameters [1], defining the final evaluation indicators. The evaluation indicators used in German standardised evaluation are the saving of travel time, the balance of public transportation operations, the debt service for infrastructure, the maintenance costs for with-case and without-case, the balance of accident and the balance of emissions from CO_2 and other pollutants. Here the term “balance” represents the difference in the performance between the with-case and without-case. In the table “parameter_energy_emission_blatt_9_3”, the converting parameter for CO_2 and other emissions are defined. For example, the CO_2 emission factor *c* for electric propulsion is 414 g/kWh, according to German standardised evaluation.

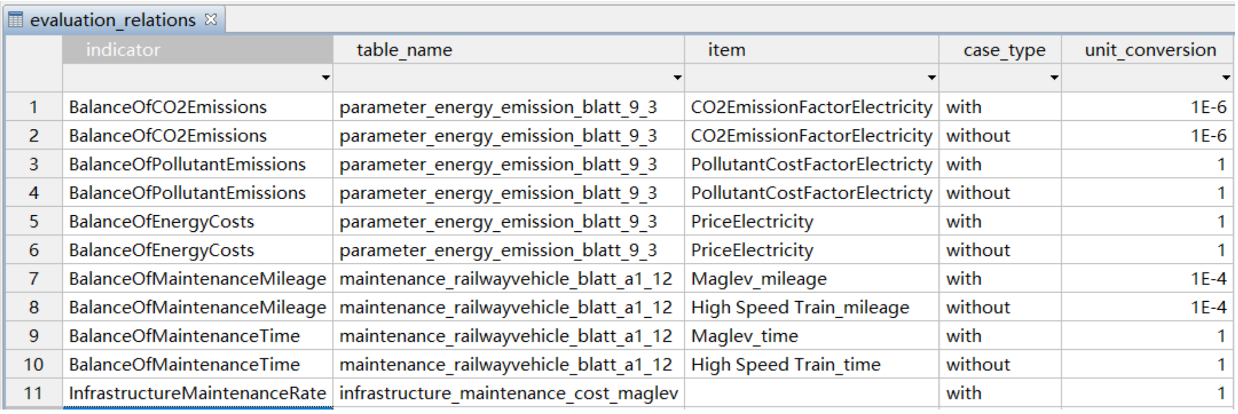


indicator_final_blatt_14

	item	value	unit
1	SavingsInTravelTime	-0.004	10000 Yuan/h
2	BalanceOfCarOperation	-1	-
3	BalanceOfCO2Emissions	-0.109	10000 Yuan/tCO2
4	BalanceOfPollutantEmissions	-1	-
5	BalanceOfPuTOperatingCost	-1	-
6	DebtServiceFixedInfrasWithoutCase	1	-
7	MaintenanceCostFixedInfraWithoutCase	1	-
8	MaintenanceCostFixedInfraWithCase	-1	-
9	BalanceOfAccidentCosts	-1	-
10	BalanceOfNoiseExposure	-0.074	EUR/Leq-yr

Figure 3 – Final evaluation indicators defined in table “indicator_final_blatt_14”

The calculation of indicator values is defined within the look-up table “evaluation_relations” (refer to *Figure 4*). In this table, evaluation indicators are defined in the column “indicator”, and the table in which the indicator is located is defined in the column “table_name”. The corresponding data items within the table are specified in the column “item”. During the evaluation process, the calculation of indicator values is based on comparisons between with-case and without-case scenarios. Therefore, it is necessary to provide the corresponding project type in the column “case_type” for each indicator. Additionally, considering potential unit conversions (e.g. from yuan to ten thousand yuan, from meters per second to kilometres per hour, etc.), unit conversion parameters can be defined for each indicator flexibly in the column “unit_conversion”.



	indicator	table_name	item	case_type	unit_conversion
1	BalanceOfCO2Emissions	parameter_energy_emission_blatt_9_3	CO2EmissionFactorElectricity	with	1E-6
2	BalanceOfCO2Emissions	parameter_energy_emission_blatt_9_3	CO2EmissionFactorElectricity	without	1E-6
3	BalanceOfPollutantEmissions	parameter_energy_emission_blatt_9_3	PollutantCostFactorElectricty	with	1
4	BalanceOfPollutantEmissions	parameter_energy_emission_blatt_9_3	PollutantCostFactorElectricty	without	1
5	BalanceOfEnergyCosts	parameter_energy_emission_blatt_9_3	PriceElectricity	with	1
6	BalanceOfEnergyCosts	parameter_energy_emission_blatt_9_3	PriceElectricity	without	1
7	BalanceOfMaintenanceMileage	maintenance_railwayvehicle_blatt_a1_12	Maglev_mileage	with	1E-4
8	BalanceOfMaintenanceMileage	maintenance_railwayvehicle_blatt_a1_12	High Speed Train_mileage	without	1E-4
9	BalanceOfMaintenanceTime	maintenance_railwayvehicle_blatt_a1_12	Maglev_time	with	1
10	BalanceOfMaintenanceTime	maintenance_railwayvehicle_blatt_a1_12	High Speed Train_time	without	1
11	InfrastructureMaintenanceRate	infrastructure_maintenance_cost_maglev		with	1

Figure 4 – Index table “evaluation_relations”

As described in Section 4.1, the values of model variables are derived from simulation results or obtained through literature review. This paper adopts a methodology based on the adapted German standardised evaluation of the Hefei-Wuhu-Guangde line, with adjustments primarily focused on model variables. Variables related to rail transit technology, such as the calculation of running time and energy consumption, remain unchanged as these factors are independent of the operating country. However, variables influenced by the local economic context, such as infrastructure and train vehicle investment costs, personnel costs and energy prices, have been adjusted to reflect Chinese standards instead of using the values from the German evaluation. Details regarding the modifications to the German standardised evaluation can be found in [3].

Evaluation parameters mainly rely on the values from the German standardised evaluation, with adaptions made according to the actual conditions in China. For example, in *Figure 3*, the monetary value of time saved from travel is adjusted based on China’s gross domestic product (GDP) level [3]. The value for reduced CO_2 emissions, on the other hand, directly adopts the figures from the German standardised evaluation and converts them into RMB, because the assessment of CO_2 emission reduction should follow a unified standard. In *Figure 4*, the tables of evaluation parameters required to convert model variables into economic evaluation are defined. These parameters, such as the CO_2 emissions per kilowatt-hour of electricity, are mainly calculated based on the technical conditions of the rail transit system and are independent of the country of operations. Therefore, their values are directly taken from the German standardised evaluation.

4.3 Carrying out a standardised evaluation model

Upon determining the infrastructure data, model variables and evaluation parameters, the evaluation process commences by executing simulations and assessing the economic feasibility of scenarios for both with-case and without-case. All evaluation indicators defined in the table “indicator_final_blatt_14” can be calculated using the embedded code within Java classes developed for the evaluation model. The model variables are initially retrieved from the table group “model_variables”. Subsequently, the necessary conversion parameters are extracted from the table group “parameter_standardised_evaluation” using the lookup table “evaluation_relations”. Finally, the monetary evaluation indicator is automatically calculated by the embedded code.

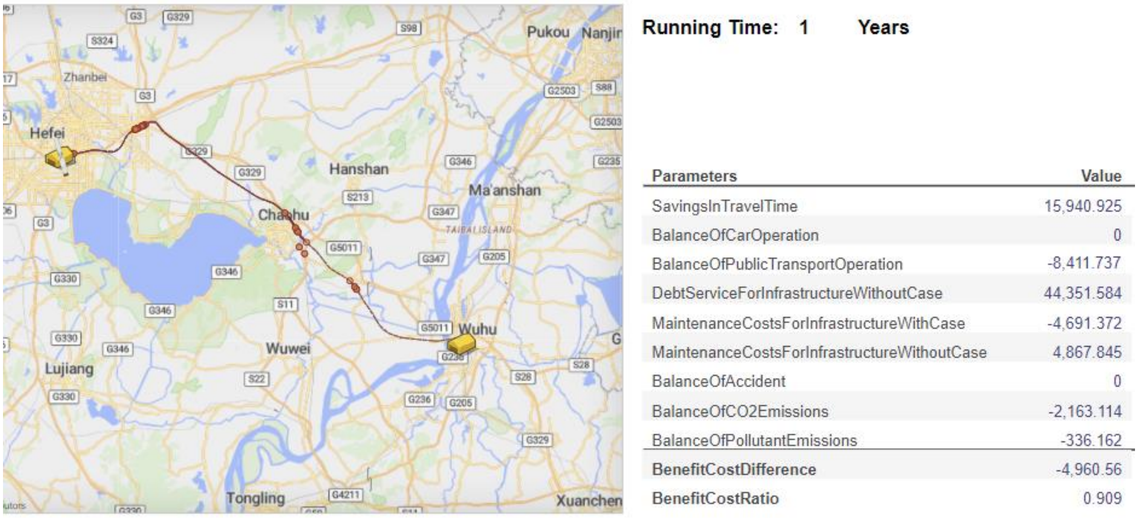
Taking the example to calculate the balance of CO_2 emissions, the energy consumption E [kWh] is provided as a model variable in the table “operation_vehicle” for both the with-case and without-case scenarios. The CO_2 emission amount can be determined using the converting parameter c defined by the item “CO2EmissionFactorElectricity” in the table “parameter_energy_emission_blatt_9_3”. The relationship between these variables is specified in the lookup table “evaluation_relations” (*Figure 4*). With the CO_2 emission amount known, the final monetary value of the CO_2 emission indicator can be calculated with the parameter p_{CO_2}, which is found in the item "BalanceOfCO2Emissions" defined in the table "indicator_final_blatt_14" (*Figure 3*). In summary, the monetarily evaluated balance of CO_2 emissions I_{CO_2} expressed as

$$I_{CO_2} = (E_{with} - E_{without}) \cdot c \cdot p_{CO_2} / 1{,}000{,}000 \tag{1}$$

where:

I_{CO_2} [10000 Yuan]:	balance of CO_2 emissions in monetary term
E_{with}, $E_{without}$ [kWh/year]:	energy consumption for with-case and without-case
c [g/kWh]:	converting parameter of CO_2 emissions depending on energy consumption
p_{CO_2} [10000 Yuan/t CO2]:	monetary converting factor for CO_2 emissions.

With the calculated evaluation indicators, the cost-benefit ratio can be determined according to German standardised evaluation procedures. The developed AnyLogic model integrates the database, Java classes for evaluation processes and a graphical user interface. The final detailed assessment results are presented in *Figure 5*. In this example, a comparison between the Hefei-Wuhu high-speed maglev line and the high-speed wheel rail project yields a benefit-to-cost ratio of 0.909.



Running Time: 1 Years

Parameters	Value
SavingsInTravelTime	15,940.925
BalanceOfCarOperation	0
BalanceOfPublicTransportOperation	-8,411.737
DebtServiceForInfrastructureWithoutCase	44,351.584
MaintenanceCostsForInfrastructureWithCase	-4,691.372
MaintenanceCostsForInfrastructureWithoutCase	4,867.845
BalanceOfAccident	0
BalanceOfCO2Emissions	-2,163.114
BalanceOfPollutantEmissions	-336.162
BenefitCostDifference	-4,960.56
BenefitCostRatio	0.909

Figure 5 – Screenshot of evaluation results of Hefei-Wuhu high-speed maglev line in AnyLogic

To further refine the evaluation outcomes, a thorough examination of the model variables and parameters is essential. The developed AnyLogic model facilitates the flexible modification of these variables and parameters through multiple rounds of simulation. This flexibility is a key advantage of modelling the evaluation process in AnyLogic, enabling the execution of numerous experiments to investigate the impact of various model variables and evaluation parameters.

5. The impact of model variables and evaluation parameters on evaluation

In the process of cost-benefit evaluation, modifications to model variables and evaluation parameters can directly influence the evaluation outcomes. This chapter employs a quantitative analysis approach utilising the AnyLogic model and its "Parameter Variation Experiment" feature.

5.1 Parameter Variation Experiment

AnyLogic provides the capability to execute simulations with varying model parameters to analyse how specific parameters impact model behaviour. This feature eliminates the need to repeatedly run the model individually or manually modify parameter values and record results for comparison after each run. Parameter variation experiments enable users to configure intricate model simulations, encompassing multiple individual model runs with alterations to one or more object parameters. Users can also evaluate the impact of random factors in stochastic models, in addition to conducting experiments with fixed parameter values. AnyLogic offers tools for observing and analysing model behaviour, allowing users to display the results of multiple model runs on a single relational graph and compare model behaviours under different parameter values.

The steps involved in conducting a parameter variation analysis are as follows:

1) Establish a new Parameter Variation Experiment;
2) Configure the experiment, specifying the parameters to be varied and their respective ranges;
3) Set up the user interface for the parameter variation experiment;
4) Execute the parameter variation experiment.

Determining which parameters to vary and their ranges is the crux of the experiment. This chapter focuses on examining the impact of changing a single variable/parameter on the evaluation results. Therefore, the parameter variation experiments can be interpreted as impact analyses for a single variable.

During the simulation and evaluation process, it is essential to fully consider the random behaviour and uncertainty in railway operations. This demands the use of stochastic distribution models for key variables and the subsequent execution of multiple simulations based on such models. In this project, because the simulation software PULSim was not directly integrated with AnyLogic, the focus was on analysing the impact of changing model variables and input parameters within AnyLogic. In the future, by embedding the PULSim module, it will be possible to directly examine the impact of random processes in micro-simulations on the evaluation results, thus enhancing the reliability of the evaluation outcomes.

AnyLogic allows users to freely define fixed and variable model variables and evaluation parameters to examine their impacts on evaluation results. However, it is also necessary to judge the variability of variables and parameters and the necessity of analysis based on the specific project context. Typically, model variables have a wide range of variability due to design flexibility, while evaluation parameters are relatively fixed to ensure fairness and standardisation across different projects. Due to the lack of consideration for the impact of high-speed maglev trains on passenger flow in Section 4.3, operational mileage and passenger count will be chosen as variable model variables. The with-case and without-case scenarios use the same layout of infrastructure, hence variables related to infrastructure are fixed in this project. Train composition planning affects operational design and final operational costs, so they are considered variable variables. Among evaluation parameters, energy consumption is considered as a crucial variable parameter due to its direct impact on energy costs and emissions. As a new model, the price of a 600 km/h speed maglev train has a high potential for variability in the future, thus it is also considered a variable parameter for study. In the future, other variable parameters can be freely defined within the developed AnyLogic platform to investigate their impact on evaluation results. The computational complexity and the availability of distribution models for specific variables should also be taken into consideration.

5.2 Study the impact of model variables on the evaluation

This study takes into account operational mileage, passenger count and train composition planning as key variables that affect the evaluation outcomes. Train composition planning entails determining the number of carriages per train and the capacity of each carriage. As parameter sensitivity analysis involves the assessment of the impact of variations in a single variable, this chapter initially explores the impacts of changes in operational mileage and passenger count. The analysis of train composition parameters, encompassing interconnected model variables like the number of carriages per train and the capacity of each carriage, will be conducted in Chapter 6.

The daily one-way passenger count and operational mileage from Hefei North City to Guangde South Station are presented in *Table 1*, which is used for investigating the impacts of single model variables. The data presented here represent actual operational statistics for the Hefei-Wuhu-Guangde high-speed wheel-rail line [19], serving as the model variables for the without-case scenarios. In the assessment in Section 4.3, the same infrastructure mileage and passenger count are also applied to the evaluation of the high-speed maglev system, without considering the changes in passenger flow due to the increased operational speed of the high-speed maglev. This certainly requires further improvement in future research. Therefore, in Section 5.2, the impact of changes in passenger count on the evaluation results is examined.

Table 1 – Passenger count and kilometres for the Hefei North City - Wuhu - Guangde South Station section

Station	**Passenger count**	**Cumulative passenger count**	**Absolute kilometres**	**Relative kilometres**	**Passenger ratio**
Hefei North City	985	985	378	0	0.0024
Hefei Station	10,562	11,547	400	22	0.0282
Feidong Station	1,768	13,315	419	41	0.0326
Zhegao Station	561	13,876	442	64	0.0339
Chaohu East Station	9,626	23,502	467	89	0.0575
Hanshan South Station	1,136	24,638	490	112	0.0603
Wuhu North Station	880	25,518	512	134	0.0624
Wuhu Station	43,734	69,252	525	147	0.1694
Wuhu South Station	1,466	70,718	537	159	0.1730
Wanhe South Station	1,622	72,340	569	191	0.1770
Xuancheng Station	9,791	82,131	595	217	0.2009
Langxi South Station	774	82,905	633	255	0.2028
Guangde South Station	1,509	84,414	660	282	0.2065

This analysis aims to evaluate the impacts of operational mileage changes by varying the length of operational mileage while keeping other parameters and model variables constant. The settings for each fixed parameter/model variable are as follows:

— Daily one-way passenger count: from Hefei North City to Wuhu Station 27,848 passengers/day
— (With project) Train composition: 10 carriages/train, with an average of 90 seats/carriage
— (With project) Energy consumption per seat kilometre: 90.07 Wh/seat•kilometre
— (With project) Vehicle price: 31.5 million RMB per carriage
— Interest rate: 1.7%.

The studied parameter for the variation experiment is referred to as the control variable in AnyLogic. In this case, the operational mileage is set as the control variable with a range of variation from 147 kilometres (Hefei North City to Wuhu Station) to 282 kilometres (Hefei North City to Guangde South Station), with an increment of 5 kilometres. As the operational mileage changes, the passenger count will also be adjusted accordingly. The passenger count value can be linearly extrapolated based on the passenger ratio defined in *Table 1*.

The impact of model variables on the assessment is shown in *Figure 6*, where the horizontal axis represents operational mileage, and the vertical axis is divided into benefit-to-cost ratio. The analysis results indicate that as operational mileage extends to Xuancheng Station (217 kilometres), there is a significant increase in the benefit-to-cost ratio and benefit-to-cost difference. However, after Langxi South Station (255 kilometres), due to a decrease in station passenger counts, the added benefits from time savings are insufficient to cover the increased costs of vehicle acquisition, maintenance and operation, resulting in a noticeable decrease in the cost-benefit ratio. Economic feasibility is achieved at Guangde South Station, where the benefits outweigh the costs.

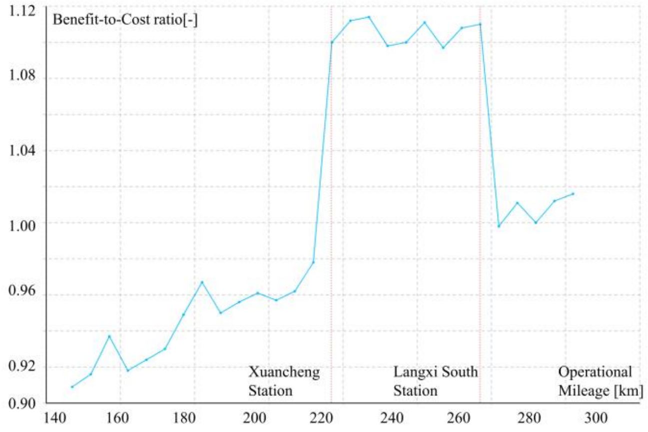


Figure 6 – Benefit-to-cost ratio as a function of operating mileage

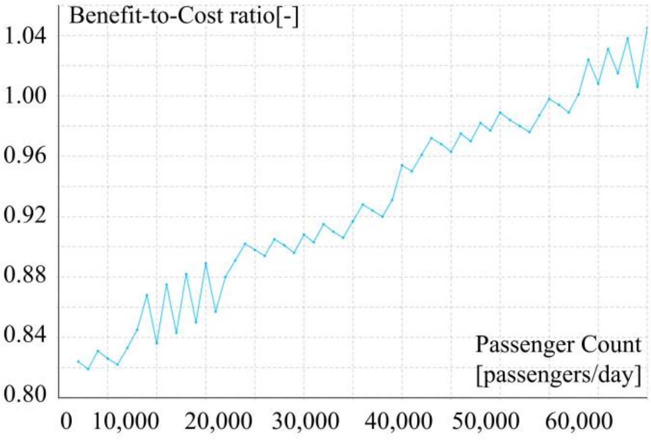
To assess the impact of passenger count variations in this project, the following settings are applied for each fixed parameter/model variable:

— Operational mileage: 147 kilometres (Hefei North City to Wuhu Station)
— (With project) Train composition: 10 carriages/train, with an average of 90 seats/carriage
— (With project) Energy consumption per unit: 90.07 Wh/seat•kilometre
— (With project) Vehicle price: 31.5 million RMB per carriage
— Interest rate: 1.7%.

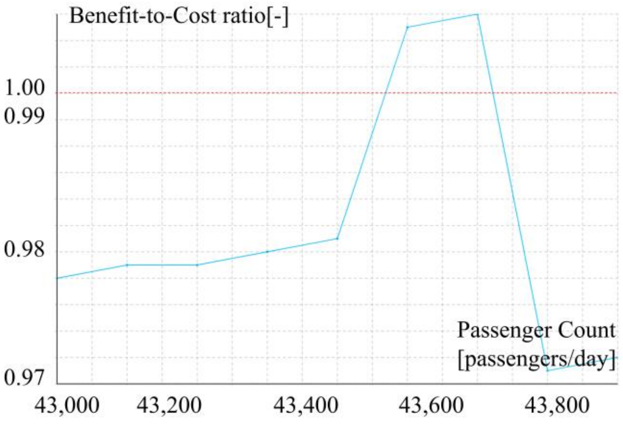
The control variable is the daily one-way passenger count from Hefei North City to Wuhu Station, ranging from 2,000 to 60,000 passengers/day, with an increment of 1,000 passengers/day.

The impact of model variables on the assessment is shown in *Figure 7*. The results indicate that the effect of passenger count growth on benefit-to-cost is not strictly monotonic. Under normal circumstances, as the passenger count increases, it generally leads to an increase in benefits and an increase in the benefit-to-cost ratio. However, when the passenger count increases to a certain number, additional vehicle purchases are required, resulting in an increase in costs at that point and a decrease in the benefit-to-cost ratio. Therefore, the benefit-to-cost ratio does not monotonically increase with the increase in passenger count.

After surpassing 53,000 passengers/day, the benefits outweigh the costs (*Figure 7a*). This result was obtained through parameter variation with an increment of 1,000 passengers/day. If the increment is reduced, the economic feasibility between costs and benefits can be achieved with a smaller number of passengers. For instance, with an increment of 100 passengers/day, economic feasibility can be achieved when the passenger count is between 43,500 and 43,600 (*Figure 7b*). Therefore, solely relying on parameter sensitivity analysis through discrete searches makes it challenging to identify the break-even points, where the minimum required passenger count leads to economic feasibility. Section 6.3 presents a method for determining the break-even points using optimisation methods.



a) 2000–60,000 passengers/day



b) 43,000–43,800 passengers/day

Figure 7 – Benefit-to-cost ratio as a function of passenger count

5.3 Analysing the impact of evaluation parameters on the assessment

In this section, the impacts of various evaluation parameters, including energy consumption per carriage, vehicle costs and interest rate, on the economic feasibility of the high-speed maglev project are analysed and assessed. While model variables can be modified during the design phase, evaluation parameters are typically fixed and cannot be directly altered by planners. Analysing the impact of evaluation parameters helps determine the critical values at which the project's benefits and costs reach a balance, ensuring economic feasibility.

Consistent with the settings in Section 5.2, the fixed model variables remain unchanged:

- Operational mileage: 147 kilometres (Hefei North City to Wuhu Station)
- Daily one-way passenger count: from Hefei North City to Wuhu Station 27,848 passengers/day
- (With project) Train composition: 10 carriages/train, with an average of 90 seats/carriage.

The fixed evaluated parameters are:

- (With project) Energy consumption per carriage: 70.09 Wh/seat•kilometre
- (With project) Vehicle price: 31.5 million RMB per carriage
- Interest rate: 1.7%.

If one of the parameters is applied for a parameter variation experiment, it becomes a control variable. The respective control variables are:

- (With project) Energy consumption per carriage: 70 to 90 Wh/seat•kilometre, with an increment of 0.2 Wh/seat•kilometre
- (With project) Vehicle price: 21,000 to 32,000 million RMB per carriage, with an increment of 100,000 RMB per carriage
- Interest rate: Varies from 0.1% to 5.0% and from -5.0% to -0.1%, with an increment of 0.1%.

Analysing the impact of evaluation parameters reveals that increasing energy consumption per carriage leads to a monotonic decrease in economic viability. The project achieves economic feasibility when the energy consumption of the high-speed maglev train falls below 78 Wh/seat•kilometre.

Similarly, a rise in vehicle costs results in a monotonic decline in financial attractiveness. The project breaks even when the price of the high-speed maglev vehicle is below 27,000,000 RMB per carriage.

As the interest rate increases, the benefit-to-cost ratio exhibits non-linear decreases. When the interest rate turns positive, the benefits are no longer sufficient to cover the costs. However, at an interest rate of approximately -1.0%, the project example reaches a break-even point, achieving economic feasibility. This interest rate can be interpreted as the internal rate of return (IRR). A negative IRR indicates that the investment project may not guarantee economic feasibility.

6. Economic feasibility study based on optimisation algorithms

Building upon the impact analysis in Chapter 5, which elucidated the relationship between model variables/evaluation parameters and the benefit-cost ratio, this chapter introduces the OptQuest optimisation engine employed in AnyLogic (refer to Section 6.1). Utilising this engine, we undertake the following tasks:

- Model variable optimisation: Identify the optimal operational mileage and vehicle configuration under specified parameter conditions (see Section 6.2).
- Critical parameter value identification: Determine the critical parameter value at which the break-even point is reached to ensure economic feasibility (see Section 6.3).

6.1 OptQuest heuristic optimisation engine and integration with AnyLogic

OptQuest is a commercial software used for optimising complex systems, and it can be coupled with simulation modules, providing built-in optimisation algorithms [21].

Scatter search is the foundational algorithm of OptQuest, and it is a population-based heuristic optimisation method that includes five functions:

1) Diversification: Used to generate a set of different solutions that form the basis for the initial search.

2) Improvement: To enhance the quality of solutions (typically measured by the objective function value) or feasibility (usually defined by constraints) by adjusting control variables and solutions.
3) Reference set update: Used to maintain and update solutions generated in the main iteration loop of the scatter search.
4) Subset generation: Generates subsets for obtaining the final solution.
5) Solution combination: Combines solutions, typically two or more feasible solutions from the subset, to generate new solutions.

In addition to scatter search, OptQuest integrates various other optimisation techniques, including experimental design, cross-entropy, genetic algorithms, particle swarm optimisation, synchronous perturbation stochastic approximation, linear integer programming, enumeration and more.

The optimisation process integrated into AnyLogic involves repeating simulations of the model with different parameters. The OptQuest engine employs sophisticated algorithms to change controllable parameters between simulations to find the best parameters for solving the problem. A generic AnyLogic optimisation process includes the following steps:

1) Create the optimisation environment;
2) Define optimisation variables, specifying which variables will be treated as control variables;
3) Create an optimisation user interface;
4) Specify the function to be maximised or minimised (objective function);
5) Define constraints and requirements;
6) Define simulation termination conditions;
7) Define optimisation termination conditions;
8) Run the optimisation process.

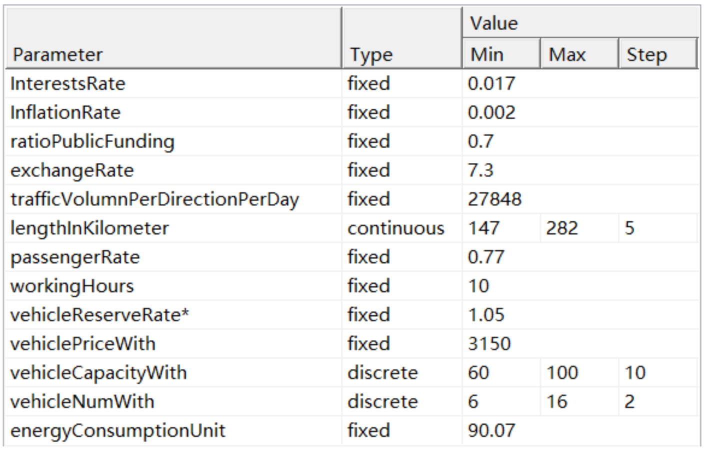
This paper will employ the OptQuest engine for both model variable optimisation and critical parameter value identification. Both tasks can be categorised as optimisation problems. For model variable optimisation, the goal is to maximise the benefit-cost ratio. For critical parameter value identification, the objective is to determine the minimum or maximum value of an evaluation parameter while maintaining a benefit-cost ratio of 1.

Traditional approaches for economic assessments, such as the German standardised evaluation, only compare a pre-defined limited number of operational alternatives, whereas optimisation algorithms can search for the optimal solution within the solution space based on the results of operational simulations. For example, when deriving the optimal vehicle configuration, the combination of the number of carriages per train and the average passenger count per carriage, defined within the value range, will be established as control variables to construct the solution space for operational alternatives. The range of these control variables is defined based on technical feasibility. The optimisation algorithm evaluates their economic viability within the solution space through simulation, discarding those solutions that are not economically viable (benefit-cost ratio less than 1), and searches for the solution with the best benefit-cost ratio. This project uses macroeconomic control variables for optimisation. Once microsimulation software is integrated with this platform, it will be possible to assess the economic impact of specific new technologies, such as the automatic train operation (ATO) system, at a microscopic level, examining their contribution to reducing passenger travel time and energy consumption. This seamless integration of operational simulation and economic optimisation will yield deeper insights.

6.2 Model variable optimisation

To achieve the highest benefit-cost ratio, the operational mileage and vehicle configuration will be examined together to determine the optimal design of the model variables. The number of carriages per train, the average passenger count per carriage and the operational mileage will serve as control variables and will be adjusted during the optimisation process. Other variables and parameters will remain fixed, consistent with the variable/parameter sensitivity analysis in Chapter 5. The optimisation control variables and their respective ranges are as follows:

- Number of carriages per train: 6 to 16 carriages/train
- Average passenger count per carriage: 60 to 100 passengers/carriage
- Operational mileage: A range from 147 kilometres (Hefei North City to Wuhu Station) to 282 kilometres (Hefei North City to Guangde South Station).

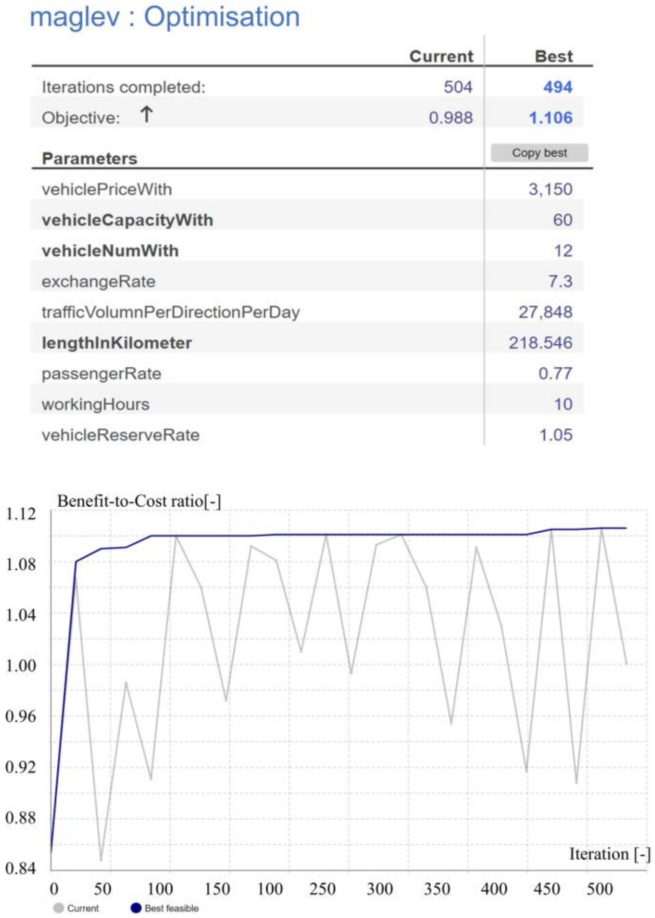


Parameter	Type	Value		
		Min	Max	Step
InterestsRate	fixed	0.017		
InflationRate	fixed	0.002		
ratioPublicFunding	fixed	0.7		
exchangeRate	fixed	7.3		
trafficVolumnPerDirectionPerDay	fixed	27848		
lengthInKilometer	continuous	147	282	5
passengerRate	fixed	0.77		
workingHours	fixed	10		
vehicleReserveRate*	fixed	1.05		
vehiclePriceWith	fixed	3150		
vehicleCapacityWith	discrete	60	100	10
vehicleNumWith	discrete	6	16	2
energyConsumptionUnit	fixed	90.07		

Figure 8 – Control variable settings for model variable optimisation

Figure 8 illustrates the control variable settings. Utilising the established parameters, an optimisation experiment is implemented in AnyLogic. The objective of this optimisation is to maximise the benefit-to-cost ratio. Upon running the optimisation experiment, the operational design of the model variables that yield the maximum benefit-to-cost ratio is determined (*Figure 9*). The optimal model variables are summarised as follows:

- Number of carriages per train: 12 carriages/train
- Average passenger count per carriage: 60 passengers/carriage
- Operational mileage: 218,546 kilometres (Hefei North City to Xuancheng Station).



maglev : Optimisation

	Current	Best
Iterations completed:	504	494
Objective: ↑	0.988	1.106

Parameters	
vehiclePriceWith	3,150
vehicleCapacityWith	60
vehicleNumWith	12
exchangeRate	7.3
trafficVolumnPerDirectionPerDay	27,848
lengthInKilometer	218.546
passengerRate	0.77
workingHours	10
vehicleReserveRate	1.05

Figure 9 – The results for model variable optimisation

This solution necessitates the configuration of 10 high-speed maglev trains, with each train accommodating 720 passengers. In contrast, for the without-case scenario, 15 high-speed wheel-rail trains are required, with each train accommodating 600 passengers. Through the optimisation experiment, this solution achieves a benefit-to-cost ratio of 1.106, representing an improvement compared to the benefit-to-cost ratio of 0.909 for the Hefei to Wuhu route [3].

By setting a specific goal and specified operational conditions and design alternatives, optimisation experiments can determine the optimal combination of multiple model variables. This functionality seamlessly integrates the entire design process, encompassing modelling, evaluation and optimisation. This integrated approach facilitates continuous improvement in transportation planning through an automated and iterative process.

6.3 Identification of critical parameter value

Determining the critical value of a model variable or evaluation parameter to reach a break-even point is crucial during the evaluation process. This critical value provides valuable insights and guidance regarding the minimum requirements for ensuring economic feasibility. The study conducted in Chapter 5 demonstrates that identifying the critical value can be challenging when the change in benefit-to-cost ratio with respect to a specific parameter is not monotonic.

Optimisation experiments can effectively assist in identifying critical parameter values. In this case, the optimisation interface requires setting the constraint that the benefit-to-cost ratio must be greater than or equal to 1. The optimisation experiment then aims to identify the critical value of the model variable or evaluation parameter that satisfies this constraint. The parameter under investigation is set as the optimisation objective, either to be minimised or maximised. The remaining model variables and evaluation parameters are kept constant.

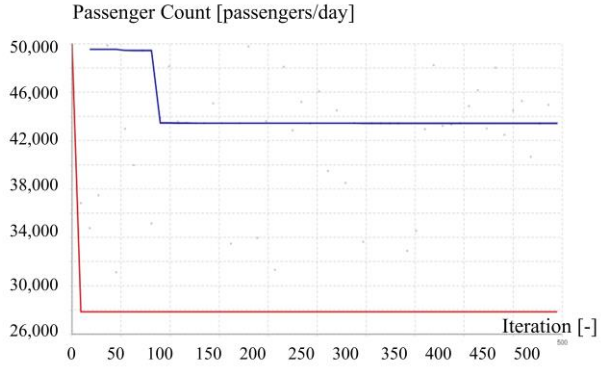
This section focuses on investigating the following parameters: daily one-way passenger count, energy consumption, vehicle costs and interest rate. These investigated parameters are set as control variables. *Table 2* presents the settings for these control variables. The "objective" column indicates the desired direction of optimisation. For instance, to determine the critical passenger count for achieving economic feasibility, the minimum required passenger count needs to be calculated. Therefore, the objective is set to "minimise" to find the minimum number.

Table 2 – Parameters for identification of critical value

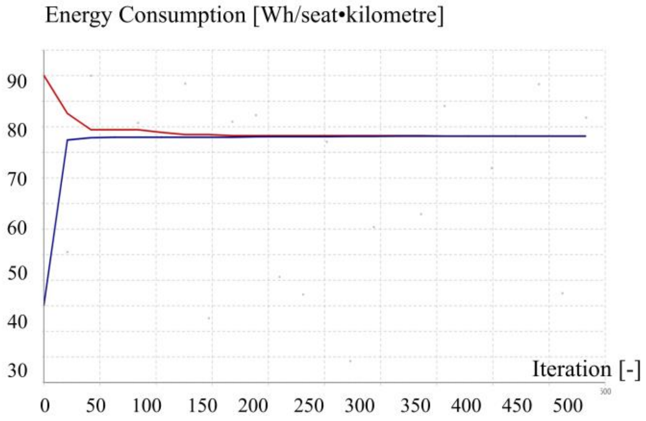
Control variable	**Objective**	**Range**
Daily one-way passenger count [passengers/day]	minimise	27,848 – 50,000
Energy consumption [Wh/seat•kilometre]	maximise	30.00 – 90.07
Vehicle price [million RMB per carriage]	maximise	21.0 – 31.5
Interest rate [%]	maximise	-1 – -0.0001

Figure 9 presents the final results for critical value identification. In this figure, the x-axis represents the corresponding optimisation iterations, and the y-axis represents the critical value. The blue line represents feasible solutions, while the red line represents infeasible solutions encountered during the search process. The critical values are determined by the feasible solutions from the final iterations. The analysis results indicate the critical values for achieving economic feasibility as follows:

- Minimum daily one-way passenger count: 43,428 passengers/day
- Maximum energy consumption: 78.127 Wh/seat•kilometre
- Maximum vehicle price: 27.21 million RMB per carriage
- Maximum interest rate: -0.7%.

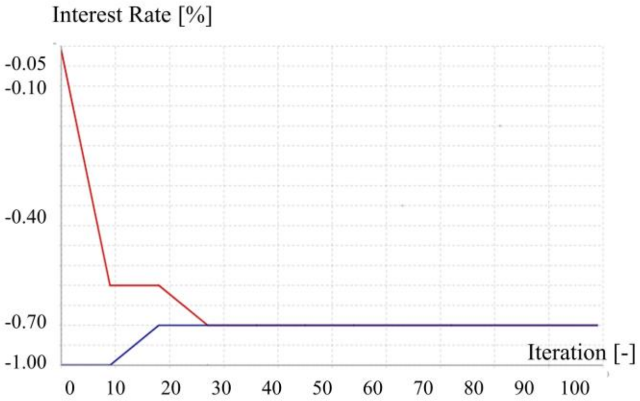


a) Minimum daily passenger count



b) Maximum energy consumption

c) Maximum vehicle price



d) Maximum interest rate

Figure 10 – Determining parameter boundary conditions for profitability

7. Conclusion and further research

The paper is based on the results of the adapted German standardised evaluation of the Hefei-Wuhu-Guangde line. The limitations of traditional evaluation methods that can only be based on existing manually set schemes are discussed. By developing and applying the integrated modelling, evaluation and optimisation software for economic evaluation, the impacts of various model variables and evaluation parameters have been deeply studied. Based on the optimisation algorithm, the optimised model variables are derived. The critical value of evaluation parameters has been determined, to ensure that the benefits are greater than the costs. By optimising operational parameters, this solution delivers a 22% improvement in the benefit-to-cost ratio, from 0.909 to 1.106, compared to the Hefei to Wuhu route. This demonstrates its potential for enhancing the economic viability of high-speed maglev systems.

The research results show that the software platform based on universal simulation, analysis and optimisation is capable of effectively providing decision-makers with quantitative and transparent decision-making solutions. Meanwhile, during the simulation process, the software platform can support a more accurate and detailed perspective than traditional spreadsheet-based evaluations. Through analysing the change of model variables and evaluation parameters, the software platform is capable of supporting planners with insights into the variables and parameters. In addition, guided by the macroeconomic benefit-cost ratio, the optimisation algorithm deduces the optimal design concept and calculates the critical value to ensure the economic feasibility between benefits and costs. The research results of the project are of great significance, providing strong support for the decision-making of high-speed maglev systems to be applied in a large-scale manner. This study introduces several methodological innovations that directly address the aforementioned research gaps:

- Integrated modelling and evaluation software: By developing a specialised software platform for the economic evaluation of high-speed maglev lines, this research enables a detailed representation of the influence of each parameter and variable on the evaluation outcomes. This tool allows for a more nuanced understanding of how various factors interact within the economic model, providing insights that were previously unattainable.
- Automated optimisation algorithm: The introduction of an optimisation algorithm represents a significant advancement over traditional manual methods. This algorithm automatically searches the solution space for optimal configurations, reducing the reliance on designer experience and manual adjustments. It systematically evaluates numerous design alternatives, identifying those with the best benefit-cost ratios and ensuring that the economic feasibility of projects is maximised.
- Holistic evaluation framework: The software developed in this study facilitates a comprehensive evaluation process that includes both parameter and variable analysis as well as solution optimisation. This holistic approach allows for a more robust and accurate assessment of high-speed maglev projects, encompassing a wider range of factors than previously considered.
- Adaptation to local contexts: By adapting the German standardised evaluation to the specific context of the Hefei-Wuhu-Guangde line, this research underscores the importance of contextualising evaluation methods. This adaptation process not only demonstrates the flexibility and applicability of the developed software but also enhances the relevance and accuracy of economic assessments for specific projects.

The use of existing reference and statistical data for parameters like energy consumption and operation time suggests difficulty accessing or generating project-specific data. This dependence can limit the accuracy and specificity of evaluation results. The absence of consideration for random factors in the current project indicates a limitation in capturing the stochastic nature of real-world operations. The current optimisation process relies on heuristic algorithms, limiting the potential for advanced computational techniques that could enhance both accuracy and efficiency, particularly when dealing with complex, non-linear interactions between variables. Furthermore, the use of AnyLogic's personal edition for simulation, analysis and optimisation presents limitations in scalability and accessibility for enterprise-level applications.

A critical challenge lies in the unavailability of high-speed maglev trains for empirical validation. This lack of real-world operational data impedes the ability to test and verify the simulation and evaluation results, introducing inherent uncertainty into the model's predictive accuracy and applicability. This limitation directly impacts the research's credibility and generalisability. Drawing definitive conclusions about the feasibility and performance of high-speed maglev systems solely based on simulated outcomes becomes difficult, hindering our ability to confidently assess their real-world potential. The following directions deserve special attention during the feature development:

- Integration with micro-simulation systems: Many parameters, such as energy consumption and train operation time, are derived from available reference and statistical data. During future research and development, this project can achieve large-scale system collaborative simulation by integrating microscopic driving dynamics of trains and operation simulation software, which is not only beneficial for providing more accurate and real-time data for evaluation but also greatly reduces dependence on external data sources and improves the accuracy and applicability of analysis results.
- Support for random behaviour: This project did not consider random factors. The developed simulation and analysis platform can effectively establish uncertainty models for various variables, and integrate them with simulation and analysis software, in order to quantify uncertainties and find more powerful and robust solutions.

- Sensitivity analysis: The current parametric variable analysis method can further integrate with the sensitivity analysis function, creating a more general and visual experimental plan, and supporting the analysis of the dependence of simulation results on model variables and evaluation parameters.
- Data-driven machine learning: The OptQuest optimisation module inside of AnyLogic is mainly inspired by heuristic algorithms. Especially, data-driven machine learning has shown powerful capabilities in the past few years. Through massive data simulation, especially the uncertainty of model variables and evaluation parameters, as well as the dynamic behaviour of microsimulation, machine learning can construct artificial neural networks with nonlinear correlations between various variables/parameters and evaluation results, which can significantly improve the accuracy and computational performance of evaluation.
- Diversified user interface and independently distributable modules: The current simulation, analysis and optimisation platform is based on the AnyLogic personal education edition. To achieve enterprise-level applications, the user-friendly operating interface is worth further development, achieving the flowability and customisation of analysis and optimisation modules, and developing software packages that can be independently distributed. Users can directly apply simulation evaluation software to simulate, analyse and optimise transportation infrastructure investment projects without installing AnyLogic software.

In summary, the enhanced methodology for standardised evaluation has proven its effectiveness in practical applications, not only for urban and regional public transport projects but also for high-speed maglev systems. Moreover, the algorithm assists planners in identifying more economically feasible systems through parameter studies and optimisation. The developed platform and algorithm can effectively guide planners towards the most economically optimal solution and identify the critical value of model variables and evaluation parameters to achieve economic feasibility.

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崔勇；于卿；乌尔里希•马丁

高速磁悬浮列车经济可行性优化：基于仿真的变量和参数分析方法

Abstract:

这项研究引入了一个先进的软件平台和流程，用于高速磁悬浮列车系统的国民经济定量评价。该方法通过参数变化实验和自动解搜索克服了传统方法的局限性。利用改进的德国标准化评估方法，这项研究展示了集成建模、评估和优化软件如何深入分析各种变量和参数对经济结果的影响。通过使用优化算法，该软件不仅可以确定关键评估参数以确保收益超过成本，还可以推导出优化的模型变量。通过设定宏观经济效益-成本比率作为目标指导设计概念的优化，并可以通过研究发现确保经济可行性的关键值。与现有的合肥-芜湖线相比，所提出的解决方案使该比率提高了 22%（1.106 比 0.909），突出了其在大规模实施磁悬浮方面的潜力。未来的发展方向包括与微观模拟系统集成、支持随机行为、敏感性分析、数据驱动的机器学习以及为更广泛的适用性增强用户界面设计。研究结果强调了该软件为高速磁悬浮列车系统的经济可行性研究提供稳健数据驱动见解的能力，这是基础设施项目评估向前迈出的重要一步。

Keywords:

标准化评估，高速磁悬浮，模态变量，评估参数，优化，经济可行性，关键值