Evaluating the impact of operational improvement measures on European railway network:

A comparative study between individual and combined mitigation strategies in railway infrastructure

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University of Groningen
Spatial Planning and Design

Bram Fidder
S4453255

Supervisor: dr. T. Busscher
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Abstract

This study evaluates the impact of operational improvement measures on the European railway network by comparing individual and combined mitigation strategies. Recent research underscores the need for effective strategies to address the impacts of extreme weather events on railway infrastructure (Ochsner et al., 2022; Menoni et al., 2012). The research question guiding this study is: "How do individual versus combined mitigation strategies impact operational improvement measures in railway infrastructure?"

The Shift2Rail (S2R) initiative, launched by the European Commission, aims to enhance the sustainability, efficiency, and competitiveness of the European railway system by cutting life-cycle costs, doubling railway capacity, and increasing reliability and punctuality. Despite advancements, a critical gap remains in integrating climate mitigation insights with operational improvement measures.

This study investigates the effectiveness of infrastructural improvements, technological innovations, and policy reforms, assessing their impact on life cycle cost reduction, capacity increase, and performance increasing measures. A comparative cross-sectional research design analyzes 106 S2R projects to determine whether individual or combined strategies yield higher operational impact scores.

The findings reveal that combined strategies have a higher mean operational impact score than individual strategies. A statistical test confirms a statistically significant difference, supporting the hypothesis that combined strategies have a higher operational impact score.

Future research should use more diverse data sources and can be done in another context, since S2R focuses mainly on technological innovations. This can be due to the involvement of academic institutions.

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1. Introduction

Recent research by Ochsner et al. (2022) emphasizes the importance of understanding the impacts of extreme weather events on railway infrastructure. This study systematically reviewed literature on the effects of flooding, emphasizing the importance of how different strategies are implemented in railway infrastructure. However, there was no agreement whether these strategies should be combined or individual. The study of Menoni *et al.* (2012) claims that combined strategies have more impact on resilience, the methodology shows that combined strategies can better address the multiple vulnerabilities caused by climate change.

In parallel, to reduce the amount of greenhouse gas emissions, the European Commission aims to increase the usage of trains and create a Single European Railway Area (SERA). In June 2014 the EU transport council founded the Shift2Rail Joint Undertaking (S2R) with the vision: 'To deliver, through railway research and innovation, the capabilities to bring about the most sustainable, cost-efficient, high-performing, time driven, digital and competitive customer-centered transport mode for Europe.' (Shift2Rail, 2020) The initiative officially ended in 2020 but has since been established under 'Horizon Europe', which is a program of the European Union to promote the development of scientific and technological research. (Directorate-General for Research and Innovation, 2021). S2R seeks to be focused on research and innovation in market-driven solutions. The project has three main goals to increase its operationality:

- Cutting the life-cycle cost of railway transportation as much as 50%
- Doubling railway capacity
- Increasing reliability and punctuality by as much as 50%

(Shift2Rail, 2020)
Within the S2R there are various mitigation strategies designed to increase the operationality of the European railway network. These range from technological innovations towards policy reforms.

Despite the significant progress in understanding the impacts of extreme weather events on railway infrastructure and the robust initiatives aimed at enhancing the sustainability and efficiency of the European railway network, there remains a critical gap in the integration of these two areas. The existing research, including the study of Ochsner et al. (2022) and Menoni et al. (2012), provides valuable insights into the effects of climate change and the benefits of combined mitigation strategies. However, there is a lack of comprehensive studies that explore the effect of individual or combined strategies on the operationality in railway infrastructure.

To combat the impacts of climate change on railway infrastructure in Europe there should be an overall picture on what various strategies can be implemented to increase the operationality of the railway infrastructure, and since little is known about what the effect is of these strategies. An increase in this knowledge can ensure that Europe's railway infrastructure can be more resilient towards climate change since decisions about climate mitigation strategies can be made in a scientifically substantiated manner. This research can also be the starting point for more research on how different strategies influence the operationality.

1.1 *Research aim*

Given the lack of knowledge about what the impact is of climate mitigation strategies on measures taken to increase the operationality of railway infrastructure, this research aims to conduct a case study on the S2R. This research aims to identify what a better approach is to increase the operationality of the railway system, individual strategies or combined strategies. The research question proposed with this aim is: ‘How do individual versus combined mitigation strategies impact operational improvement measures in railway infrastructure?’

1.2 *Structure of the research*

In the sections that follow, the study will further conduct the research. First the theoretical framework will explain the different variables, but first the context of the S2R is explained. The independent variable is explained and is about 3 different strategies; infrastructural improvements, technological innovations and policy reforms. The dependent variable is explained in the next paragraph. The operational impact score is explained and the measures that belong to it. Then the conceptual model is discussed and the expectations of the research are forecasted. The methodology section will be the next section where it is discussed how the study is conducted. The results of the study are discussed in the fourth chapter and the conclusion and discussion are the fifth and last chapter.

2. Theoretical framework

2.1 *Shift 2 Rail project*

Haltuf (2016) has attempted to explain how the Shift2Rail project works.

The S2R project is a joint undertaking in which member states aim to transform the railway system of countries of the European Union in a more competitive, efficient and sustainable manner.

Within the project there is one 'master plan of S2R' that has certain objectives in different prioritizations;

- Finalize the 'Single European Railway Area'
- Increase attractiveness and competitiveness of the European railway system
- Retain and consolidate the leadership on the global market
- Improve services and system quality
- Reduced system costs
- Simplified business process

To realize these goals the project has been structured around five Innovation Programs (IP's) which cover all different technical and process subsystems of the rail system. Besides these 5 innovation projects also 5 topics are included that count for all innovation projects, these all can be seen in figure 1.

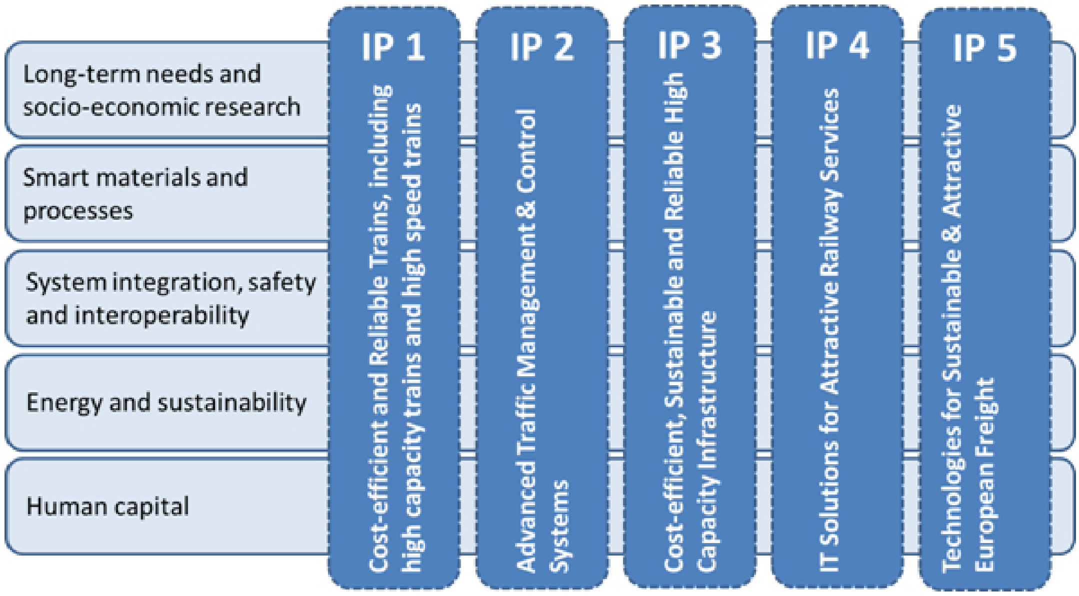

Figure 1; Innovation Programs (Shift2Rail, 2019)

Within the Innovation Programs certain projects are developed to successfully obtain the goal of the program. When all the innovation programs were achieved the master plan should be accomplished.

2.2 *Climate mitigation strategies*

Climate mitigation strategies within the S2R initiative are a set of strategies and actions to mitigate potential negative impacts of climate change. Possible mitigation strategies are a broad set of different interventions varying from infrastructure improvements, technological innovations and reforms in policies and operational changes.

2.2.1 Infrastructural improvements

Infrastructural improvements are necessary to make the railway infrastructure more resilient to extreme weather events such as higher temperatures, floods and storm surges. An example of Garmabaki (2021) is that extreme rainfall can lead to damage of the railway infrastructure, and a solution for this might be better drainage systems with a higher drainage capacity then the current systems.

An assessment has been done on potential impacts of climate change on railway infrastructure in the southern part of the United Kingdom. Climate change is almost certainly impacting the railway infrastructure here in 2115. Some mitigation options were given such as rock revetment which worked in all possible climate scenarios. However an increased seawall would not work since the waves would become higher due to physical forces. (Roca *et al.*, 2016)

In this research, Infrastructural improvements refer to physical adjustments to stationary parts of the railway infrastructure.

2.2.2 Technological innovations

Technological innovations are key to make railways more climate resilient. Predictive analytics and AI can help to make railway companies more anticipatable and recover from climate related challenges. (Rajamäki *et al.*, 2023) By integrating technological innovations into railway projects the railway operators are better able to develop for example the infrastructural improvements on certain locations which are most prone to climate change effects. McKinsey (2018) also states that the usage of digital tools such as AI and predictive analysis is crucial for improving railway infrastructure and operations. The combination of the tools can also for example help to make real time actions if there is a climate related incident. The difference with infrastructural improvements is that technological innovations are mainly developing technologies that are not direct physical adjustments on the stationary parts of the railway infrastructure.

2.2.3 Policy reforms and operational changes

Policy reforms and operational changes are quite important as they can change the landscape decisions are made in. A risk assessment is needed to be aware of the possible climate change effects on railway infrastructure (Palin *et al.*, 2021). Palin et al’s (2021) risk assessment both considered nowadays and future weather events and its impact on the infrastructure.

A framework (figure 2) which is made by Shakou *et al.* (2019) is a guideline for governments, railway operators and other actors to decide when to take certain strategies for critical infrastructure and if the strategies are taken for the short, medium or long term. The paper states that implementing the framework for critical infrastructure is currently a golden opportunity since old critical infrastructure needs replacement and while there is a trend in urbanisation and population growth there is more need of critical infrastructure.

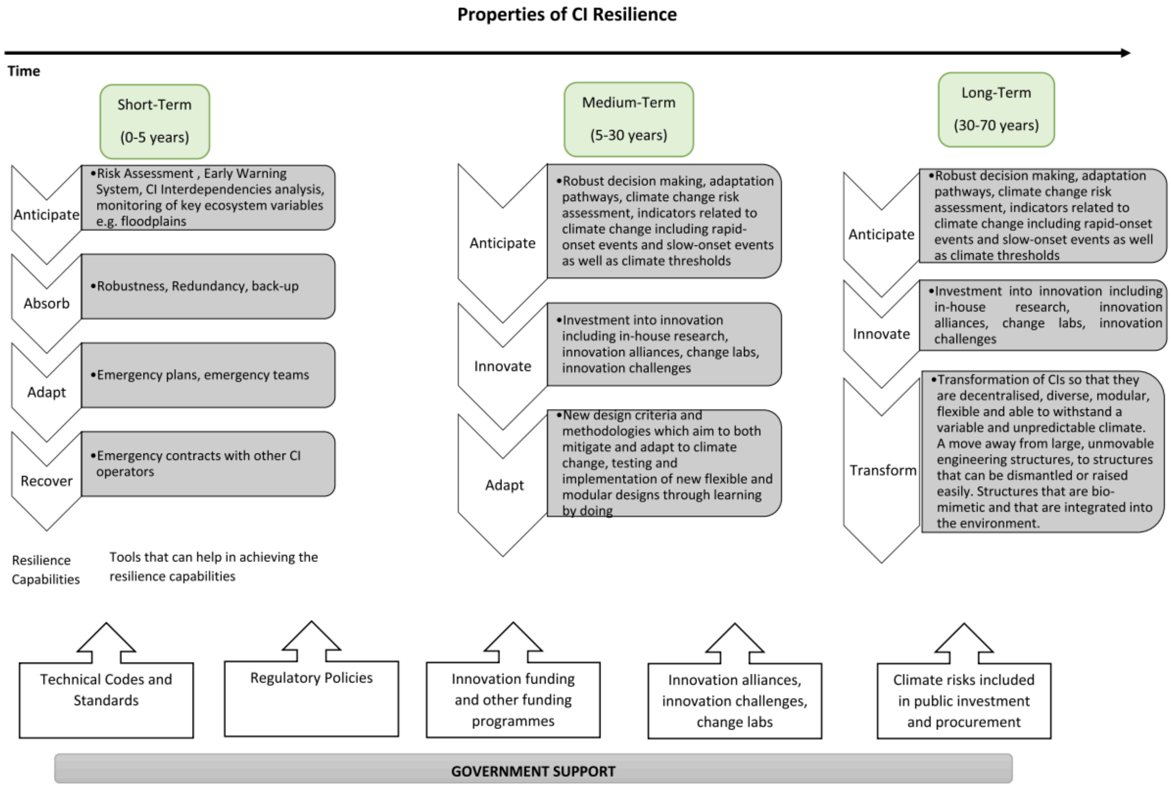

Figure 2; Framework for climate resilient critical infrastructure (Shakou *et al.*, 2019)

2.3 Operational Improvement Measures in Railway Infrastructure

Operational improvement measures in railway infrastructure are essential for enhancing the performance, efficiency, and reliability of railway systems. These measures can be categorized into three main areas: life cycle cost cutting, capacity increasing, and performance increasing measures. These measures are chosen since S2R focusses on these 3 measures. For the research an operational impact score is calculated to see if projects have an objective in using these measures. To determine the operational impact score a basic knowledge is required on what kind of measures are taken, this chapter will clarify life cycle cost cutting, capacity increasing, and performance increasing measures.

2.3.1 Operational Impact Score

The operational impact score ranges from 0 to 3. A score of 0 indicates that none of the measures are in use, representing the minimal operational impact. In contrast, a score of 3 signifies that all measures are fully implemented, representing the maximum achievable operational impact and indicating optimal implementation and effectiveness of all measures.

2.3.2 Life Cycle Cost Cutting Measures

Life cycle cost reduction measures aim to minimize the total costs associated with the operation and maintenance of railway infrastructure over its entire lifespan. Several measures for this have been explained in this paragraph. Predictive maintenance is about utilizing data analytics and predictive modeling to anticipate equipment failures before they occur. This measure can significantly reduce unplanned downtime and maintenance costs. For example, predictive maintenance systems can monitor the condition of tracks and signals, predicting when they will need servicing. (Pedregal et al., 2004) A study by Sakdirat Kaewunruen, Jessada Sresakoolchai, and Yi-hsuan Li (2021) composed a list on what the most common maintenance activities are. This can be seen in figure 3. This list is helpful because the materials can be bought in advance, as it is known what maintenance activity requires what actions.

Causes	Actions
Loose bolts or clips in fastening systems	• Adjust the parts and check if the fastening system is corresponding to the standard. • If the fastening systems are unacceptable after testing, they need to be replaced immediately.
Base plates get serious corrosion, broken or displacement	• The failure parts should be replaced immediately and check the impact factors.
Aging phenomenon or damage occur inelastic materials	• The elastic material should be replaced if it is broken down, and the aging material should be repaired to the allowable safety value.
Cracks occur in fixed components or bolted concrete	• Determine the contaminants leading to cracking, such as chlorides, carbon dioxide sulfates, etc. • Use epoxy resin or polyurethane material to seal cracks to prevent the damage from deterioration of erosion.

Figure 3 ((Maintenance causes & actions, (Sakdirat Kaewunruen , Jessada Sresakoolchai, Yi-hsuan Lin, 2021))

By implementing comprehensive asset management systems the railway infrastructure assets' lifespan is extended and resource use is optimized. Effective asset management ensures proactive maintenance, preventing failures and avoiding expensive emergency repairs. This approach is supported by a life cycle costs analysis framework that integrates the performance of railway infrastructure and cost models to assess the impact of various management decisions (Rama & Andrews, 2016).

2.3.3 Capacity Increasing Measures

Capacity increasing measures focus on expanding the capacity of railway infrastructure to accommodate more trains and passengers. Various measures are described in this paragraph. First, a capacity evaluation tool aims to increase the capacity of railway infrastructure by providing recommendations on potential physical investments to increase future capacity (Lai & Barkan, 2009). Optimized scheduling is key to increasing railway capacity. The study by Li et al. (2020) introduced an optimized train path selection model that minimizes travel times using advanced algorithms. Their experiments demonstrated a significant reduction in travel time and an increase in railway operational capacity.
The implementation of advanced signaling systems, such as the European Train Control System (ETCS) in Austria, reduces headways (distance between trains) between trains, and thereby increasing line capacity (Schöbel and Permiakova, 2021). A case study by Ljubaj, Mikulčić and Mlinarić (2020) on a simulation tool employed in railway infrastructure proved that there is a possibility of increasing the capacity by 50%. Simulation tools can therefore be considered as a solution to increase the capacity of railway infrastructure.

2.3.4 Performance increasing measures

Considering that punctuality and reliability are closely interconnected, these measures will be considered under one definition: performance increasing measures. Improving reliability involves reducing the frequency and impact of service disruptions, which in turn enhances punctuality by ensuring timely and consistent railway operations.

The study by Hidirov and Guler (2019) writes about a Reliable, Available and Maintainable (RAM) analysis. This analysis was introduced by the EU and was performed on all railway track components. This analysis aims to minimize the risks associated with reliability, availability and maintenance problems, thereby improving overall operational performance.
As railway operations increase the complexity of the railway network also grows. With limited budgets, operators must make choices on where to invest in new railway infrastructure. This study provides a guide for addressing such dilemmas and making choices to increase railway infrastructure reliability. (Meng *et al.*, 2020)
Employing real-time monitoring technologies can help to detect and address potential issues before they cause service interruptions. This measure helps in maintaining a high level of reliability in railway operations and gives a first conceptual design in how to improve the rail infrastructure critical safety and maintenance related questions (Edwards *et al.*, 2021).
According to Al-Douri, Tretten and Karim (2016) is ICT (information and communication technology) key to increase accessibility and punctuality in railway infrastructure. Fast communication of delays can increase how fast train operators can react towards delays.

Palmqvist et al (2017) writes about influencing factors on punctuality in railway infrastructure in Sweden. There were identified 4 main factors; Weather, Timetable, Operational and Infrastructure related failures. For each factor an example of a measure will be introduced except the operational factor since this study is focussing on that.

Blackwood, Renaud and Gillespie (2022) investigated the impacts of different climate change related events on railway infrastructure and proposed a list with possible solutions. They emphasized on nature based solutions and also summarized current measures taken. A measure taken against extreme temperatures was for example the installation of sprinkler systems, however a nature based solution could be to construct green corridors which provide shading.
Lee *et al.* (2017) proposed a simulation-based approach for timetabling, utilizing a linear programming model to effectively allocate time supplements and buffer times to reduce the average delay. Such simulations can help to increase punctuality of railway infrastructure. Expanding infrastructure, such as adding extra tracks or new switches, can improve punctuality by providing alternatives in case of a malfunction, allowing the operations to continue on parallel tracks (Patra, Kumar and Kraik, 2010)

By implementing these operational improvement measures, railway infrastructure can become more efficient, reliable, and capable of meeting the increasing demands placed upon it. Many implemented measures have effect on more than only the referred to measure.

2.4 *Relationship dependent and independent variable*

The relationship between the dependent and independent variables in this study is important for understanding how climate mitigation strategies influence operational improvement measures. The dependent variable in this context is operational improvement measures, which is directly affected by the independent variable climate mitigation strategy, both individual and combined strategies. Insights in the literature confirms this relationship; Garmabaki et al. (2021) emphasize that infrastructural improvements, such as drainage systems are essential for mitigating the effects of extreme weather events such as heavy rainfall. These improvements directly contribute to reducing operational disruption and maintenance costs, since the drainage system prevents damage to the railway infrastructure. The importance of predictive analytics and AI are being discussed by Rajamäki et al. (2023). These technological innovations enable railway operators to react and address potential issues proactively, which increases performance and can help to reduce life cycle costs.

2.5 Conceptual model

The conceptual model (figure 4) claims that climate mitigation strategies (independent variable) directly influence operational improvement measures (dependent variable). For instance, infrastructural improvements can mitigate flood risks, thus enhancing performance by reducing delays due to waterlogged tracks.

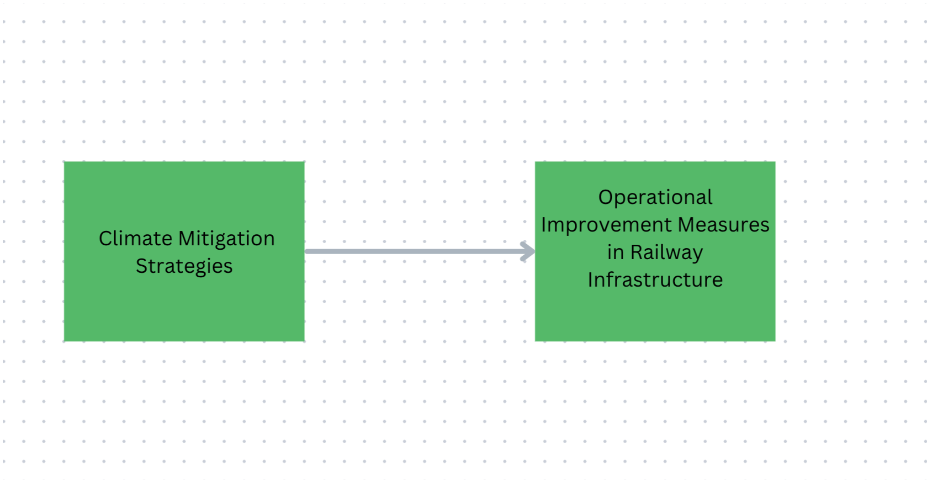

Figure 4 (author, 2024)

2.6 Hypothesis/Expectations

The hypothesis of this research is that combined climate mitigation strategies will have a more significant impact on operational improvement measures in railway infrastructure compared to individual strategies. Research by Menoni et al. (2012) suggests that combined strategies are more effective in addressing the multiple vulnerabilities caused by climate change, enhancing infrastructure resilience.
Also, Ochsner et al. (2022) emphasize how important it is to understand and implement diverse strategies to combat the adverse effects of extreme weather events on railway systems, however this study does not focus on the combination of various strategies together.
Therefore, this research expects that projects that combine strategies such as infrastructural improvements, technological innovations, and policy reforms will in a combination cause better operational impact scores than the projects only using 1 strategy.

3. Methodology

3.1 *Design*

This research conducted a comparative cross-sectional research design aimed to find the differences in operational impact scores between two groups: 0 (individual) and 1 (combined mitigation strategies). This research design is chosen to effectively compare the means of the 2 different groups of operational impact first the groups are determined this process is explained in paragraph 4.2.1. In paragraph 4.2.2 the data collection for the operational impact is explained.

3.2 *Procedure*

3.2.1 Preparation

The research will follow a systematic structure for the data collection and its analysis on the basis of the independent variable

Case selection: All S2R projects were selected to structure individual and combined strategies. Some projects lacked an active website, so they were disregarded.
The selected cases were classified into two group:

1. (Some) employing individual strategies
    a. Infrastructural improvements
    b. Technological innovations
    c. Policy reform and Operational changes
2. (some) employing combination of strategies
    a. Infrastructural improvements & Technological innovations
    b. Technological innovations & Policy reforms
    c. Infrastructural improvements & Policy reforms
    d. All Strategies

The cases were composed in the following way:
Each project of S2R will be investigated and eventually an overview is created on which project has implemented which measure. To facilitate the identification, the research used specific code words or actions that aligned with the different strategies.

For instance for Infrastructural improvements: Focus for mentions of physical changes or enhancements to the railway infrastructure. This includes for example the implementation of switches, crossing, track systems, or any other modifications to the railway infrastructure.

Technological innovations had things like: Focus for mentions of technological advancements and innovations in the projects. This might be the creation of systems that increase reliability, new operational plan systems.

Lastly policy reforms and operational changes: Focus for mentions on changes in policy systems or operational frameworks. This can be for example: maintenance schedules, safety protocols. Some projects may also have used more than 1 strategy and were considered as the combination of strategies. After the preparation the research considered that group 0 (individual strategies) had 74 cases and group 1 (combined strategies) had 32 cases.

3.2.2 Data Collection

The operational improvement measures are categorized according to the 3 different categories explained in the variable: *Operational Improvement Measures in Railway Infrastructure.* Each category had some specific measures which can be found in paragraph 2.3.1

1. Life cycle cost cutting measures
2. Capacity increasing measures
3. Performance increasing measures

The analysis was done in the following way. Each project was analyzed in such a way to see if a particular strategy(s) had an objective on the measure taken. If a measure was taken it was counted for the operational impact score, this can be seen in table 1. The S2R website had an overview of all projects. To obtain the information needed, the objective heading was consulted. The link to all the projects overview is: https://rail-research.europa.eu/research-development/

Individual or combined mitigation strategy?	Did the measure cut life cycle costs?	Was the measure capacity increasing?	Was the measure performance increasing?

Table 1; Example how the calculation was done

All 106 cases had been collected, analyzed and were then prepared for statistical analysis.

3.3 *Data analysis*

The data analysis was performed by using IBM SPSS Statistics software through the following steps. The null hypothesis (H0) asserts that there is no difference in the operational impact scores between projects employing individual strategies and those employing combined strategies. The alternative hypothesis (Ha) contends that there is a significant difference. The Mann-Whitney U test will be utilized to assess these hypotheses due to the non-normal distribution of the data.

1. **Descriptive statistics:**
   The mean, standard deviation and standard error for operational impact scores were calculated for each group to form the descriptive statistics.
2. **Check assumptions:**
   The Shapiro-wilk test was conducted to see if the data follows an equal distribution. The test indicates that the data does not follow a normal distribution, for both groups the p-values are < 0.001. Due to the violation of normality, a non-parametric test was used for testing the Mann-Whitney U test. The levene's test is ignored since a non-parametric test is used
3. **Mann-Whitney U Test**
   The Mann-Whitney U test was conducted whereas the grouping variable was defined as: Group 0: Projects employing individual strategies & Group 1: Projects employing combined strategies. The dependent variable was the operational impact.

3.4 *Ethical considerations*

In conducting the research on operational improvement measures on the European railway network some ethical considerations must be addressed to make this study credible and whole. First the research used publicly available data, so no personal or private information is accessed or revealed. Secondly the study is conducted transparently, within the methodology, data sources and data analysis everything is clearly documented and accessible.

4. Results

4.1 *Results of the preparation*

This section will report the findings of the quantitative study. In appendix 1 an excel sheet can be found where this result section is based on. In total, there were 105 projects within the S2R joint undertaking.

4.1.1 Distribution among strategies

In Table 2 the distribution among strategies is visible, underneath the table the results will be discussed. The strategies are ordered in terms of number of projects

Type of Strategy	**Number of projects (% of total)**
Technological Innovations	63 projects (60%)
Technological Innovations & Policy Reforms	16 projects (15,24%)
Infrastructural Improvements & Technological Innovations	14 projects (13,33%)
Policy Reforms	6 projects (5,71%)
Infrastructural Improvements	3 projects (2,86%)
All measures	1 project (0,95%)
No Measures	1 project (0,95%)
Infrastructural Improvements & Policy Reforms	0 projects (0%)

Table 2; *Distribution strategies among projects*

The distribution is quite evident, most projects are technological innovations. The category is most dominant in both single and in a combination with one of the other measures.
This outcome underlines that for the S2R project 89,5% of the projects have some involvement of technological innovations. An example is the combination with policy reforms is 15,24% of the projects. Within S2R many projects have this overlap since new technologies are being used or implemented and this is regulated via policy reforms or operational changes. The project MOVINGRAIL for example has the emphasis on testing Moving Block Signaling and how to operationalize this. (Rob Goverde, 2020).

There are only 17 projects where infrastructural improvements are involved. The notable lack of infrastructural improvements projects may be due to the involvement of many universities in the projects, as these institutions focus on innovation and research rather than direct physical implementation.

4.1.2 Realization of operational impact scores

This section will provide valuable insights on why certain measures were accounted for in a project. It helps to understand on what basis the results were formed. Both individual and combined strategy projects will be discussed.

Individual:

- INNOWAG for example had its emphasis on using predictive maintenance, and an increased usage of RAMS. Also the project aimed to increase the capacity. This project therefore has an operational impact score of 3.
- ST4RT had the focus on promoting railway infrastructure and making it more accessible in the digital world. No operational measures were taken so the operational impact score was 0.
- SMART and SMART2 both focussed on developing a real time yard management and obstacle system. These measures both ensure a higher performance since less discrepancies are expected. The operational impact score for these projects both was 1.

Combined:

- IN2SMART2 focussed on reducing the time for maintenance and its costs. Since the time of maintenance is reduced the reliability becomes higher. That resulted in this project the operational impact score was 2.
- SHIFT2MAAS had its emphasis on the development of apps to make railway infrastructure more accessible. This has no direct effect on the operationality, therefore the operational impact score is 0.

4.1.3 Descriptive statistics

The descriptive statistics for the operational impact score based on the type of strategy Individual (group 0) and combined (group 1) are summarized in Table 3. The mean operational impact score for projects using individual strategies (N=74) is 0,91 with a standard deviation of 0,797, while for projects using combined strategies (N=32), the mean score is 1,41 with a standard deviation of 1,132.

Group	N	Median	IQR	Mean	Standard Deviation	Range
0 (individual)	74	1.00	2	0.91	0.797	0-2
1 (combined)	32	1.00	2	1.41	1.132	0-3

Table 3; Descriptive statistics

4.2 *Results of analysis*

4.2.1 Normality Tests

The results of the Kolmogorov-Smirnov and Shapiro-Wilk tests indicate that the operational impact scores do not follow a normal distribution for both individual and combined strategies groups (p < .001), as shown in Table 4.

Group	**Test**	**Statistic**	**degree of freedom (df)**	**Significance (sig)**
0 (Individual)	Kolmogorov-Smirnov	0,237	74	<0,001
	Shapiro-Wilk	0,797	74	<0,001
1 (group)	Kolmogorov-Smirnov	0,174	32	0.015
	Shapiro-Wilk	0,857	32	<0,001

Table 4; Tests of Normality

Since the data do not follow a normal distribution, the independent sample t-test can’t be conducted. So therefor a Mann-Whitney U test is consulted, since this test can be conducted without a normal distribution

4.2.2 Mann-Whitney U Test

The Mann-Whitney U test results, presented in Table 5 and 6, show a statistically significant difference in operational impact scores between projects employing individual strategies and those employing combined strategies (U = 892.500, p = 0.035). Projects using combined strategies have a higher mean rank (62.61) compared to those using individual strategies (49.56).

Strategy Type	**N**	**Mean Rank**	**Sum of Ranks**
Group 0 (Individual)	74	49.56	3667.50
Group 1 (Combined)	32	62.61	2003.50

Table 5. Mann-Whitney U Test Results (1)

Test Statistics

Test Statistic	Operational Impact Score
Mann-Whitney U	892.500
Wilcoxon W	3667.500
Z	-2.107
Asymp. Sig. (2-tailed)	0.035

Table 6. Mann-Whitney U Test Results (2)

The null hypothesis (H0) was: There is no significant difference in operational impact score between projects using individual and combined strategies.
The alternative hypothesis (H1) was: There is a significant difference in operational impact score between projects using individual and combined strategies.
The p-value is the most important value in the Mann-Whitney U test and is in this case 0.035. This means that the H0 is rejected and the H1 is approved. This results in that the test has found enough evidence to conclude that there is a significant difference in operational impact scores between individual and combined mitigation strategies.

5. Conclusion

In this research, 106 S2R projects were analyzed to gain an understanding on how individual and combined mitigation strategies influenced the operationality of railway infrastructure. The study has proven that combined mitigation strategies significantly enhance the operational improvement measures. The S2R initiative, with its goals being life cycle cost reduction, capacity increasing and performance increasing measures proves that a combined approach results in higher operational impact scores.

The findings align with existing literature that advocate for combined strategies in enhancing infrastructure resilience Menoni *et al.* (2012). By revealing that combined mitigation strategies offer broader enhancements in operational capabilities, this study underlines the importance of integrating different climate mitigation strategies to optimize operationality of railway infrastructure. The study also showed that within the S2R project the main strategy was on technological innovations since 89,5% of the projects had some involvement in this strategy.

However, this study has some limitations. Since the predominant focus was on technological innovations over infrastructural improvements and policy reforms, the project might reflect the interests and capabilities of the academic and research institutions involved, rather than the practical necessities of railway operations. This is an area that can be explored in future research. Additionally, the reliance on publicly available data and the classification of projects based on available descriptions may introduce biases. Some projects had for example an extensive list of objectives and how these were achieved, others had only a short summary of the projects.

Future research should address these limitations by incorporating more diverse data sources and considering a broader range of practical implementations. Also future research can delve into the differences in costs between strategies and if this might influence the selection of strategies. As said earlier, new research can use another context since the involvement of universities might have a substantial effect on the strategies used. For policymakers in railway infrastructure this study is also relevant since they have significant arguments to use combined strategies instead of individual strategies.

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7. Appendices

***Appendix A**; Projects and the Strategies*

Innovation Pillar	**Project**	**Infrastructural improvements**	**Technological innovations**	**Policy Reforms and operational changes**	**Infrastructural improvements & Technological innovations**	**Technological innovations & Policy reforms**	**Infrastructural improvements & Policy reforms**	**All Measures**	**None**	**Other**
Innovation Pillar 1	RUN2RAIL		1							
Innovation Pillar 1	SAFE4RAIL		1							
Innovation Pillar 1	SAFE4RAIL-2		1							
Innovation Pillar 1	SAFE4RAIL-3		1							
Innovation Pillar 1	CARBODIN		1							
Innovation Pillar 1	CONNECTA		1							
Innovation Pillar 1	CONNECTA-2		1							
Innovation Pillar 1	CONNECTA-3		1							
Innovation Pillar 1	GEARBODIES		1							
Innovation Pillar 1	MAT4RAIL		1							
Innovation Pillar 1	NEXTGEAR		1							
Innovation Pillar 1	PINTA		1							
Innovation Pillar 1	PINTA2		1							
Innovation Pillar 1	PINTA3		1							
Innovation Pillar 1	PIVOT		1							

Innovation Pillar 1	PIVOT2		1								
Innovation Pillar 1	RECET4RAIL		1								
Innovation Pillar 2	MISTRAL		1								
Innovation Pillar 2	MOVINGRAIL					1					
Innovation Pillar 2	OPTIMA					1					
Innovation Pillar 2	PERFORMINGRAIL					1					
Innovation Pillar 2	VITE		1								
Innovation Pillar 2	EMULRADIO4RAIL		1								
Innovation Pillar 2	ETALON		1								
Innovation Pillar 2	GATE4RAIL		1								
Innovation Pillar 2	CYRAIL		1								
Innovation Pillar 2	4SECURAIL					1					
Innovation Pillar 2	AB4RAIL		1								
Innovation Pillar 2	ASTRAIL		1								
Innovation Pillar 2	X2RAIL-1		1								
Innovation Pillar 2	X2RAIL-2				1						
Innovation Pillar 2	X2RAIL-3		1								
Innovation Pillar 2	X2RAIL-4		1								
Innovation Pillar 2	X2RAIL-5		1								
Innovation Pillar 3	IN2SMART2				1						
Innovation Pillar 3	IN2STEMPO				1						

Innovation Pillar 3	IN2ZONE				1							
Innovation Pillar 3	MOMIT		1									
Innovation Pillar 3	S-CODE				1							
Innovation Pillar 3	STREAM		1									
Innovation Pillar 3	IN2DREAMS				1							
Innovation Pillar 3	IN2SMART					1						
Innovation Pillar 3	DAYDREAMS		1									
Innovation Pillar 3	FAIRSTATIONS ONS		1									
Innovation Pillar 3	FUNDRES				1							
Innovation Pillar 3	ASSETS4RAIL		1									
Innovation Pillar 3	IN2TRACK	1										
Innovation Pillar 3	IN2TRACK2	1										
Innovation Pillar 3	IN2TRACK3	1										
Innovation Pillar 4	IP4MAAS			1								
Innovation Pillar 4	it2Rail		1									
Innovation Pillar 4	MAASIVE					1						
Innovation Pillar 4	MY-TRAC		1									
Innovation Pillar 4	RIDE2RAIL		1									
Innovation Pillar 4	SHIFT2MAAS					1						
Innovation Pillar 4	SPRINT					1						
Innovation Pillar 4	ST4RT		1									

Innovation Pillar 4	EXTENSIVE		1							
Innovation Pillar 4	GOF4R			1						
Innovation Pillar 4	CO-ACTIVE				1					
Innovation Pillar 4	COHESIVE		1							
Innovation Pillar 4	CONNECTIVE		1							
Innovation Pillar 4	ATTRACKTIVE		1							
Innovation Pillar 5	INNOWAG		1							
Innovation Pillar 5	LOCATE					1				
Innovation Pillar 5	M2O				1					
Innovation Pillar 5	OPTIYARD		1							
Innovation Pillar 5	SMART		1							
Innovation Pillar 5	SMART 2		1							
Innovation Pillar 5	DYNAFREIGHT				1					
Innovation Pillar 5	FFL4E				1					
Innovation Pillar 5	FR8HUB				1					
Innovation Pillar 5	FR8RAIL		1							
Innovation Pillar 5	FR8RAIL II		1							
Innovation Pillar 5	FR8RAIL III			1						
Innovation Pillar 5	FR8RAIL IV		1							
Innovation Pillar 5	DACCELERATE					1				
Innovation Pillar 5	ARCC		1							

Innovation Pillar 6	LINX4RAIL		1							
Innovation Pillar 6	LINX4RAIL2		1							
Innovation Pillar 6	MVDC-ERS		1							
Innovation Pillar 6	RAILS		1							
Innovation Pillar 6	TAURO		1							
Innovation Pillar 6	TER4RAIL			1						
Innovation Pillar 6	TRANSLATE4RAILS		1							
Innovation Pillar 6	FLEX-RAIL									1
Innovation Pillar 6	HYPERNEX					1				
Innovation Pillar 6	B4CM		1							
Innovation Pillar 7	NEAR2050			1						
Innovation Pillar 7	OPEUS		1							
Innovation Pillar 7	PLASA					1				
Innovation Pillar 7	PLASA-2					1				
Innovation Pillar 7	SILVARSTAR		1							
Innovation Pillar 7	SMARTE					1				
Innovation Pillar 7	TRANSIT		1							
Innovation Pillar 7	DESTINATE		1							
Innovation Pillar 7	FINE 1				1					
Innovation Pillar 7	FINE-2					1				
Innovation Pillar 7	GOSAFE RAIL		1							

Innovation Pillar 7	IMPACT-1			1						
Innovation Pillar 7	IMPACT-2							1		
Innovation Pillar 7	BENRAIL					1				
Innovation Pillars 1 & 2 & 7	Roll2Rail		1							
Innovation Pillars 2 & 3 & 7	In2Rail				1					
Innovation Pillars 5 & 7	SMARTRAIL								1	
	TOTAL	3	63	6	14	16	0	1	1	1

Appendix B; *Individual strategies & measures taken*

Innovation Pillar	**Project**	**Life cycle cost cutting measures**	**Capacity increasing measures**	**Performance increasing measures**
Innovation Pillar 1	RUN2RAIL	TRUE	FALSE	TRUE
Innovation Pillar 1	SAFE4RAIL	TRUE	FALSE	TRUE
Innovation Pillar 1	SAFE4RAIL-2	FALSE	FALSE	FALSE
Innovation Pillar 1	SAFE4RAIL-3	FALSE	FALSE	FALSE
Innovation Pillar 1	**CARBODIN**	TRUE	TRUE	FALSE
Innovation Pillar 1	**CONNECTA**	TRUE	FALSE	TRUE
Innovation Pillar 1	**CONNECTA-2**	TRUE	TRUE	TRUE
Innovation Pillar 1	**CONNECTA-3**	TRUE	TRUE	TRUE
Innovation Pillar 1	GEARBODIES	TRUE	FALSE	TRUE
Innovation Pillar 1	**MAT4RAIL**	TRUE	TRUE	FALSE
Innovation Pillar 1	**NEXTGEAR**	TRUE	TRUE	FALSE
Innovation Pillar 1	**PINTA**	TRUE	TRUE	TRUE
Innovation Pillar 1	**PINTA2**	TRUE	TRUE	TRUE
Innovation Pillar 1	**PINTA3**	TRUE	TRUE	TRUE
Innovation Pillar 1	**PIVOT**	TRUE	TRUE	TRUE
Innovation Pillar 1	**PIVOT2**	TRUE	FALSE	TRUE
Innovation Pillar 1	**RECET4RAIL**	TRUE	FALSE	TRUE
Innovation Pillar 2	**MISTRAL**	FALSE	FALSE	TRUE
Innovation Pillar 2	**VITE**	FALSE	FALSE	FALSE
Innovation Pillar 2	**EMULRADIO4RAIL**	FALSE	FALSE	TRUE
Innovation Pillar 2	**ETALON**	FALSE	FALSE	TRUE
Innovation Pillar 2	**GATE4RAIL**	FALSE	TRUE	FALSE
Innovation Pillar 2	**CYRAIL**	FALSE	FALSE	TRUE
Innovation Pillar 2	**AB4RAIL**	FALSE	FALSE	TRUE
Innovation Pillar 2	**ASTRAIL**	FALSE	FALSE	TRUE
Innovation Pillar 2	**X2RAIL-1**	FALSE	TRUE	TRUE
Innovation Pillar 2	**X2RAIL-3**	FALSE	TRUE	TRUE
Innovation Pillar 2	**X2RAIL-4**	FALSE	TRUE	TRUE
Innovation Pillar 2	**X2RAIL-5**	FALSE	TRUE	TRUE
Innovation Pillar 3	MOMIT	FALSE	FALSE	FALSE
Innovation Pillar 3	**STREAM**	TRUE	FALSE	TRUE
Innovation Pillar 3	**DAYDREAMS**	TRUE	TRUE	FALSE

Innovation Pillar 3	FAIRSTATIONSONS	FALSE	FALSE	TRUE
Innovation Pillar 3	ASSETS4RAIL	TRUE	FALSE	FALSE
Innovation Pillar 3	IN2TRACK	TRUE	TRUE	FALSE
Innovation Pillar 3	IN2TRACK2	TRUE	TRUE	TRUE
Innovation Pillar 3	IN2TRACK3	TRUE	TRUE	FALSE
Innovation Pillar 4	IP4MAAS	FALSE	FALSE	FALSE
Innovation Pillar 4	it2Rail	FALSE	FALSE	FALSE
Innovation Pillar 4	MY-TRAC	FALSE	FALSE	FALSE
Innovation Pillar 4	RIDE2RAIL	FALSE	FALSE	FALSE
Innovation Pillar 4	ST4RT	FALSE	FALSE	FALSE
Innovation Pillar 4	EXTENSIVE	FALSE	FALSE	FALSE
Innovation Pillar 4	GOF4R	FALSE	FALSE	FALSE
Innovation Pillar 4	COHESIVE	FALSE	FALSE	FALSE
Innovation Pillar 4	CONNECTIVE	FALSE	FALSE	FALSE
Innovation Pillar 4	ATTRACKTIVE	FALSE	FALSE	FALSE
Innovation Pillar 5	INNOWAG	TRUE	TRUE	TRUE
Innovation Pillar 5	OPTIYARD	FALSE	TRUE	TRUE
Innovation Pillar 5	SMART	FALSE	FALSE	TRUE
Innovation Pillar 5	SMART2	FALSE	FALSE	TRUE
Innovation Pillar 5	FR8RAIL	TRUE	FALSE	TRUE
Innovation Pillar 5	FR8RAIL II	FALSE	FALSE	TRUE
Innovation Pillar 5	FR8RAIL III	TRUE	TRUE	TRUE
Innovation Pillar 5	FR8RAIL IV	TRUE	TRUE	FALSE
Innovation Pillar 5	ARCC	FALSE	FALSE	TRUE
Innovation Pillar 6	LINX4RAIL	FALSE	FALSE	FALSE
Innovation Pillar 6	LINX4RAIL2	FALSE	FALSE	FALSE
Innovation Pillar 6	MVDC-ERS	FALSE	FALSE	FALSE
Innovation Pillar 6	RAILS	FALSE	FALSE	TRUE
Innovation Pillar 6	TAURO	TRUE	TRUE	TRUE
Innovation Pillar 6	TER4RAIL	FALSE	FALSE	FALSE
Innovation Pillar 6	TRANSLATE4RAILS	FALSE	FALSE	TRUE
Innovation Pillar 6	FLEX-RAIL	FALSE	FALSE	FALSE
Innovation Pillar 6	B4CM	FALSE	FALSE	FALSE
Innovation Pillar 7	NEAR2050	FALSE	FALSE	FALSE
Innovation Pillar 7	OPEUS	FALSE	FALSE	FALSE
Innovation Pillar 7	SILVARSTAR	FALSE	FALSE	FALSE

Innovation Pillar 7	TRANSIT	TRUE	FALSE	FALSE
Innovation Pillar 7	DESTINATE	FALSE	FALSE	FALSE
Innovation Pillar 7	GOSAFE_RAIL	TRUE	FALSE	TRUE
Innovation Pillar 7	IMPACT-1	FALSE	FALSE	FALSE
Innovation Pillars 1 & 2 & 7	Roll2Rail	TRUE	FALSE	TRUE
Innovation Pillars 5 & 7	SMARTRAIL	FALSE	FALSE	FALSE

Appendix C; *Combined Strategies & measures taken*

Innovation Pillar	Project	Life cycle cost cutting measures	Capacity increasing measures	Performance increasing measures
Innovation Pillar 2	**MOVINGRAIL**	FALSE	FALSE	TRUE
Innovation Pillar 2	OPTIMA	FALSE	FALSE	FALSE
Innovation Pillar 2	**PERFORMINGRAIL**	FALSE	TRUE	TRUE
Innovation Pillar 2	**4SECURAIL**	FALSE	FALSE	FALSE
Innovation Pillar 2	**X2RAIL-2**	FALSE	TRUE	TRUE
Innovation Pillar 3	**IN2SMART2**	TRUE	FALSE	TRUE
Innovation Pillar 3	**IN2STEMPO**	FALSE	FALSE	TRUE
Innovation Pillar 3	**IN2ZONE**	TRUE	TRUE	TRUE
Innovation Pillar 3	**S-CODE**	TRUE	TRUE	TRUE
Innovation Pillar 3	**IN2DREAMS**	TRUE	FALSE	TRUE
Innovation Pillar 3	**IN2SMART**	TRUE	FALSE	FALSE
Innovation Pillar 3	FUNDRES	FALSE	FALSE	FALSE
Innovation Pillar 4	**MAASIVE**	FALSE	FALSE	FALSE
Innovation Pillar 4	**SHIFT2MAAS**	FALSE	FALSE	FALSE
Innovation Pillar 4	**SPRINT**	FALSE	FALSE	FALSE
Innovation Pillar 4	**CO-ACTIVE**	FALSE	FALSE	FALSE
Innovation Pillar 5	**LOCATE**	TRUE	FALSE	TRUE
Innovation Pillar 5	**M2O**	TRUE	TRUE	TRUE
Innovation Pillar 5	**DYNAFREIGHT**	TRUE	TRUE	TRUE
Innovation Pillar 5	**FFL4E**	TRUE	TRUE	FALSE
Innovation Pillar 5	**FR8HUB**	TRUE	TRUE	TRUE
Innovation Pillar 5	DACCELERATE	FALSE	TRUE	FALSE
Innovation Pillar 6	**FLEX-RAIL**	FALSE	FALSE	FALSE
Innovation Pillar 6	**HYPERNEX**	FALSE	FALSE	TRUE
Innovation Pillar 7	**PLASA**	TRUE	FALSE	TRUE
Innovation Pillar 7	**PLASA-2**	TRUE	FALSE	FALSE
Innovation Pillar 7	**SMARTE**	TRUE	TRUE	TRUE
Innovation Pillar 7	**FINE 1**	TRUE	FALSE	FALSE
Innovation Pillar 7	**FINE-2**	TRUE	FALSE	FALSE
Innovation Pillar 7	**IMPACT-2**	TRUE	FALSE	TRUE
Innovation Pillar 7	BENRAIL	FALSE	FALSE	FALSE
Innovation Pillars 2 & 3 & 7	In2Rail	TRUE	TRUE	TRUE