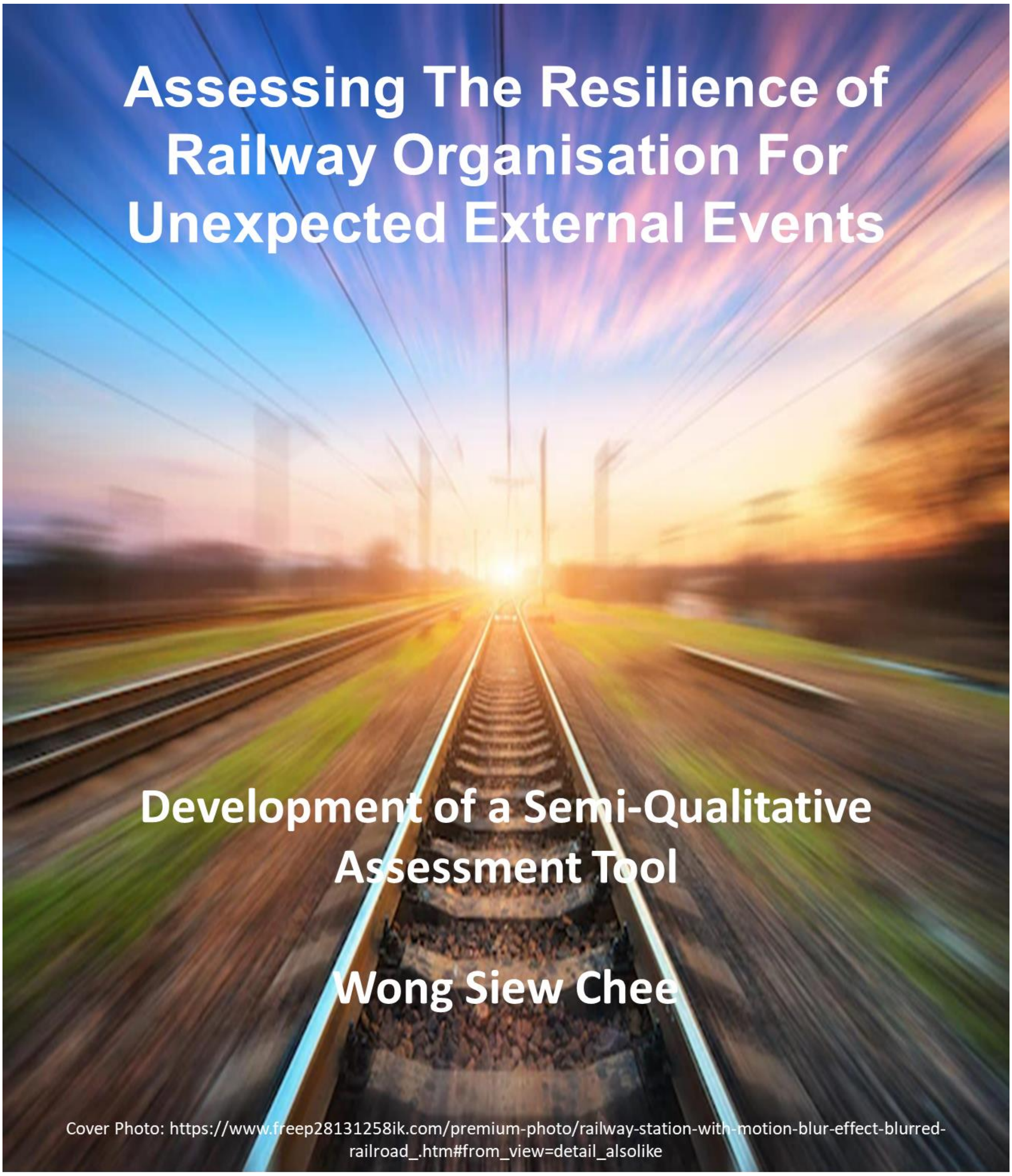
Delft University of Technology

Assessing The Resilience of Railway Organisation For Unexpected External Events

Development of a Semi-Qualitative Assessment Tool

Wong Siew Chee



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Assessing The Resilience of Railway Organisation

For Unexpected External Events

Development of a Semi-Qualitative Assessment Tool

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Preface

Time flies and it has been more than six months since I embarked on the final lap of my Master's degree journey in search of a suitable graduating thesis topic. It was a challenging start on settling a topic of interest that I can work on. I am grateful to both of my daily supervisors Professor Alfredo and Professor Hongrui, for their time and advice given in the searching process. Besides them, I am also grateful to my supervisors back at my workplace whom I have also approached to, when searching for potential ideas and that is where the topic of Railway Resilience comes about. A big thanks to Professor Niels who readily accepted my invitation to be the Chairman of my Graduation Committee. It has been a fruitful journey to be able to continue the last lap under their supervision and guidance despite their busy schedule.

Working in the field of Systems Assurance for years, Railway Resilience is a new concept to me, though from the research conducted in this thesis, this area has been a discussion point for many years. Many industries are aware of the importance of being resilient, and in the railway transportation sector, there are also calls for more awareness to be made on increasing the resilience of the sector. And especially to be well prepared for unexpected events or triggering points that can affect the operation of the railway and all its affiliated systems, structures, railway users, etc. Resilience is a complex topic and there is no definite international guideline or technical specification that one can follow to understand what railway resilience really constitutes. Through the writing of this thesis, I am able to better comprehend what Railway Resilience is, why it is important, what have been done by the many researchers in the academic field who seek to play a part in enhancing the resilience of the railway transportation system.

Last but not least, I am grateful to my family and friends back in Singapore who have provided their utmost support in times of doubts encountered during this intense journey on writing this thesis. Beside them, peers from the Transport and Planning faculty have also provided support to one and other as everyone shares their experiences. To end, I am appreciative to be given the opportunity to pursue my Master's Degree at TU Delft as it has broadened my horizon and provided me with a different perspective of what transportation planning is. I look forward to sharing the knowledge and experience gained at this top-ranking university in the Netherlands.

Thank you,

Siew Chee

November 2023

Executive Summary

The railway transportation system is a critical infrastructure that supports the functionality of a country through ways like the transportation of people from point to point to carry out their daily activities i.e., work, study, and leisure; the timely transportation of freight within a country or cross-borders, contributing to economic development, etc., thus it has to be effective in its operation and service provision. Normal operation can get affected when railway systems such as trains, signalling systems, etc. fail to operate, railway infrastructures are damaged, occurrences of collisions or derailment. These events result in inconveniences caused to railway users, loss in service confidence and decline in revenue. Hence, railway organisations continuously put in effort to reduce the occurrence of railway disruptions that are within their means to prevent.

However, there have been reports on railway disruptions caused by events that are uncontrollable within the means of the organisations. On 07 September 2023, torrential rain poured over Hong Kong, causing serious floods. In a press release by the railway operating company, the Hong Kong MTR, stations and train operations were severely impacted due to severe flooding on the railway tracks, resulting in the closure of sections of the railway network *(Hong Kong MTR Corporation Limited, 2023)*. Stations facilities such as the escalators, lifts, platform screen doors, etc. are also damaged and these require a period of restoration time. On 26 August 2023, the Polish intelligence services were investigating a possible hacking incident to the railway whereby hackers manage to transmit a signal triggering emergency stop of trains near the city of Szczecin *(BBC News, 2023)*. In a report published by the European Union Agency for Cybersecurity of the cyber threat landscape of the transport sector, 21% of these incidents occurred in the railway sector and the Railway Undertakings and Infrastructure Managers are mostly the targeted victims (*ENISA Transport Threat Landscape*, 2023).

The railway transportation system faces continuous '*threats*' despite the continuous effort put in by railway organisations to provide mitigation measures. This thesis has classified these *'threats'* as expected and unexpected. Expected *'threats'* refer to events whereby their potential of disrupting the operation of the railway transportation system is anticipated, thus mitigation measures can be implemented in advance so as to eliminate or prevent the event from happening. On the other hand, unexpected '*threats*' refer to events whereby the occurrences cannot be controlled and sometimes it can be unpredictable. For example, the occurrences of sudden flooding at areas along the railway network with no history of occurrences, the hacking of information technology systems used in the railway systems, political changes leading to closure of borders, etc. Improving the resilience of railway systems, infrastructures and railway organisations when operating in an environment with these threats is one of the keys to ensure railway operation. Resilience in the railway context is the "*process that makes the railway system flexible to disturbing events by allowing the system to have a certain degree of deviation from its intended performance" (Nipa et al., 2023)*. Resilience comprises of Robustness, Redundancy, Resourcefulness and Rapidity, forming the 4R Resilience Framework.

The objective of this thesis is to study how the resilience of a railway organisation, in view of the occurrences of 2 unexpected external events (i.e., climate change and cyber-attack), can be assessed by incorporating the elements of the 4R Resilience Framework to its operation and management. The assessment work is carried out through a semi-qualitative tool created by this thesis which adopts a systematic approach by making use of a 5-stages cycle framework shown in Figure i. Stage 1 involves the identification of resilience attributes to represent the resilience of a railway organisation and its operating assets. Attributes belonging to the Technical (hardware and software) and Organisational (internal and external) domains have been identified with further explanations on how they are relevant to the 4R Resilience Framework provided in the appendices. These attributes are then

evaluated against qualitative criteria in order to assess the current state of resilience performance that the organisation exhibits. As resilience is an 'intangible' property, this characteristic has been converted to measurable format by assigning discrete values to the evaluation criteria, so that a resilience score can be obtained for each attribute.

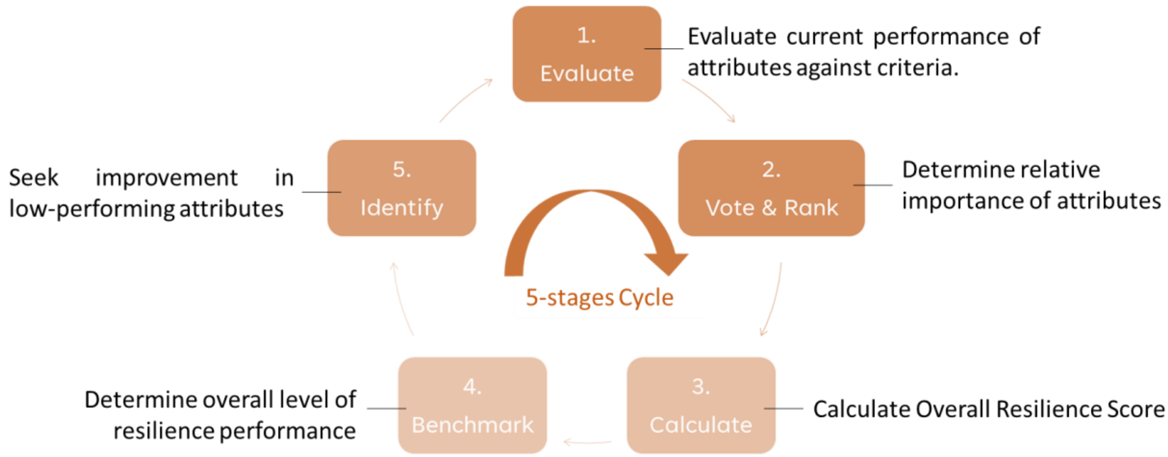

Figure i: 5-stages cycle

Step 2 involves a combination of voting and ranking process. The top management or decision-makers of the railway organisation using this tool are to cast their votes based on whether they think the attributes are critical to resilience assessment. The vote-count of each attribute is tallied and ranked in accordance with the highest vote-counts (ranked first) to the lowest vote-counts (ranked last) which is then used to determine the weightages of the respective attributes that reflect their relative importance. A combined Rank Ordered Centroid-Technique for Order of Preference by Similarity to Ideal Solution (ROC-TOPSIS) method is used to calculate objective weightages in Step 3. An overall resilience score considering all attributes is then calculated. In Step 4, the resilience score at attribute-level and at overall-level are benchmarked against a coloured resilience table i.e., Low-Medium-High, which provides indication on the resilience performance. In Step 5, the aim is to identify attributes falling under the Low category which are easily identifiable and highlighted in the assessment tool, whereby more resilience-building measures are needed in order to improve the resilience performance.

Validation is a critical step as there is a need to determine the effectiveness of the tool. Survey questionnaire is used to gather feedback on the applicability of the resilience attributes and its associated evaluation criteria; the method of weightage calculation at attribute-level, the user interface as well as the overall usefulness of the tool. More than 60% of the survey respondents think that all the resilience attributes and all the evaluation criteria proposed by this thesis are applicable, while there are some who think otherwise and their views on non-applicability. Discussion on these feedback and details can be referred to in the main report. In general, the survey result obtained is positive with more than 97% of respondents feedback that the assessment tool is at least moderately useful in conducting the resilience assessment. Some of the positive feedback include the creation of an awareness on the importance of railway resilience, the provision of a systematic approach in evaluating the resilience performance of a railway organisation. There are also rooms for improvement such as the expansion of the resilience attributes to a more detailed level, the incorporation of other railway assets, etc.

Ways of how this tool can be applied are listed in the report. Simulated example of how the tool fits into the before-after resilience assessment framework created and how low-performing attributes can be improved, are provided. As mentioned in the earlier paragraph, this thesis has provided attributes from the Technical and Organisational domains. Attributes from the Economic domain are suggested for consideration. Similar to risk management, resilience management is a proactive approach and resilience assessment is a continuous task. Higher level of resilience can reduce the level of risk that a railway organisation faces when '*threats*' happened because preventive measures have been put in place as much as possible. The higher the level of resilience, the lower the level of risk which in this case the risk of severe railway disruption that the railway organisation will face. The continuous assessment by using this tool helps the top management/decision-makers to make informed decisions on how the available resources that the organisation has, can be allocated so as to prioritise in attributes with concern. It is also a mean to use the overall resilience score as a Key Performance Indicator that the organisation should target to achieve.

In conclusion, the assessment tool developed by this thesis is a feasible method that can be used to assess the resilience of a railway organisation and to provide tangible indication. It is a preliminary tool as noting the fact that there are rooms for improvement from the survey and through the scientific and in-practice perspectives that this thesis has gathered. There are also potential areas of consideration such as the incorporation of the measurement of vulnerability and susceptibility that a railway organisation faces in the emergent of unexpected external events whereby this could be a field of research on how these factors can be quantified, making the resilience assessment more wholistic. As this thesis has only considered the Rolling Stock in the derivation of the tool, future research can also look into the identification of attributes and evaluation criteria, thereby formulating 'basic' resilience assessment recipes for other railway systems and infrastructures that railway organisation can adopt.

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List of Abbreviations

COTS	Commercial-Off-The-Shelf
DAT	Direct Assignment Technique
ENISA	European Union Agency for Cybersecurity
EU	European Union
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
MCDA	Multi-Criteria Decision Analysis
O&M	Operation & Maintenance
RE	Resilience Engineering
RS	Rolling Stock
R4	Robustness, Redundancy, Resourcefulness, Rapidity
ROC	Rank Ordered Centroid
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TOSE	Technical, Organisational, Economic, Social
T&C	Testing & Commissioning

1. INTRODUCTION

1.1. Overview

An effective railway transportation system with well-optimized infrastructure and network connectivity is of paramount importance because the transportation system is identified as a critical infrastructure that supports the functionality of a country *(Yang et al., 2022)*. One key function is ensuring the effective commute of millions of passengers from point to point to carry out their daily activities such as work, study, leisure, etc. Another key function is to support the freight transportation between countries. This function plays a critical role in the supply chain and it brings about economical benefits. Thus, it is important that the integrity of the railway system is being uphold and maintained.

When railway operation gets disrupted, it brings about negative outcomes and experiences to the users of the systems. This group of users refers to the passengers, freight companies and to the companies that manage the railway systems. Negative outcomes involving railway passengers can include serious safety concerns to passengers when trains derailed or collided, services reliability issue when there are frequent train breakdowns or services cancellation and punctuality issue when railway services not on time. When railway disruption gets serious such as lasting for more than the acceptable period of time set by the railway operating companies, alternative transportation modes might have to be arranged by the railway operating companies for the affected passengers so that they can continue with their activities. In some instances, railway operating companies might be required to provide monetary compensation to passengers as ticket refunds. These negative events will eventually lead to customer service dis-satisfaction, loss in confidence and reputation of the railway operting companies. On the other hand, when freight deliveries are delayed, freight items such as perishable products get spoilt, supply chains and businesses are affected. It can lead to businesses having to incur additional costs such as expedited shipping charges, potential penalties for late deliveries. All these eventually lead to economical loss.

To avoid experiencing these negative outcomes, railway organisation thus invest heavily in ensuring the functionality and operability of the railway assets. Railway assets refer to the electrical and mechical systems such as the rolling stocks, signalling systems, power supply system, etc.; civil infrastructures such as the stations and platforms, railway tracks, bridges, depots, etc. The investment made can start from the design of the railway systems and infrastructures, to the maintenance of these assets and eventually to the proper disposal. This thesis opined that it is within the control of the railway organisations to minimise the occurrence of system failures or railway disruptive events that are predictable and expected. This can be done by designing systems with high reliability, availability, maintainability and safety; ensuring prompt and effective maintenances for these railway assets are conducted, timely replacement of railway assets that are not functioning, etc. However, there has been an increase in occurrences of 'external events' that are not controllable and not within the means of railway organisations to prevent it from happening. Some of these external events will be elaborated in the next section. Since these uncontrollable external events bring about negative impacts to railway operation and are unavoidable, hence, how ready are these railway organisations in gearing themselves to operate in such environment and why do they need to comprehend their readiness?

1.2. Problem Statement and Research Gap

The railway transportation system faces continuous '*threats*' despite the continuous effort put in by railway organisations to provide mitigation measures. This thesis has classified these *'threats'* as expected and unexpected. Expected *'threats'* refer to events whereby their potential of disrupting the operation of the railway transportation system is anticipated, thus mitigation measures can be implemented in advance so as to eliminate or prevent the event from happening. The probability of these events such as failure of system components, weakening of infrastructures, etc. can be predicted. On the other hand, unexpected '*threats*' consist of events whereby the occurrences cannot be controlled and sometimes unpredictable. For example, the occurrences of sudden flooding at areas along the railway network with no history of occurrences, political changes leading to closure of borders, etc.

The scope of this thesis looks at 'unexpected' external events because there is an increasing occurrence of railway assets and infrastructures facing with external events that affect the physical conditions and its intended operation, thus affecting the operation safety and the overall service level being provided *(Amoaning-Yankson & Amekudzi-Kennedy, 2017)*. These external events can be unintentional and intentional. Unintentional events include natural causes for example severe weather i.e., heatwaves, thunderstorms, snowstorms due to extreme climate change *(AR6 Synthesis Report, 2023)*, epidemic pandemic such as the Covid-19 pandemic *(Global Railway Review, 2023)* which almost brought worldwide railway transportation systems to a halt. Intentional events can include cybersecurity attacks targeting railway Information Technology systems, ticketing systems *(Bonneau et al., 2022; European Union Agency for Cybersecurity, 2023)*, terrorism or industrial or cyber sabotage. Despite the effort and investment put in by railway organisation to keep the railway transportation system as robust as possible, the earlier quoted impacts caused by these external events showed that railway organisation are still vulnerable towards unexpected external threats. Aside to staying well-prepared to counter the occurrences of expected events that lead to system failures, how can a railway organisation determine whether if their current operating patterns and means are also adaptable to the occurrence of unexpected external events. This relates to the concept of Resilience.

Railway resilience is defined as the '*ability of a railway system to provide effective services in normal conditions, as well as to resist, absorb, accommodate and recover quickly from disruptions or disasters that inevitably happens*' *(Bešinović, 2020).* Most papers from literatures formulated mathematical and optimization models, simulation methods, or conduct data-driven analyses to study how the physical resilience of railway infrastructures and assets can be determined and enhanced by analysing the vulnerabilites of the assets. The papers mainly focus on areas such as the operability of railway systems, the interconnectivities between systems, propagation of failures in railway networks, etc. Additionally, these methods are tools that can assist to further establish in-depth understanding and analyses on the performance of the railway systems at tactical and operational levels. In view of the large number of railway assets own, the management level of the railway organisation who usually are the key decision-makers, requires information at strategical level to know the overall resilience level of their railway assets so that resilient-building efforts can be pin-pointed for detailed plans to be developed. Understanding the critical aspects and attributes of railway resilience in facing the external events can provide greater guidance in scoping the level of preparedness that railway organisation should have, the acceptable level of disruption such as the extent of reduced railway system performance allowed, the amount of recovery effort needed *(Tierney & Bruneau, 2007)*.

This thesis opined that aside to ensuring the resilience of physical railway assets as much as possible, the resilience of the organisation should also be ensured. Assets are seen as the front-end systems in getting the transportation system running. The organisation on the other hand, is seen as the critical backbone or back-end, which manages not only the railway systems and infrastructures but also the human assets i.e., ground staff, operation teams, management staff, etc. and management aspect. It is so far not fully addressed in literatures on how the resilience of railway organisation can be defined by considering both the front-end and the back end and measured and this forms the core of this thesis. This thesis would like to create an assessment approach that can be used as a form of decision-making strategy at strategic level, serving to inform and support decision-makers of the railway organisation to determine its overall resilience level with respect to the operation of its railway assets and the functionality of the organisation. It helps the organisation to recognise if the level of preparedness that the organisation has is adequate and if no, what are the areas that more initiatives can be put in.

1.3. Research Objectives

The first objective of this thesis is to study how the resilience of a railway organisation can be assessed. Figure 1 below illustrates the before-after assessment framework that this thesis has considered on how the resilience assessment can be established. Step 1 is to identify areas that define the resilience of the railway organisation. These areas that should maintain resilient when operating in an environment subjected to continuous threats from the occurrence of external events. Step 2 is to consider how the resilience of the identified areas can be assessed and portrayed to the management level/decision-makers/stakeholders. These 2 steps allow the management level to have a better overview and understanding on the readiness of the organisation and assets. After knowing how the organisation has performed in the respective areas, Step 3 is to identify areas with resilient deficiencies whereby resilient-building effort can then be implemented. The management level can then decide the scope and extent of enhancement work that the organisation will need to engage since there could be potential limitations such as availabilities of fundings and resources. This allows stakeholders to strike a balance and prioritise their work. In Step 4, the new resilience can again be re-assessed on a periodic and even a need-to basis after the improvement works have been implemented.

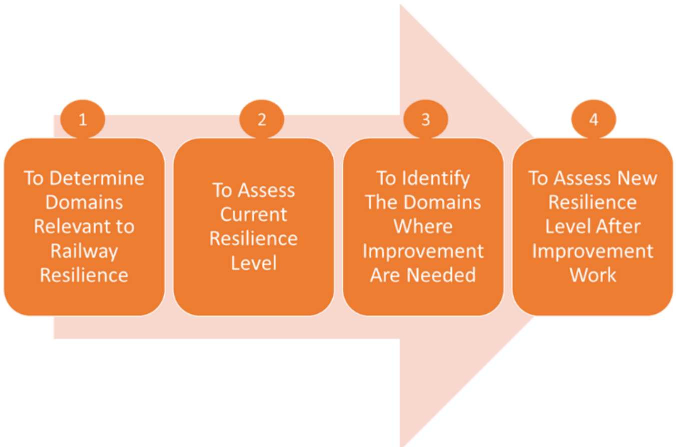


Figure 1: Before-after resilience assessment framework

The second objective is to determine how the outputs from a resilience assessment can be translated to a form of tangible resilient measurement after the information has been-consolidated and in what format that it can be presented to the decision-makers.

1.4. Research Questions

The main research question formulated is as follows:

How to assess the resilience of a railway organisation to prioritise actions that can improve its preparedness for unexpected external events impacting railway operation?

To address the main research question, the following sub-research questions have been identified:

1. *Which unexpected external events will become a priority for railway organisations due to their strong operational impacts?*
2. *How can the resilience of a railway organisation be defined while providing insightful information for management decision on actions implementation?*
3. *What are the attributes that can affect the resilience of a railway organisation?*
4. *How can the resilience of a railway organisation be evaluated, measured, and improved?*

1.5. Outline of Thesis Structure

The outline of the thesis structure is shown in Figure 2. Chapter 1 provides a background overview of the research topic with the research objectives and questions identified. Chapter 2 covers the literature review conducted in order to gain deeper insights on the research topic. Chapter 3 illustrates the resilience assessment approach proposed by this thesis, whereby the conceptual framework to guide the assessment work establishment and the development of the semi-qualitative assessment tool are detailed. Chapter 4 elaborates on the validation work conducted to determine the effectiveness of the assessment tool and the outcomes of the results are also being discussed. A feedback loop is drawn between Chapters 3 and 4 as the outcomes from the validation of the assessment tool might require the update of the assessment approach. Chapter 5 provides elaboration on how the assessment tool can be utilised. Chapter 6 finally concludes this research project as well as some future recommendations for consideration.

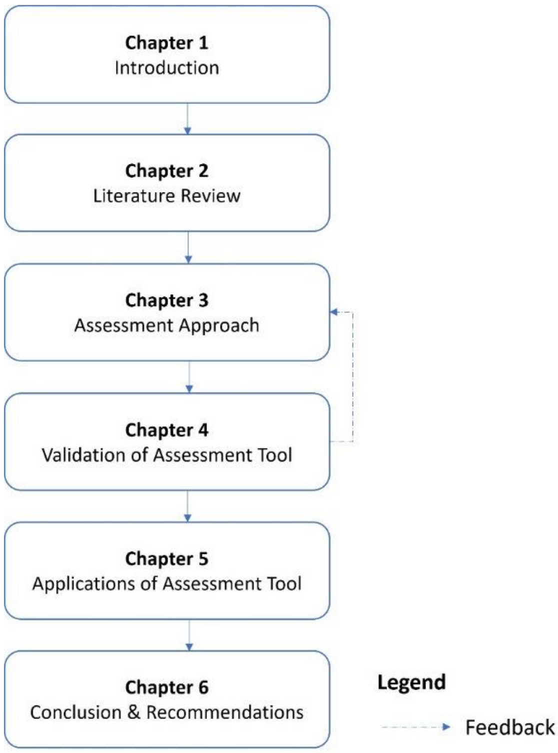


Figure 2: Thesis structure

2. LITERATURE REVIEW OF RESILIENCE IN RAILWAY CONTEXT

The focus of this chapter is on the literature review conducted in areas which include the definition of resilience and in the railway context, the unexpected external events that can affect railway operation and the associated impacts, what are the domains that represent the resilience of railway organisation represented and how this characteristic can be assessed.

2.1. Goals

The goals of conducting the literature analysis are to gain deeper understanding on the research topic through existing literatures and also it serves as the inputs to the establishment of the conceptual model of this thesis which will be elaborated in the next chapter.

2.2. Resilience

Understanding what resilience refers to is essential before determining why there is a need for railway resilience. Resilience is seen to be an inherent property or capability of a system to be able to recover to its original or pre-defined state after experiencing from an external shock or a change that has disrupted its original state. Quoted from the United Nations Office and Disaster Risk Reduction *(Secretary-General & Reduction, 2016)*, resilience is defined as "*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management*". It is the ability of the system to bounce back to its original state when faced when hit with unexpected demand *(Dinh et al., 2012)*.

From the literature search conducted, there are varying definitions of resilience adopted by different industries. In a paper by *(Nipa et al., 2023)*, the authors of this paper have conducted a thorough literature study and summarised the definition of resilience used in various disciplines such as the supply chain, asset management system, transportation system, critical infrastructure sector, etc. From this study, 25 commonly-adopted terms that are used to define resilience have been identified and among these, the top 4 frequently related terms are Robustness, Redundancy, Resourcefulness and Rapidity. These 4 terms are also being identified in the 'R4 Resilience Framework' developed by *(Tierney & Bruneau, 2007)* as part of a disaster research. The specific meaning of each of these 4 terms (4Rs) is extracted from the paper and shown in Table 1.

Table 1: Top 4 adopted terms related to Resilience – 4Rs (Tierney & Bruneau, 2007)

Term	Meaning
Robustness	*Refers to the absorptive capability of the system to withstand a certain level of functionality loss caused by a disaster.*
Redundancy	*Refers to the availability of alternative components that enable the system to sustain a certain level of damage but keeping its functionality.*
Resourcefulness	*Refers to the availability of emergency materials and human resources to quickly recover from a disaster.*
Rapidity	*Refers to the time that the affected system takes to restore to its pre-defined level of performance after a disaster.*

The roles of the 4Rs for transportation system can be explained by using the 'Resilience Triangle' adapted from *(Zhou et al., 2019)* and illustrated in Figure 3 below. The baseline for resilience in transportation system constitutes 2 perspectives i.e., (1) the ability to ensure continuous operation when encountering with a disruption (the Disruption Phase) and, (2) the amount of time and resources to restore the system to its pre-defined performance level after the disruption has occurred (the Recovery Phase). The Disruption Phase occurred from time t_0 to t_1, whereby at t_1, the performance of the system denoted by $P(t_1)$ is at its lowest value. This phase encompassed the Robustness and Redundancy components. Immediately after the Disruption Phase when the performance of the transportation system starts to improve gradually to t_2, this is the Recovery Phase whereby the service level of the system has been restored to its stable state and it is denoted as $P(t_2)$. This phase involves the Resourcefulness and Rapidity components. The shaded area in the graph refers to the level of resiliency loss, which can also mean the amount of extra effort needed to bring the resilience level back. With adequate preparedness measures in place, the aim is to minimise the loss in system performance, *'P'*, throughout both phases.

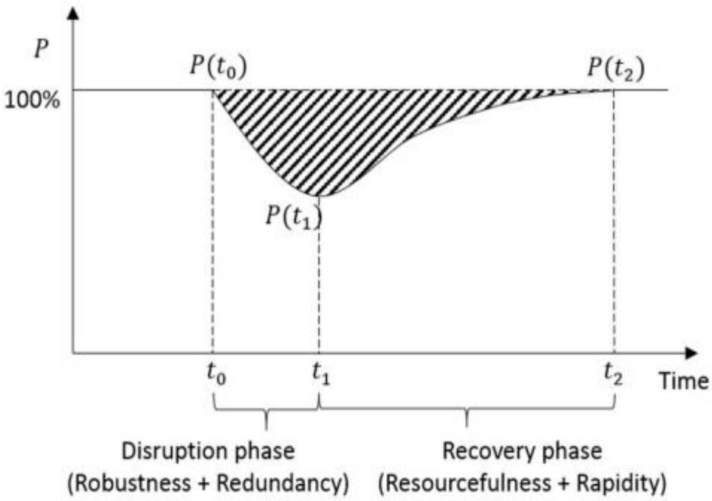


Figure 3: 2 Phases of resilience measurement
(Zhou et al., 2019)

2.2.1. Railway Resilience

In the context of railway transportation system, different definitions of resilience have been identified in the literatures, and observed with minimal deviation from the definitions given in the R4 Resilience Framework. For instant, the railway transportation system is a type of system. It is also a critical infrastructure to the society and it is also part of the transportation sector. Table 2 summarised the different definitions that have been identified and deemed applicable for the railway transportation system *(Nipa et al., 2023)*. It is opined that this is subjective as it is dependent on how one categorises the railway transportation system.

Table 2: Resilience definitions for railway transportation system

Discipline	Meaning
System Resilience	Refers to the ability of the system to adapt to disturbing events and to recover quickly and at the same time, ensuring a consistent performance.
Railway Resilience	Refers to the 4 terminologies as shown in Table 1 above. It is the dynamic process that makes the railway system flexible to disturbing events by allowing the system to have a certain degree of deviation from its intended performance.

Critical Infrastructure Resilience	Refers to the ability of the system to recover to a pre-defined level of functionality after experiencing the disturbing events in a minimum amount of time.
Transportation Sector Resilience	Refers to the ability of the network to continue operating during an unexpected event by making use of its inherent attributes to reduce the impacts of from the unexpected event and for recovery actions to be carried out immediately.

These definition eventually are also aligned with the definition defined by the United Nations Office and Disaster Risk Reduction as mentioned in Section 2.2 i.e., "*to be able to adapt and recover to its pre-defined initial level of functionality after encountering disruptive events*". Aside to the definitions shown in Table 2, there seems not to be an universal definition applied for the railway sector. Adopting the keyword search method using 'railway resilience' conducted on Google Scholar to search for latest articles, some of the defintions adopted by the different authors have been tabulated in the table below.

Table 3: Different definition of railway resilience

Authors	Ability (Of Asset/ System)	Impacts (From)	Outcomes
(Ilalokhoin et al., 2023)	Withstand	External Shock	Internal system to recover to its pre-disrupted state.
(Köpke et al., 2023)	Withstand	Cyber-Physical Threats to Railway Infrastructures	To retain system's functions and structures.
(Z. Zhang et al., 2023)	Absorb, recover	Disaster i.e., Covid pandemic	System to be able to absorb and recover from perturbations.
(Lu et al., 2022)	Absorb	Disruptive events such as railway incidents, natural disasters, terrorist attacks	System to remain robust during normal operation and resilient to disruptive events.
(Ma et al., 2022)	Absorb, Resist, Recovery	Incidents	System to have the ability to absorb impact before incident, resist ability during and recovery ability after incidents.
(Bešinović, 2020)	Provide, Resist, Absorb, Accommodate, Recover	Disruptions	System to provide effective service during normal conditions, and able to resist, absorb, accommodate, recover quickly.
(Wan et al., 2018)	Absorb, Maintain	Disturbances	System able to maintain its basic structure and function and to be able to recover to the pre-defined level of service with acceptable time and cost.

It is observed that the adaptation of 'Railway Resilience' is highly dependent on the environment, fields of work and the eventual outcomes of the researches that researchers would like to achieve. Similarly, most of these definitions look into the responses of how railway systems are able to withstand, absorb the external impacts and at the same time have the capability to retain its robustness, functionality and intended operation.

The keyword search method using Google Scholar and Scopus is used to identify what are the latest publications in relation to Resilience in Railway. Research work studied how the resiliency of railway infrastructures and assets can be determined and enhanced by assessing the performance of these railway assets. Some latest examples are identified below:

1. The condition monitoring of physical railway track components such as crossings and switches and its performance due to flooding is being studied by using machine learning method (*Sresakoolchai et al., 2023)*. Condition monitoring allows the actual condition and extent of deterioration to be known, and when necesssary, replacement work can be carried out promptly by Infrastructure Managers. Flooding caused damages to the structures which if left unrepaired, it can cause serious safety impacts such as railway derailment. This can be seen as part of the robustness strategy being considered by putting in place measures to enhance the robustness of the structures, in preparation for any flooding that could happen.
2. The use of belief-rule based method to study the resilience of High-Speed Railway buildings towards seismic conditions is 1 of the latest publications in 2023 to look into ways of improving the strength of the structures *(Tang et al., 2023)*, in order to increase the safety level. This can be seen as part of the robustness strategy being considered.
3. The unprecedented Covid-19 pandemic has brought about unexpected and detrimental effect to the public transport sector. Services see a decline in ridership as companies require staff to Work-From-Home, educational institutions adopted online-learning schemes at homes in order to reduce and support medical calls for reduction in the virus transmission between human and to minimise close contacts and interaction with one another, thus affecting the demand of public transportation drastically. Thus, this event has brought about a rise in academic research looking at the effect of Covid-19 on the public transportation system during the outbreak. One example is the study conducted by *(Z. Zhang et al., 2023)* that looks into assessing the quantitative resilience performance of the metro in the United States affected by Covid-19 using data-driven analytical method. Resilience performance such as the robustness, rapidity, recovery of the network line were being analysed during and also post-pandemic when the seriousness of Covid-19 has declined subsequently.
4. In the Recovery Phase of the R4 Resilience Framework, mitigation measures must be taken to quickly revert the railway operation to its original level or pre-defined service level within a short timeframe. Aside to looking into preventive measures that can limit the occurrences of railway disruption, railway operators are now also looking into ways of rescheduling their operating trains by adjusting the timetable schedule. In the paper by *(Yin et al., 2023)*, an optimization model using mixed integer linear programming approach is developed with the objective function to maximize the resilience of the network when facing disruptions. A train rescheduling framework is developed to see the usefulness of considering track layouts which allows short-turning operations and the availability of trains in all the depots.
5. The incorporation of Resilience Engineering in the engineering process of systems to detect and respond to unexpected events effectively as mentioned in this paper by *(Moerman et al., 2019)* whereby the resilient performance of the maintenance carried out on rolling stock is being determined. This leads to another latest topic such as devising more intelligent and sophisticated condition-monitoring tools to provide better assessment and realisation of the actual health status of these railway assets since early detection of the assets condition as part of the maintenance regime is also a key role in ensuring the resilience.

2.3. Impacts of Unexpected External Events on Railway Operation

Why is a resilient railway transportation system necessary and important? Through literature review, this will help to address sub-research question 1. With reference to Figure 3 in Section 2.2, railway organisations and users want to keep the extent of any railway disruption to be as low as possible, and if the need arises, to ensure the level of recovery to be maintained as high as possible. Events that disrupt railway operations bring about widespread impacts to the availablity and performance of the transporation system. Some of these undesirable impacts include inconveniences caused to railway users due to disrupted travelling modes, financial loss to railway operating companies as revenue is affected, additional costs and resources are needed to kick-in necessary recovery measures such as the provision of replacement buses to affected users or the provision of travel fares' compensation, etc. In view of these undesirable impacts, it is critical for the railway transportation system and the operating companies to be as resilient as possible. How does resilience help when facing with external events? Building up resilience gears up the operating companies to minimise the extent of damage or undesirable impacts that can be sustained in some of the following ways:

- The damages inflicted on the physical railway infrastructures.
- The safety of railway users.
- The propagation of railway disruption from localised impact to network-wide impact.
- The negative financial and social impacts.
- The loss in reputation and confidence that railway users have with the railway operating companies.

Having identified the pros of instilling resilience, next would be to identify what these external events to the railway transport sector could be. As stated in Section 1.1, unexpected external events can be caused by intentional and unintentional actions. Table 4 has summarised some of these external events which are seen as threats that the railway transportation system faced due to these actions. Unintentional action can be caused by natural actions, human or technical failures while intentional action is mostly attributed to human interventions.

Table 4: Examples of unintentional and intentional actions to railway transportation system

Intentionality of Action	Category	Examples of Threats
Unintentional	Natural-caused	Climate Change causing Flood, Earthquakes, Extreme temperatures, Snowstorms, Landslides.
	Human-caused	Insufficient proficiency or competency in the work to be done; fatigue at work causing loss of attention or awareness; lack of communication or interaction; display of poor leadership skills and management in the railway organisation; failure to adhere to protocols and procedures.
	Technical-caused	Systems fail to function or malfunction, systems redundancy fails to kick-in to ensure continuous operation.
Intentional	Human-caused	Arson, vandalism, terrorism, sabotage.
	Cyber-caused	Hacking of IT systems, Intrusion, Manipulation of Data.

The literature review will look into 1 unintentional and 1 intentional event which pose increasing concern that the railway sector should pay more attention due to the negative impact of these events and helps to address sub-research question 1.

2.3.1. Climate Change

The external event that commonly led to railway disruption is identified to be caused by extreme weathers due to climate change. Climate change can lead to extreme weathers such as extreme heatwaves, rise in sea level leading to potential floods at low-lying areas or heavy storms. In July 2022, Network Rail had to stop operation due to a fire that happened on the railway route between Peterborough and London King's Cross which was caused by the heatwaves, leading to trains cancellation and delayed *(BBC News, 2022)*. In October 2019, Typhoon Hagibis landed in Japan causing severe flooding, leading to the scrapping of 10 shinkansen worth 15 billion yen as they were submerged under water *(The Japan Times, 2019)*. Extreme high temperature experienced in some European countries like Spain and Belgium had also led to railway operators cancelling certain train schedules due to cases of fire near tracks, or the existing trains' air conditioning systems were unable to provide enough cooling in the saloons reported in 2022 (Geerts E., 2022). In February 2022, the arrival of Storm Eunice had led to operators in some parts of the Western Europe to halt train operation for hours. These events threaten the operation and functionality of the physical railway infrastructures whereby 'hazards' caused by these extreme weathers bring about the risk or harm to the operation as well as to the safety of all passengers and staff. In March 2023, an analysis was conducted whereby papers on the topic of resilience were being reviewed and categorized according to the types of disasters or hazards *(Nipa et al., 2023)*. Figure 4 shows that 22% of the papers are related to the resilience of transportation infrastructures impacted by natural disasters and 15% are attributable to natural and human-caused disasters.

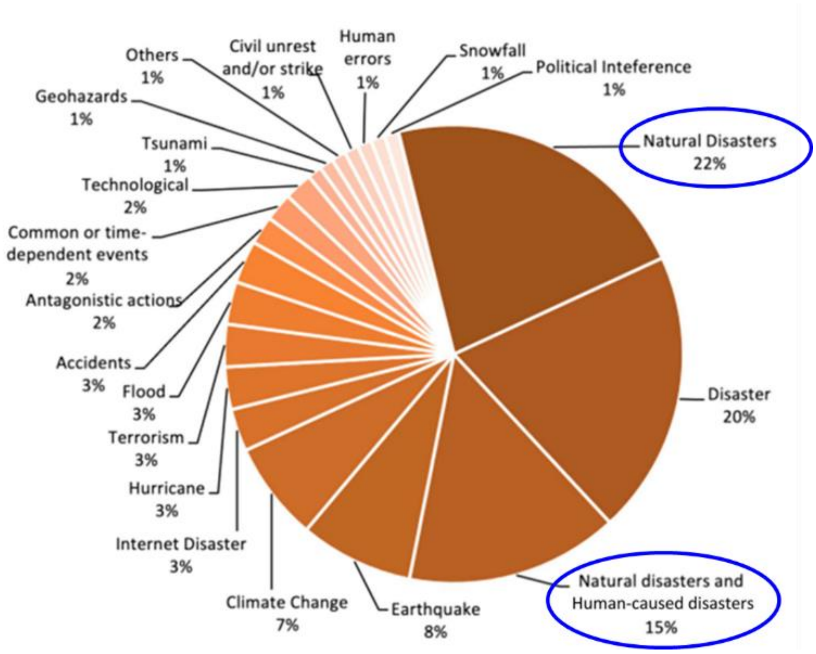


Figure 4: Distribution of papers based on disaster types affecting transportation infrastructures (Nipa et al., 2023)

The table below has collated from some papers *(Chan & Schofer, 2016; Kostianaia et al., 2021; Palin et al., 2021; Ferranti et al., 2022)* on the types of damages that railway infrastructures can sustain due to the above-mentioned weather conditions. In addition, this thesis has also assessed if the various types of damages bring about short or long-term direct impact to railway operation and the discussions are also included in the table. A common indirect impact would be the loss in revenue since railway service is being disrupted.

Table 5: Types of damages to railway infrastructures

Types of Weather Conditions	Common Damages to Railway Infrastructures	Short-Term or Long-Term Impact?
Extreme High Temperature	• Thermal expansion of the civil structures such as buckling of tracks and components, expansion of bridges, etc. • Desiccation of earthworks is possible.	Long-term impact as change-out of the physical rails would be needed. This would involve shutdown of the affected sections of the railway line. In addition, re-alignment of the tracks has to be conducted subsequently.
Extreme Low Temperature	• Damage to overhead lines. • Cracking of rails. • Accumulation of snow over the tracks inhibiting track operation.	Long-term impact since rectification work of the affected infrastructure has to be conducted. If the weather condition does not permit repair works to be done, extra delay to operation on the track is possible. This would also involve shutdown of the affected sections of the railway line and even stations.
Heavy Rainfall	• Flooding over track sections installed at low-lying area and even underground railway tunnels, stations and/or depots. • Railway assets submerged under water subjected to failure and malfunction. • Railway tracks might give way due to soil erosion i.e., failure of earthwork, landslides, etc.	Long-term impact since rectification work of the affected infrastructure has to be conducted. If the weather condition does not permit repair works to be done immediately, extra delay to operation on the track is possible. This would also involve shutdown of the affected sections of the railway line.
Strong Wind	• Toppling of objects such as trees, debris on at-grade railway tracks. • Damage to overhead lines and/or toppling.	Impact can be short-term since removal of the debris of on the tracks can be immediate. Rectification of any collapse of overhead lines might need longer rectification work, thus long-term impact.

The United Nation Intergovernmental Panel on Climate Change (IPCC) has recently published their Sixth Assessment Report *(Pörtner & Roberts, 2023)* which summarises the latest updates on global climate change, the impacts and associated risks, the mitigation measures and how countries around the world should adapt to this climate change. The working committee updated that extreme weather is on the increasing trend to remain happening for the years ahead and with this, climate change is expected to continue. Adapted from the assessment report, Figure 5 below showed the extent of impact of climate change on the different disciplines listed on the left-hand column of the figure.

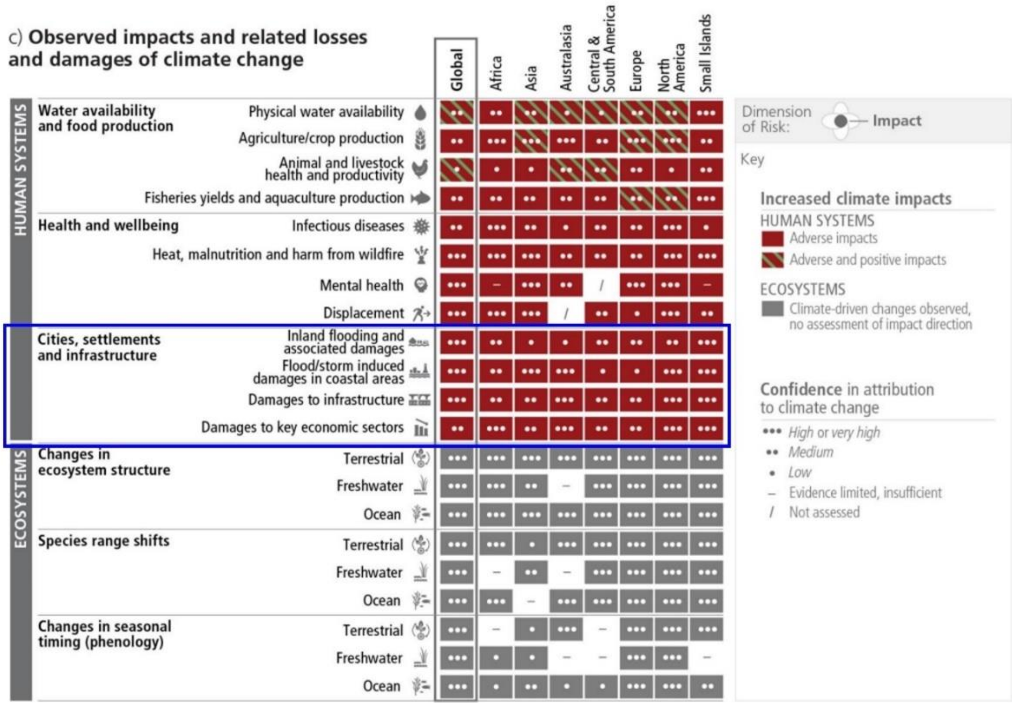


Figure 5: Observed impacts and related losses and damages of climate change (Pörtner & Roberts, 2023)

The IPCC has classified transportation discipline under the Under Human Systems – Cities, settlements, and infrastructure category. As seen from the figure, infrastructures under this category are expected to be affected by adverse conditions and most of the impacts faced globally have high or very high attribution rate from climate change. The assessment report did not specifically detail the exact impacts that the railway transportation sector will face. Aside to facing with structural damage, indirect impacts can be disruptions of services, safety concern to railway users, loss in economies due to the reduction in revenue service, damage of operating assets and even changes have to be made to the existing scheduling or cancelling routes. Compensation in monetary form could also have to be provided and extra un-planned resources might be needed to rectify the damages to resume railway service as soon as possible.

Thus, this thesis opined that the transportation sector should be taking actions to prepare themselves for the years ahead. Reasons being firstly, railway infrastructures built many years ago might not be able to withstand the current ambient conditions in view that the design requirement specified at that time might not have considered the impact of changing climate. For instant, the structure load requirement for the civil infrastructures might be specified to withstand a lower wind speed, thus measures would have to be carried out now to reinforce the robustness of the structures. Secondly, as the travel demand increases over the years, the increase extent of railway usage could have reduced the lifespan of the railway assets and coupled with the extreme weather conditions, it could have exacerbated the damages as identified in Table 5. Thirdly, in terms of preparedness for the future weather change, adequate measures or requirements to adapt to these changes should be incorporated in existing or new development of railway assets now as part of the resilient effort to prepare themselves to ever-changing conditions and especially the incorporation of such resilient requirements should already be considered upfront during the project planning and design phases.

Climate change is something that will not disappear or be resolved easily in the short term, and with assessment reports providing indication that it could just only be getting more serious in the times to come, it remains unavoidable and railway organisations should critically take the problems that these external events bring about into their planning and management of the railway assets for the long run.

2.3.2. Cyber-Attack

Cyber-attack is the intentional damage inflicted on the railway transportation system to create chaos to the Information Technology systems used in the railway environment such as the signalling systems whereby mostly are computer-based, fares ticketing systems, mobile applications, servers, databases, etc. hence causing threat to services and operations. In March 2023, the European Union (EU) Agency for Cybersecurity (ENISA) of the cyber threat landscape of the transport sector has published an analysis report on the major incidents encountered mostly in the EU as well as significant incidents reported from other parts of the world included. The trends and types of threats to the transport sector which included the maritime, railway and road transportation systems and the aviation sectors, for the study period from January 2021 to October 2022 have been analysed (*ENISA Transport Threat Landscape*, 2023). Figure 6 below shows the breakdown of incidents occurring in each sector and 21% of the incidents happened in the railway, mostly targeting the Railway Undertakings and Infrastructure Managers.

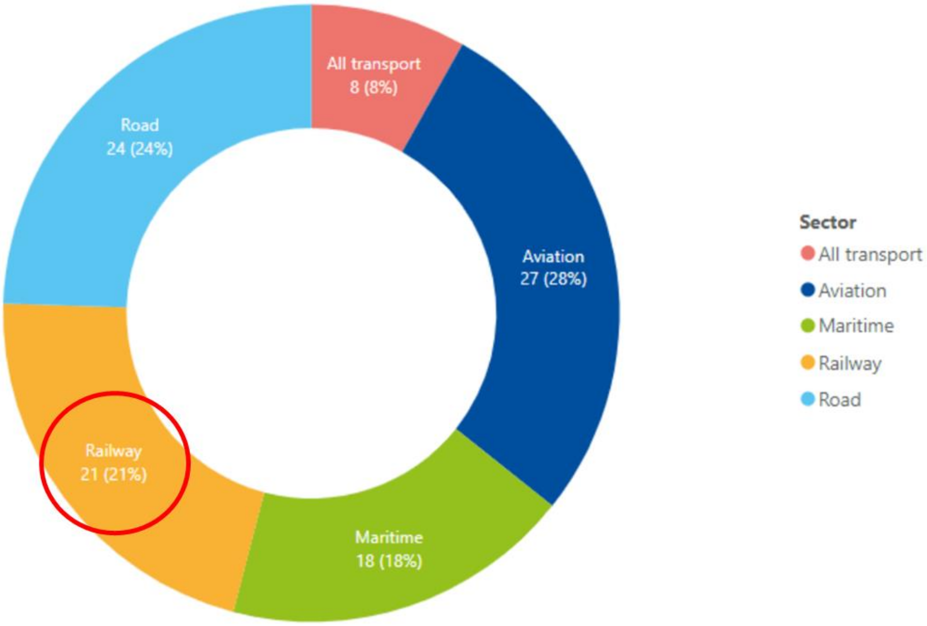


Figure 6: Annual observed incidents in each sector
*(*ENISA Transport Threat Landscape*, 2023)*

Figure 7 shows the types of cyber threats that the railway sector faced. The top 2 threats of serious concern are ransomware and data-related threats i.e., 45% and 25% respectively.

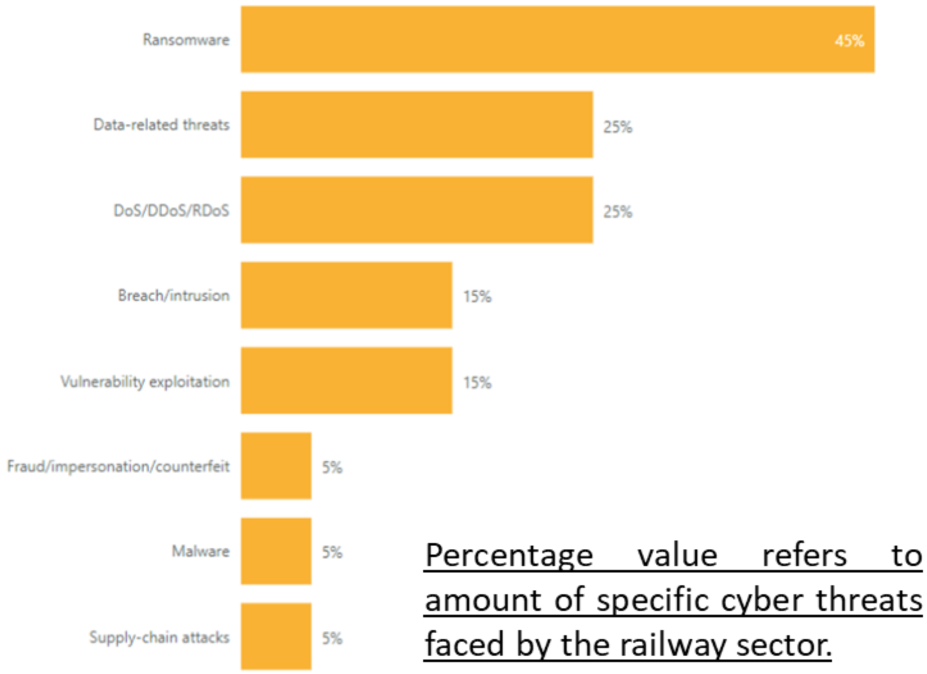


Figure 7: Prime threats encountered for the railway sector
*(*ENISA Transport Threat Landscape*, 2023)*

In October 2022, Denmark's railway operating company, the Danish State Railways encountered a nationwide service disruption for several hours *(Smith, 2022)*. In March 2022, the Italian State Railway encountered a ransomware attack affecting stations' ticket sales machines, passengers information screens and even tablets being used by railway staffs *(Briginshaw, 2022)*. In a newspaper article extracted from the 26th Intelligent Transport Systems World Congress in 2022 *(Toh & Baharudin, 2019)*, experts identified that legacy railway electronic systems that are developed many years ago highly did not consider 'digitalization' in the development, hence with the emerging of technology and IT knowledge of hackers, systems such as the signalling system, train control systems, etc. tend to be one of the vulnerabilities. When the functions of systems get compromised, it brings about safety concern with the operation of the railway systems and also the impacts on the railway users. Modern railway systems such as the European Rail Train Management System, Communications-Based Train Control, etc. adopted digitalization as it allows faster connectivity, enhanced transmission of train controls and commands, allowability for huge data storage of data analysis and storage, etc. Thus, the more digitalized the railway transportation system, the more prone it is to cyber-attack. The biggest risk identified in this article by *(Kapoor, 2022)* shared that when the railway network is being connected to an external network, it allows hackers to access the railway networks either through third-party peripherals, systems which could be Commercial-Off-The-Shelf (COTS) products and even information that are stored online i.e., 'in the cloud' *(Ravdeep et al., 2022)*.

Thus, there is a need to adapt the railway sectors to prevent any cyber-security attacks. In October 2020, the EU has funded a project – SAFETY4RAILS, looking into methods or tools that can increase the safety and improve the recovery of railway and metro transportation that are subjected to cyber, physical and cyber-physical attacks *(SAFETY4RAILS, 2020; Bonneau et al., 2022)*. The aim of this project is to increase the overall resilience of the railway infrastructures against such attacks. In the paper by *(Köpke et al., 2023)*, the tools developed by SAFETY4RAILS allows detection of any abnormalities to the infrastructure before, during and after the impact, and subsequently to assess the resilience of the infrastructure by looking at the propagation of performance loss when being subjected to such attacks. By improving the security and resilience of the railway infrastructures, it improves the preparedness of the railway organisation when facing with sudden cyber-attacks and thus, would require shorter response time to recover the system. It is opined that these tools can provide faster real-time update of the infrastructure resilience, and it aids in the speedy recovery and restoration effort especially during the Recovery Phase of the R4 Resilience Framework.

There are many measures already available in place that are able to prevent or minimise the occurrences of cyber-attacks as well as the establishment of cyber-security standards for railway sectors to use such as Technical Specification 50701 Cybersecurity for Railway Application *(European Standards, 2021)*. However, there is also a need to raise the awareness within the railway organisation to stay vigilant and advocate the importance and seriousness that cyberattacks can bring to railway, although the frequency of occurrence might not be very high. Therefore, in this paper by *(Hytönen et al., 2023)*, it shared that incorporating 'Systematic Cyber Threat Intelligence' to business continuity plan is able to improve the organisational awareness on this topic by supporting the decision-making process 'throughout the resilience cycle'.

2.4. Domains and Attributes

Section 2.3 has identified 2 unexpected external events whereby the damages to the railway transportation system is imminent. Thus, what are the domains that railway organisations should then prepare themselves to be resilient in. '*Domain*' is defined as a group that contains a set of related attributes which describe the properties or characteristics of the subject matter, area of interest or theme. There are no specific guidelines on what are the resilience domains that railway organisation should consider. Firstly, this thesis opined that this could be due to no standard definition of railway resilience. Secondly, the definition of *'resilience'* perspectives could be subjective and varies from organisation to organisation and how the management level of the organisation operates might differ too. Thus, it is challenging to define a specific guideline on what railway organisation resilience should constitute. Through reading the relevant papers on online databases, resilience domains and attributes that researchers adopted are being identified. The following sections will elaborate what are the definition of resilience domains and resilience attributes being identified from the literatures.

2.4.1. Resilience Domains

Using the keywords "resilience of railway organisation", a search conducted on Google Scholar and Scopus have returned with 1 closely related research paper by *(Y. Zhang & Pan, 2020)* which looks into improving the organisational domain of the China's railway transportation industry from lessons learnt during the Covid-19 pandemic. As quoted from the paper, organisational resilience is defined as "*the prevention before the crisis and the rapid response after the crisis to restore the original state level and seek opportunities for organisational development*". The authors of the paper have identified the followings areas whereby organisations can enhance their resilience in. The thesis has attempted to further elaborate on the relevancy.

1. To keep close awareness of the happenings in the surrounding environment.
   When an organisation is well-aware of the situations occurring in the environment, it will help the organisation to prevent itself from entering into a crisis, and even if the organisation does inadvertently entered into a crisis, it would already have pre-planned preventive and recovery measures in place, that can help to reduce the negative impacts it might encounter, and to restore the services as fast as possible.
2. To improve the psychological resilience of employees.

Employees are also seen as critical asset of the organisation. When the psychology state of an individual is resilient, employees will be more attentive to their work environment, more readily to resolve issues or identify symptoms even before the events occur, hence contributing to the resilience of the organisation.

3. To create a sense of trust between the top management and the employees and among them.
   The top management should empower their staff to take the necessary actions, to devise plans to prepare for any events and on the other hand, the employees should trust the leadership of the top management that they will lead or guide the organisation to tide over the unexpected external event.
4. To maintain adequate organisational resources.
   Aside ensuring the amount of resources and fundings available for daily operation, adequate reserves should also be set aside to prepare the organisation in the event of crisis, such as emergency responses.
5. To maintain an organisational structure that is both rigid and flexible.
   This type of structure helps in the communication aspect within the organisation, such as the reporting structure and convey of information from frontline staff back to the top management, when decisions are required to be made.

A review of papers on resilience in disciplines/sectors closely related to railway such as critical infrastructures and transportation sector in general are also subsequently being conducted. In the paper by *(Labaka et al., 2016)*, the author of this paper summarised that the resilience of critical infrastructures can be categorised into 4 domains with its associated definition shown in Table 6. These 4 domains are Technical, Organisational, Economic, Social (TOSE).

Table 6: 4 Domains of resilience being identified

Domains	Definition
Technical	The ability of the organisation/ physical system to perform properly when subjected to a crisis.
Organisational	The capacity of the decision-makers to lead, make decision and take the necessary actions to avoid or reduce the impact from the crisis.
Economic	The ability of the organisation to face additional costs (unexpected) from the crisis.
Social	The ability of the society to aids crisis responders in the event of a crisis.

In the paper by *(Hytönen et al., 2023)*, resilience refers to the inherent property of the organisation to react and recover faster from shocks or 'stressful events' and this paper investigates from the *organisational domain* perspective. When the functions of an organisation are resilient, the organisation can handle unexpected situations more confidently and able to 'bounce back' from setbacks to its original function quickly. When people in the organisation are able to handle stress arising for unexpected situations better, this will lead to higher work productivity. When they are better equipped to face with these events, service quality is ensured too due to their readiness to ensure the continuous operation of the railway systems such as providing quicker and effective emergency responses. Hence, with reduction in incurring extra costs due to disruptions or unforeseen events, organisations can also allocate resources more effectively. A resilient organisation is able to better manage risks and to identify the opportunities to improve operational efficiency *(Yang et al., 2022)*. This concept is quite similar to the proposal by (*Y. Zhang & Pan, 2020)*. In another paper by *(Nipa et al., 2023)*, a comprehensive review on all resilience-related papers of transportation critical infrastructures, with the aim to create a list of dimensions that can be used to represent the resilience level of the '*physical segments of the transportation infrastructures*' is conducted. In Figure 8, the author has also summarised that for a transportation system to be considered resilient in the TOSE framework, there are ten dimensions/parameters as shown in the left-hand side of the figure that preferably should achieve a certain level of performance. The resilience of the physical railway assets and infrastructures and its technical performance are important as they are the important actors that ensure the operability of the whole transportation system and network. The organisational domain can be seen as an intrinsic characteristic of how the organisation functions and the different disciplines work together to develop strategies to reduce the impacts when experiencing external stress or shocks.

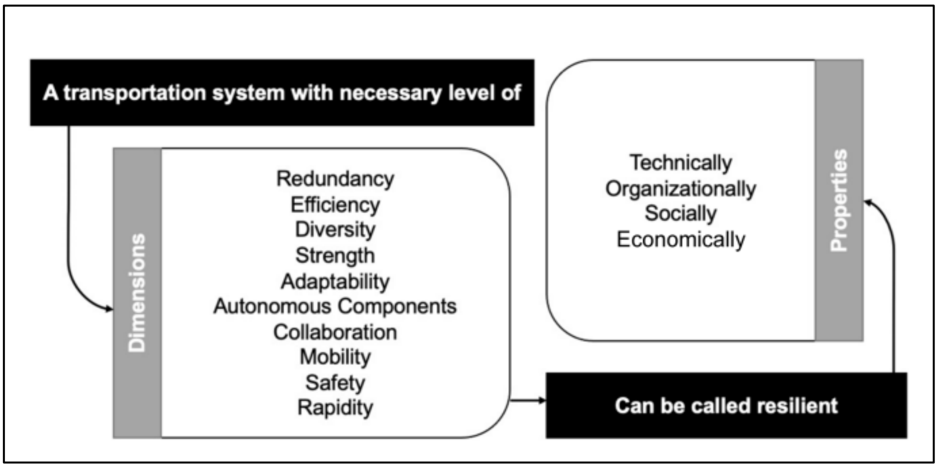


Figure 8: Transportation resilience dimensions
(Nipa et al., 2023)

2.4.2. Resilience Attributes

In the transportation sector inclusive of other industries such as maritime, aviation and road, *(Ahmed & Dey, 2020)* has summarised from the literatures some common attributes that are being used to assess the resilience related to these transportation industries. They are reliability, restoration time, shortest path, travel time, vulnerability, cost, travel demand, etc.

In the paper by *(Janić, 2018)*, the author looked into modelling the 'dynamic resilience' of a railway network when it gets impacted by disruptive events by understanding the changes to indicators related to infrastructure, operation, economic as well as social-economic performances that are used to estimate the resilience performance. From this paper, the failure of the railway infrastructure not only affects the operation and causing inconveniences to the demand of passengers, but it also brings about additional cost to the railway organisation too. The damaged infrastructure will need to be repaired and be brought back to its intended serviceable condition. To be able to do so, it is also dependent on the scale of damage which determines if the repair work can be done in isolation, or whether if carrying out the repair work will also affect the ongoing operation of the remaining railway service. This would require additional labour and resources. From the economic perspective, aside to additional cost incurred due to the unforeseen events, railway organisation might also have to spend on alternative modes to ease the inconveniences caused during disruption or provide some monetary compensation or ticket refund in additional to the revenue loss due to the downtime of the network. These can be minimised if in the first place, the resilience of the technical infrastructure has been maintained. From this cause-and-consequence scenario, Table 7 below has summarised the 4 areas whereby the author opined that resilience can be assessed and attributes related to these areas can be derived.

Table 7: Indicators and associated definitions

Areas	Definition
Infrastructure	Physical and Operation Conditions of the Railway Assets.
Operational	Transport services scheduled along the particular routes, Seating Capacity, Transport Work/Capacity.
Economic	Costs of cancelled and long-delayed transport services imposed on the stakeholders i.e., railway company and passengers.
Social-Economic	The compromised accessibility and consequent prevention of the user/ passenger trips and contribution to Gross Domestic Product.

Figure 9 below adapted from *(Rehak et al., 2018)* showed the areas whereby attributes relating to the Technical and Organisational domains for critical infrastructures can be considered.

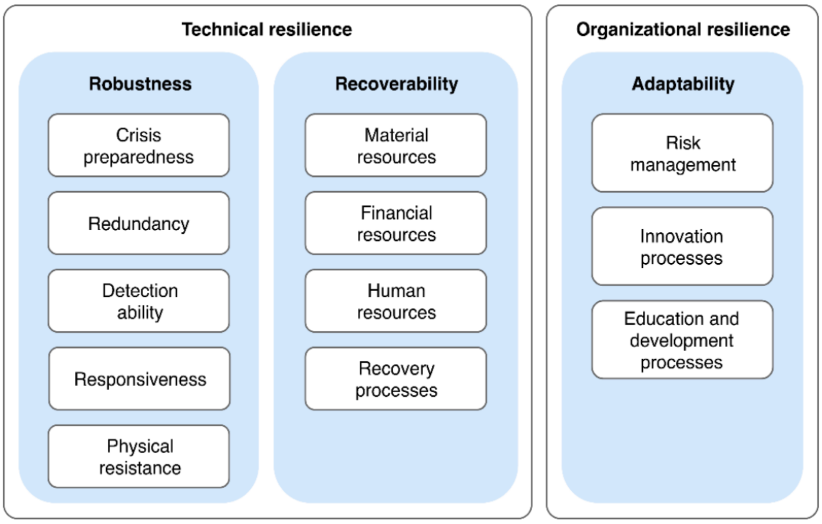


Figure 9: Resilience attributes for critical infrastructures elements (Rehak et al., 2018)

Technical resilience constitutes the Robustness and Recoverability aspects of the physical infrastructures such as the incorporation of redundancy and improving the resistance of the physical elements, the ability of the infrastructures to detect anomalies, etc. while organisational resilience considers the adaptability of the organisation to crisis with processes in place such as the ability to learn from past occurrences of crisis in order to further enhance the resilience, to identify potential enterprise risks as well as embarking on innovations. It is observed that properties of the R4 Resilience Framework are also being incorporated in Figure 9. In the paper by *(Trucco & Petrenj, 2023)* which investigates the types of metrics that can be used to represent Technical Resilience, the study identified that metrics can be categorized into 3 areas namely attributes-based, topological-based and performance-based. Attributes-based metrics aim to measure the resilience at a '*specific moment*' such as the robustness, the probability of failure or the performance of the system at a specific moment of the system disruption. Topological-based metrics focus on the structural aspects of the structure while performance-based metrics measure the performance of the system during the Disruption and Recovery Phases of the Resilience Triangle. In the paper by *(Yang et al., 2023)*, the authors have identified relevant properties that critical infrastructures should demonstrate resilience in through their comprehensive literature search. Resilience performance should be demonstrated since the pre-crisis/ disruption stage, during the disruption stage, the post-disruption stage and the preparation stage that follows it. The attributes summarised from the literature analysis are firstly categorised to capabilities or properties, for examples safety, recovery efforts, redundancy, robustness, security, vulnerabilities, etc.

In the paper by *(Lee et al., 2013)*, the paper dwells into identifying the characteristics that a resilient organisation should exhibit. In general, aside the need to display having the 'resilience ethos', the author of the paper has also identified 4 other areas that organisation should have and through the use of survey, questions pertaining to these 4 areas are being created. These 4 areas include having the situational awareness, the capabilities to manage crisis, the capacity to be adaptive and establishment of business continuity plans. These areas are identified since it is deemed that when an organisation is aware of the danger or crisis that loomed, the organisation is already well-equipped with the necessary measures already in place and would not be in a 'caught-off-guard' situation.

In summary, it can be observed that aside to the hard-skill aspect, soft-skill aspects are also as important and should be considered when determining what are the domains that railway organisations should be resilient in. As quoted from ARUP, a Railway Consultancy Firm, "*resilience in rail requires consideration of organisational, technological, environmental, societal and physical systems*" (Arup, 2023). It does not involve silo management of any of these components or just by engineering interventions. It is opined that this would be the idealistic way of resilience management, however, in reality, there could be constraints limiting this application. The TOSE framework is observed to be the 4 important pillars of resilience and has been adopted in researches such as by *(Bruneau et al., 2003; Cantelmi et al., 2021; Trucco & Petrenj, 2023)*. It can be seen that resilience of a system or organisation is assessable by a combination of attributes from different domains. The abilities of a system to reduce the chances of encountering external shock, to absorb and recover quickly is due to the results of the R4 Resilience Framework and these are '*inter-related through technical, organisational and social*'.

2.5. Evaluation Approaches

Most of the railway resilience research focus on the quantification of the vulnerability of the railway infrastructures by adopting computational methods on assessment. Areas of work include looking at the impact to railway network connectivity such as the propagation of damage when a disruption occurs, the inter-dependencies between the railway assets, the extent of the impacts to end-users, etc. Some of these areas of work are listed below. The methods used usually are data-driven, topological-oriented, simulation-based and as well as optimisation-based. These algorithms help to assess the railway infrastructures at a deeper level and from the technical resilience perspective. By understanding the extent of vulnerability of the infrastructures, measures can then be taken to enhance the technicality of the assets and networks.

a. Optimisation model that models the railway transport system by looking at the interdependencies between traffic management of the railway infrastructure, rolling stock, passengers and the restoration works to be carried out after encountering multiple disruptions from the passengers' perspectives by *(Bešinović et al., 2022)*.
b. Evaluation model that measures the resilience by calculating multiple abilities with consideration of multi-source data including passenger flow, train diagram, passenger travel choice behaviour, network topology by *(Ma et al., 2022)*.
c. Linear programming model on the rescheduling of rolling stock timetable such as through cancelling of trains, re-timing of trains or re-ordering when a disruption is encountered by *(Zhu & Goverde, 2019)*.

d. Optimisation model to determine the railway resilience by looking at the proportion of satisfied passengers demand after experiencing a disruptive event by *(Jin et al., 2014)*.
e. Simulation model to determine the impacts of external disruption by studying the increase in travel time and reduction in railway capacity identified as the resilience indicators by *(Adjetey-Bahun et al., 2014)*.

Besides algorithmic methods that can be used to create resilience models, a search on other evaluation or assessment methods are also identified. In the study by *(Linkov et al., 2018)*, a three-tier approach has been recommended as a guideline that can be used to determine the extent of resilience assessment and the types of methodology/tools that would be useful in carrying out the assessment in general. This recommendation has been integrated with the tiered approach that the United States regulatory agencies use for risk assessment.

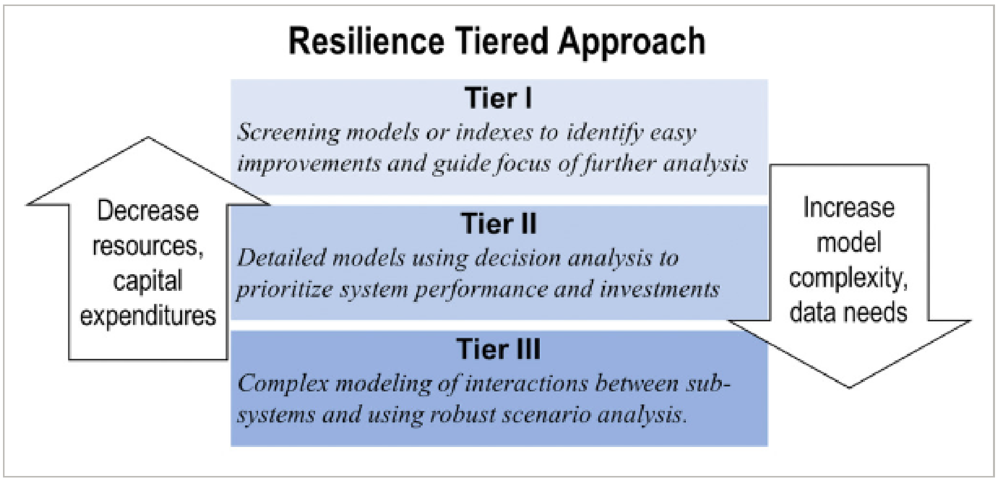


Figure 10: Tiered-approach to resilience assessment (Linkov et al., 2018)

Shown in Figure 10 above, as the tier level increases, the extent of resilience assessment needed would be larger as it involves more complexity and more in-depth analysis which require more data. **Tier I** involves identifying the functions of the systems, the industry or the scope of application and the constituting components. The focus is to develop preliminary understanding of the intra- and inter-systems functions and interactions with the operating surrounding. **Tier II** involves deeper analysis by looking at the internal structure of the systems after the high-level guide focus in Tier I has been conducted. This tier is more detailed as it requires the analysis of the interactions between the components making up the structure and this will provide more information and clarity to the organisation management when prioritizing areas of improvements which are more critical and urgent. **Tier III** involves the modelling of the actual system whereby there is a need to fully grasp the system behaviour and functions such as identifying all the system components, understanding, and analysing how the deterioration in the performance of the components affects and which parts of the system will be affected. This will then allow more specific management decision to be undertaken to identify the specific tasks to resolve the problem. Tier III will also require the identification and study of all scenarios that potential crisis might happened to the systems and all the consequences it brings.

In another paper by the same author *(Linkov et al., 2013),* it is suggested that resilience matrixes would be useful to effectively determine the resiliency level. The Resilience Matrix shown in Figure 11 extracted from the same paper has tried to map the system domains i.e., physical, information, cognitive and social aspects along the event management cycle that is being developed by the National Academy of Sciences for disaster resilience cycle i.e., Plan, Absorb, Recover and Adapt.

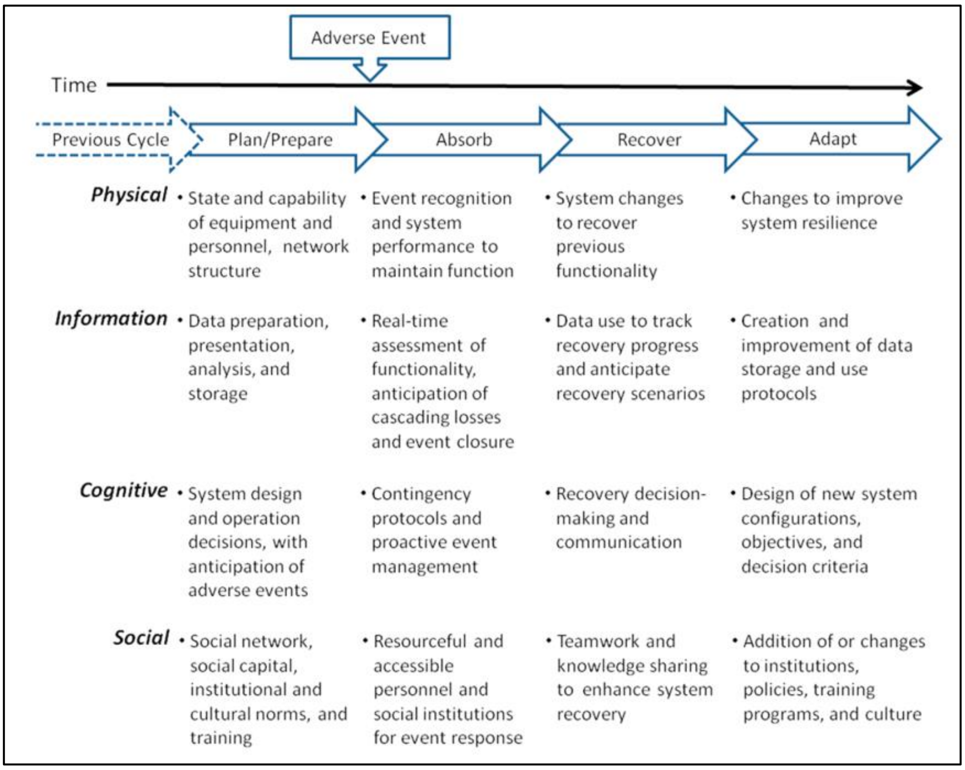


Figure 11: Resilience matrix
(Linkov et al., 2013)

Each of the cell provides the guidelines on how the resilience factors can be considered. For example during the Plan stage of the physcial domain, the "*state and capability of the equipment and personnel and network*" has to be considered. This is deemed to be similar to the technical resilience mentioned in earlier sections whereby the design aspects of the system has to be ensured during the planning phase.

The research by *(Ostadi et al., 2023)* has summarised that in the field of resilience, commonly used methods include optimization model, simulation models, logic models, cognitive maps, etc. Aside to these mathematical and optimization approaches, in this book chapter by *(Sharma et al., 2021)*, the author has adopted the method of resilience heat map to represent the resiliency level of the different railway infrastructures. By adapting the system domains i.e., Physical, Information, Cognitive and Social identified by *(Linkov et al., 2013)* that can be used to assess resilience for actionable policy, *(Sharma et al., 2021)* created individual matrix for infrastructures like the signalling system, railway track as shown in Figure 12 below. These matrices are subsequently being converted to colour-coded resilience heat maps in Figure 13.

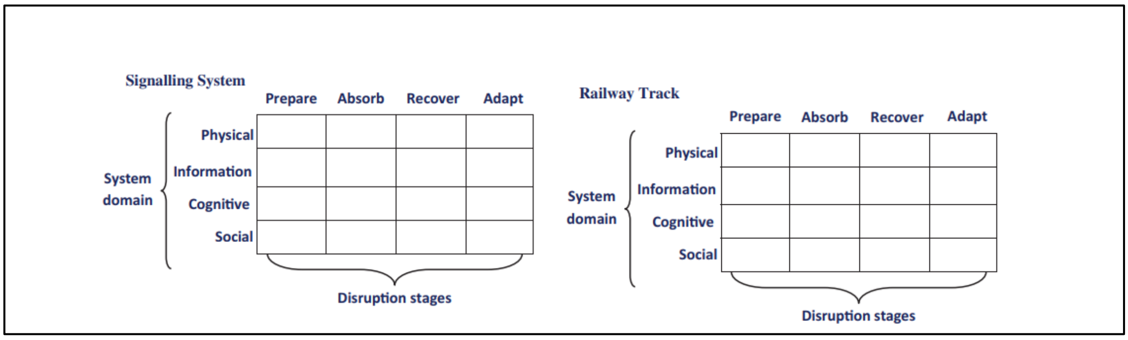


Figure 12: Resilience matrix for railway infrastructures (Linkov et al., 2013)

Railway Track	Prepare	Absorb	Recover	Adapt
Physical	0.05	0.07	0.26	0.45
Information	0.59	0.24	0.45	0.04
Cognitive	0.21	0.28	0.25	0.23
Social	0.49	0.51	0.08	0.09

Figure 13: Resilience heat map for railway track (Linkov et al., 2013)

The resilience heat map can be used for evaluation to identify areas of vulnerabilities through easy visualisation, and decision-makers can then prioritise the interventions and enhancement work to improve the overall system resilience. Areas in red indicate the highest risk since it has the lowest resilience score while green means the lowest risk. It is opined that this type of assessment method is easy in terms of representing the resilience of the system to the top management, as not all members could be the subject matter of experts.

Another possible method is the 'indicator-based resilient assessment' tool which can be used to evaluate and improve the resilience of critical infrastructures such as the transportation system, communications and defence by *(Yang et al., 2023)*. The authors use indicators as it is 'less abstract' and can show the changes in the resilience level. This allows stakeholders to be better informed before making any decisions. The challenge would be to identify the suitable indicators before resilience can be measured. The eventual tool can be in qualitative, semi-qualitative or quantitative formats which would then require different input information. The algorithm works as described in earlier sections can be considered as the quantitative approach. Semi-quantitative approach will provide 'general numerical classification' information, excluding the need for mathematical models, while qualitative approach eliminates the need for any numerical descriptor, and it is subjective since it is dependent on whether if the person who uses it, is the subject matter of expert. Another form of assessment method is through the use of Resilience Analysis Grid by *(Hollnagel, E., 2015)*, which defined the assessment of 4 basic abilities of an organisation or system's resilient performance namely, the abilities to response, monitor, learn and anticipate. The rating of each of these abilities uses the Likert-type scale i.e., Deficient, Unacceptable, Acceptable, Satisfactory, Excellent (whereby each has their own definition) for assessment. The author has also highlighted that the set of survey questions to be asked, pertaining to each of the ability has to be related to the organisation or system's performance so that the interventions required to improve the system resilience can be made.

Section 2.5 has identified the different evaluation approaches that have been created by researchers to assess and/or quantify resilience either qualitatively or quantitatively or both. There is no definite preference on which of the method is the best, as each approach has their uniqueness and application. The eventual aim of these approaches is to be provide the best format to assess the resilience of a system, or organisation as accurately and as informative as possible.

To address sub-research question 1, the literature review has shown the growing concerns posed by the top events i.e., extreme weather and cyber-security attack because they continue to bring about challenges to railway operation and management. These emerging threats are imminent, forcing railway organisation to be constantly on the look-out to review their existing policies and efforts to remain adaptable and thrive in facing these disturbances. Despite reckoning that these threats are unavoidable, there lies limitations and constraints in the amount of effort that railway organisation can embarked on to improve their preparedness thus, extending the need to prioritise their initiatives and concurrently keeping the railway organisation as resilient as possible. The literature analysis has also identified the ways of how resilience can be represented and that research has been conducted whereby railway resilience at a more in-depth level i.e., operational level can be studied through the use of analytical tools, for instant at network level and also even at infrastructural level.

In relation to the research question, the literature review has shown that a method that can provide the management or decision makers of the railway organisation with a gauge of its overall resilience performance in the midst of the growing concerns posed by the external threats, is currently unavailable. This thesis opines that with a top-down approach by firstly establishing a better overall understanding is crucial, before the organisation embarks on determining the suitable strategies or initiatives needed to build-up their resilience level or even adopting more detailed studies to analyse the resilience performance. This assists organisation to identify resilient-deficient areas where resilience is low more efficiently, before progressing with more in-depth analysis or the use of analytical tools. Thus, a conceptual model based on the insights gathered from the literature review has been established to aid in the resilience assessment process, and this is explained in the next chapter.

3. THE ASSESSMENT APPROACH

After in-depth understanding of what constitutes railway resilience and the importance of resilience in this industry due to the various undesirable impacts that can be caused by the external events, an overview of how the different hierarchical levels of a railway organisation contributes to resilience is provided in this chapter. This is followed by the development of a conceptual model based on the insights gained from the literature review to see how the resilience assessment can be carried out, and thus addressing the research questions identified in Chapter 1. The resilience assessment methodology and development process proposed by this thesis are finally provided.

3.1 Resilience Within the Hierarchy of a Railway Organisation

The common hierarchy of an organisation consists of 3 levels i.e., strategic, tactical and operational shown in Figure 14. Each level has their own roles and contributions to the function and management of an organisation *(Schmidt & Wilhelm, 2000; Khalifa, 2021)*. The resilience of an organisation can also be represented by using the 3 levels. This thesis has constructed the following figure to explain how the different level of decision-making within a railway organisation influences the resilience.

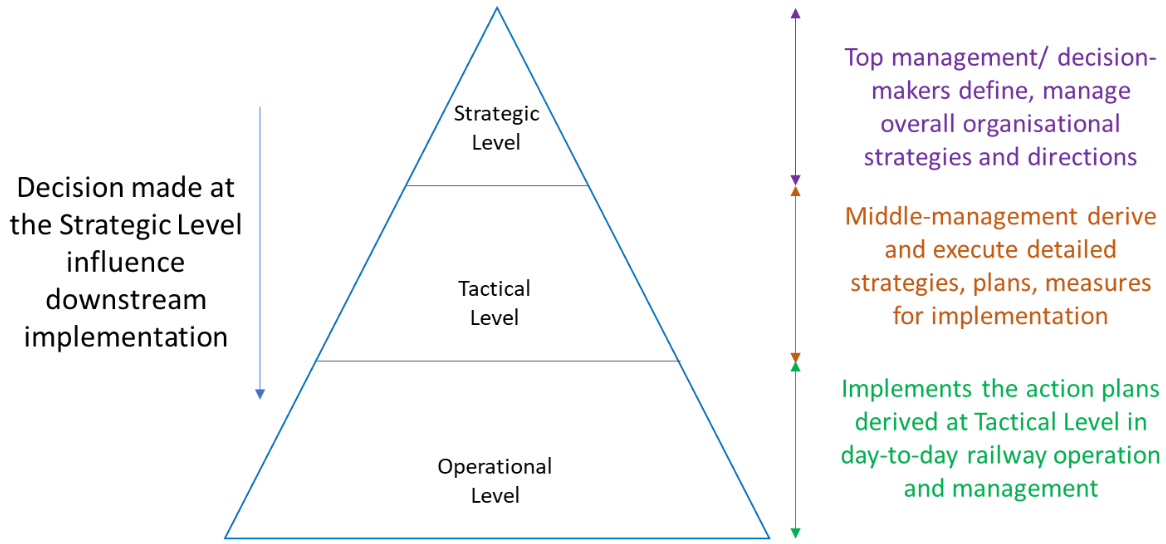


Figure 14: Resilience model of a railway organisation

The top management or decision-makers make high-level decisions that guides the organisation in achieving its goals and mission. For this to be conducted effectively, it is crucial that this group of people has access to information on the overall performance of the organisation before they can decide what resilient strategies are required. The resilience strategies formulated at the strategic level are cascaded downward the hierarchy of the organisation and to the next level. The middle management at the tactical level focuses on the implementation of these broader strategic goals and objectives such as in the day-to-day decision-making and planning to ensure that the operation of the organisation run efficiently and effectively. As the last level of the hierarchy, the group of staff at the operational level seek to incorporate and implement the measures, actions created at tactical level in the daily operation of the railway assets.

From the literature review, the resilience modelling tools are more applicable for use at the tactical and operational level such as assessing the resilience of the railway network, the systems and components, etc. It is not identifiable from literature searches on how the overall resilience performance at the strategic level can be made known.

3.2 Conceptual Model

From the insights gathered from the literature review, this thesis has constructed a conceptual model shown in Figure 15, illustrating how the resilience of a railway organisation comes into play when ensuring the continuous operation of the railway transportation system and the organisation in the midst of the occurrences of external events. The concept of system control design adapted from *(Alfredo N., 2022)* has been referenced to for the construction of the conceptual model whereby the relationship between the resilience of the railway organisation, the disturbances i.e., the external events, and the desired railway services to be provided to railway users, are shown.

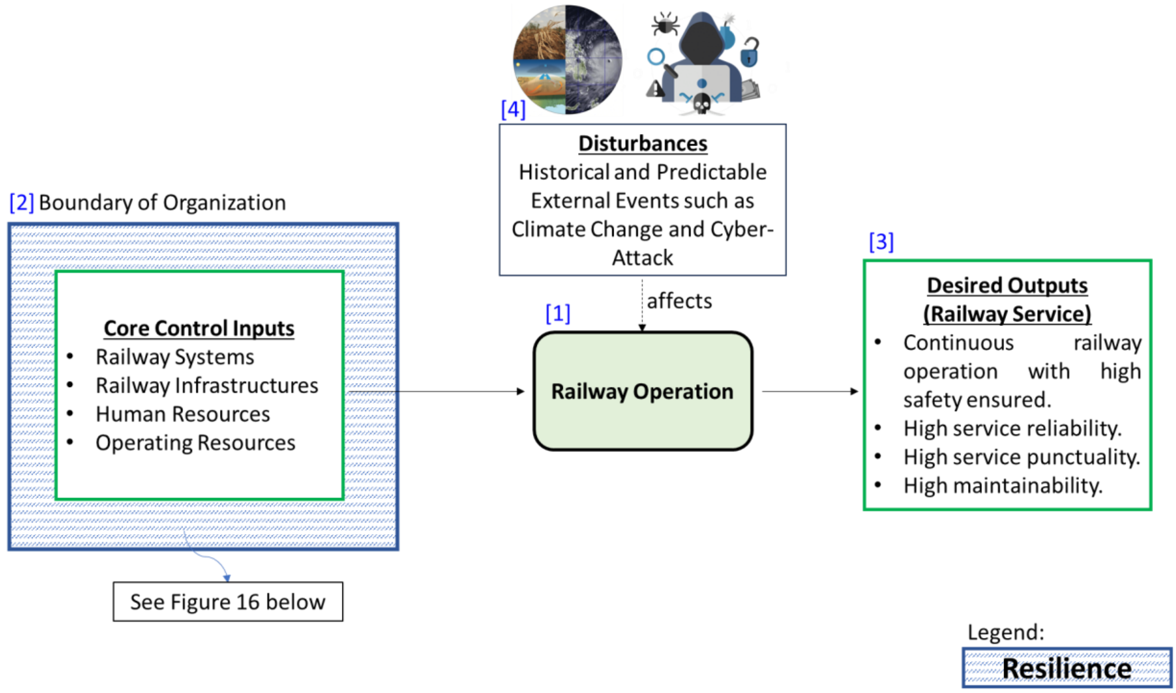


Figure 15: Conceptual model

Denoted by [1], the railway operation in the centre of the figure is seen as the 'process' to be controlled. Denoted by [2], the left-hand side of the figure showed the core control inputs whereby the thick blue line showed the boundary of the organisation constituting these core control inputs and certain level of resilience. These inputs refer to variables needed to ensure the smooth operation of the 'process'. Variables identified include the railway systems such as rolling stock, signalling system, power supply system, etc., railway infrastructures such as railway tracks, stations, depots, level crossings, etc., human resources which refer to the personnel who operate and maintain the railway assets, operating resources such as financial resources, materials and supplies, administrative resources, etc. Around the core control inputs is a level of resilience. Both of these aspects make up the capability of the railway organisation to function effectively. With the core inputs being controlled and a certain level of resilience ensured, the outputs desired to achieve from the 'process' denoted as [3] includes continuous railway operation with high-level of safety, high service reliability, high maintainability and high availability. However, there are disturbances that can affect this 'process' and they are identified as the occurrences of unexpected external events i.e., climate change and cyber-attack in the literature analysis. These disturbances can be past events and upcoming events whereby occurrences are predictable to a certain extent. Denoted as [4], these disturbances are considered as inputs to the 'process' whose impacts cannot be controlled, and the preceding chapter has summarised how they can affect railway organisation and railway operation. Even in the presence of these disturbances, the desired outputs as mentioned earlier are still expected to be achieved as much as possible.

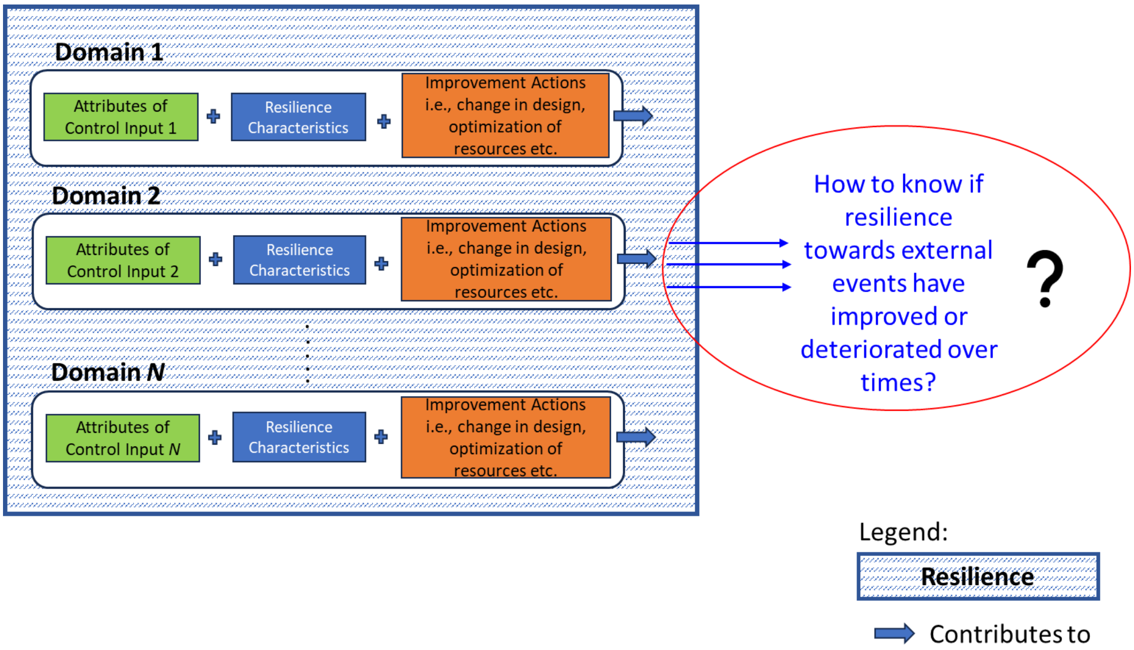


Figure 16: Resilience of Railway Organisation (continuation from Figure 15)

Further to this from the literature analysis, railway resilience is an intangible property. It reinforces the capability of the railway organisation to function as smoothly as possible and to attain the desired outputs in the presence of the disturbances. Continuation from Figure 15, Figure 16 showed that the overall resilience performance of railway organisation can be build-up by the resilience of the different domains of the control inputs. Each of this domain consists of the attributes relevant to the domain, the resilience characteristics for examples robustness, redundancy, being exhibited and the different ongoing or past improvement actions that railway organisation has considered to enhance resilience. These actions can include the improvement in design of the railway systems and infrastructures, the optimized planning of operating resources, the use of detailed algorithm tools to aid in the identification and analysis of resilient-deficient areas. However, resilience performance changes over times with the evolvement of emerging external events. It is not identifiable from literature searches on how the strategic level of the organisation can know if the resilience towards external events have improved or deteriorated over times. Thus, the red oval in Figure 16 forms the core of the research boundary for this thesis.

3.3 Development of Assessment Method

By understanding what constitutes the resilience of a railway organisation and how this intangible property can be determined, this thesis sees that a systematic form of assessment method is needed. This section details the work involved in the development of an assessment method by this thesis. The goals to be achieved are firstly being highlighted, followed by the assessment step framework defined to guide in the development, how it addresses the main and sub-research questions, the development methodology taken and finally, the assessment method itself.

3.3.1 Goal

The goal is to create an assessment method that reveals the resilience performance of the railway organisation. Below are the objectives of the assessment method in order to achieve the goal:

1. To be straightforward for easy comprehension by the users.
   The target audience/users can be the management level or any decision-makers of the railway organisation which can constitute members with different expertise and domain knowledge. Since not everyone could be subject matter of expert in understanding resilience, the content has to be easy to understand and easy to use.
2. To eliminate any degree of subjectivity that can be contributed by the users.
   It is foreseen that potential degree of subjectivity could be invited since opinions from the management level/decision-makers are involved in making assessment and decision. Thus, the degree of subjectivity has to be reduced as much as possible.
3. To be able to review the resilience attributes easily and to allow the content from the assessment to be updated easily.
   This will encourage the progressive review of resilience level to ensure that existing railway operation and management policies are updated and adequate, in response to facing with different types of emerging threats and external events.
4. To provide visual representation on the performance of the resilience attributes.
   This will allow users to better identify attributes that are underperforming, which indicate that these are the areas whereby improvement is needed.

With these, an assessment tool is decided to be developed. The tool should identify the resilient attributes being considered by the railway organisation, low-performing resilience attributes so that areas are easily identifiable for change and to eventually provide a resilience indication of the whole entity.

3.3.2 Assumptions

The list of assumptions made throughout the development of the assessment tool is shown below:

1. The scope of the railway organisation defined in this research work involves the ownership, design, operation, and maintenance of the railway assets, instead of each area of work being managed by separate railway entities.
2. Resilience of the day-to-day operation of the railway organisation is positive, hence assessment of attributes for daily operation is not considered. Assessment of the resilience in this thesis consider essential attributes that characterise the resilience against unexpected external events, which complements the daily resilience.
3. Economic and Social domains are not being considered at this phase of the work.
4. Asset-specific is adopted in assessing the technical resilience. One asset will be used in this thesis to elaborate how the attributes are selected. Further elaboration is provided in the subsequent sections.

3.3.3 Development of the Assessment Tool

Figure 17 below is the assessment framework created by this thesis to answer the sub-research questions through step-by-step development of the assessment tool. The figure has identified which step will answer which sub-research question and the execution of all steps will address the main research question.

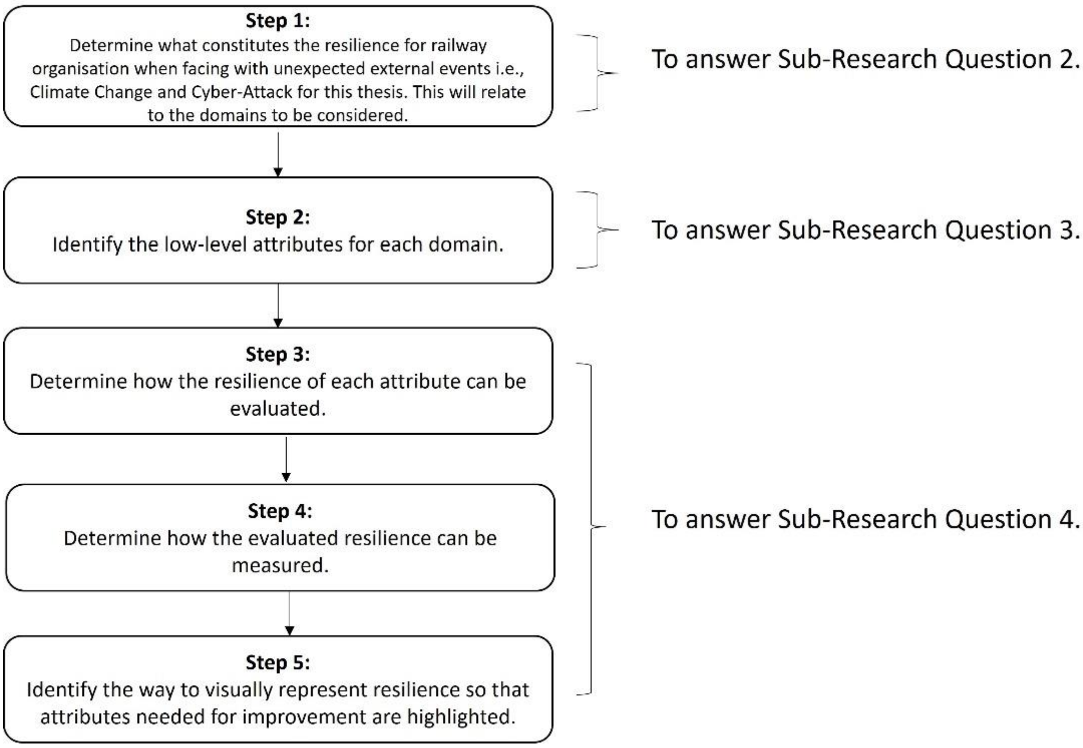


Figure 17: Assessment framework

1. **Step 1** is to define the definition of resilience being adopted in this thesis. It will be related to the critical domains ought to be considered to represent the resilience of railway organisation when facing with unexpected external events. Step 1 will answer sub-research question 2.
2. **Step 2** is to brainstorm and identify the resilience attributes, its associated definition and how it plays a part in the resilience representation under each domain. Step 2 will answer sub-research question 3.
3. **Step 3** is then to determine how the resilience of each resilience attribute can be evaluated.
4. **Step 4** is to translate this evaluation into a tangible form of measurement.
5. **Step 5** is to consolidate these evaluation and measurement conducted in the previous steps into a single platform, so that an overview of the resilience performance of the organisation can be reviewed easily and with areas of concerns being highlighted. Steps 3 to 5 aims to address sub-research question 4.

Details of each step are elaborated below.

Step 1: Resilience Representation – Domains to be Considered

The definition of the resilience of railway organisation adopted in this research work has to be set and this is illustrated in Figure 18 below. It is the incorporation of the properties from the R4 Resilience Framework to the identification of attributes used to assess the resilience of the Technical and Organisational domains. Only these 2 domains are being considered at this phase of the work. Technical domain covers the 'hardware and software' aspects of the railway assets that the railway organisation owns. From Figure 18, these assets can include the railway systems such as the rolling stock, the signalling systems, the power systems, etc. as well as railway infrastructures such as the stations, railway tracks, depots, etc. In the case of railway infrastructures, the software aspects would not be considered and attributes will have to be tailored to the asset under review. Technical domain is deemed important because railway assets are seen as the front-end players that support the operation of the railway transportation system and the first to sustain damages and affect railway operation when external events occur. The resilience of this domain has to be ensured as it relates to the basic technicality and operability of the assets. The resilience of this domain shall made up of the resilience of all the railway assets. Organisational domain, on the other hand, covers the back-end management and operation of the railway organisation as a whole in ensuring its functionality and efficiency.

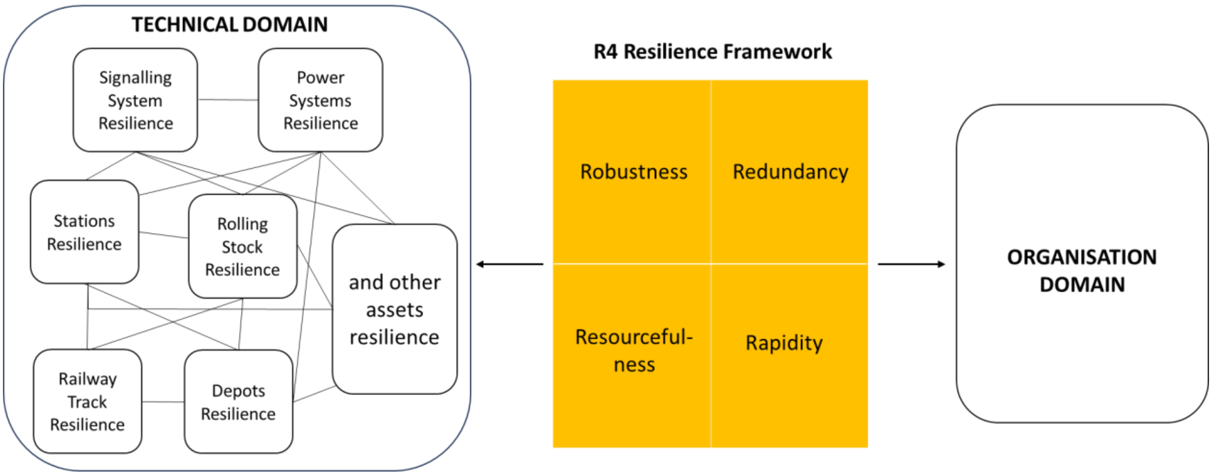


Figure 18: Domains identified to represent railway organisation resilience

Step 2: Domains Representation – Identification of Attributes

I. Asset-Specific Attributes for Technical Domain

From the technical domain perspective, the rolling stock has been selected to demonstrate what are the resilient attributes against extreme weather conditions and cyber-security attacks that can be considered. By understanding how the asset-specific attributes can be identified, the assessment tool can be further expanded by adding attributes of the other assets that the railway organisation manages. It allows railway organisation to better comprehend attributes that require more resilience enhancement work to increase the resilience level for the particular asset since different railway assets might have additional and/or different attributes to be considered as they get impacted differently by the 2 external events identified. This asset-specific consideration will not have any impact on the organisational domain since it is related to the intrinsic way of corporate management and governance. Regardless of the types of external threats identified, how an organisation manages their resilience should remain the same throughout and should not be tailored to be event specific.

II. Technical Resilience Attributes (Rolling Stock)

The objective to build up the technical resilience is to have the ability to reduce the probability of system failure and its associated consequences if any failure does occur, and to have the fast recovery time or process to bring the system back to its original intended operating mode.

Figure 19 below illustrates the approach in the identification of attributes associated with technical resilience for rolling stock. The aim is to ensure the continuation of railway services as much as possible with minimised impacts and to ensure fast recovery. Technical resilience has been categorised into 2 sub-domains i.e., hardware and software resilience. This thesis has defined hardware and software resilience as the ability of the system and its components to continue with its functionality and intended operation in an environment with external events that can occur unexpectedly. The resilience characteristics being considered by hardware and software resilience are as follows:

I. **Hardware Resilience**: Robustness, redundancy, failure detection and correction, rapid recovery.
II. **Software Resilience**: Redundancy, software safety, monitoring, cyber-security protection, rapid recovery.

Hardware and software resilience are considered for rolling stock since it comprises of both hardware systems and software systems for it to operate. On the other hand, if the railway asset to be considered for example is the railway track, it will not be affected by cyber-security attack since it is a civil infrastructure, hence attributes related to software resilience will not be applicable. Thus, this explains why asset-specific attributes are proposed by this thesis to be used instead of a standardised list of attributes for technical domain.

In the hardware resilience sub-domain, the attributes are classified into 4 categories namely Design, Operation, Maintenance and Asset Renewal. These 4 categories are identified with reference to a product lifecycle process starting from the planning phase which is the specification of design requirements, moving on to the actual operation and maintenance of the assets and to the renewal of the systems. The disposal phase of assets is not being considered. In the software resilience sub-domain, the attributes are being classified into 2 categories namely Design and Maintenance.

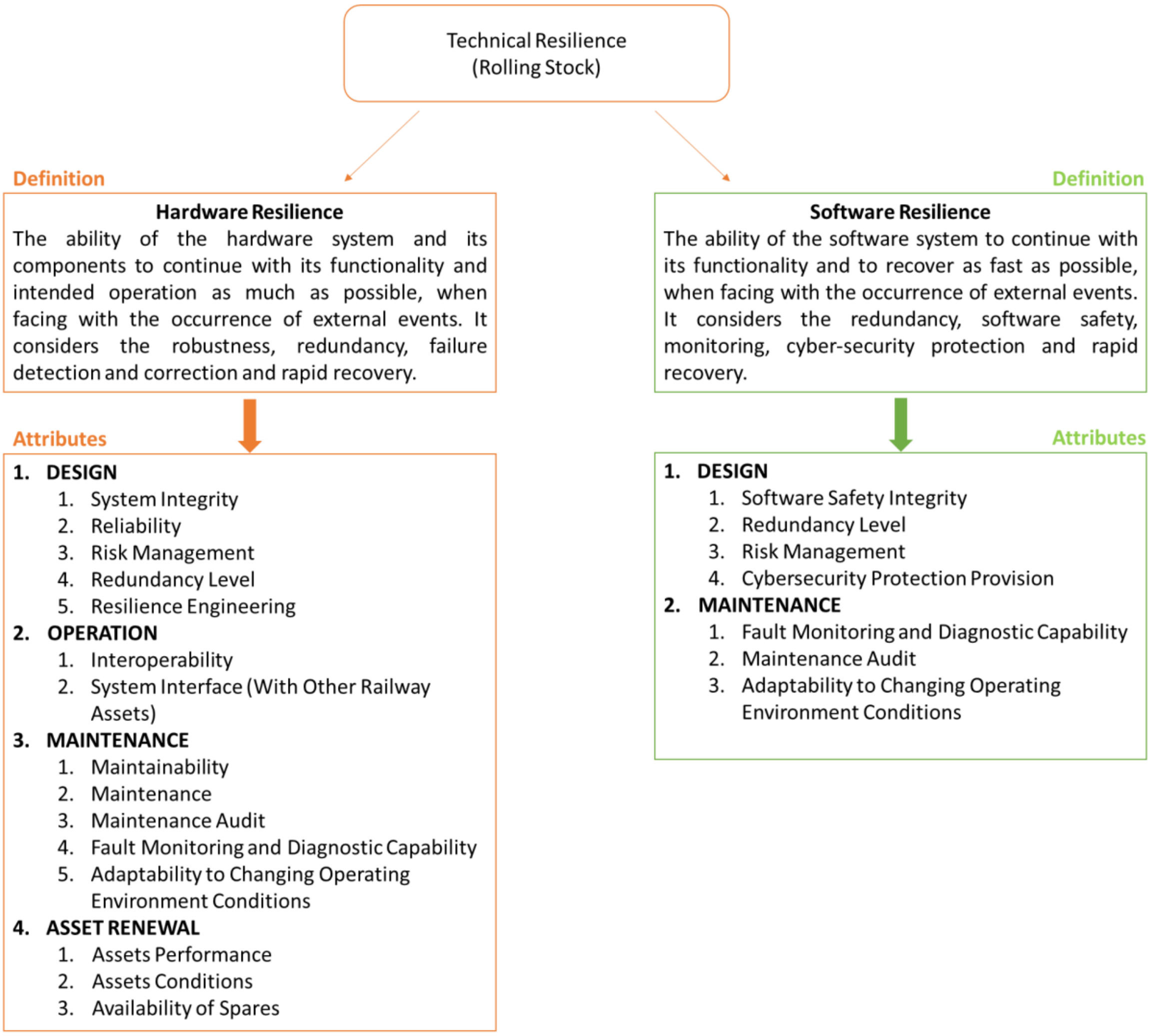


Figure 19: Identification of technical resilience attributes

Under each of these categories in Figure 19 are the resilience attributes determined to be applicable and selected by this thesis. Further explanation on the relativity of the R4 Resilience Framework to these attributes are appended in Appendix A.

III. Organisational Domain

Base on ISO 22316 Security and resilience – Organisational resilience *(International Organisation for Standardization, 2017)*, organisational resilience is defined as the '*ability of an organisation to absorb and adapt in a changing environment'*. In this thesis, organisational resilience is defined as the effort that railway organisation puts in to gear themselves up in getting well prepared to continue with organisation operation in response to facing any external events. Illustrated in Figure 20, the blue line demarcates the boundary of the railway organisation. Aside to the control and management of the environment within the organisation i.e., Internal Environment, railway organisation will also have to interact with the environment external to the organisation i.e., External Environment.

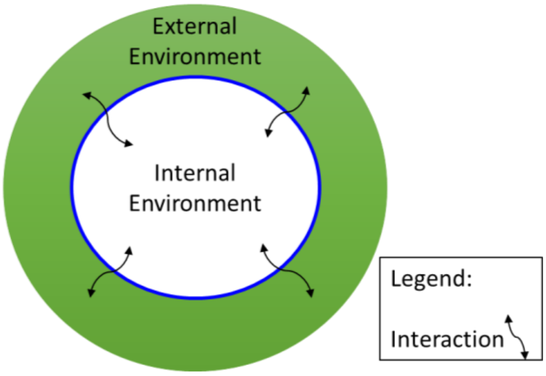


Figure 20: Internal and external interaction of an organisation

Resilience is then being classified into Internal and External Resilience sub-domains in Figure 21 below. For each of the classification, the attributes are identified by considering aspects that ought to be resilient in its preparedness in facing the occurrence of the external events and its relativity to the R4 Resilience Framework.

I. **Internal Resilience**: The ability of the organisation to be resilient in its ways of internal corporate management, process management as well as stakeholders' management.
II. **External Resilience**: The ability of the organisation to be resilient in its engagement with the external environment.

Further explanation on the list of attributes identified representing Internal and External Resilience and its relativity to the R4 Resilience Framework are appended in Appendix B.

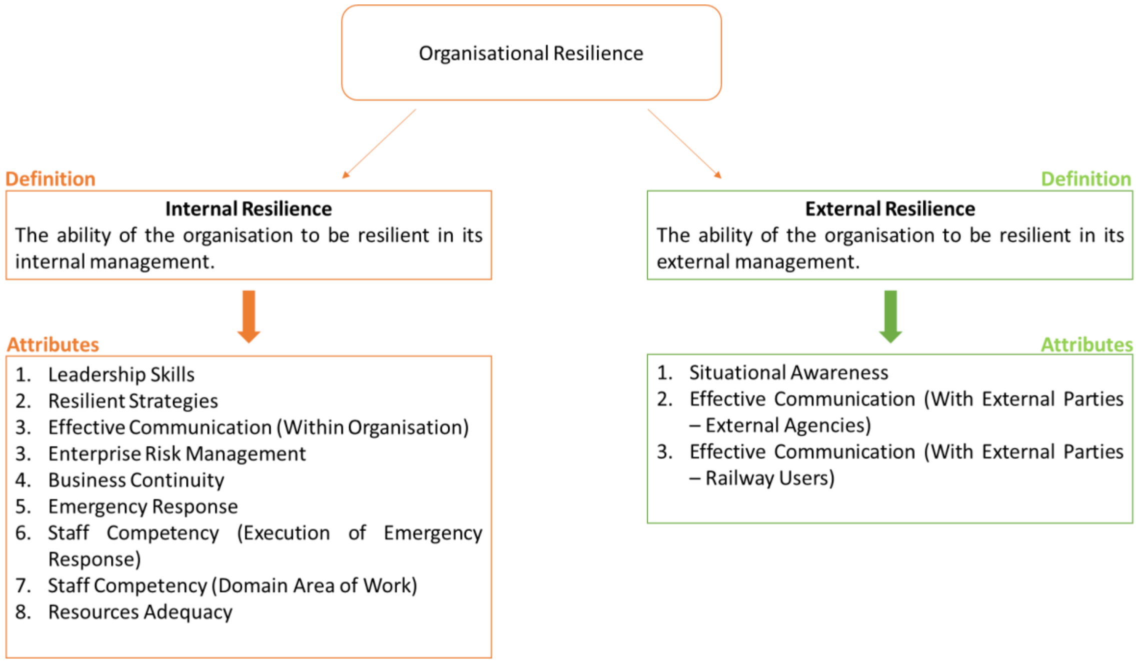


Figure 21: Identification of organisational resilience attributes

3.3.4 Design of Assessment Tool

After the identification of resilience attributes, the next phase of the work as stated in Figure 17 is to determine how the resilience level can be evaluated, measured and areas of improvement to be identified. The assessment tool created therefore has to fulfil these 3 criteria and are elaborated in the following steps i.e., Evaluation, Measurement and Visualisation. The assessment tool is designed using Microsoft Excel.

Step 3: Evaluation

This thesis has considered the Tier I assessment approach – "*Screening models and indexes to identify easy improvements and guide focus of further analysis*", with reference to the tiered resilience assessment framework proposed by *(Linkov et al., 2018)*, in the design of the assessment tool so as to provide strategic evaluation. Tier I level is considered in view of some limitations that the research has at this phase of work i.e., the availability of information and data needed for the detailed modelling and actual analysis of organisational structure and railway operation, which are needed for Tiers II and II consideration. In addition, Tiers II and III would also require decision-making activities from corporate management for the in-depth identification of resilient strategies and detailed modelling tailored to the organisation, which are unavailable at this phase of work. Aside to the gathering of information through the papers read during the conduct of the literature review, other sources of information such as online publications made by organisations, past working experience and engineering judgement also serve as consideration to the development of the assessment tool.

Step 3 is to determine how the resilience can be evaluated and this is fulfilled by Figure 22 below which illustrates a stepwise approach adopted in the development process. As mentioned in Section 3.3.1, 1 of the objectives is to eliminate the level of subjectivity that the management level would have when carrying out the evaluation work. The setting of the evaluation criteria thus has to be straight-forward. The evaluation of each attribute is based on a set of 'discrete' semi-qualitative criteria assigned to it which includes 4 levels of resilience from low to high. Each level has a representative quantitative score i.e., 1 to 4, and qualitative description associated with each score. A single indication is selected out of the 4 levels after the attribute has been evaluated. This indication reflects the resilience of the particular attribute, i.e., indicator 1. The combined indicator scores for a group of attributes will give the resilience indication for that particular domain. Once all the domains have been evaluated, the output to be obtained through the use of the tool will be the combined indicative score of all the considered domains. This is depicted by the blue square box on the right-hand side of Figure 22, which is the overall resilience level of the railway organisation being assessed.

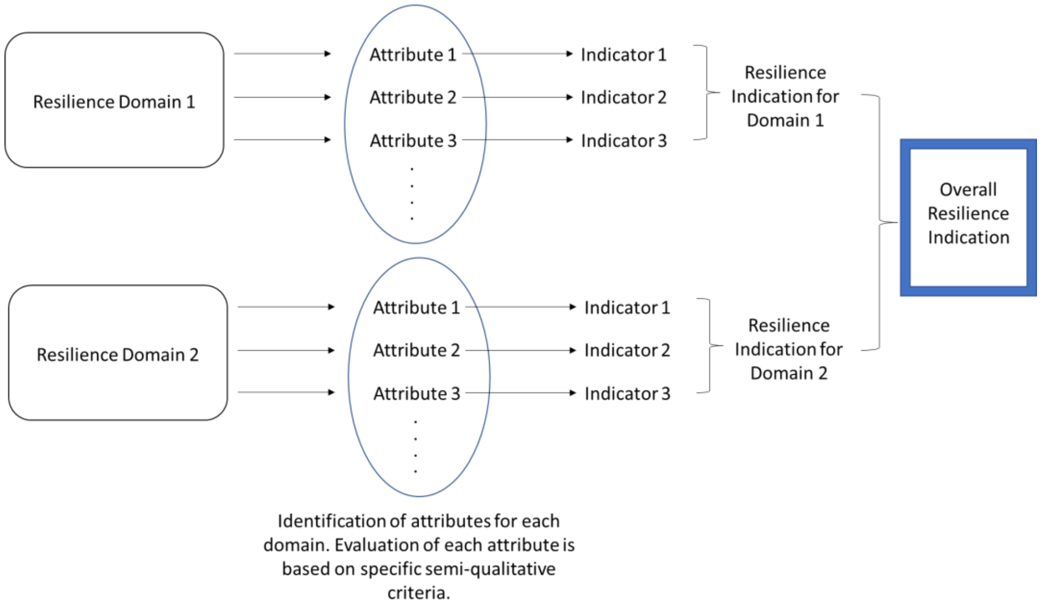


Figure 22: Stepwise approach to measure resilience level

Step 4: Measurement

Step 4 is to determine how the evaluated resilience can be translated to a tangible measurement format and to derive the resilience level of the railway organisation. A snapshot of the user interface of the assessment tool in excel format is shown in Figure 23 below. The outputs obtained from Steps 1, 2 and 3 are imported to Columns A and B, C, D and E respectively. The evaluated indicator score for a single attribute is named as '*Evaluated Attribute Score*' in Column E. The measurement of the attribute scores and the eventual resilience measurement for the railway organisation are derived from Columns F through L.

A	B	C	D	E	F	G	H	I	J	K	L
Resilience Domain	Sub-Domains	Associated Attributes	Evaluation Criteria	Evaluated Attribute Score	Attribute Weightage	Weighted Attribute Score	Sub-Domain Score	Sub-Domain Weightage	Weighted Sub-Domain Score	Weighted Domain Score	Domain Weightage
	Hardware Resilience										
		System Integrity	1 : < 25% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. 2 : 25% to 50% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. 3 : 50% to 75% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. 4 : 75% to 100% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. * Latest version of design standard is taken as of conducting this resilience assessment.								
			1 : Reliability parameters are not specified in the Technical Design Requirements and assets unable to demonstrate high reliability upon system validation								

Figure 23: Snapshot of user interface of assessment tool

The derivation of Step 4 follows the framework drawn in Figure 24 and elaborated as follows. Weightage calculation is conducted at attribute-level, sub-domain level and domain-level and follows a bottom-up approach.

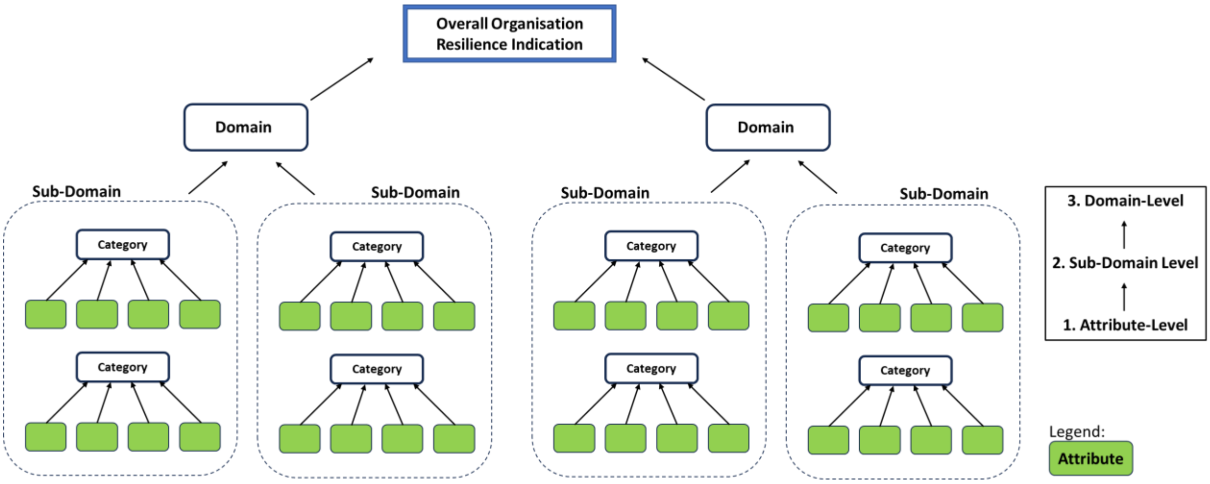


Figure 24: Weightage Derivation Framework

I. Attribute-Level Weightage

The 1st step of the measurement is to determine the weightage to be assigned to each attribute i.e., '*Attribute Weightage*' in Column F. Instead of providing the flexibility in allowing the tool users to assign a suitable weightage, Multi-Criteria Decision-Making technique is considered to ensure the objectivity and avoid any degree of biasness that can be included in determining what is the suitable weightage to be used. Reference to this paper by *(Ezell et al., 2021)*, 2 types of weighting methods have been introduced i.e., ratio assignment and approximate methods. Ratio assignment method established weights that correspond to the subjective preferences of the users when they answer certain questions being raised, while approximate methods established weights based on the ordinal rankings of the attributes based on their relative importance.

A technique has been considered to reduce this level of subjectivity so that a common value of the '*Attribute Weightage*' can be obtained. This is explained by using the following scenario. The weightage calculation spreadsheet used in the assessment tool is appended in Appendix C.

Scenario Illustration

The 'Design' category of the 'Hardware Resilience' sub-domain has been used as an example for illustration. Assume a panel of 10 decision-makers from a railway organisation is required to assess the resilience of the organisation. In reality, each decision-maker would have different preference on the '*Attribute Weightage*' as their view on the importance of the attributes to the resilience assessment might differ.

2 different weighting techniques have been considered i.e., Direct Assignment Technique (DAT) and Rank Ordered Centroid (ROC) Technique. Before using these 2 techniques, the panel of 10 decision-makers is being posted 1 question: *"Is the attribute critical or not critical to the assessment of resilience?"*. If the attribute is deemed as critical, a vote of 1 is provided and no vote i.e., 0 if it is not. After all members have provided their inputs, the total number of votes for each attribute is summed and tabulated under column '*Total Vote (1)*'. This process applies to both of the weightage techniques that will be elaborated below. Note that the vote-count used in the illustration below is randomly assigned.

The 2nd step is to determine the '*Attribute Weightage*'. Explanation of how each of the 2 techniques can be used in calculating the attribute weightage are as follows:

A. <u>Ratio Assignment – Direct Assignment Technique (DAT)</u>

A.1 Refer to Figure 25, the vote for each attribute (v_i) is obtained by the voting process whereby i refers to the particular attribute.

Under the column '*Weightage (2)*', the respective attribute weightage (w_i) is calculated by normalizing v_i against the total number of votes obtained for all the attributes under the category by using the following formula. This process is repeated for all the individual categories.

$$w_i = v_i / \sum_{i=1}^{m} v_i \, , i = 1,2, \ldots , m \, , \qquad (1.1)$$

Where:

m represents the total number of attributes for the particular category.

A.2 All weights within a category must add up to 1 i.e.,

$$\sum_{i=1}^{m} w_i = 1 \qquad (1.2)$$

Attribute Weightage Calculation

(1) Each member is to answer the question:
Qn: Is the attribute critical / not critical to the assessment of resilience?
If Critical, insert 1.
If Not Critical, insert 0

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	Total votes (1)	Weightage (2)
Hardware Resilience													
Design	System Integrity	1	0	1	1	1	0	1	0	1	0	6	=6/30=0.20
	Reliability	1	0	1	1	1	1	1	0	0	1	7	0.23
	Risk Management	1	1	0	1	1	1	1	0	1	1	8	0.27
	Redundancy Level	1	1	1	0	0	0	1	0	0	1	5	0.17
	Resilience Engineering	0	0	1	0	0	1	0	0	1	1	4	0.13
											Sum	30	1.00

Figure 25: DAT weightage calculation

B. <u>Approximate Assignment – Rank Ordered Centroid (ROC) Technique</u>

B.1 Refer to Figure 26, the ROC technique requires the importance of the attributes to be ranked first. This technique assumes that there is no other supporting information on how much 1 attribute is important relative to the others *(Barron & Barrett, 1996)*. Thus, the vote-count for each attribute is used to help in the ranking process. This method eliminates the possibility of the panel of decision-makers being unable to reach a consensus on the ranking order.

The attribute with the highest number of votes (highest criticality) will be ranked as 1. Under the column '*Weightage (2)*', the respective attribute weightage is calculated by using the following formula,

$$w_i = (1/m)\sum_{K=i}^{m} {}^{1}/_{K} \quad (1.3)$$

Where:

m represents the total number of attributes within a category,

K represents the ranking level of the *i-th* attribute within a category.

B.2 By using the formula 1.2, all weights within a category must add up to 1 i.e.,

$$\sum_{i=1}^{m} w_i = 1$$

Attribute Weightage Calculation

(1) Each member is to answer the question:
Qn: Is the attribute critical / not critical to the assessment of resilience?
If Critical, insert 1.
If Not Critical, insert 0

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	Total votes (1)	Rank	Weightage (2)
Hardware Resilience														
Design	System Integrity	1	0	1	1	1	0	1	0	1	0	6	3	0.16
	Reliability	1	0	1	1	1	1	1	0	0	1	7	2	0.26
	Risk Management	1	1	0	1	1	1	1	0	1	1	8	1	=(1/5)*(sum(1+1/2+1/3+1/4+1/5)=0.46
	Redundancy Level	1	1	1	0	0	0	1	0	0	1	5	4	0.09
	Resilience Engineering	0	0	1	0	0	1	0	0	1	1	4	5	0.04
											Sum	30		1.00

Figure 26: ROC weightage calculation

Table 8 summarises the weightage values obtained by DAT and ROC technique. It can be seen that for attributes with the most and least number of votes i.e., Risk Management and Resilience Engineering, there is a big difference in the weightage values calculated by both methods, whereas the difference is minor for attributes ranked in the middle.

Table 8: Weightage values calculated by DAT and ROC

Resilience Attributes	Total votes	Ranking Level	DAT	ROC
System Integrity	6	3	0.20	0.16
Reliability	7	2	0.23	0.26
Risk Management	8	1	0.27	0.46
Redundancy Level	5	4	0.17	0.09
Resilience Engineering	4	5	0.13	0.04

Figure 27 below further illustrates the comparison made between the weightage values calculated by both methods. It is observed that a linear relationship is obtained by using DAT while an exponential relationship is obtained with the ROC technique. It can be observed that a much higher weightage is assigned for the attribute with the greatest vote-counts i.e., higher importance in the ROC technique. In addition, the range of weightage allocation (between the highest and lowest importance) is much wider for the ROC technique as compared to DAT, thus in terms of differentiating the importance among the attributes, the ROC technique offers a better advantage.

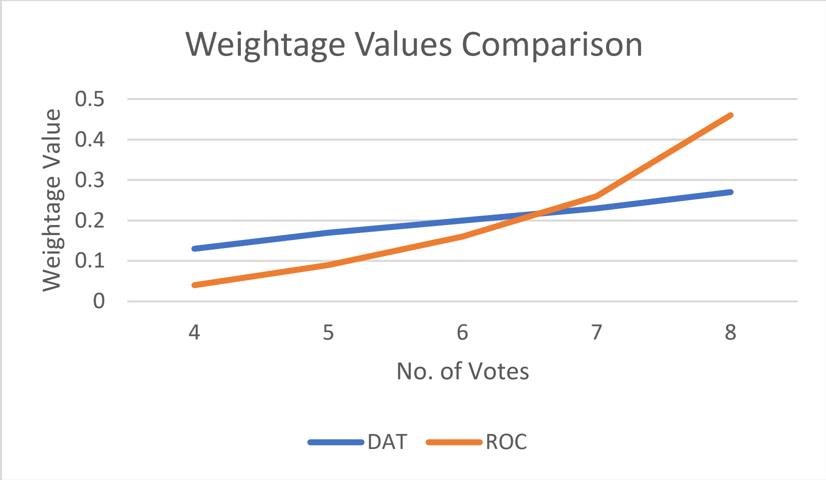


Figure 27: Weightage values comparison

The level of resilience of the railway organisation calculated by both methods is shown in Table 9. Both methods have assumed the same evaluated attribute score and the same vote-counts for each attribute. There are attributes with the same vote-counts thus ranking is randomly assigned in ROC for this group. The difference in score is very small i.e., 0.04 points. Though the difference is small, it can make an impact if the scores lie around the boundary of each band i.e., 1.99 to 2.01 and 2.99 to 3.01 of the Resilience band table.

Table 9: Overall resilience score obtained by DAT and ROC technique

	DAT	ROC
Overall Resilience Score	3.51	3.47

When more categories have attributes with same vote-counts, it is observed that the change in the overall resilience score is very minimal. A trial is made to increase the number of attributes with same vote-counts. The overall resilience score obtained is as follows:

Table 10: Overall resilience score (with more attributes having same vote-counts)

	DAT	ROC
Overall Resilience Score	3.53	3.44

It is shown in Table 10 that the overall resilience score has increased for DAT as compared with Table 9 while it has decreased for ROC, though the change is small. For categories with more attributes, the probability to encounter the situation of attributes with same-vote counts would be higher than categories that have 2 or 3 attributes, hence, the more likely that another round of ranking is needed.

From the above analyses, this thesis has tabulated the pros and cons that both techniques exhibited in Table 11. The ROC technique is eventually being selected as the method to calculate the attribute weightage in the assessment tool. It is preferred for an exponential behaviour of weightage allocation whereby a bigger differentiation in terms of weightage allocation is present. Acknowledging there is the possibility that 2 or more attributes could have the same number of votes when using the ROC technique, hence when such a situation arises, the instruction given in the tool is that the panel of members will have to further discuss and determine the most importance and rank them accordingly i.e., no 2 attributes can have the same ranking.

Table 11: Pros and cons of DAT and ROC technique

	DAT	**ROC Technique**
PROS	i. Does not require ranking of attributes. Direct weightage assignment by using the vote counts for each attribute. ii. Less computational effort needed in using the calculation formula.	i. Provides a wider weightage differentiation range between the highest and lowest rank as follows an exponential relationship.
CONS	i. Provides a smaller weightage differentiation range between the highest and lowest rank as it follows a linear relationship. ii. Allows attributes with the same vote to have the same weightage, thus minimal differentiation in relative importance of attributes in such situation. iii. Recalculation of weights needed when attributes are included or removed.	i. Requires ranking of the attributes first by utilising the vote-counts with the highest number of votes being ranked as 1st. ii. The use of votes is affected by the number of members/ users involved in the resilience assessment. There is a possibility that 2 or more attributes can have the same number of votes. In this situation, no 2 attributes shall have the same ranking by ROC technique. The solution is the panel of decision-makers are to discuss and rank the attributes again. iii. More computational effort needed in using the calculation formula. iv. Recalculation of weights needed when attributes are included or removed.

The '*Weighted Attribute Score*' for each attribute under Column G is calculated as:

$$W_i = A_i \times w_i \tag{1.4}$$

Where:

W_i represents Weighted Attribute Score,

A_i represents Evaluated Attribute Score,

w_i represents Attribute Weightage.

II. Sub-Domain Level Weightage

The 3rd step of the measurement is to determine the weightage to be assigned to each sub-domain i.e., '*Sub-Domain Weightage*' in Column I.

The '*Sub-Domain Score*' (S_t) under Column H is calculated as:

$$S_t = \sum_{i=1}^{m} W_i \quad (1.5)$$

Where:

t represents the particular sub-domain,

S_t represents the Sub-Domain score,

W_i represents Weighted Attribute Score for all attributes within a sub-domain.

The '*Sub-Domain Weightage*' (W_t) under Column I is derived by using the equal weighting method i.e., divided equally among the total number of sub-domains considered in the assessment tool and it is 4 in this case, thus the sub-domain weightage would be 0.25 each.

The '*Weighted Sub-Domain Score*' under Column J is calculated as:

$$WS_t = S_t \times W_t \quad (1.6)$$

Where:

WS_t represents the Weighted Sub-Domain Score,

S_t represents the Sub-Domain score,

W_t represents the Sub-Domain Weightage, t=1, 2, …, T.

*$W_t = {}^{1}/_{T} = {}^{1}/_{4} = 0.25$. It is divided equally by the total number of sub-domains (T) in the whole assessment and there are 4 in this illustration i.e., hardware resilience, software resilience, internal resilience, external resilience.

III. Domain-Level Weightage

The 4th step is to determine the weightage to be assigned to each domain i.e., '*Domain Weightage*' in Column K.

The '*Weighted Domain Score*' (WD_U) for each domain under Column K is calculated as:

$$WD_U = \sum WS_t \quad (1.7)$$

Where:

U represents the particular domain, either technical or organisation,

WD_U represents the Weighted Domain Score,

WS_t represents the Weighted Sub-Domains Scores within a Domain.

The '*Domain Weightage*' (W_D) under Column L will be divided equally by the total number of domains (D) being considered.

*$W_D = {}^{1}/_{D} = {}^{1}/_{2} = 0.50$. It is divided equally by the total number of domains *(D)* in the whole assessment and there are 2 in this illustration i.e., technical and organisational.

What have been included in the assessment tool till this phase of work have achieved the first 3 objectives stated in Section 3.3.1 i.e., the tool has to be straightforward, has to be easy to use and to allow the review of attributes to be conducted easily. The removal or addition of attributes to the tool is easy and would only require minimal amendments to the mathematical formulas included in the spreadsheet.

Step 5: Visualization - The Output

The final step of calculation would be to determine the overall resilience of the railway organisation and is calculated as:

$$Overall\ Resilience\ Score\ = (WD_{Technical} \times W_{Technical}) + (WD_{Organisational} \times W_{Organisational}) \tag{1.8}$$

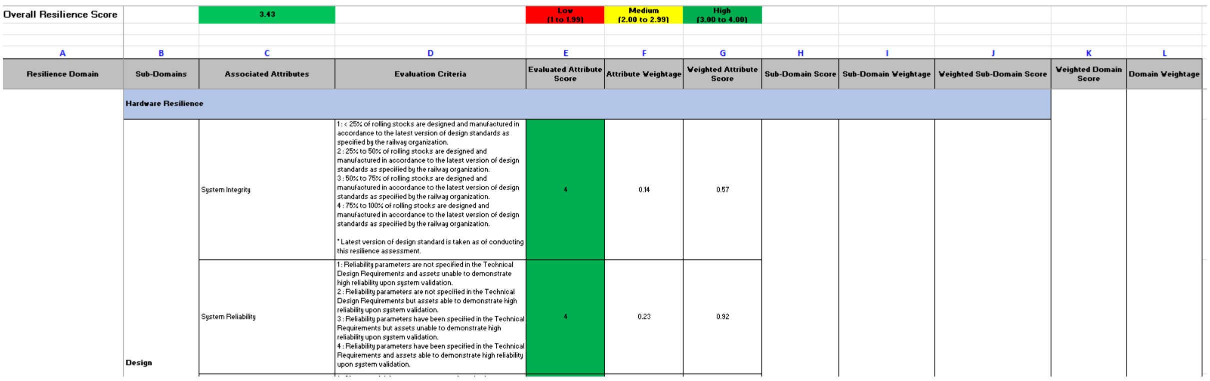
The fourth objective stated in Section 3.3.1 is to provide a form of quick resilience visualisation of attributes that are under-performing. The use of resilience heat map with 3 different resilience levels shown in Table 12 is adopted.

Table 12: Resilience band table

Low (1.00 to 1.99)	Medium (2.00 to 2.99)	High (3.00 to 4.00)

The 3 bands of resilience level are created based on the 4 evaluation levels that each set of evaluation criteria has. The 'Evaluated Attribute Score' and the 'Overall Resilience Score' are then benchmarked against the resilience band table to determine the resilience performance.

Figure 28 provides a snapshot of the user interface of the semi-qualitative assessment tool developed. Details of the whole assessment tool is appended in Appendix D. MS Excel version of the tool is also attached to the softcopy submission of the thesis report.



Overall Resilience Score: 3.43 — Low (1 to 1.99) | Medium (2.00 to 2.99) | High (3.00 to 4.00)

A Resilience Domain	B Sub-Domains	C Associated Attributes	D Evaluation Criteria	E Evaluated Attribute Score	F Attribute Weightage	G Weighted Attribute Score	H Sub-Domain Score	I Sub-Domain Weightage	J Weighted Sub-Domain Score	K Weighted Domain Score	L Domain Weightage
	Hardware Resilience										
		System Integrity	1 : < 25% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. 2 : 25% to 50% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. 3 : 50% to 75% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. 4 : 75% to 100% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organization. * Latest version of design standard is taken as of conducting this resilience assessment.	4	0.14	0.57					
	Design	System Reliability	1 : Reliability parameters are not specified in the Technical Design Requirements and assets unable to demonstrate high reliability upon system validation. 2 : Reliability parameters are not specified in the Technical Design Requirements but assets able to demonstrate high reliability upon system validation. 3 : Reliability parameters have been specified in the Technical Requirements but assets unable to demonstrate high reliability upon system validation. 4 : Reliability parameters have been specified in the Technical Requirements and assets able to demonstrate high reliability upon system validation.	4	0.23	0.92					

Figure 28: Snapshot of assessment tool

Figure 29 provides an overview of the resilience performance of the attributes for both technical and organisational domains. This table is also available as a separate spreadsheet. This overview provides quick visualization to the management/decision-makers/stakeholders of the railway organisation on the summarised resilience performance of the organisation and as well at attribute-level, thereby meeting the fourth objective stated in Section 3.3.1.

Overall Resilience Score	3.43	Low (1 to 1.99)	Medium (2.00 to 2.99)	High (3.00 to 4.00)

Resilience Domain	Sub-Domains	Associated Attributes	Evaluated Attribute Score
Technical (Rolling Stock)	Hardware Resilience		
	Design	System Integrity	4
		System Reliability	4
		Risk Management	4
		Redundancy Level	4
		Resilience Engineering	2
	Operation	Interoperability	2
		System Interface (With other railway assets)	4
	Maintenance	System Maintainability	4
		Conduct of Maintenance	4
		Conduct of Maintenance Audit	4
		Fault Monitoring and Diagnostic Capability	2
		Adaptability to Changing Environment Conditions	4
	Assets Renewal	Asset Performance	4
		Asset Conditions	4
		Availability of Spares	2
	Software Resilience		
	Design	Software Safety Integrity	4
		Redundancy Level	2
		Risk Management	4
		Cybersecurity Protection	4
	Maintenance	Fault Monitoring and Diagnostic Capability	2
		Conduct of Maintenance Audit	4
		Adaptability to Changing Environment Conditions	4
Organizational	Internal Resilience	Leadership	4
		Resilient Strategies	2
		Effective Communication (Within Organization)	4
		Risk Management	4
		Business Continuity	4
		Emergency Responses	4
		Staff Competency (In Execution of Emergency Responses)	4
		Staff Competency (In Domain Area of Work)	4
		Adequacy of Resources	4
	External Resilience	Situational Awareness	4
		Effective Communication (With External Agencies)	4
		Effective Communication (With Railway Users)	4

This summary table provides an overview of the consolidated results from the Assessment Tool worksheet.
Hold the cursor over each attribute for details of the evaluation criteria.

Figure 29: Overview of resilience performance

This thesis has constructed a 5-stages cycle framework as the process for the systematic evaluation of the organisation resilience shown in Figure 30. The sequence of how the assessment tool is to be used also follows this cycle. This also relates back to Figure 1 in Section 1.3, whereby it fits into the before-after assessment framework, for continuous resilience improvement since it is a repetitive process. The role of each stage is elaborated below:

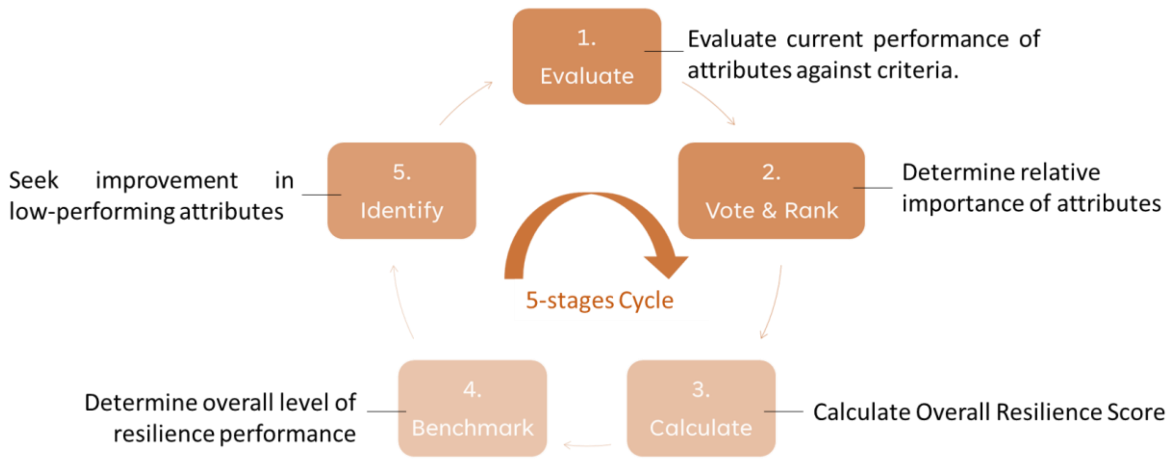


Figure 30: 5-stages cycle framework

- Stage 1 Evaluate: To know the resilience performance by evaluating current performance of each attribute against pre-defined set of evaluation criteria.
- Stage 2 Vote & Rank: To determine the relative importance of each attribute towards the resilience building in the organisation business model.
- Stage 3 Calculate: To calculate and obtain the overall resilience score which will provide the resilience performance indication to the decision-makers at the strategic level.
- Stage 4 Benchmark: To benchmark the quantitative score obtained Stage 3 against the resilience heat band to provide qualitative indication.
- Stage 5 Identify: After the decision-makers have an indication of the resilience performance in Stage 4, it helps them to further decide what are the necessary policy measures, action plans needed to be implemented, or areas that need to be put on hold.

To answer to the main research question of '*How to assess the resilience of a railway organisation to prioritise resilience-building measures that can improve its preparedness in facing the occurrence of unexpected external events impacting railway operation?',* the semi-qualitative assessment tool created in Chapter 3 has provided a mean to assess the resilience and to identify areas of improvement. Suitable resilient attributes are identified based on its role in characterizing the technical and organisational resilience when facing with the external events considered in this thesis i.e., extreme weathers and sudden cyber-security attack, and at the same time to embed the essence of the R4 Resilience Framework in the identification. The attributes identified for technical resilience are specific to the asset and rolling stock has been used as an example for illustration. The tool can be expanded easily by adding attributes for all assets managed by the railway organisation.

Aside to the use of qualitative description in the set of evaluation criteria, the use of numerical score is also being considered to aid in the measurement of the resilience performance. The use of the resilience band table is the last step of evaluation which allows the tool users to identify attributes that are under-performing when it falls into the Low category. With this information, the railway organisation is then able to prioritise their improvement measures which are critical to the railway operation. When attributes under the Low band is highlighted, it allows the management level to further discuss in details on the improvement work and if required, to proceed with Tiers II and III approaches mentioned in *(Linkov et al., 2018)*, which involves more tactical and operational strategies.

4. VALIDATION OF THE ASSESSMENT TOOL

This chapter describes the approach adopted in validating the assessment tool developed. The goal to be achieved from the validation work is firstly provided, followed by elaboration on the methodology used. The outcomes of the validation work and discussion are finally provided.

4.1. Goal

The goal for the validation is to determine the effectiveness of the assessment tool as a method used in assessing the resilience of the railway organisation at strategic level when Tier I approach is adopted. In order to achieve this goal, 3 areas of evaluation have been identified as follows:

1. **Area 1** – To assess the applicability of the resilience attributes, evaluation criteria identified in this thesis and if there are any other potential attributes that could have been considered under Technical and Organisational domains.
2. **Area 2** – To gather feedback on the calculation method and the improvement identification approach used in the tool.
3. **Area 3** – To gather feedback on the overall usefulness of this tool and on any areas of improvement that can be considered.

4.2. Methodology

Assessing the effectiveness of an assessment tool involves evaluating how well the assessment tool has incorporated the intended knowledge or subject matter. For instance in the studies by *(Daud et al., 2023; Rezaei et al., 2023)*, researchers created questionnaires as their assessment tool to assess the safety of ride-hailing car and to conduct a study on the short-form travel behaviour during Covid-19 pandemic. In their research, the validity and reliability of their questionnaires are being evaluated in order to ensure that any error that may be included is kept to the minimum. From *(Brink, 1993)*, validity assessment is to determine whether if the tool has actually measured what it is supposed to measure, while reliability assessment is associated with the consistency and stability of the tool.

In this thesis, the use of questionnaire is selected as the method to validate the applicability of the tool. Validity assessment *(Aaron Moss, 2021)* can address all 3 areas stated in Section 4.1 whereby the questions will help to evaluate how the content of the assessment tool developed in Chapter 3 has been relevant and representative of the subject matter. The review of the resilience attributes by respondents with respect to its applicability and evaluation criteria is especially important for this thesis. Areas 2 and 3 are addressed in the questionnaire whereby questions related to the ROC-weightage calculation method, the improvement identification method, the overall user interface, the achievement of the goals are raised. In addition, the reliability assessment in this thesis would also be applied whereby the reliability of these questions is gauged.

From *(Revicki, 2014)*, "*reliability assessment involves examining the agreement of 2 or more measures of the same thing".* Reliability assessment is conducted by gauging how well these questions reflect the same thing which is the usability of the tool in this thesis. If the responses received contradicts with each other, it means that the questions raised in the questionnaire could be unreliable in gauging the usefulness of the tool *(Middleton, 2019)*. There are different statistical methods whereby reliability of the survey can be assessed such as test-retest reliability, inter-rater reliability, parallel forms reliability and internal consistency reliability *(Middleton, 2019)*. In this thesis, the use of internal consistency reliability has been adopted. Quoted from *(Zach, 2020)*, internal consistency refers to "*how well a survey, questionnaire, or test actually measures what you want it to measure*". The way of measurement is to use the statistic i.e., Cronbach's Alpha (α) that determines the correlations between the questions in the survey. After the calculated alpha value is determined, it is benchmarked against the following table which shows the level of internal consistency. The higher the level of internal consistency, it represents the higher the reliability of the survey or questionnaire i.e., it is a reliable method to determine the usefulness of the assessment tool.

Table 13: Levels of Cronbach's Alpha (Zach, 2020)

Cronbach's Alpha	Level of Internal Consistency
$\alpha \geq 0.9$	Excellent
$0.8 \leq \alpha < 0.9$	Good
$0.7 \leq \alpha < 0.8$	Acceptable
$0.6 \leq \alpha < 0.7$	Questionable
$0.5 \leq \alpha < 0.6$	Poor
$\alpha < 0.5$	Unacceptable

4.3. Questionnaire Design

A scenario-based scenario on how the assessment tool is to be used, is stated in the questionnaire. Respondents are asked to assume that they are part of a diverse team working in a railway organisation whereby the team has been tasked to use the assessment tool to assess the resilience of their organisation and 2 goals have been assigned to the team as follows:

i. To evaluate the resilience performance of the railway organisation at strategic level.
ii. To identify resilient-deficient attributes, so that further analysis and improvement actions can be taken.

The 5-stages cycle framework in Figure 30 is used to provide a systematic way to guide the respondents through the questionnaire as it is also how they would be when using the tool. A mixture of open-ended and close-ended questions are prepared. Open-ended questions are useful to gather qualitative insights, and this helps to identify if there are other attributes that ought to be considered, weaknesses and strengths of the tool, and any other areas of improvement. Close-ended questions using Likert-scale of 1 (not at all useful, strongly disagree, not effective at all) to 5 (extremely useful, strongly agree, extremely effective) are used to grade the questions seeking feedback from the respondents with respect to the methodology and usefulness of the tool in meeting the 2 goals being set. Web-based Qualtrics survey platform has been used in the preparation of the questionnaire and it can be accessed through the URL (*Wong, S.C., 2023*) and the survey is distributed via email invitation.

4.4. Target Respondents

A defined group of respondents working in the railway sectors that are railway asset owners, rolling stock manufactures and railway operators is targeted. As the topic is related to the railway and rolling stock, railway technical terms and jargon used would be easily understandable by them. Respondents from this niche area is also selected in order to address Area 1 set out in Section 4.1 whereby concrete feedback on the applicability of the resilience attributes for rolling stock and organisation management is desired as the context would be more relatable. The survey questionnaire is distributed to 150 respondents.

4.5. Pilot Test

Before the actual set of questionnaire is being sent out to the target respondents, a pilot test on the draft questionnaire is being sent to a small group of personnel working in the railway industry with similar profile as the target respondents. The aims of the pilot test are to ensure that:

i. The situation-based scenario, the objectives of the resilience assessment activity to be undertaken by the team and how the tool is to be used, have been clearly conveyed through the descriptives in the questionnaire.
ii. The survey can be completed within a reasonable period of time.
iii. The drafted questions have been clearly phrased so as to avoid ambiguity, and if there are questions that need to be added and/or removed.

4.6. Results and Discussions

A total of 99 responses are received. These responses are reviewed and are detailed in the following sections in the order of the 3 areas set out in Section 4.1.

4.6.1 Validity Assessment – Resilience Attributes

Table 14 summarised the results on the applicability of the resilience attributes for the Technical and Organisational domains. Each respondent is allowed to select more than 1 attribute which they think is not applicable. Aside to getting respondents to review the attributes and then to select attributes that they opined are not applicable, the questionnaire has also sought for respondents to provide qualitative views on why they opined the attributes that they have selected are not applicable and also if there are other hardware resilience attributes worth consideration. Detailed breakdown on the number of responses that are not applicable for each attribute can be referred from Figure 45 to Figure 48 in Appendix E.

Table 14: Results summary for applicability of resilience attributes

Domain	**Technical Domain**		**Organisational Domain**	
Sub-Domain	**Hardware Resilience**	**Software Resilience**	**Internal Resilience**	**External Resilience**
Total No. of Attributes Identified by Thesis	15	7	9	3
Total number of responses received	131	118	108	100
Total number of responses received as '**All attributes are Applicable**"	82	75	95	94
Total number of responses received for attributes that are **Not Applicable**	49 (≈ 37.4%)	43 (≈ 36.5%)	13 (≈ 12.0%)	6 (≈ 6.0%)
Top attributes that are feedbacked as **Not Applicable**	• Conduct of Maintenance Audit • System Interface (With other railway assets)	• Conduct of Maintenance Audit • Adaptability to Changing Environment Conditions • Redundancy Level	• Leadership • Adequacy of Resources	• Effective Communication (With Railway Users)
Are there any attributes that are not being selected?	No	No	Yes. • Emergency responses	No

			• Risk management	

Table 14 showed that more than 60% of the responses received have feedbacked that all the attributes identified for each of the domain are applicable for resilience assessment with the organisational domain receiving the highest number of responses. In terms of non-applicability, the 'Hardware Resilience' sub-domain has received the highest number of responses at 37.4% while 'Software Resilience' sub-domain at 36.5%. The table has also listed the top attributes which received the highest number of responses that are not applicable for consideration for each sub-domain. For 'Hardware Resilience' sub-domain, the attributes are conduct of maintenance audit and system interface with other railway assets; for 'Software Resilience' sub-domain, the attributes are conduct of maintenance audit, adaptability to changing environment and redundancy level. For 'Internal Resilience' sub-domain, the attributes are leadership and adequacy of resources while for 'External Resilience' sub-domain, the attribute is effective communication with railway users.

The following sub-sections listed some of the qualitative feedback received from respondents on why they have selected the resilience attributes that they think are not applicable. Unclear responses are firstly being filtered. The listing is categorised by the sub-domains. The overview of all the responses is appended in Appendix F. This thesis has also attempted to discuss these feedback.

4.6.1.1 Hardware Resilience Attributes

1. System Reliability

Feedback: *"Train bought should be reliable in the first place."*

Discussion: Yes, agree with this feedback. Rolling stocks are designed to meet a certain level of design reliability during the manufacturing phase. The intention to consider this attribute is to ensure that all rolling stocks are designed and validated to be reliable before being put into revenue service. If the trains are not able to achieve the specified level of reliability, but yet are being put into service, special attention will need to be paid to when facing the external events. In addition, the reliability of the rolling stock deteriorates over time. Thus, it is also possible to consider the attribute on Operational Reliability as a form to assess the Robustness of the asset.

2. Risk Management

Feedback: *"Risk management is a tool to assess the system but does not directly contribute to the hardware resilience."*

Discussion: Yes, agree with this feedback. With the availability of such tool, the ways of how the rolling stock gets affected by the external events that can lead to system failure are being identified, so as to ensure that adequate mitigation measures are incorporated to the system design in the first place. If such systematic identification procedure is absent, there is no assurance that the rolling stock would be able to revert back to service as soon as possible, after facing the external events.

3. Redundancy Level

Feedback: *"Redundancy level serves as an addition layer of protection."*

Discussion: Yes, agree with this feedback. Redundancy is to ensure that when the 'primary' layer of protection fails, the rolling stock can continue if coincidentally, system failure occurs during the occurrence of external events.

4. Interoperability

Feedback: *"Rolling Stock (RS) fleet operating in different network depends on its operating mode i.e., Automatic Mode, Coded Manual Mode, Restricted Mode."*

Discussion: This thesis opined that this comment is more relevant to the type of trainborne and trackside signalling system that the rolling stock is being equipped with. However, the attribute in this context refers to the rolling stock itself. Thus, if the design of the train is able to operate unanimously on different network, it serves as a form of infrastructure redundancy. Next consideration will then be on the type of signalling systems that are used on the different network itself, whether it allows different train type to operate on it. A good example is the standardisation of the European Rail Traffic Management System used in European railway networks.

5. Conduct of Maintenance Audit

Feedback: *"Audit is carried out to ensure proper documentation and records, and not directly contributing to the resilience of the hardware."*

Discussion: Audit ensures that the maintenance regimes and rectification work have been promptly carried out as required. In the event disruption occurred, there is a possibility that back-tracking of work history will be needed to review if protocols have been adhered to and to identify if there are any lacking areas.

6. Adaptability to Changing Environment Conditions

Feedback: *"Usually govern by specifications in relation to international standards, even with changing environment, it is often late and can be subjective and risk appetite."*

Discussion: This thesis opined that it is not late to implement changes to improve the resilience such as via additional design provisions/reinforcement, the use of more condition monitoring tools, etc. The extent of risk appetite would be dependent on the railway organisation on how much risk the company is willing to bear, when the rolling stock encounters failure due to the external events. Immediate assets that the organisation owns might not be able to be changed for the changing environment condition, however, it allows more stringent or better design specification to be specified for new trains to be procured. The intention of this attribute is allowing organisation to own a better sensing of how its existing stock will react, and thus able to take the necessary preventive measures for the operation of existing fleets as well as reviewing how the resilience for new fleets can be enhanced.

The questionnaire has also asked respondents if there are any other attributes pertaining to hardware resilience that they think can be considered in Table 15. This thesis opined that some of these suggestions are ways that can help to improve the design of the rolling stock which in turn helps to improve the robustness and thus are not attributes. The table below has tabulated attributes that can be considered and also suggested ways to improve the robustness of the rolling stock.

Table 15: Other hardware resilience related attributes

Possible Attributes	Ways To Improve Resilience
- Capacity – load-related failures - Longevity – age-related failures - Survivability – preparedness against kinetic attacks such as military threats - Supply chain management - Lifecycle of rolling stock components - Conduct of operations audit - Measurement of Response time to fault incident – failure management is essential factor to maintain operability to achieve hardware resilience. Means of Recovery to be considered in hardware design since it could randomly fail despite having redundancy. - Failure rate of rolling stock/ components - System Mean Time Failure - Competency and thoroughness of system assurance and maintenance teams.	- Comprehensiveness of system testing - Sub-systems interdependency - The consideration of lessons learnt - Human factor impact on the hardware - Obsolescence forecasting

The suggested ways to improve resilience are related to the system design, functionality, or scope of work that might need to be considered during the design of the rolling stock or before the train is put into revenue service such as the comprehensiveness of system testing, the level of sub-systems interdependency that the rolling stock design has catered for, the incorporation of lessons learnt from past incidents, the level of human factor considered in the design, etc. On the other hand, the possible attributes are applicable for in-depth resilience assessment at tactical and/or operational level such as evaluating resilience by examining the lifespan of rolling stock components, the failure rates, the amount of time taken to respond to incident, the number of load and age-related failures encountered as well as the competency level of the personnel involved.

4.6.1.2 Software Resilience Attributes

1. Redundancy Level

Feedback: *"Depending on the hardware redundancy, software cannot control this. Redundancy level serves as an addition layer of protection."*

Discussion: Hardware redundancy is 1 of the aspects to improve the level of resilience. This also applies for software. Software fault tolerance is 1 of the techniques that can be considered for redundancy. Similar to how it is done for hardware, critical software functions, data, components, etc. are duplicated. Thus, software redundancy is workable *(Jerome H. Saltzer & M. Frans Kaashoek, 2021)*. Redundancy is to ensure that when the 'primary' layer of protection fails, the rolling stock can continue to operate in the event of external events.

2. Risk Management

Feedback: *"Risk management is a tool to assess the system but does not directly contribute to the hardware resilience. Software design architecture to be reviewed rather than from risk perspective."*

Discussion: Yes, agree with both feedback. With the availability of such tool, the ways of how the rolling stock gets affected by cyber-attacks and the consequences can be systematically identified, so as to ensure that adequate mitigation measures are incorporated such as to the software design architecture. This will help to enhance the robustness of the software used. If there is no such systematic procedure in place for risk identification, there is no assurance that the rolling stock would be able to revert back to service as soon as possible, after facing the external events; as well as the progressive release of security patches to protect the software.

3. Cybersecurity Protection

Feedback: *"Rolling stock is more mechanical than software. Such protection should be at the Command and Control."*

Discussion: It is not absolutely true that rolling stock are more mechanical than software. Rolling stock today are installed with onboard computers and communication systems, making them susceptible to remote exploitation. If attackers can gain unauthorized access to these systems, they may be able to take control of the train's functions or disrupt its operation. Aside to the signalling system and the integrated supervisory and control system, rolling stock could also be installed with COTS, making third-party exploitation easy *(Bastow, 2014)*.

4. Adaptability to Changing Environment Conditions

Feedback: *"Robustness of software should not be environmental dependent."*

Discussion: Do not agree with the feedback that software should not be environmental dependent. It is necessary for software developer to keep abreast of the different and new ways of how change cyber-attacks can affect software used by rolling stock.

Table 16 has tabulated other software resilience attributes that can be considered.

Table 16: Other software resilience related attributes

Possible Attributes	Ways To Improve Resilience
- Recovery Management. - Conduct of software assessment or audit. - Competency of software engineers. - Awareness of emerging threats by software personnel. - Competency and thoroughness of software assurance and maintenance teams. - Extent in the use of COTS software of which failures could reduce the resiliency of the overall system. - Disaster recovery and business continuity planning. - Ease to upgrade – replacement of the software and not restricted to only 1 OEM.	- Awareness of unexpected system behaviour/ response and unintended outcome. - The migration to new technology with minimal or no disruption to system functionality. - The consideration of lessons learnt. - Software patch. - Data backup and restoration assurance

No feedback pertaining to the non-applicability of both internal and external resilience attributes is received. Table 17 has summarised on attributes for these 2 sub-domains that can be considered.

Table 17: Other internal and external resilience related attributes

Possible Attributes (Internal Resilience)	Possible Attributes (External Resilience)
- Monitoring and assessing level of preparedness and operational readiness. - Safety Culture. - Succession planning of key personnel and knowledge management.	- Effective communication with the community such as household located near railway tracks that are damaged. - Mental preparedness of the stakeholders of the railway organisation in terms of trust and confidence. - Relationship with suppliers, OEMs, resiliency of railway operator. -

4.6.2 Validity Assessment –Evaluation Criteria

Table 18 summarised the results on the applicability of associated evaluation criteria proposed by this thesis. Breakdown on the number of responses that are deemed as not appropriate for each attribute can be referred from Figure 49 to Figure 52 in Appendix E.

Table 18: Results summary for applicability of evaluation criteria

Domain	**Technical Domain**		**Organisational Domain**	
Sub-Domain	**Hardware Resilience**	**Software Resilience**	**Internal Resilience**	**External Resilience**
Total No. of Attributes Identified by Thesis	15	7	9	3
Total number of responses received	131	113	107	100
Total number of responses received for evaluation criteria for '**All attributes are Appropriate**'	80	85	94	93
Total number of responses received for attributes with evaluation criteria that are **Not Appropriate**	51 (≈ 38.9%)	28 (≈ 24.8%)	13 (≈ 12.1%)	7 (≈ 7.0%)
Top attributes whose evaluation criteria are feedbacked as **Not Applicable**	• Conduct of Maintenance Audit • System Integrity • Availability of Spares	• Conduct of Maintenance Audit • Adaptability to Changing Environment Conditions	• Leadership • Business Continuity	• Effective Communication (With Railway Users)
Are there any attributes that are not being selected?	No	No	Yes. • Resilient strategies • Emergency responses	No

			• Risk management	

Similarly, each of the sub-domain has received more than 60% of responses that the criteria proposed for all associated attributes are applicable for evaluation. Most of the responses are received for the 'Hardware Resilience' sub-domain at 38.9%, followed by 'Software Resilience' sub-domain at 24.8%. Similarly, the criteria proposed for the conduct of maintenance audit has also received the highest number of feedback on its appropriateness for both categories, whereby it also has the highest number for non-applicability. For 'Hardware Resilience' sub-domain, 3 of the attributes i.e., conduct of maintenance audit, system integrity and availability of spares, received the highest number of responses; for 'Software Resilience' sub-domain, 2 attributes i.e., conduct of maintenance audit and adaptability to changing environment conditions received the highest number of responses. These 2 attributes are also being feedbacked as to be not applicable as stated earlier.

The following sub-sections have listed some of the attributes whereby the proposed evaluation criteria are feedbacked as not appropriate. Overview of all the responses is appended in Appendix F.

4.6.2.1 Hardware Resilience Attributes

1. System Reliability

Feedback: *"System reliability should focus on actual reliability performance that is achieved during Operation & Maintenance (O&M). Need to track and monitor continuously, for early detection of deteriorating trends. Reliability figure should consider period during revenue service, to avoid early failures."*

Discussion: Yes, agree with feedback. With actual monitoring of reliability performance during O&M, it can better reflect the performance of the rolling stock that have been in service.

2. Interoperability

Feedback: *"Current rolling stock fleets on different lines are not design for interoperability."*

Discussion: This feedback is situation dependent. This attribute might be applicable to countries/networks whereby rolling stocks can interoperate on the various lines.

3. Conduct of Maintenance

Feedback: *"Should emphasize on the effectiveness of maintenance that is implemented during O&M phase. Operators should have competencies and abilities to review effectiveness of OEM's maintenance procedures and develop/modify/adapt maintenance regimes for the actual system, when necessary. OEM usually quote recommended maintenance regimes. Responsible an experienced operators should do more beyond the recommended instructions."*

Discussion: This feedback can be applied to the operational level whereby more in-depth measurement method or scale can be used. Conducting extra and beyond of what have been recommended by the OEM is dependent on the capability and adequacy of resources that the Operator has. Benchmarking on the basic requirement would be the minimum level of maintenance required. Thus, the use of adherence to OEM recommendation as the evaluation criteria.

4. Asset Performance

Feedback: "*In depth review and achievement of KPIs set. 'Performance' should mean scorecard marked against supposed design on paper? E.g., a relay should last X number of cycles, else get low score. Carbody should last 30 years else the material or workmanship should get a low score.*"

Discussion: The types of KPIs to be used will be dependent on the railway organisation at tactical level. At strategic level, this thesis opines that there must firstly have the initiative in place to review of technical asset performance. The latter feedback would relate more to the operational level of how the performance of the assets at subsystem and even at Line Replaceable Unit level can be assessed.

4.6.2.2 Software Resilience Attributes

1. Redundancy Level

Feedback: *"Critical Components are hardware."*

Discussion: There is growing aware on the importance on the redundancy provision for critical software components too.

2. Risk Management

Feedback: *"This criterion is focused solely on availability of risk management protocols. Risk management will not be effective if the protocols are available but are not followed."*

Discussion: Yes, agree with feedback. Hence, the evaluation criteria focus on how much software-related risk are being mitigated by the organisation. If protocols are available yet not followed, this could mean a low resilience.

3. Conduct of Maintenance Audit

Feedback: *"Frequency of maintenance audits does not ensure that the intended outcomes of the maintenance audits will be achieved. It's more important to address the purpose, resources, methods, criteria, etc., for the maintenance audits. Minimal software maintenance. But to ensure proper software upgrade process due to asset renewal."*

Discussion: The purpose, resources, methods, criteria, etc., for maintenance audits are to be defined at tactical or even operational level. If a railway organisation does not even see the importance to conduct maintenance audit, there is then no purpose to specify the different elements as mentioned above. Asset renewal is also part of the resilience enhancement initiative. Old rolling stocks that are manufactured in the early years might not be able to withstand or have incorporated the necessary preventive measures to protect itself from the latest threats from cyber-security. Hence, this feedback can be related to tactical or operational level of resilience assessment.

4. Adaptability to Changing Environment Conditions

Feedback: *"Potential threats should already be considered in their product design."*

Discussion: Consideration of potential threats during the product design would only covers threats that are uncovered at the point of design. However, as cyber threats are evolving and emerging, there is a need to progressively ensure that the existing software are able to withstand itself from cyber-attacks. Hence, leading to the need to ensure review of the software adaptability to changing environment conditions.

4.6.2.3 External Resilience Attributes

No feedback pertaining to the proposed criteria for internal resilience has been received. There is only 1 feedback pertaining to the external resilience as follows:

1. Effective Communication with Railway Users

Feedback: *"Study and understand the trend of ridership might be more applicable."*

Discussion: The current proposed criteria are based on the number of communication channels in place to convey the disruption of railway operation to railway users. Understanding the trend of ridership might be applicable for normal daily operation, whereby the resilience of daily operation is not within the scope of this thesis.

4.6.3 Reliability Assessment

A set of 6 questions in assessing the usability of the assessment tool using the Likert-scale for grading is included in the questionnaire and are used in the reliability assessment, before the quantitative results are further elaborated in the subsequent sections. As stated in Section 4.2, the internal consistency of the questionnaire is being determined. Details of the calculation to determine the Cronbach's Alpha (α) is appended in Appendix G. From the analysis, an α-value of 0.92 has been calculated and referring to Table 13, it showed that an excellent level of internal consistency has been achieved. Thus, this set of questions is reliable to be posed to the respondents in seeking feedback.

4.6.4 Attribute-Level Weightage Assignment Technique

Getting feedback on the ROC technique adopted for the weightage calculation is 1 area that the thesis wants to find out if it is a useful method. Figure 31 shows the results obtained. Majority of the respondents think that the ROC technique is 'Moderately useful' and above. There is 1 respondent who has selected 'Not at all useful' and the justification is that voting and ranking are subjective. In this thesis, the voting system requires decision-makers to answer only 1 question to guide the ranking procedure required by the ROC technique. However, it is further considered that in the event whereby 2 or more attributes have the same vote-counts, another round of discussion would be needed to differentiate the ranking.

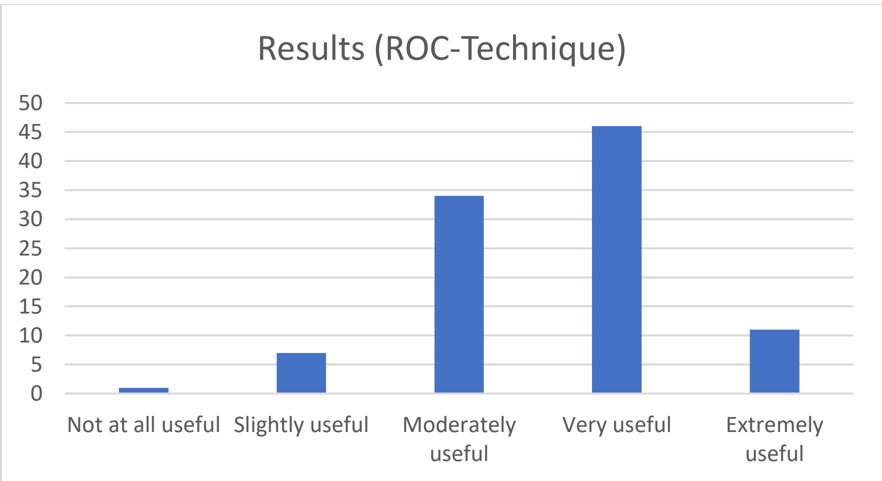


Figure 31: Results on usefulness of ROC technique

Even if all attributes in the same category has the same vote-counts and the panel of decision-makers have discussed and ranked accordingly, it is still the attributes that are ranked first and second which will see a greater difference between each other as shown in Figure 27 in the earlier section. The change in weightage for attributes ranked in the middle is small. The 'Internal Resilience' sub-domain shown in Figure 32 has been used as an illustration. This sub-domain consists of 9 attributes. The downward exponential trend showed that the biggest difference occurs between the attribute ranked 1 and 2, i.e., 0.11 point as calculated in Table 19.

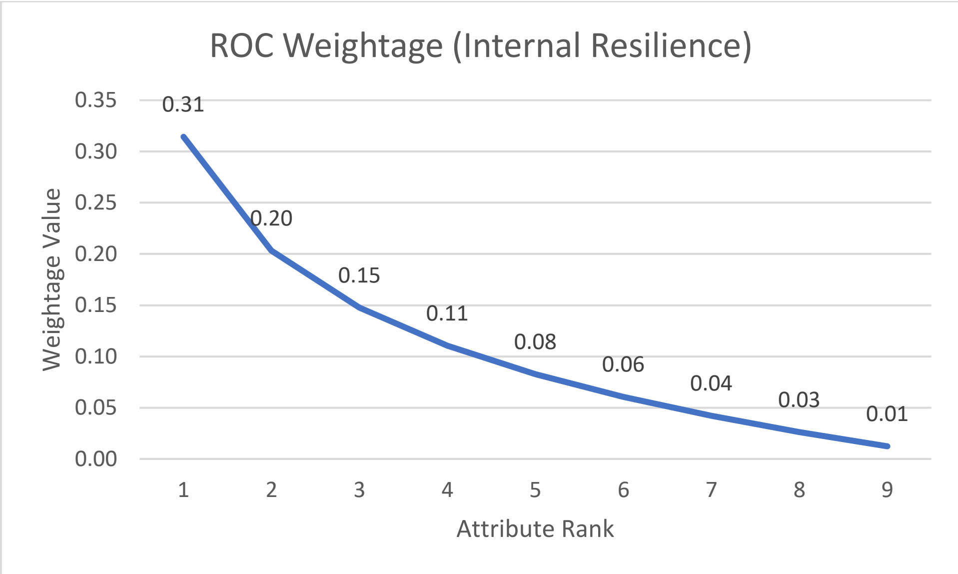


Figure 32: ROC weightage trend for 9 attributes

Table 19: Weightage difference between 9 attributes

Attribute Rank	1	2	3	4	5	6	7	8	9
Weightage Difference with the Previous	-	0.11	0.06	0.04	0.03	0.02	0.02	0.02	0.01

An analysis is further conducted to see how the weightage value changes when the number of attributes decreases and increases. Using the 'Internal Resilience' sub-domain as an illustration, Figure 33 showed the trends for 8, 9 and 10 attributes that have equal vote counts and are ranked again after discussion. The figure showed that as the number of attributes decrease, the weightage assigned to the attribute that is ranked first will get higher, and the weightage for attribute ranked the last will be lower. In addition, the difference in the weightage values for attributes ranked first and second gets wider as the number of attributes in a category decreases. This is shown in Table 20.

The differences for the middle-ranked attributes do not have a big gap. As the number of attributes get higher, the differentiation in weightage among the attributes get smaller as the weightage allocation gets more dispersed. Therefore, in the situation where there are attributes with equal vote-counts when using the ROC technique, it is important to identify the first and second attribute since larger portion of weightage will be assigned. If these attributes have high evaluated attribute weightage, this will increase the category score when multiply with the evaluated attribute score.

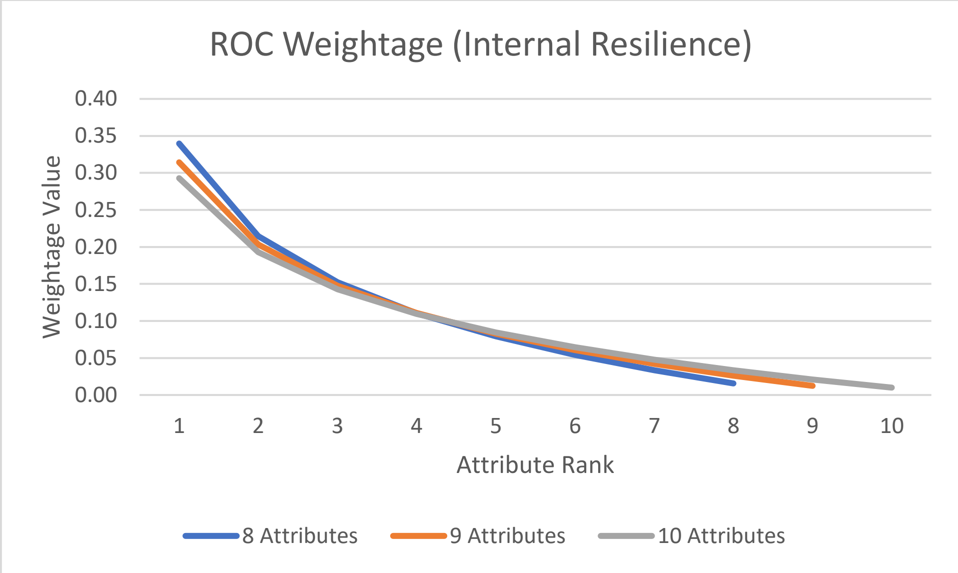


Figure 33: ROC weightage trend for different number of attributes

Table 20: Weightage differences for different number of ranked-attributes

Attribute Rank	1	2	3	4	5	6	7	8	9	10
Weightage Difference (8 Attributes)	-	0.13	0.06	0.04	0.03	0.03	0.02	0.01	-	-
Weightage Difference (9 Attributes)	-	0.11	0.05	0.04	0.03	0.02	0.02	0.02	0.01	-
Weightage Difference (10 Attributes)	-	0.10	0.05	0.03	0.03	0.02	0.01	0.02	0.01	0.01

It is opined that both DAT and ROC techniques are feasible in allocating the weightage, with the ROC technique offering more differentiation as compared to DAT which offers a linear relationship. By using ROC technique, it offers a much wider weightage differentiation for categories with lesser attributes too. On the other hand, though the weightage allocation to attributes within a category is linear, DAT is based on the actual number of votes provided by the panel of members, thus, eliminating the introduction of some level of subjectivity through the re-ranking process that ROC technique requires if there are attributes with equal vote-counts.

4.6.5 User-Interface of Assessment Tool

In the situation-based scenario, the goals to be achieved by the team of users from the railway organisation are made known to the respondents.

1. Goal No. 1

To be able to evaluate the resilience performance of the railway organisation at strategic level.

2. Goal No. 2

To be able to identify resilient-deficient attributes so that further analysis and improvement actions can be taken.

The questions are raised to ask respondents on the effectiveness when using the assessment tool to achieve the 2 goals as mentioned above. The results are shown in the following figure.

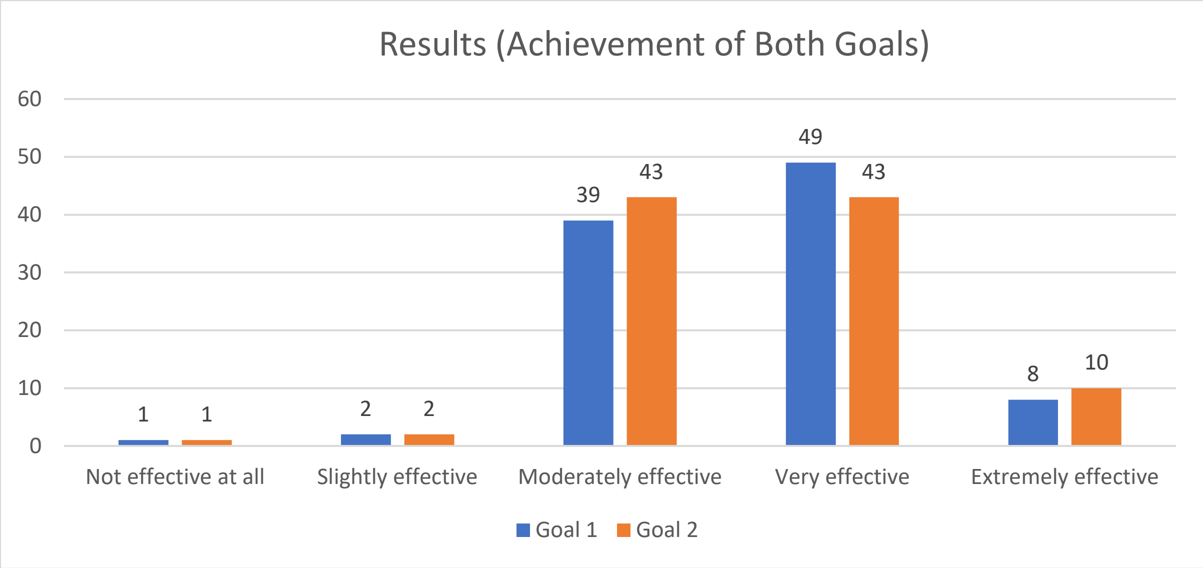


Figure 34: Effectiveness of assessment tool in achieving both goals

97% of the respondents have feedbacked that the semi-qualitative format is at least moderately effective in achieving both goals. Aside to whether the design and incorporation of resilience elements in the assessment tool are able to meet the 2 goals, questions pertaining to the user interface such as the layout and the use of resilience heat map to differentiate the resilience performance of each attribute are raised. Figure 35 and Figure 36 below showed that majority of the respondents agree that the layout of the tool and the use of resilience heat map are at least easy to comprehend.

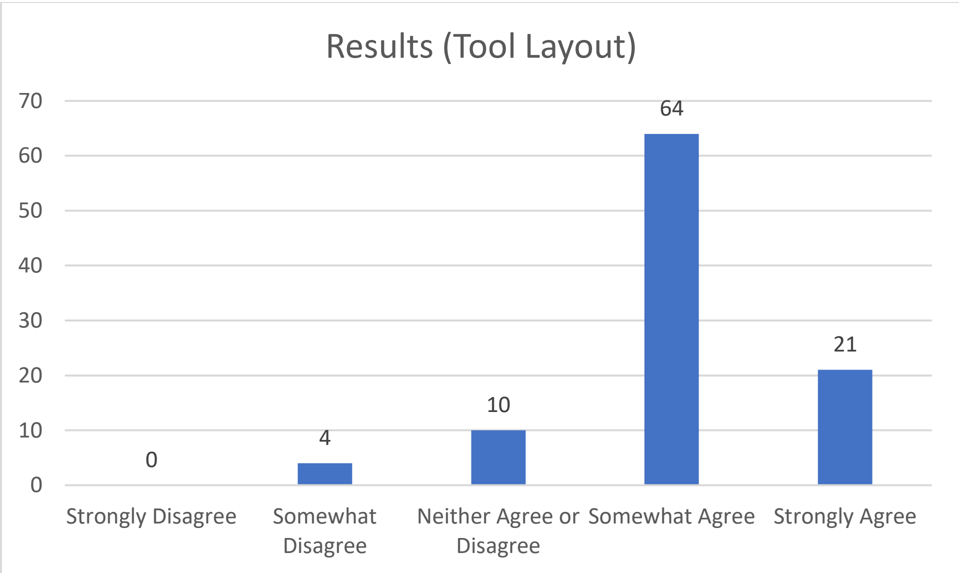


Figure 35: Feedback on tool layout

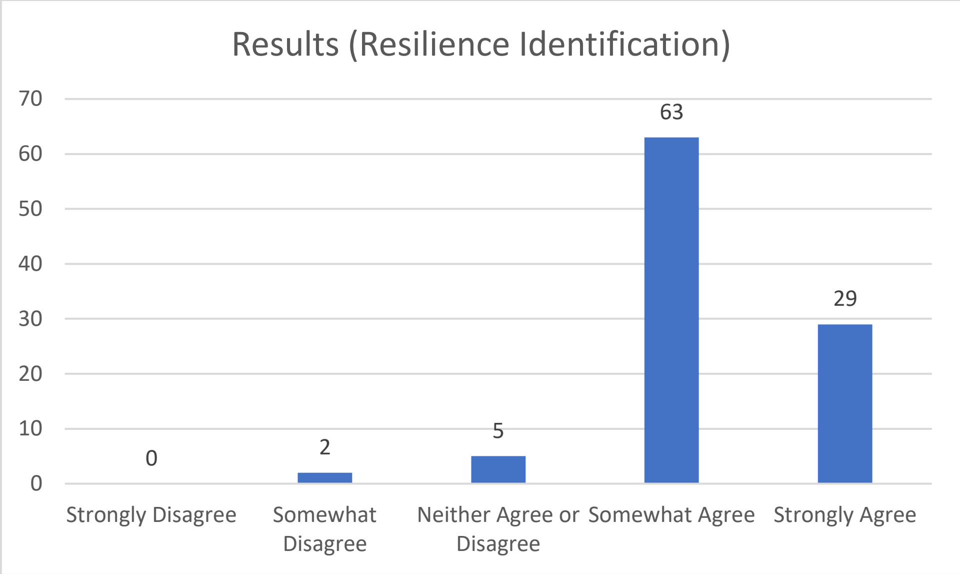


Figure 36: Feedback on resilience differentiation method

Finally, 1 concluding question on how useful the respondents think the tool is when using it to conduct resilience assessment of the railway organisation, is raised. 97% of the respondents shown in Figure 37 feedbacked that the tool is at least moderately useful in conducting the assessment, though there are still 3 respondents who think it is slightly useful and not useful at all.

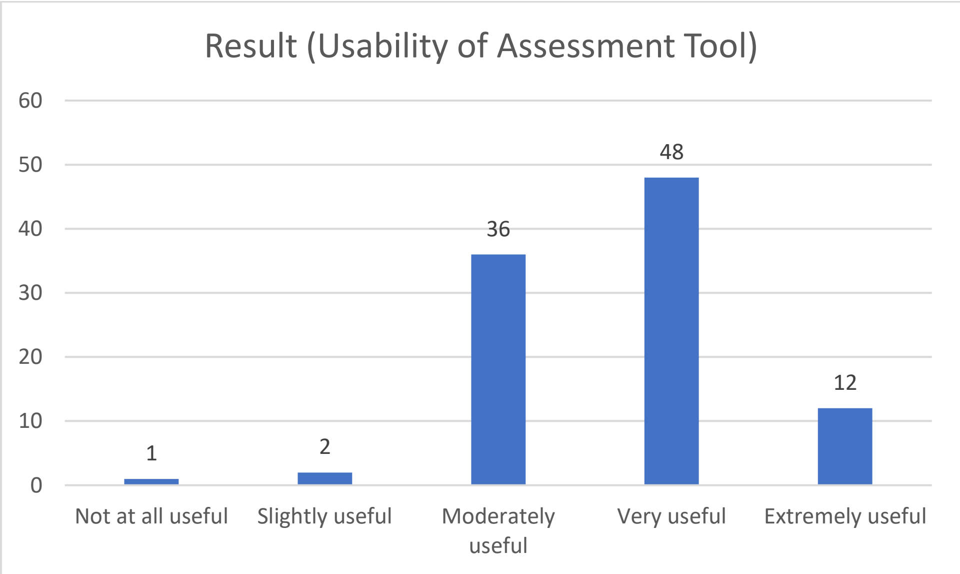


Figure 37: Feedback on usability of assessment tool for resilience assessment

4.6.6 Suggested Improvement

The survey has also sought respondents to provide their opinions on the strengths and weaknesses that the assessment tool could have and if there are any other areas of improvement. These are summarised in the following and the details can be referred to Appendix H and Appendix I.

From the list of strength points provided, respondents felt that the semi-qualitative assessment tool is a starting point that has created the awareness on the importance of building up resilience. It has provided a systematic way in identifying the constituents of resilience for both technical and organisational domains and it allows users to be able to quickly identify areas of improvement. It serves as a consolidated platform whereby the different personnel in the railway organisation can understand the overall performance and prioritise what needs to be done.

However, there are respondents who feel that it is still subjected to certain level of subjectivity as the tool is semi-qualitative. It would be challenging to develop a full quantitative tool. Sources of subjectivity can arise from the users of the tool such as their level of knowledge in the attributes and their encounters experienced during the course of their work. Some felt that the attributes can be more refined in order to better capture the resilience model. This thesis thinks this would be the next level of resilience assessment approach. Aside to this, the other weakness highlighted is that the assessment tool could be tedious in using as there is a need to firstly understand the definition of the respective attributes and how it is to be evaluated before the actual assessment work can be done. There is a suggestion that the assessment tool can be software-based so as to ease the use of it. This thesis acknowledges that first timers to the tools might find it complicated initially however it is inevitable as there is the need for users to accustom themselves to the definition and usage via the user guidelines provided in the tool first. The subsequent steps will be easy to proceed.

On the areas of improvement, the first would be to make the assessment tool more user-friendly and to speed-up the assessment work as some respondents find that it is quite effort consuming as understanding of the domains and categories are required. The second area is to include other railway assets in the assessment which this has been recognised by this thesis. The scope of work at this phase of the research as stated in Section 3.3.2 is to determine an appropriate way to assess the resilience of the railway organisation and only the Rolling Stock has been considered for asset-specific consideration. The third area is the possible validation of the tool by applying it in the real-world application. A respondent has also queried at which phase should this tool be used for instance at the tender phase so that all stakeholders involved are clearly aware of the level of resilience performance before, and subsequently to identify the areas for improvement. This thesis opined that resilience assessment is an ongoing process and it should not be limited at the tender phase.

4.7. Other Discussions

The above sections have shown how the 3 areas of evaluation stated in Section 4.1 have been assessed via the conduct of survey questionnaire. The effectiveness of the assessment tool is evaluated from the relevancy of the resilience attributes and its associated evaluation criteria to be as representative of the resilience for technical domain of the Rolling stock and the organisational domain of a railway organisation; the usage of the tool in terms of its user interface i.e., whether it is easy to understand, whether the method of how weightage calculation is carried out in order to differentiate the importance of the attributes and at the same time to reduce the incorporation of subjectivity to the usage is effective; whether respondents think that the tool has achieved the research objectives stated in Section 1.3; to whether in general it is a useful tool or method to translate the intangible resiliency to a tangible scale. Aside to these, the following sections provide other discussion topics.

4.7.1 Validity Assessment

Both Table 14 and Table 18 showed that most respondents opined the validity of the resilience attributes and evaluation criteria proposed for the organisational domain are highly applicable, while there are varying views on the applicability of the proposed inputs for the technical domain of the rolling stock though more than 60% of the responses received deemed the proposed are all applicable. Though the results in both tables showed a high number of resilience attributes and the evaluation criteria that might not be applicable, the percentage value showed that these constitute to less than

10% of the total number of responses that each category received, except for the not applicability of the conduct of maintenance audit and adaptability to changing environment conditions, which slightly exceeded 10%. Hence, this thesis opined that these attributes and its associated criteria are still valid and applicable for resilience assessment.

4.7.2 Depth of Attributes Identified

Moving on to the qualitative feedback received on the non-applicability of the attributes and evaluation criteria. It is observed that the alternative views from the respondents are more relatable to deeper level of resilience assessment. Reference to the figure below on the resilience tiered approach, the alternative views can be considered under Tier II and Tier III assessment approach, whereby the detailed modelling of the resilience of the technical and organisational aspects is to be considered. This thesis opined that there is no right or wrong answer since there is no international guideline that can be referred to. The more the attributes are considered and the deeper the level of detailed assessment, it helps railway organisation to be more well-prepared in improving their resilience against the external events.

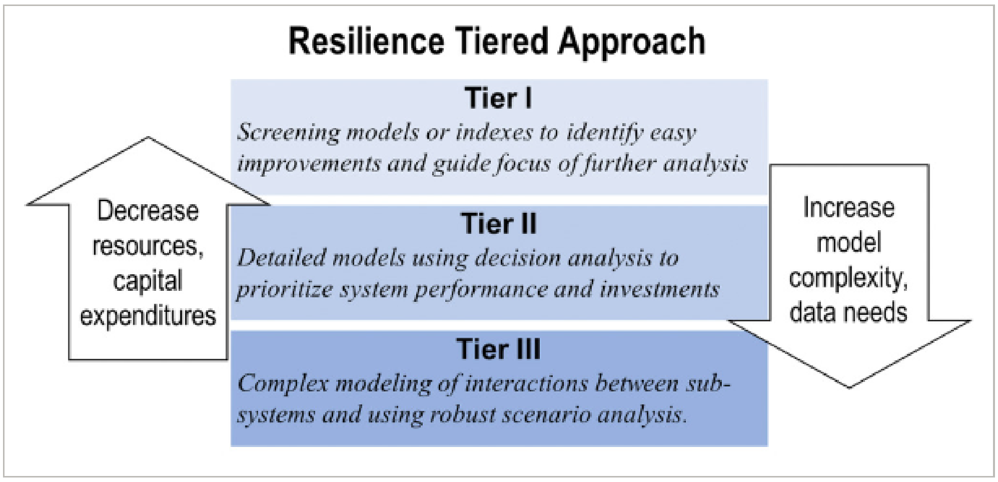


Figure 38: Tiered-approach to resilience assessment
(Linkov et al., 2018)

4.7.3 Use of Objective Weights – Proposed ROC-TOPSIS Method

Though the Vote & Rank process proposed in this thesis is based on answering only 1 question i.e., whether if the members think that the attribute is critical to the assessment, respondents feel that it could still be subjective. ROC technique is not a subjective method. It is a quantitative method used in Multi-Criteria Decision Analysis to determine the overall ranking of the attributes based on their performance across multiple criteria i.e., which in this thesis, it is the criticality of the attribute determined by different users. ROC technique then calculates a weighted average of these rankings and then the weightage is assigned accordingly by using Formula (1.3).

Thus, in response to the feedback on the subjectivity of the Vote & Rank process, this thesis has proposed the combined use of ROC and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method as the improved solution in determining the weightage by eliminating subjectivity. TOPSIS was developed by Hwang and Yoon *(Hwang & Yoon, 1981)* whereby the performance of the alternatives/attributes are evaluated by the extent of their '*similarity*' with the ideal solution. In this thesis, the definition of '*similarity*' is the criticality performance of the attributes determined by the members. TOPSIS adopts the proximity principle to determine the criticality performance by using the Euclidean Distance from the positive ideal solution and negative ideal solution. Positive ideal solution is the sum of the best criticality values of each attribute, while negative ideal solution is the sum of the worst criticality values for each attribute. The optimal performance of each attribute is then the one whereby it has the shortest distance from the positive ideal solution and the furthest distance from the negative ideal solution. The derivation of this optimal performance is then translated to the objective weightage to be used in the assessment tool.

The ROC technique still remains as differentiation in attribute weightage distribution with respect to their relative importance is still preferred, instead of a linear distribution from DAT. An overview of the formulation steps adopted in the combined ROC-TOPSIS method is shown below. An example of how ROC-TOPSIS method is adopted by the set of design-attributes of the hardware resilience sub-domain is illustrated in Appendix J.

Formulation Steps

1. **Determine vote-counts for each attribute.**
2. **Rank attributes base on vote-counts.**
3. **Calculate Subjective Weightage (ROC)** – Use the same formula (1.3) for the ROC Technique shown below:

$$w_i = (1/m)\sum_{K=i}^{m} {}^{1}/_{K}$$

Where:

m represents the total number of attributes within a category, $i = 1,2, \dots, m$,

w_i represents Attribute Weightage,

K represents the ranking level of the *i-th* attribute within a category.

4. **Calculate Objective Weightage (TOPSIS)** – Use TOPSIS to convert subjective weights to objective weights. The formulas derived are as follow:

4.1 Establish Decision Matrix X, i.e., X_{ij}.

The decision matrix is established with *m* Attributes (A) and *n* Members (M) in Table 21.

Table 21: Structure of decision matrix

	M_1	M_2	..	M_j	..	M_n
A_1	x_{11}	x_{12}	..	x_{1j}	..	x_{1n}
A_2	x_{21}	x_{22}	..	x_{2j}	..	x_{2n}
:	:	:	..	:	..	:
A_i	x_{i1}	x_{i2}	..	x_{ij}	..	x_{in}
:	:	:	..	:	..	:
A_m	x_{m1}	x_{m2}	..	x_{mj}	..	x_{mn}

4.2 Normalize Decision Matrix

The normalization of the decision matrix is conducted using the following formula:

$$\bar{X}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (2.1)$$

4.3 Establish Weighted Normalized Decision Matrix Y, i.e., Y_{ij} (Use weights by ROC)

The weighted normalized decision matrix is established using the following formula:

$$Y_{ij} = \bar{X}_{ij} * w_i \quad (2.2)$$

4.4 Determine Positive Ideal (A^+) and Negative Ideal (A^-) Solutions

The positive ideal solution (A^+) is determined and negative ideal solution (A^-) are determined by the followings:

$$A^+ = \{Y_1^+, Y_2^+, \ldots, Y_j^+, \ldots Y_n^+\} \quad (2.3)$$

$$A^+ = \left\{\left(\max_i Y_{ij} \,\middle|\, j \in n\right)\right\} \quad (2.4)$$

$$A^- = \{Y_1^-, Y_2^-, \ldots, Y_j^-, \ldots Y_n^-\} \quad (2.5)$$

$$A^- = \left\{\left(\min_i Y_{ij} \,\middle|\, j \in n\right)\right\} \quad (2.6)$$

4.5 Determine Euclidean Distance from A^+ (d_i^+) and from A^- (d_i^-), Optimal Performance Score (D_i) for each attribute

a. The Euclidean Distance from the positive ideal solution (d_i^+) and the negative ideal solution (d_i^-) is computed by using the following formulae:

$$d_i^+ = \sqrt{\sum_{j=1}^{n}\left(Y_{ij} - Y_j^+\right)^2} \quad (2.7)$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(Y_{ij} - Y_j^-\right)^2} \quad (2.8)$$

b. The optimal performance score (D_i) is computed by using the following formula:

$$D_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (2.9)$$

4.6 Determine Objective Weight for Each Attribute (O_i)

The objective weight is computed by using the following formula:

$$O_i = \frac{D_i}{\sum_{i=1}^{m} D_i} \quad (2.10)$$

It is expected that the votes given by members to be random in the real-world application. However, there could still be the possible situations whereby a member thinks all attributes are critical, a member thinks all attributes are not-critical, and/or a mixture whereby partial attributes are critical. Thus, the following scenarios are conducted to understand the impact of the criticality given by the members, $\mathbf{M}_n$, on the behaviour of $\mathbf{O}_i$ when ROC-TOPSIS method is used. Details can be referred to Appendix K.

4.7.3.1 Scenario 1 – Extreme Case

The design-attributes of the hardware resilience sub-domain is used as an example.

Scenario 1 is whereby 1 member voted ***not-critical for all*** attributes, and the remaining members voted ***critical for all*** attributes. The analysis is conducted to see what happens when the number of members that voted ***not-critical for all*** attributes increases. The ranking of the attributes remains the same throughout. The result is shown in the figure below.

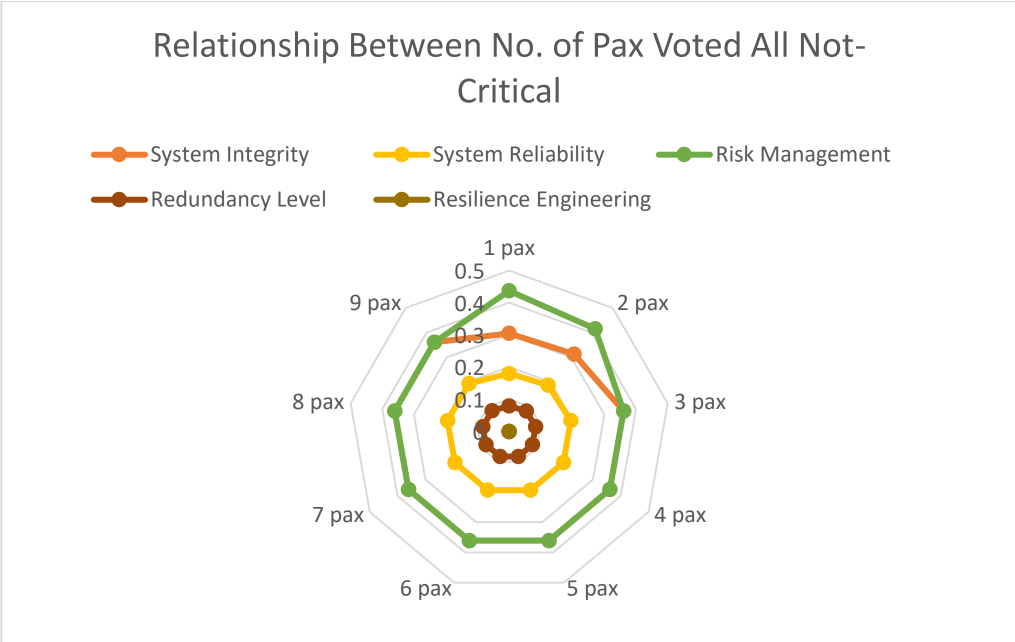


Figure 39: Relationship when number of M voted not-critical for all attributes increase

The behaviour of $\mathbf{O}_i$ for each attribute fluctuates when maximum 2 number of members voted not-critical for all attributes (except Resilience Engineering). When the number increases from 2 onwards, the fluctuation remains stationary. Resilience Engineering is ranked last and has an objective weight of 0.037. From this study, it is observed that as long as 1 member voted not-critical for all attributes, it will affect the eventual $\mathbf{O}_i$ for the last ranked-attribute, giving it a null weight, even if there are 9 other member who think this attribute is critical. Thus, to use this ROC-TOPSIS method, there is a need to impose the rule that no 1 member is allowed to vote not-critical for all attributes.

4.7.3.2 Scenario 2 – Random Case

Scenario 2 is whereby 1 member voted ***not-critical for all*** attributes, and the remaining members voted ***random criticality*** for the other attributes whereby the inputs are randomly inserted by this thesis. The analysis is conducted to see what happens when the number of members that voted ***not-critical for all*** attributes increases and if the $\mathbf{O}_i$ for the last-ranked attribute gets affected when 1 member votes not-critical for all attributes. The result is shown in the figure below.

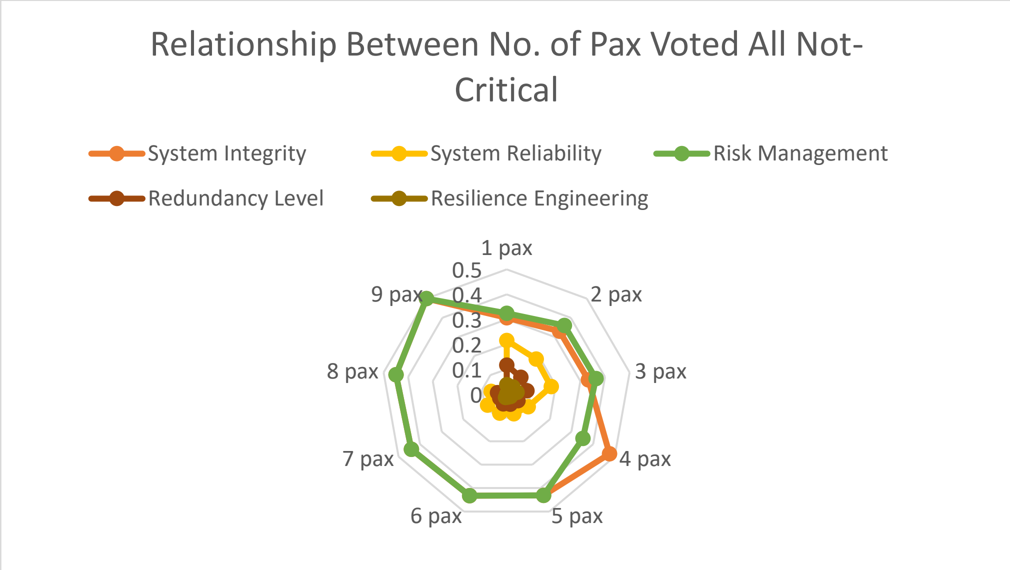


Figure 40: Relationship when number of M voted not-critical for all attributes increase

The behaviour of $\mathbf{O}_i$ for each attribute fluctuates and this is expected due to the randomness of the criticality provided by the members and the change in ranking of the attributes when the number of M voted not-critical increases. In this scenario, Resilience Engineering is also made to rank last. Comparing with the previous scenario, when 1 member voted not-critical for all attributes, $\mathbf{O}_i$ for the last ranked-attribute will not be given a null weight. And in this example, a null weight is observed until 7 members voted not-critical for all attributes.

4.7.3.3 Scenario 3 – Change in Numbers of Attributes

Scenario 3 examines the behaviour of $\mathbf{O}_i$ when there is a decrease in number of attributes from 5 to 2, and an increase in the number of attributes from 5 to 7. The analysis is conducted to see what happens when the number of members that voted ***not-critical for all*** attributes increases and if the $\mathbf{O}_i$ for the last-ranked attribute gets affected when 1 member votes not-critical for all attributes.

With the change in number of attributes, both changes see the same behaviour as Scenario 1 whereby the last-ranked attribute observes a null-weight when 1 member voted not-critical for all attributes.

In summary, there are 2 pointers that need to be established before using this improved method of the assessment tool.

1. The team of members involved in the resilience assessment task must be briefed on the definition of the resilience attributes and evaluation criteria at the same point of time so as to ensure every member received the same level of information before conducting the assessment. This is to further eliminate a source of subjectivity associated with the members' understanding of resilience.
2. No 1 member is allowed to vote not-critical for all attributes i.e., members have to vote at least critical for 1 attribute.

4.7.4 Response to 'Not-effective' of Assessment Tool

In the feedback on the effectiveness of this tool to assess the resilience, the survey has received 1 feedback on 'not effective at all'. The feedback is as follows:

“System resilience can be represented as a 2-dimensional graph of system performance versus time, to indicate how system performance is affected by a shock event. It is not clear how this tool is used to measure system resilience in relation to robustness, vulnerability, susceptibility, and recovery from the shock event.”

The intent of this research work is not to derive the 2-dimensional performance of the railway system in the aftermath of the shock event in relation to the robustness, vulnerability, susceptibility, and recovery. Though this aspect is important, this thesis tries to evaluate railway organisation resilience in terms of its preparedness and readiness in performing in the resilience attributes that have been identified based on the roles they play before and after the 2 external events as identified Section 1 in Robustness, Redundancy, Rapidity and Resourcefulness. This helps railway organisation to gear up to be ready to face the occurrence of the 2 external events, so as to reduce the undesirable impact to railway operation, organisational management as much as possible. Hence, this is why as stated in the research objectives in Section 1.3, the before-after assessment framework is proposed. It has created an awareness on the importance of understanding and inculcating the resilience stint. This thesis opines that as a stepping stone, it is firstly essential to establish what constitutes resilience (the 4R Resilience Framework) of the railway organisation in its preparedness against the shock event, and how it can be assessed.

In general, the proposed resilience attributes and evaluation criteria by thesis are applicable for consideration, with minimal deviation otherwise. Some of the feedback received for example on the high non-applicability of ‘conduct of maintenance audit’ might seem not important to the respondents, however, when given a further thought on the role that this attribute plays, it is actually important. In the event when the rolling stock gets affected by these external events, which is when organisation will start to dwell further into whether the daily maintenance has been done conscientiously.

Though there are positive feedback received and majority of the respondents has feedbacked that the systematic approach of the semi-qualitative tool from assessing the resilience to the determination of the resilience level to the identifying of areas for improvement is useful and effective, there are still room for improvement such as the ease of use, the consideration of more refined attributes etc. The subjectivity with the initial proposed ROC technique has also been removed by the use of objective-weights through the ROC-TOPSIS method. The final semi-qualitative assessment tool in MS Excel format will be submitted together with the report. To conclude, the semi-qualitative assessment tool has been validated to be a plausible approach to assess the resilience of railway organisation.

5. APPLICATIONS OF THE ASSESSMENT TOOL

This chapter provides elaboration of how the assessment tool can be used in resilience assessment for railway organisation.

5.1 Before-After Resilience Assessment

The first objective mentioned in Section 1.3 is to determine how the resilience of a railway organisation can be assessed by making use of the before-after resilience assessment framework in Figure 41. An example of how this tool is used and fits into the framework is illustrated in the following example.

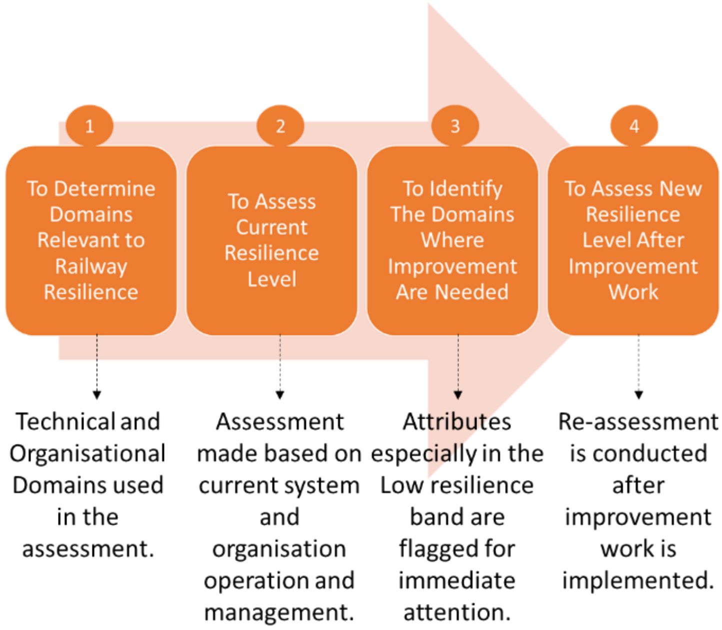


Figure 41: Before-after resilience assessment framework

Example Illustration

The management of a railway organisation that owns, designs, operates, and maintains their fleets of rolling stock would like to know the organisation resilience performance in facing the emergence of adverse threats, as they begin to get aware of the criticality of the negative impacts that these threats bring about as it has not been in their consideration in the past years of operation. The assessment tool is used to provide them with a current assessment. By following the framework in Figure 41,

Step 1:

The set of attributes from the technical and organisational domains included in the assessment tool in Appendix D is used.

Step 2:

Based on the current availability of assets and operation management, the resilience level is being assessed by using the tool. The simulated evaluation and assessment score is shown in Appendix L. The assessment showed that the overall resilience score is 2.80. Though the overall score falls under Medium-resilience band, however there are 7 red-flagged attributes falling under the Low-resilience band.

Step 3:

The 7 red-flagged attributes that the organisation is has low performance in are tabulated in the table below.

Table 22: Attributes with low resilience (before improvement)

Resilience Domains	Associated Attributes	Evaluated Attribute Score
Technical Domain	Resilience Engineering	1
	Fault Monitoring and Diagnostic Capability (Hardware Resilience)	1
	Availability of Spares	1
Organisational Domain	Fault Monitoring and Diagnostic Capability (Software Resilience)	1
	Leadership	1
	Resilient Strategies	1
	Situational Awareness	1

Because the railway organisation is unaware of the importance of railway resilience in the past, these 7 attributes highlighted the immediate attention that the management level should look into. Their fleets of rolling stocks are manufactured many years ago and these trains would not have been installed with advanced condition monitoring tools since the notion of enforcing Reliability Centred Maintenance is actively advocated in the recent years. In addition, the importance of incorporating resilience engineering into system design and organisation culture are not as strong in the older days.

The management decided to take on measures that are implementable within a short timeframe such as retrofitting suitable fault diagnostic and condition monitoring tools on existing rolling stocks, advocating the importance of resilience and within the organisation by setting up a committee dedicated to lead by example, to identify strategies that help to improve the resilience of the organisation, the incorporation of this new aspect in the design requirement for the new purchase of trains, etc.

Step 4:

After improvement measures that can address the red-flagged items within a short period of time have been implemented, the same resilience assessment is conducted again and updated in Table 23.

Table 23: Attributes with low resilience (after improvement)

Resilience Domains	Associated Attributes	Evaluated Attribute Score
Technical Domain	Resilience Engineering	2
	Fault Monitoring and Diagnostic Capability (Hardware Resilience)	2
	Availability of Spares	1
Organisational Domain	Fault Monitoring and Diagnostic Capability (Software Resilience)	2
	Leadership	2
	Resilient Strategies	2
	Situational Awareness	2

The overall resilience score in the overview of the assessment shown in Appendix L has now improved to 2.98 with 1 attribute i.e., availability of spares, still in the low band. In practice, it is to note that implementation of improvement measures require time since discussions, analyses and implementing the appropriate solutions take time. The buy-in of resilience from all stakeholders are necessary and this takes effort and time to change the culture within the organisation. However, it provides an overarching view to the management on the areas of concern which require immediate attention.

5.2 Incorporation of Other Railway Assets

Aside to rolling stock considered in the assessment tool, the format of the tool allows railway organisation, i.e., Infrastructure Managers and Railway Undertakings to include attributes of all other assets easily. The core of the resilience assessment which is the most important step is to firstly ensure a systematic way that allows the complete identification of resilience attributes as wholistic as possible, focusing on the hardware and software resilience of the technical domain followed by the internal and external resilience of the organisational domain. This also explains why an asset-specific method for identifying the attributes is suggested by this thesis. For example, the software resilience category does not apply to civil works; the consideration of the signalling system can be split into trackside and trainborne signalling equipment since the impacts of unexpected external events affect these 2 areas of provision differently, attributes pertaining to the interfaces between the railway assets can also be identified. By using asset-specific method, it also serves as a mean for more specific and better understanding of the resilience performance of each asset and thus, engineers specialized in the particular systems can focus specifically on the asset for improvement. In addition, management level of the railway organisation can also better prioritise the allocation of resources in areas whereby resilience-building effort is urgently needed.

5.3 Resilient-building Initiatives

Step 3 of the before-after resilience framework shown in Figure 1 considers the implementation of resilient-building initiatives in attributes whereby the assessed resilience performance is low. This is 1 of the objectives of this thesis i.e., to encourage railway organisation to seek continuous resilience improvement in view of emerging external threats and increase vulnerabilities of organisations.

From the technical domain perspective, resilient-building initiatives seeks to improve the Robustness and Redundancy of the railway systems and infrastructures in aspects such as improving design requirement, reinforcing the robustness and redundancy level of existing railway assets, the use of advanced technology to better inhibit the possible occurrences of railway disruption caused by the unexpected external events as much as possible. In terms of design requirement, railway organisation can include the specification of more stringent design requirement for new purchases of railway assets or the construction of new infrastructures so as to ensure 'better compatibility' with the 'new' operating environment conditions. For existing railway systems and infrastructure, review of the existing performance and conditions are needed to identify if changes or more strengthening effort are needed to improve the existing conditions. The other consideration can be the installations or embedment of more sophisticated condition-monitoring equipment as part of the system basic functionality as the way forward so that faster and more accurate detection of system anomalies or deteriorating assets conditions can be analysed and thus, maintenance or asset replacement can be promptly carried out.

1 of the resilience attributes is on situational awareness. Aside to keeping well-informed on the evolution of external events and threats through information sharing, railway organisation can consider cooperating closely with weather forecasting organisation and other authorities on the

better prediction of occurrences of extreme weather conditions, so that railway organisation can be better informed in advance. With this, railway organisation can also conduct scenario simulations to better understand the possible impacts and thus derive event-specific emergency response plans. Scenario simulations can also help railway organisation in the identification of points of failures or vulnerable sections of the railway network prone to experience impacts from the extreme weather conditions, thus preventive measures can be implemented.

From the organisational domain perspective, the results from the assessment tool serves as a platform to create awareness within the organisation on the overall resilience performance. Improving the working culture and advocating the importance of railway resilience are not actions that can be executed within a short period of time. It requires a long-term planning such as stressing the importance within the organisation as well as getting the buy-ins from all internal and external stakeholders. For instant, some stakeholders might not see the need to invest many resources and capital in this area as they think that the occurrence of external events is very low. With 'concrete' evaluation made by using the assessment tool, it provides some form of persuasive points for all stakeholders to work towards achieving improved organisational resilience.

5.4 Consideration of Economic Domain

In the literature review, aside to the Technical and Organisation pillars considered in the TOSE framework, Economic is the other pillar of resilience. This thesis has only considered the Technical and Organisation pillars. In the survey responses, there is also feedback received on the consideration of money as 1 of the resilience attributes. This thesis has thus put forth in Table 24 resilience attributes relevant to the Economic pillar that can be considered by railway organisations in building up the organisation resilience level.

Table 24: Suggested resilience attributes for economic pillar

Economic Pillar	Explanation
Risk Management	To develop robust risk management strategies and to ensure sufficient insurance coverage to order to help to mitigate the financial impacts that unexpected external events bring about such as the extra expense on the repair works to the infrastructures, the extra resources needed to execute the recovery works, monetary compensation to affected railway passengers, freight companies, etc.
Availability of Financial Reserves	To build and maintain reserves that serves as a form of financial buffer in times of the occurrences of unexpected external events. These reserves can be used to compensate the additional expenses to be incurred and to sustain ongoing operation during periods of reduced revenue service.
Provision of Continuous Infrastructure Investment	Continuous investment in infrastructure maintenance and improvement is necessary to ensure the long-term operation of a railway organisation. Well-maintained railway infrastructures can support efficient operations and attract customers with reduction in unexpected railway disruption. Aside to infrastructure, it allows other initiatives such as investment in weather forecasting and better condition monitoring tools to be used.

Provision of Contingency Transport Routes or Measures	Aside to the execution of emergency responses, railway organisation should also plan for alternative travel routes and modes to facilitate the affected passengers or activities and to be done as cost efficient as possible.
Diversification of sources of revenue	For Railway Undertakings and Infrastructure Managers, dependence on 1 source of revenue can make the organisation economically vulnerable. The duration of service downtime is dependent on the scale of external events. Thus, organisations can seek diverse business portfolios aside to managing and operating the railway transportation system.

5.5 Resilience in Risk Management

Resilience is the ability to adapt and recover from adversity, while risk is the potential for negative outcomes or harms to happen. Resilience helps to manage and mitigate risk by improving the ability to adapt to changing circumstance and to recover to its intended operation. In the paper by *(Johnsen & Veen, 2011)*, the concept of resilience was *"explored as a strategy in the risk assessment to improve safety, security and quality of service"* of the critical communication infrastructures in the railways. Thus, the setting of a resilience target can be used as a KPI target for the railway organisation to achieve, in facing the unexpected external events. The overall resilience score in the assessment tool can be used as the KPI target. Similar to risk management, resilience management is a proactive approach. The management of the railway organisation will need to determine what level of resilience is needed and is achievable, in order to maintain the essential functions and railway services in face of the unexpected external events. The incorporation of resilience into risk management will require a resilience assessment of the current level of resilience whereby this is considered by the assessment tool. From the output, areas of vulnerability or criticality are being identified so that resilience strategies can be devised and act as the mitigation measures.

This helps as it encourages railway organisation to incorporate resilience planning as part of the mission of the organisation. Developing long-term strategic plans that have anticipated potential changes in railway operation from potential impacts caused by unexpected external events, the trend of technological advancements, and economic conditions are some ways whereby it makes the railway organisation more adaptable and more resilient. The more resilient the railway organisation is, the better they are equipped in the 4R Resilience Framework in facing the adverse external events, and the lower the level of risk sustained when the external events happened.

6. CONCLUSION AND RECOMMENDATIONS

This chapter concludes the research work conducted for this thesis, how the research questions identified have been addressed, insights derived from the work and also provides recommendations for considerations.

6.1 Conclusion

The railway transportation system is a complex socio-technical system which encompasses the railway systems and infrastructures, people, and processes. The report has presented an overview on what does resilience constitutes in the railway context through the 4R Resilience Framework. Ensuring the robustness and redundancy of the systems and infrastructures are the basic key elements in ensuring the day-to-day functionality and operation of the system. Resilience of these railway assets is something whereby the railway industry has recognised its importance and the impacts it has on the transportation system in face of unknown/ill-defined threats and unpredictable events. Factors relating to people, procedures and workflows, management structure and organisational culture, etc., are also contributing elements that affect resilience in terms of the level of preparedness and operational readiness. Resourcefulness within the organisation and the ability to respond rapidly in the aftermath stage of such threats are additional critical components in preparing the railway organisation.

6.1.1 Addressing the Research Questions

From the literature review conducted and the survey responses, it can be ascertained that railway resilience is becoming more important with evidence showing the increasing threats that the industry will face from the external events. Thus, it is important for railway organisation to be aware of the level of their resilience which is the first objective of the thesis i.e., to determine how the resilience of a railway organisation can be assessed and has formulated a set of main and sub-research questions.

From the literature analysis, it is studied that a method that can 'quantify' the intangible characteristic of resilience and to identify areas for resilience improvement for the railway organisation at strategic level by providing an overarching view and information to the top management or decision-makers, is unavailable. Therefore, the semi-qualitative assessment tool developed by this thesis is able to help. The essence of the 4R Resilience Framework has been incorporated in the identification of technical and non-technical aspects pertaining to the management of the rolling stock and organisation. A top-down approach is used whereby the domains i.e., Technical and Organisational are firstly identified, followed by the next level of details i.e., sub-domains such as Design, Maintenance, Operation and lastly at the last level i.e., the attribute-level.

This thesis has developed a systematic 5-stages cycle whereby the evaluation, quantification and identification of resilience are incorporated to the assessment tool and allows the repetitive use of the tool for continuous assessment. Figure 42 below shows how the execution of each step helps to address the sub-research questions, and in turn addressing the main research question.

<u>Main Research Question</u>

How to assess the resilience of a railway organisation to prioritise actions that can improve its preparedness for unexpected external events impacting railway operation?

- The resilience of a railway organisation can be assessed through combined qualitative and quantitative method whereby the resilience performance of the railway organisation against pre-defined qualitative criteria associated with the technical and organisational domains considered in this thesis, are evaluated. The resilience performance levels are measured by assigning numerical values to the different resilience levels of the qualitative criteria and subsequently being calculated using mathematical method.

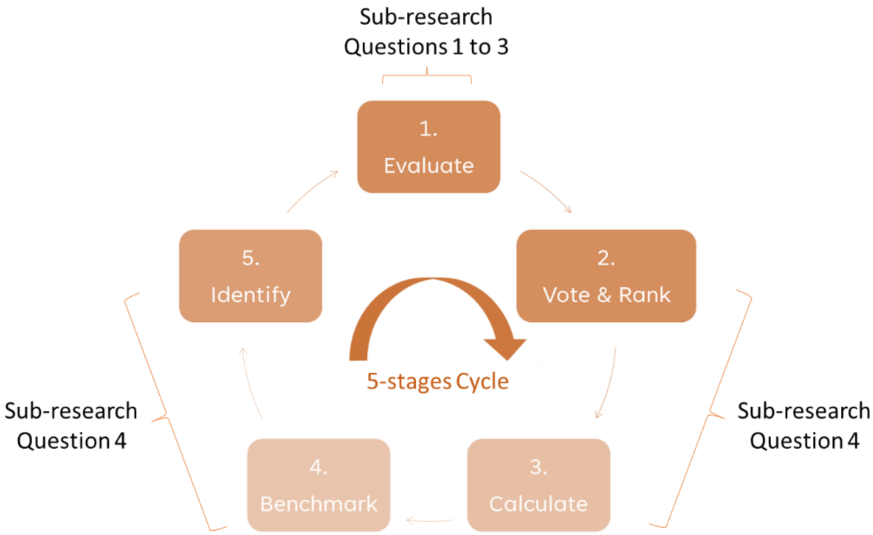


Figure 42: Implementation of 5-stages cycle framework to address research questions

<u>Sub-Research Questions</u>

1. *Which unexpected external events will become a priority for railway organisations due to their strong operational impacts?*

➢ Under Step 1 (Evaluate), the literature analysis has gathered information showing the extent of damages in terms of economical loss, service disruptions, damages to railway assets, loss of human lives, etc. caused by climate change and cyber-attack with evidence showing that these external events are evolving and that railway organisations should be well-prepared in countering these events.

2. *How can the resilience of a railway organisation be defined while providing insightful information for management decision on actions implementation?*

➢ Under Step 1 (Evaluate), a top-down approach is proposed by this thesis to define the resilience. Firstly, the resilience of a railway organisation is defined through the TOSE domains. As there is no international guideline available moment, this thesis opined that the resilience attributes considered by the railway organisation has to be tailored to the business model of the organisation as of now, but minimally, the technical and organisational domains are important considerations. In this thesis, the scope of research has examined the application of the technical and organisational domains, whereby sub-domains i.e., hardware resilience, software resilience, internal resilience and external resilience are identified.

3. *What are the attributes that can affect the resilience of a railway organisation?*

➢ After the identification of sub-domains as part of Step 1 (Evaluate), the attributes considered under the sub-domains or categories whereby the 4R Resilience Framework should be evident, are identified. The resilience of these attributes is evaluated by using the semi-qualitative criteria tagged to it.

4. *How can the resilience of a railway organisation be evaluated, measured, and improved?*

- This sub-research question is addressed through Steps 2 to 5. Definitive evaluation and measurement are carried out through the assessment of the resilience performance against the criteria assigned to each attribute. This thesis considers the evaluation of the resilience criteria for each attribute in measurable format so as to reduce the level of subjectivity and to be based upon on the actual performance of the organisation. The relative importance that each attribute has in the business model of the railway organisation is determined by the assigning of weightages. Mathematical method is subsequently used to determine the overall resilience score that the railway organisation has.
- Attributes that fall under the low resilience of the band table are flagged red, so that it means immediate attention should be paid to by the organisation and to seek improvement work.

6.1.2 Insights Gathered from Scientific and In-Practice Perspectives

6.1.2.1 Scientific Perspective

In Figure 43, a top-down approach should be used for attribute identification as this is in-line with the way of how high-level decisions that guide an organisation towards achieving its long-term goals are made at the strategic level and subsequently refined and at the lower tactical and operational levels. This approach also ensures that all areas are identified systematically. A bottom-up approach should be used for resilience assessment in order to obtain the high-level organisation resilience. The attribute-layer corresponds to the operational level within an organisation whereby all the actions and activities needed to be carried out for the smooth operation of the railway transportation system take place, thus the layer that contributes to the performance and the layer needed to be enhanced.

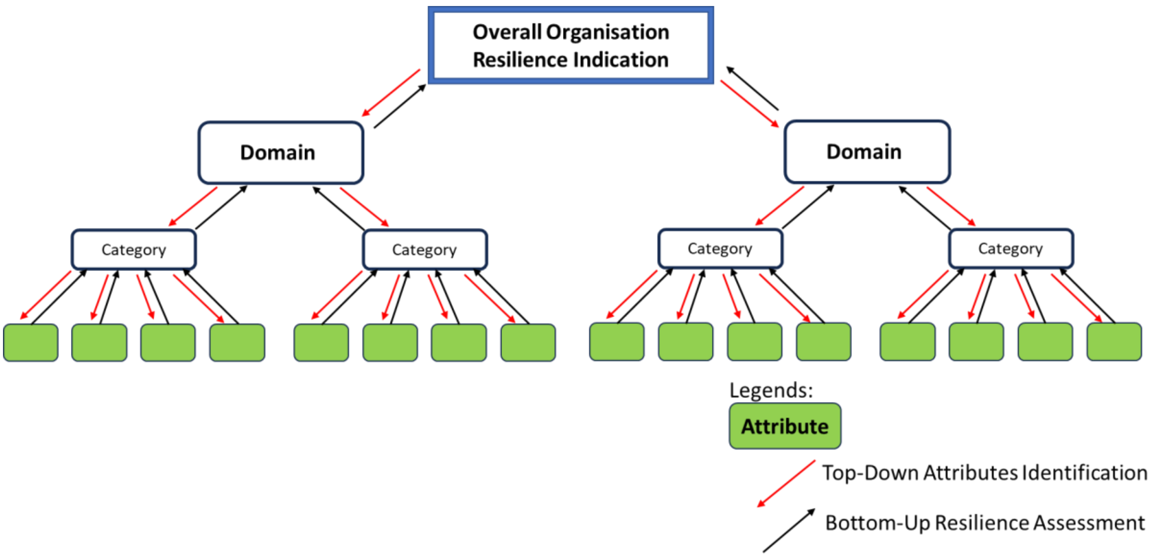


Figure 43: Directions of attributes identification and resilience assessment

6.1.2.2 In-Practice Perspective

Resilience is a concept. Through the literatures and personal knowledge, there is no one 'resilience assessment guideline' that is available and one that suits all railway organisations. This can be attributed to the fact that different railway organisations have different business models and operation boundaries, working cultures, other constraints such as economically or politically, etc. Despite these restraints, this thesis opined that the attributes considered in the assessment tool could form the foundation level of any resilience assessment to be adopted by railway organisations, as it has covered the 2 core domains of the TOSE framework, aside to the Economic and Social domains that should also be considered. The technical domain has ensured the identification of resilience attributes along the product/asset lifecycle i.e., from concept design till asset renewal, whereas the organisational domain has considered contributing attributes from the managing level till the lower working level i.e., staff that execute the emergency response plans as well as the cooperation with parties external to the organisation.

This thesis has learnt through the qualitative responses from the survey that there are different opinions and views on the importance of resilience. Some respondents think that attributes at more in-depth level should be used in order to provide a more wholistic representation of the organisation resilience. Two respondents feedbacked that there is nothing much they can contribute to improve the overall resilience due to their limited influential capacity. We could have derived a method or tool to help with the assessment in order to provide an overarching result to the management of the railway organisation. However, in terms of putting the notion of resilience to practice, it is important that the idea of resilience is firstly being cascaded down from the top level to the working level and to get the buy-ins from all internal and external stakeholders. The top-down advocating of resilience within the organisation is the starting point in contributing to the building up of the overall organisation resilience, against not only to climate change and cyber-attacks, but also to any other external events that can threaten the normal operation of the railway transportation system and organisation.

One respondent shared that as he works for the railway operator, it is challenging for railway operator to influence the robustness and redundancy aspects of the rolling stock since the design of the assets is not under the purview of the operator. In this situation for instance, if the designer of the rolling stock and the operator of the rolling stock belong to two different railway organisations, ideally the resilience of the whole railway transportation system is ensured if both organisations play their part. However, in reality, this might not be the case. Hence, should different sets of attributes be required so as to be tailored to the role of each railway stakeholders? This brings to another question for future consideration.

This assessment tool helps to promote the awareness of resilience in the railway industry, as well as acting as a method that allows frequent review and assessment of its resilience effort in operating its assets as well as managing the operation of the organisation and contributing to the resilience of the whole railway transportation system. Though the tool is in the preliminary stage, it sets the stepping-stone for such assessment method to be adopted, for better and more research work on the quantification of resilience performance to be done. The railway transportation system comprises the involvement of many railway stakeholders. If each and every stakeholder ensures resiliency operating in an environment with emerging threats, ideally the whole system is quick to recover and bounce back from any disruptions encountered.

The resilience attributes considered in this thesis focus on the application of the 4R Resilience Framework against climate changes and cyber-attacks. Aside to these, there are other events such as geopolitical issues such as border disputes or political instability that can affect cross-border railway connections, change in environmental regulations which require the modification to railway operations or use of materials, economic downturns leading to a reduction in the need for railway transports, etc. Hence, there should be a set of resilience attributes that a railway organisation should evaluate themselves against with, and against all forms of external events. It has not considered the level of susceptibility and vulnerability of the systems and organisation to the unexpected events which in-depth study or further research is needed to determine how these 2 characteristics can be assessed and quantified.

6.2 Recommendations

Below are recommendations listed for future research consideration.

6.2.1 Expand Target Audiences

The survey in this thesis has gathered inputs from railway practitioners with experiences in the railway transportation system in an urbanised country. It is good to expand the pool of target respondents to more practitioners working in other countries such as countries whereby their railway transportation system has ever been damaged by external events; countries with extensive railway networks and systems to manage and with big organisational structures, etc. This can provide a more wholistic evaluation on the applicability, as well as the possibility to identify additional attributes not considered in this thesis. In addition, we can also analyse if the set of attributes applies to railway organisations in countries with different railway networks such as metros, heavy rails since different regions or networks will have different operating patterns to serve the needs of their users.

6.2.2 Validation Method – Conduct of Interviews

The survey method is used in this thesis to assess the applicability of the resilience attributes and evaluation criteria. The questionnaire is disseminated via email to the group of respondents. There is the possibility that the respondents have differing knowledge on railway resilience prior to the start of the survey. Hence, instead of using survey via email to gather feedback on the applicability of the resilience attributes and evaluation criteria, the applicability of these elements can be presented to a panel of decision-makers of a railway organisation or experts in the field of resilience, and through the conduct of face-to-face interviews, feedback is received. This procedure ensures that the panel evaluators receive the same set of information and explanation before evaluation on the applicability commences. The diagram below illustrates the proposed procedure that can be used.

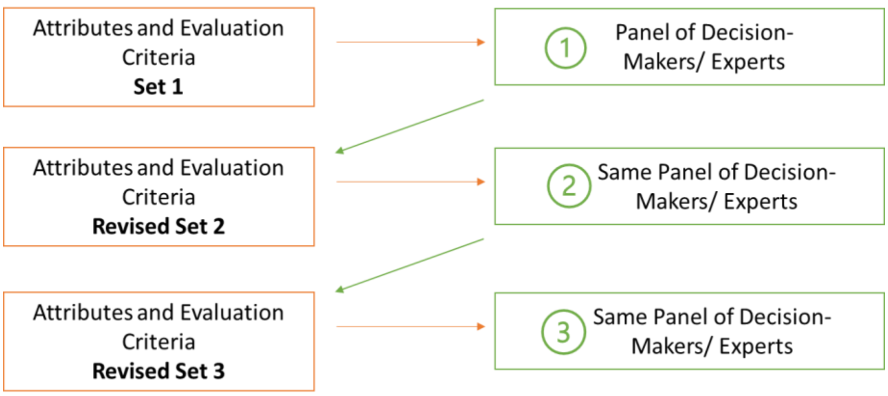


Figure 44: Applicability of resilience attributes through interviews

In Figure 44, the feedback obtained from the first round of presentation of Set 1 and interview is incorporated and updated in the Revised Set 2, whereby it is later presented again to the same group of people. This process is repeated 1 more time to the same panel in order to ensure consistent convey of information and ensured all resilience aspects to suit the railway organisation business and operating model have been considered.

6.2.3 Level of Assessment

From the survey responses, suggested resilience attributes that can be included are more at a detailed level i.e., operational/ tactical. The deeper the level of resilience assessment, the more finite/detailed the attributes and its associated evaluation criteria will have to be. 1 of the responses has suggested the assessment at component level. Though this is a viable way, there are thousands of components installed on a rolling stock. There is a need for the railway organisation to consider if there is a need to assess the resilience model of the components in their preparedness against extreme weather and cyber-attack. In addition, the more detailed the assessment, it is possible that more resources such as money and labour would be needed to carry out the work. This can lead to another debate if this is essential. The level of assessment also depends on the railway assets being considered. This thesis considers the assessment of rolling stock, however, when other railway assets such as stations, railway tracks are to be added, is it viable and easy to assess down to the bolts and nuts level. And whether if the railway organisation has the capability and resources to do so which has to be considered. Further research can also look into creating resilience assessment 'recipes' for the different railway systems and infrastructures.

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APPENDIX A RESILIENCE ATTRIBUTES FOR TECHNICAL DOMAIN

A.1 Hardware Resilience Attributes

Table 25: Attributes and Explanations (Hardware Resilience)

Hardware Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
System Integrity	Robustness	**Robustness:** To ensure that the rolling stock is designed with high quality level so as to withstand the mechanical stresses and strains that can be encountered with the changing operating environment. Aside to withstanding mechanical stresses, the design provision of the rolling stock with sufficient protection means to continue functioning in adverse weather conditions for example running on water-ponded tracks due to wet weather, should be available. It is essential to note that owners of rolling stocks might specify different design standards and requirements for the fleets of trains that they are going to procure. There are a few international rolling stock design standards such as the European Standards, the International Union of Railways standards, the International Standards Organisation (ISO) standards, the Japanese Industrial Standards, etc. Thus, the design standards to be adopted vary across countries as well as the specific requirements of the railway organisation. Some of the existing older fleets of rolling stocks could have been designed in accordance with the older versions of standards, or standards that might have been obsoleted. Thus, it is not feasible to specifically indicate the type of latest standard to be used in the evaluation criteria. > The percentage of trains rolling stocks that are designed adopting the latest version of design standards specified by the railway organisation is being used as the evaluation criteria. The definition of 'latest version' of design standards would be determined at of the time when the resilience assessment is being conducted. When a higher percentage of assets are designed using older standards, it serves as form of notification that more attention will have to be paid on the older trains.

Hardware Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
System Reliability	Robustness	**Robustness**: Reliability is defined as *"the ability to perform as required, without failure, for a given time interval, under given conditions"*, as extracted from the standard EN50126 (British Standard, 2017) for railway application. The specification of reliability requirements during the design phase ensures that the rolling stock has achieved a certain level of design reliability upon system validation. This gives some level of confidence that the reliability of the rolling stock is ensured. > The specification of reliability requirements for the design and achievement of the requirement upon system validation (before the rolling stock is being put into revenue service) is used as the evaluation criteria.
Risk Management	Robustness, Resourcefulness, Rapidity	**Robustness**: Based on EN50126 (British Standard, 2017) for railway application, safety specification is one of the requirement. With risk management procedures but not limited to hazard identification and analyses, etc. in place, potential operational hazards pertaining to rolling stock when operating under the occurrence of the external events can be identified in the early phase. This allows mitigation measures to be incorporated to the design and operation of the system, thus reducing the negative impacts. **Resourcefulness & Rapidity**: By better understanding how the rolling stock might fail when operating under the different adverse weather conditions and under different cyber-security attacks, railway organisations can also better understand the resources needed to ensure fast recovery effort. This allows pre-emptive measures to be put in place. The types of risk management procedures/systems needed is dependent on the needs of the railway organisation. > The availability of protocols in place to mitigate all the risks is used as the evaluation criteria.
Redundancy Level	Redundancy	**Redundancy**: To ensure that critical components are being identified and designed with redundancy provision, in order to ensure continuous operation thus

Hardware Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
		minimise the rolling stock downtime when the main component has failed. By assessing and identifying the critical rolling stock components that will get badly affected by the external events, adequate redundancy can be catered to. The redundancy approach to be undertaken is dependent on the industry standards and requirement of the railway organisation. The other redundancy consideration is the availability of fleetwide rolling stock spares that are able to be used as replacement when components on operating trains are damaged. > The extent of critical components of the rolling stock being provided with adequate redundancy is used as the evaluation criteria.
Resilience Engineering (RE)	Robustness	**Robustness**: According to Mr. Erik Hollnagel, the definition of Resilience Engineering has evolved over the years. In his book, it is seen as "*the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions*" *(Hollnagel, E., 2016)*. The focus has now expanded from maintaining the intended system operation under expected conditions to under both '*expected and unexpected'* conditions. The aim is to minimise the disruption impacts, to enhance the safety, reliability, maintainability and eventually, the overall system performance. Having design redundancy, provision of error detection and monitoring devices for early fault detection so that corrective maintenances can be taken are some of the RE approaches. > The identification and incorporation of RE concept in the design of the rolling stock is being used as the evaluation criteria.
Interoperability	Redundancy, Resourcefulness, Rapidity	**Redundancy**: With the different fleets of rolling stock able to operate unanimously on different networks or lines, it acts as a form of fleetwide redundancy.

Hardware Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
		Resourcefulness & Rapidity: Operators can deploy rolling stocks from unaffected areas, stabling yards, or depots to quickly resume the railway operation, thus minimising disruption. This attribute might not be easy for implementation since it will involve a lot of design planning and feasibility studies to determine the applicability of this concept on the different network lines and infrastructures that the organisation owns. > The percentage of all the rolling stock that the organisation owns that is able to operate interchangeably is being used as the evaluation criteria.
System Interface (With other railway assets)	Robustness	**Robustness**: Though the asset-specific attributes are being identified, the rolling stock interfaces with other railway systems and infrastructures during operation. It is important to be aware of how the failure of the interfacing systems can affect the operation of the rolling stock. For example, if the railway track buckles easily when experiencing high temperature, it is important that railway organisation is aware of it because this brings about safety issue to the operation of the train as it might lead to derailment. > The consideration of how the operation of the rolling stock can be impacted by the failure of its interfacing railway systems and structures is being used as the evaluation criteria.
System Maintainability	Robustness	**Robustness**: Maintainability is defined as " *the ability to be retained in, or restored to, a state to perform as required, under given conditions of use and maintenance"*, as extracted from the standard EN50126 (British Standard, 2017) for railway application. By specifying maintainability requirement, it ensures that maintenance tasks can be carried out effectively and in the shortest time possible. This will improve the availability of rolling stocks needed for operation as well as back-ups in the event any of the operating fleets failed to operate after encountering external events.

Hardware Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
		> The specification of maintainability requirements during the design and achievement of the requirement upon system validation (before the rolling stock is being put into revenue service) is used as the evaluation criteria.
Conduct of Maintenance	Robustness	**Robustness**: Rolling stocks have to undergo frequent maintenance activities in order to ensure its functionality and working condition. Train manufacturers will specify the types and frequency of maintenance that assets owners should follow. There exist 5 levels of maintenance activities (Kalinowski et al., 2020). Level 1 refers to the routine maintenance that can be conducted by the train drivers or maintenance personnel as part of their daily inspection works. Level 2 refers to more specialised maintenance activities that can be conducted by trained maintenance personnels. Level 3 maintenance can be the system overhaul and requires advanced diagnostic tools and works have to be done in the workshops or dedicated facilities. Level 4 maintenance refers to major overhaul of rolling stock components or refurbishment of the asset and extended period of system downtime is usually needed. Lastly, Level 5 maintenance refers to the decommissioning of the rolling stock at the end of their lifecycle. It is opined that Levels 1 and 2 maintenances are the basic levels of activities that ought to be adhered to. > The adherence to the maintenance guidelines specified by train manufacturers and the consideration of different maintenance levels are used as the evaluation criteria.
Conduct of Maintenance Audit	Robustness	**Robustness**: Preventive and corrective maintenances are the basic levels of maintenance activities that need to be conducted to ensure the technicality and functionality of the railway assets. Maintenance audits or inspections serve as a form of check, to ensure that maintenance regimes are properly conducted at the specified frequency by the maintenance teams. > The frequency of periodic checks/audits conducted is being used as the evaluation criteria.

Hardware Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
Fault Monitoring and Diagnostic Capability	Robustness, Resourcefulness Rapidity	**Robustness**: Whilst operating in varying weather conditions, there might be mechanical failures such as carbody cracks that cannot be identified easily by visual inspection. With advancement in technologies, faster and more efficient condition-monitoring tools are needed to monitor and assess the health status of the railway assets and its robustness. More sophisticated means can provide accurate and provide real-time diagnosis to the maintenance teams, so that they can ensure prompt rectification works are taken to minimise operation downtime and to better schedule and manage the fleet availability for service. **Resourcefulness & Rapidity**: This is also a pre-emptive measure to ensure that sufficient rolling stock back-ups are available in the event operational fleets are damaged. Noting that these tools will add on to the maintenance cost, however, in the railway industry, predictive and condition-based maintenance are the ways forward to enhance the resilience of the railway assets. > The number of rolling stocks among all the fleets own by the railway organisation that are installed with the condition-monitoring tools is being used as the evaluation criteria.
Adaptability to Changing Environment Conditions	Robustness	**Robustness**: In facing with the changing climate leading to adverse weather conditions and the potential of cybersecurity attack as identified in Chapter 2, rolling stocks that are designed for used many years ago might not be able to withstand the existing conditions as the technical specifications made during that time might be of lower requirement. Hence moving forward, railway organisation should study and analyse the reaction of the railway assets when facing with these events. This will help railway organisation to have a better sensing of how its existing stock will react, and thus able to take the necessary preventive measures for the operation of existing fleets as well as reviewing how the resilience for new fleets can be enhanced. > The frequency of review of assets adaptability is being used as the evaluation criteria.

Hardware Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
Asset Performance	Robustness, Redundancy	**Robustness**: The design life of rolling stock is approximately 30 years. During the asset lifecycle, there should be a regular review of the asset operating performance since its working condition degrade over time, thus its actual lifespan might not be even 30 years. Performance in this case can be defined as the operational reliability of asset. Degradation of the performance can be caused by the adverse environment, rolling stock design requirement are not suitable to operate in the current environment and the necessary maintenance regime is not being adhered to. **Redundancy**: Having frequent reviews allow railway organisation to have updated information and awareness on the actual performance of their assets, allowing them to ensure that sufficient spares of rolling stocks are always available for use. It also allows railway organisation to start their asset renewal activities such as mid-life refurbishment or new buy of rolling stocks timely. > The frequency of review conducted to assess the assets performance is being used as the evaluation criteria.
Asset Condition	Robustness	**Robustness**: Another attribute to consider would be the asset condition. Railway organisation can use this as an asset management indicator by determining how much of the rolling stock should always be in good working condition. > The percentage of assets operating in acceptable condition is being used as the evaluation criteria.
Availability of Spares	Redundancy	**Redundancy:** After assessing the assets performance and condition, these 2 attributes can serve as a benchmark to the railway organisation in determining the quantity of spares that the organisation has the capability to hold. > The percentage of rolling stock serving as spares is being used as the evaluation criteria.

A.2 Software Resilience Attributes

Table 26: Attributes and Explanations (Software Resilience)

Software Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
Software Safety Integrity	Robustness	**Robustness**: Stringent software development process is required to ensure the basic functional safety integrity of software used in the control and operation of electronic systems of the rolling stock. An example is the software requirement specified in IEC 61508 Electronic Functional Safety Package (International Electrotechnical Commission, 2010). > The adoption of recognised international standards related to software development and validation as the design guidelines is being used as the evaluation criteria.
Redundancy Level	Redundancy	**Redundancy**: Software redundancy plays an important role in keeping the system to be resilient, fault tolerant and ensuring system operation availability. Critical software functionalities and components can be identified so that backups are provided. By doing so, critical software functions can continue to be executed when encountering with sudden system attacks. > The extent of critical software components being identified and provided with adequate redundancy is used as the evaluation criteria.
Risk Management	Robustness	**Robustness**: Similar to the establishment of risk management procedures for the hardware aspect, potential vulnerabilities, and points of failures with the software system can be identified and mitigated. Aside to identifying software risks that the rolling stock and its peripherals might encounter with cyber-attacks, internal software risks such as coding errors can also be identified. This allows mitigation measures to be incorporated to the design and development of the software, thus reducing the negative impacts. > The availability of protocols in place to mitigate all the risks is used as the evaluation criteria.

Software Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
Cybersecurity Protection	Robustness	**Robustness**: To protect and enhance the security and safety of the software, network, and data against malicious external attacks, it is necessary to provide different forms of cybersecurity protection to the system. Some of these guidelines are published in internationally recognised standards such as ISO 27001 Information Security Management Systems (International Organisation for Standardization, 2022), ISO 27032 Information Technology Security Techniques — Guidelines for Cybersecurity (International Organisation for Standardization, 2012), etc. The type of guidelines to be used shall be in accordance with the requirement as specified by the railway organisation. > The level of cybersecurity protection being provided to protect the system is being used as the evaluation criteria.
Fault Monitoring and Diagnostic Capability	Robustness	**Robustness**: The incorporation of monitoring and diagnostic capabilities helps real-time performance of the software to be collected and assessed. Areas of weaknesses or potential vulnerabilities can be identified on a regular basis so that prompt rectification work such as the application of patches to the software, operating systems, firmware can be conducted. This also helps to strengthen the resiliency of the system in view of evolving new ways to attack the system. > The consideration of implementing software monitoring solutions is being used as the evaluation criteria.
Conduct of Maintenance Audit	Robustness	**Robustness**: Similar to the need for maintenance on hardware systems, software maintenance is equally important to ensure that critical functionalities are maintained, any software bugs being identified are being fixed and ensuring that the security level of the software are being kept up to date with industry standards. > The frequency of periodic checks/audits conducted is being used as the evaluation criteria.

Software Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
Adaptability to Changing Environment Conditions	Robustness	**Robustness**: Cybersecurity threats such as malware, remote control, data tampering, etc. affects the software operation of the back-end systems of the rolling stock. Attacks through interfacing systems and third-party components are possible too. Threats are emerging with the advancement in digitalization. Railway organisation should keep themselves updated with the latest threats and review to ensure that the software protection is robust. This will help railway organisation to have a better sensing of how the software function can be affected by cyber threats, and thus able to take the necessary preventive measures. > The frequency of review of software adaptability is being used as the evaluation criteria.

APPENDIX B RESILIENCE ATTRIBUTES FOR ORGANISATIONAL DOMAIN

B.1 Internal Resilience Attributes

Table 27: Attributes and Explanations (Internal Resilience)

Organisational Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
Leadership	Robustness	**Robustness**: The display of management and leadership skills by the senior management of the organisation is important. Firstly, it must show the determination of the organisation to embed the essence of resilience towards its preparedness effort against the external events identified. Secondly, when the senior management can lead by example, it gives greater confidence to all staff to follow the direction given. Thirdly, when external events do occur, the senior management should have the capability to make quick and sound decisions when the need arises. > The set-up of a resilient review committee (or similar) comprising of senior management and identified suitable leaders dedicated to review and foster the implementation of resilience in the policies set out by the organisation is used as the evaluation criteria.
Resilient Strategies	Robustness	**Robustness**: Implementation of resilient strategies and plans within the organisation should be reviewed frequently for its applicability. This is to ensure that strategies stay updated and applicable for its use in the management of the organisation and railway assets. > The frequency of review of resilient strategies by the top management or the resilient review committee is being used as the evaluation criteria.
Effective Communication (Within Organisation)	Robustness	**Robustness**: Process management within the organisation must be resilient too. Aside to having a good leadership team as mentioned above, the resilience goals, visions and initiatives have to be effectively cascaded or conveyed to all departments as well as staff. It ensures the smooth flow of information, coordination and collaborate among all stakeholders. Additionally, channels for feedback,

Organisational Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
		questions, and clarifications from all stakeholders to the senior management should also be available for 2-ways communication. It helps to align the resilience goals that the organisation has set, keeping everyone informed and at the same time to minimise potential conflicts. > The availability of communication channels for effective communication within the organisation is being used as the evaluation criteria.
Risk Management	Robustness, Redundancy, Resourcefulness, Rapidity	**Robustness, Redundancy, Resourcefulness & Rapidity**: Enterprise Risk Management is a risk management approach that allows organisation *"to identify, assess, and prepare for potential losses, dangers, hazards, and other potentials for harm that may interfere with an organisation's operations and objectives and/or lead to losses.* (*Enterprise Risk Management (ERM)*, 2022). Similar to technical resilience, railway organisation will be able to assess how the occurrence of the external events can affect the operation of the organisation, thereby implementing measures in resilient-deficient areas as early as possible, so as to minimise the negative impacts. > The availability and implementation of such framework is being used as the evaluation criteria.
Business Continuity	Robustness, Redundancy, Resourcefulness, Rapidity	**Robustness, Redundancy, Resourcefulness & Rapidity**: The occurrence of any unforeseen events should not deter the ability of the railway organisation to continue with its service provision to unaffected railway users as well as to the organisation functionality. From the article "Business Continuity Planning," 2023, business continuity is seen as the process by putting in place measures to "*prevent and recover from potential threats*" to the organisation". > The availability and implementation of business continuity plan is being used as the evaluation criteria.
Emergency Responses	Resourcefulness, Rapidity	**Resourcefulness & Rapidity**: Emergency response plan is necessary in response to the occurrence of external events. This is usually

Organisational Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
		draft-up in advance by conducting risk assessment and anticipating the measures and types of emergency response procedures required to be implemented. It allows organisation to review the extent of resources such as manpower, emergency equipment and supply, back-up operation plan, etc. needed to respond to these events. It helps organisation to ensure that adequate resources are always available. It also serves as a training guide to familiarise all involved personnel within the organisation on the steps to be taken and how to expedite work during the recovery effort. > The availability and implementation of event-specific emergency response plan is being used as the evaluation criteria.
Staff Competency (In Execution of Emergency Response Plans)	Robustness, Resourcefulness	**Resourcefulness & Rapidity**: Aside having the emergency response plans, operational personnel should also be well trained to familiarise themselves with the procedures in executing the plans, instead of getting caught off-guard when events occur. > The competency of the staff in executing the procedures is being used as the evaluation criteria.
Staff Competency (In Domain Area of Work)	Robustness, Resourcefulness	**Robustness:** Aside to being competent in the execution of emergency response plans, staff should also be sent for regular training in order to upkeep their proficiency in their domain area of work so as to stay relevant and updated with the changing external environment i.e., the impacts that the external events can lead to. > The number of staff being trained yearly to keep their skillset relevant and adaptable to the changing external environment is being used as the evaluation criteria.
Adequacy of Resources	Resourcefulness	**Resourcefulness**: Having the processes made as resilient as possible, this should be supplemented with adequate resources needed for execution. Resources can refer to manpower, materials resource, finance, and any other resources needed in carrying out the emergency response, business continuity, etc.

Organisational Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
		> Review of the adequacy of resources is being used as the evaluation criteria.

B.2 External Resilience Attributes

Table 28: Attributes and Explanations (External Resilience)

Organisational Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
Situational Awareness	Robustness	**Robustness**: It is very important for railway organisation to always be kept updated on the emerging causes of the external events identified and the emergent of new potential threats that can happen. This require the organisation to be kept abreast of events happening in the surrounding. Some of the ways to keep updated can include the exchange of information amongst railway organisations, collaboration with meteorological agencies to study on the evolution of climate change, participating in resilience-themed exchange forums. By keeping updated, organisation can then assess the applicability of their existing measures and plans, and to revise if necessary. If need arises, new measures can be devised. Aside to being aware of the situations, this also makes organisation to be well-aware of the latest trends or what fellow peers in the railway industry are doing, or what are the issues that others are encountering, thereby taking necessary preventive measures. > The availability of such implementation process is being used as the evaluation criteria.
Effective Communication (With External Parties – External Agencies)	Rapidity	**Rapidity**: This aspect relates to the joint collaboration effort with external agencies during the recovery phase after the disruption. Some of these external agencies include the police, the civil defence, etc. Strong collaboration with other agencies is required to ensure the smooth execution of the emergency responses as each agency knows their roles and responsibilities and recovery effort can be jointly

Organisational Resilience Attributes	Relativity to R4 Resilience Framework	Explanation
		carried out as fast as possible. Simulation of the actual disruption and the conduct of emergency drills can be held to improve familiarity with the roles that each participant holds. > The availability of communication protocol with external agencies is being used as the evaluation criteria.
Effective Communication (With External Parties – Railway Users)	Rapidity	**Rapidity**: When railway disruption occurs, railway users will want to be kept updated on the extent of disruption so that they can make the necessary changes to their travel plans. When this is inadequately provided, it leaves frustration to the users. This can leave a negative impression and loss of confidence with the railway organisation. It is therefore important that information is promptly disseminated so as to keep users informed. When railway users are kept 'involved' and 'informed', the recovery effort can be expedited. > The availability of communication means being put in place is being used as the evaluation criteria.

APPENDIX C ATTRIBUTE WEIGHTAGE CALCULATION (ROC TECHNIQUE)

Attribute Weightage Calculation

(1) Each member is to answer the question:
Qn: Is the attribute critical / not critical to the assessment of resilience?
If critical, insert 1.
If not critical, insert 0

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	1. Total votes	2. Rank	3. Calculate Weightage (ROC)
Hardware Resilience														
Design	System Integrity	1	0	1	1	1	0	1	0	1	0	6	3	0.16
	Reliability	1	0	1	1	1	1	1	0	0	1	7	2	0.26
	Risk Management	1	1	0	1	1	1	1	0	1	1	8	1	0.46
	Redundancy Level	1	1	1	0	0	0	1	0	0	1	5	4	0.09
	Resilience Engineering	0	0	1	0	0	1	0	0	1	1	4	5	0.04
											Sum	30		1.00
Operation	Interoperability	1	1	1	1	1	1	1	1	1	1	10	1	0.75
	System Interface (With other railway assets)	0	1	1	0	1	0	0	0	1	1	5	2	0.25
											Sum	15		1.00
Maintenance	Maintainability	0	0	1	1	0	1	1	0	1	1	6	4	0.09

	Maintenance	1	1	1	1	1	1	1	1	1	0	9	1	0.46
	Maintenance Audit	1	1	1	1	1	1	1	1	1	0	9	2	0.26
	Fault Monitoring and Diagnostic Capability	1	1	1	1	1	0	0	1	0	0	6	5	0.04
	Adaptability to Changing Operating Environment Conditions	1	1	1	1	1	1	1	1	1	0	9	3	0.16
											Sum	39		1.00
Assets Renewal	Assets Performance	0	0	1	1	0	1	1	0	1	1	6	2	0.28
	Assets Conditions	1	1	1	1	1	1	1	1	1	0	9	1	0.61
	Availability of Spares	1	1	1	1	1	0	0	1	0	0	6	3	0.11
											Sum	21		1.00
Software Resilience														
Design	Software Safety Integrity	1	1	0	1	1	1	0	0	1	1	7	3	0.15
	Redundancy Level	1	1	1	1	1	0	0	1	1	1	8	1	0.52
	Risk Management	1	1	1	1	1	0	0	1	1	1	8	2	0.27
	Cybersecurity Protection Provision	1	1	0	1	1	1	0	0	1	1	7	4	0.06

											Sum	30		1.00
Maintenance	Fault Monitoring and Diagnostic Capability	0	0	1	1	0	1	1	1	1	1	7	1	0.61
	Maintenance Audit	1	1	0	1	1	1	0	0	1	1	7	2	0.28
	Adaptability to Changing Operating Environment Conditions	0	0	0	1	1	0	1	1	1	1	6	3	0.11
											Sum	20		1.00
Internal Resilience														
Internal Resilience	Leadership Skills	0	0	1	1	0	1	1	0	1	1	6	8	0.03
	Resilient Strategies	1	1	1	1	1	1	1	1	1	0	9	6	0.06
	Effective Communication (Within Organisation)	1	1	1	1	1	1	1	1	1	0	9	7	0.04
	Enterprise Risk Management	1	1	1	1	1	1	1	1	1	1	10	1	0.31
	Business Continuity	1	1	1	1	1	1	1	1	1	1	10	2	0.20
	Emergency Response	1	1	1	1	1	1	1	1	1	1	10	3	0.15
	Staff Competency (Execution of Emergency Response Plans)	1	1	1	1	1	1	1	1	1	1	10	4	0.11
	Staff Competency (Domain Area of Work)	0	0	0	0	0	1	1	1	1	1	5	9	0.01

	Resources Adequacy	1	1	1	1	1	1	1	1	1	1	10	5	0.08
											Sum	79		1.00
External Resilience														
External Resilience	Situational Awareness	1	1	1	1	1	1	1	1	1	1	10	1	0.61
	Effective Communication (With External Parties – External Agencies)	1	1	1	1	1	1	1	1	1	1	10	2	0.28
	Effective Communication (With External Parties – Railway Users)	1	1	1	1	1	1	1	1	1	1	10	3	0.11
											Sum	30		1.00

(2) After all members have cast their votes, the weightage for each attribute is to be calculated.

The weightage for each attribute is calculated by using this equation:

$w_i = (1/N) \sum_{K=i}^{N} {}^{1}/_{K}$, *N is the total number of attributes in a sub-domain.*

The attributes are to be ranked from the most important (most number of votes) to the least importance (*i*=N).

*In the event 2 or more attributes have the same number of votes, the group of members are to discuss and determined the most importance and to rank accordingly. The table below shows the 'Design' sub-domain of the 'Hardware Resilience' category used as an example to illustrate how the weightage is calculated.

Total Votes (1)	Rank	Weightage (2)
6	3	= (1/5) * (SUM(1/3+1/4+1/5)) = 0.16
7	2	= (1/5) * (SUM(1/2+1/3+1/4+1/5)) = 0.26
8	1	= (1/5) * (SUM(1+1/2+1/3+1/4+1/5)) = 0.46
5	4	= (1/5) * (SUM(1/4+1/5)) = 0.09
6	5	= (1/5) * (SUM(1/5)) = 0.04

APPENDIX D EXCEL-BASED ASSESSMENT TOOL

Please refer to the softcopy Excel file attached to this thesis report for the user guide and tool, whereby explanation of the attributes identified is also provided. The evaluation scores shown in the following are for illustrative purposes.

Overall Resilience Score	3.47	**Low (1 to 1.99)**	**Medium (2.00 to 2.99)**	**High (3.00 to 4.00)**

A	B	C	D	E	F	G	H	I	J	K	L
Resilience Domain	**Sub-Domains**	**Associated Attributes**	**Evaluation Criteria**	**Evaluated Attribute Score**	**Attribute Weightage**	**Weighted Attribute Score**	**Category Score**	**Category Weightage**	**Weighted Category Score**	**Weighted Domain Score**	**Domain Weightage**
Technical (Rolling Stock)	**Hardware Resilience**									4.96	0.50
	Design	System Integrity	1 : < 25% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organisation. 2 : 25% to 50% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organisation. 3 : 50% to 75% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organisation. 4 : 75% to 100% of rolling stocks are designed and manufactured in accordance to the latest version of design standards as specified by the railway organisation. * Latest version of design standard is taken as of conducting this resilience assessment.	4	0.16	0.63	14.12	0.25	3.53		

		Reliability	1 : Reliability parameters are not specified in the Technical Design Requirements and assets unable to demonstrate high reliability upon system validation. 2 : Reliability parameters are not specified in the Technical Design Requirements but assets able to demonstrate high reliability upon system validation. 3 : Reliability parameters have been specified in the Technical Requirements but assets unable to demonstrate high reliability upon system validation. 4 : Reliability parameters have been specified in the Technical Requirements and assets able to demonstrate high reliability upon system validation.	4	0.26	1.03					
		Risk Management	1 : Absence of risk management procedures in place to manage risks. 2 : Risk management procedures in place to manage risks and < 50% of risks have mitigation measures provided. 3 : Risk management procedures in place to manage risks and 50% to 75% of risks have mitigation measures provided. 4 : Risk management procedures in place to manage risks and all risks have mitigation measures provided.	4	0.46	1.83					
		Redundancy Level	1 : < 25% of critical components have been identified and designed with redundancy provisions. 2 : 25% - 50% of critical components have been identified and designed with redundancy provisions. 3 : 50% - 75% of critical components have been identified and designed with redundancy provisions. 4 : 75% to 100% of critical components have been identified and designed with redundancy provisions.	4	0.09	0.36					

		Resilience Engineering	1 : Need for RE not identified. 2 : Need for RE identified but not applied in system design. 3 : Need for RE identified and moderately applied in system design. 4 : Need for RE identified and actively applied in system design.	2	0.04	0.08				
	Operation	Interoperability	1 : < 25% of rolling stocks are able to operate interchangeability on different railway lines. 2 : 25% - 50% of rolling stocks are able to operate interchangeability on different railway lines. 3 : 50% - 75% of rolling stocks are able to operate interchangeability on different railway lines. 4 : All rolling stocks are able to operate interchangeability on different railway lines.	2	0.75	1.50				
		System Interface (With other railway assets)	1 : Impacts of other system failures on rolling stock not studied. 2 : Impacts of other system failures on rolling stock have been studied but no action plans prepared. 3 : Impacts of other system failures on rolling stock have been studied and draft action plans have been prepared but not implemented. 4 : Impacts of other system failures on rolling stock have been studied and action plans have been implemented.	4	0.25	1.00				
	Maintenance	Maintainability	1 : Maintainability parameters are not specified in the Technical Design Requirements and assets unable to demonstrate high maintainability upon system validation. 2 : Maintainability parameters are not specified in the Technical Design Requirements but assets able to demonstrate high maintainability upon system validation. 3 : Maintainability parameters have been specified in the Technical Requirements but assets unable to achieve high maintainability upon	4	0.09	0.36				

			system validation. 4 : Maintainability parameters have been specified in the Technical Requirements and assets able to achieve high maintainability upon system validation.								
		Maintenance	1 : Irregular maintenance conducted, did not adhere to maintenance regimes. 2 : Regular maintenance conducted and considered up to Level 3 maintenance activities. 3 : Regular maintenance conducted and considered Levels 3 and 4 maintenance activities. 4 : Regular maintenance conducted and considered Levels 3, 4 and 5 maintenance activities.	4	0.46	1.83					
		Maintenance Audit	1 : No audit is planned to be conducted in a calendar year. 2 : At least half-yearly audit is planned to be conducted in a calendar year. 3 : At least quarterly audit is planned to be conducted in a calendar year. 4 : At least monthly audit is planned to be conducted in a calendar year.	4	0.26	1.03					
		Fault Monitoring and Diagnostic Capability	1 : < 25% of rolling stocks are equipped with Condition Monitoring capabilities. 2 : 25% - 50% of rolling stocks are equipped with Condition Monitoring capabilities. 3 : 50% - 75% of rolling stocks are equipped with Condition Monitoring capabilities. 4 : 75% - 100% of rolling stocks are equipped with Condition Monitoring capabilities.	2	0.04	0.08					

	Adaptability to Changing Operating Environment Conditions	1 : No review of assets adaptability to changing environment conditions. 2 : Annual review of assets adaptability to changing environment conditions is conducted. 3 : Half-yearly review of assets adaptability to changing environment conditions is being conducted. 4 : Quarterly review of assets adaptability to changing environment conditions is being conducted.	4	0.16	0.63				
Assets Renewal	Assets Performance	1 : No review of assets technical performance is being conducted. 2 : Annual review of assets technical performance is conducted. 3 : Half yearly review of assets technical performance is being conducted. 4 : Quarterly review of assets technical performance is being conducted.	4	0.28	1.11				
	Assets Conditions	1 : < 25% of rolling stocks are in acceptable working condition. 2 : 25% to 50% of rolling stocks are in acceptable working condition. 3 : 50% to 75% of rolling stocks are in acceptable working condition. 4 : 75% to 100% of rolling stocks are in acceptable working condition.	4	0.61	2.44				
	Availability of Spares	1 : No rolling stock spares have been catered. 2 : <25% of rolling stock spares have been catered. 3 : 25% to 50% of rolling stock spares have been catered. 4 : 51% to 100% of rolling stock spares have been catered.	2	0.11	0.22				
Software Resilience									

	Design	Software Safety Integrity	1 : No adoption of international standards for software development. 2 : Software are minimally developed in accordance to international standards specified by the railway organisation. 3 : Software are partially developed in accordance to international standards specified by the railway organisation. 4 : Software are fully developed in accordance to international standards specified by the railway organisation. * Latest version of design standard is taken as of conducting this resilience assessment.	4	0.15	0.58	5.74	0.25	1.43		
		Redundancy Level	1 : < 25% of critical software components have been identified and designed with redundancy provisions. 2 : 25% - 50% of critical software components have been identified and designed with redundancy provisions. 3 : 50% - 75% of critical software components have been identified and designed with redundancy provisions. 4 : 75% to 100% of critical software components have been identified and designed with redundancy provisions.	2	0.52	1.04					
		Risk Management	1 : Absence of risk management procedures in place to manage software-related risks. 2 : Risk management procedures in place to manage software-related risks and < 50% of risks have mitigation measures provided. 3 : Risk management procedures in place to manage software-related risks and 50% to 75% of risks have mitigation measures provided. 4 : Risk management procedures in place to manage software-related risks and all risks have mitigation measures provided.	4	0.27	1.08					

	Cybersecurity Protection Provision	1 : Absence of cybersecurity protection in place to protect the software systems. 2 : Low level of cybersecurity protection in place to protect the software systems. 3 : Intermediate level of cybersecurity protection in place to protect the software systems. 4 : Advance level of cybersecurity protection in place to protect the software systems.	4	0.06	0.25			
Maintenance	Fault Monitoring and Diagnostic Capability	1 : Absence of monitoring and diagnostic tools in place for Condition Monitoring. 2 : Minimal level of monitoring and diagnostic tools in place for Condition Monitoring. 3 : Advance level of monitoring and diagnostic tools in place for Condition Monitoring. 4 : Maximal level of monitoring and diagnostic tools in place for Condition Monitoring.	2	0.61	1.22			
	Maintenance Audit	1 : No audit is planned to be conducted in a calendar year. 2 : At least half-yearly audit is planned to be conducted in a calendar year. 3 : At least quarterly audit is planned to be conducted in a calendar year. 4 : At least monthly audit is planned to be conducted in a calendar year.	4	0.28	1.11			
	Adaptability to Changing Operating Environment Conditions	1 : No review of software adaptability to changing environment conditions. 2 : Annual review of software adaptability to changing environment conditions is conducted. 3 : Half-yearly review of software adaptability to changing environment conditions is being conducted. 4 : Quarterly review of software adaptability to changing environment conditions is being conducted.	4	0.11	0.44			

Organisational	**Internal Resilience**	Leadership Skills	1 : Absence of Committee formed to review organisational resilience. 2 : Roles and responsibilities of Committee Members identified to review organisational resilience but suitable personnel not yet identified. 3 : Roles and responsibilities of Committee Members identified to review organisational resilience but suitable personnel partially identified. 4 : Roles and responsibilities of Committee Members identified to review organisational resilience and suitable personnel fully identified.	4	0.03	0.10	3.88	0.25	0.97	1.97	0.50
		Resilient Strategies	1 : No review of resilient strategies by the Resilient Review Committee. 2 : Annual review of resilient strategies by the Resilient Review Committee. 3 : Half-yearly review of resilient strategies by the Resilient Review Committee. 4 : Quarterly review of resilient strategies by the Resilient Review Committee.	2	0.06	0.12					
		Effective Communication (Within Organisation)	1 : Absence of two-way communication channels within the organisation. 2 : Presence of two-way communication channels within the organisation but open communications not encouraged in the organisation. 3 : Presence of two-way communication channel within the organisation but open communications moderately encouraged in the organisation. 4 : Presence of two-way communication channel within the organisation and open communications strongly encouraged in the organisation.	4	0.04	0.17					

		Enterprise Risk Management	1 : Absence of Enterprise Risk Management procedures in place to manage risks. 2 : Enterprise Risk Management procedures in place to manage risks and < 50% of risks have their associated mitigation measures. 3 : Enterprise Risk Management procedures in place to manage risks and 50% to 75% of risks have their associated mitigation measures. 4 : Enterprise Risk Management procedures in place to manage risks and 75% to 100% of risks have their associated mitigation measures.	4	0.31	1.26					
		Business Continuity	1 : Absence of any Business Continuity Plan. 2 : Business Continuity Plan is available but content is generalised. 3 : Business Continuity Plan is available, content has considered the occurrence of different unforeseen events but with some missing information. 4 : Business Continuity Plan is available, content has considered the occurrence of different unforeseen events with detailed information.	4	0.20	0.81					
		Emergency Response	1 : Absence of any Emergency Response Plans prepared. 2 : Emergency response plans are available but content is generalised i.e., not event-specific. 3 : Emergency response plans are available, content is event-specific but with some missing information. 4 : Emergency response plans are available, content is event-specific and with detailed information.	4	0.15	0.59					
		Staff Competency (Execution of Emergency Response Plans)	1 : < 25% of staff are trained to respond to external events. 2 : 25% to 50% of staff are trained to respond to external events. 3 : 50% to 75% of staff are trained to respond to external events. 4 : 75% to 100% of staff are trained to respond to external events.	4	0.11	0.44					

		Staff Competency (Domain Area of Work)	1 : < 25% of staff are trained yearly to upkeep their proficiency in field of work to adapt to the changing external environment. 2 : 25% to 50% of staff are trained yearly to upkeep their proficiency in field of work to adapt to the changing external environment. 3 : 50% to 75% of staff are trained yearly to upkeep their proficiency in field of work to adapt to the changing external environment. 4 : 75% to 100% of staff are trained yearly to upkeep their proficiency in field of work to adapt to the changing external environment.	4	0.01	0.05					
		Resources Adequacy	1 : No review of adequacy of resources. 2 : Annual review of adequacy of resources. 3 : Half-yearly review of adequacy of resources. 4 : Quarterly review of adequacy of resources.	4	0.08	0.33					
	External Resilience	Situational Awareness	1 : Absence of process in place to review and anticipate emerging threats to organisation and operation. 2 : Simple process in place to review and anticipate emerging threats to organisation and operation and implemented. 3 : Detailed process in place to review and anticipate emerging threats to organisation and operation but not actively implemented. 4 : Detailed process in place to review and anticipate emerging threats to organisation and operation and actively implemented.	4	0.61	2.44	4.00	0.25	1.00		
		Effective Communication (With External Parties – External Agencies)	1 : No communication established with external agencies. 2 : Close communication established with some external agencies. 3 : Close communication established with all external agencies but event-simulation not	4	0.28	1.11					

			conducted. 4 : Close communication established with all external agencies and event-simulation conducted.								
		Effective Communication (With External Parties – Railway Users)	1 : Absence of communication channels established to broadcast updates to railway users promptly. 2 : 1 to 2 communication channels have been established to broadcast updates to railway users promptly. 3 : 3 to 4 communication channels have been established to broadcast updates to railway users promptly. 4 : More than 4 communication channels have been established to broadcast updates to railway users promptly.	4	0.11	0.44					

APPENDIX E SURVEY RESULTS

E.1 Applicability of Resilience Attributes

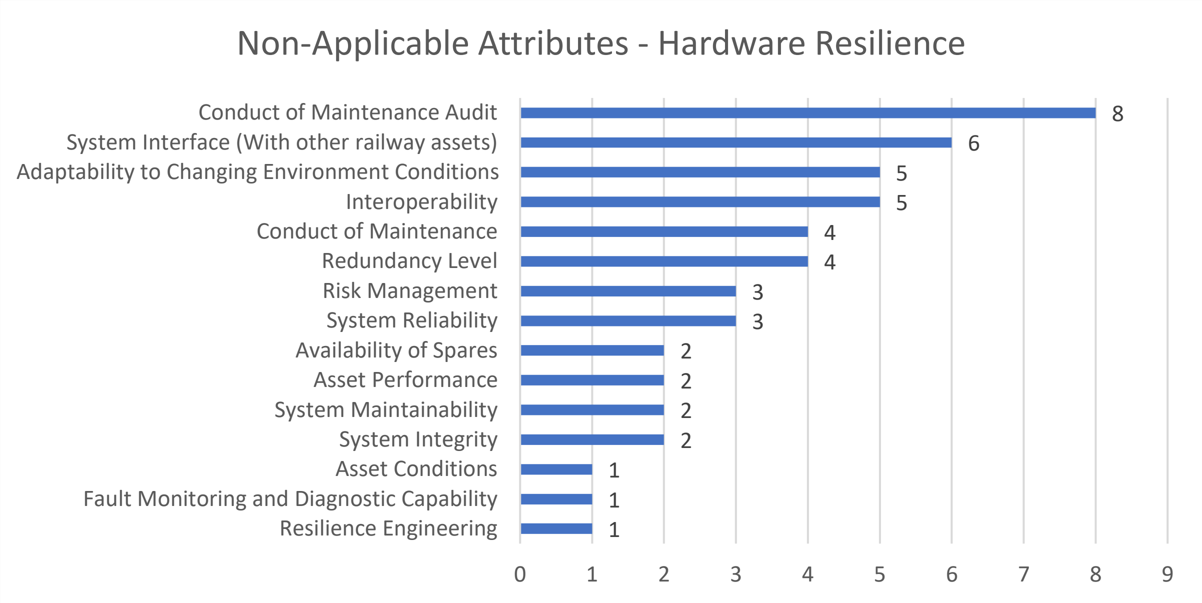

Figure 45: Results of applicability of hardware resilience attributes

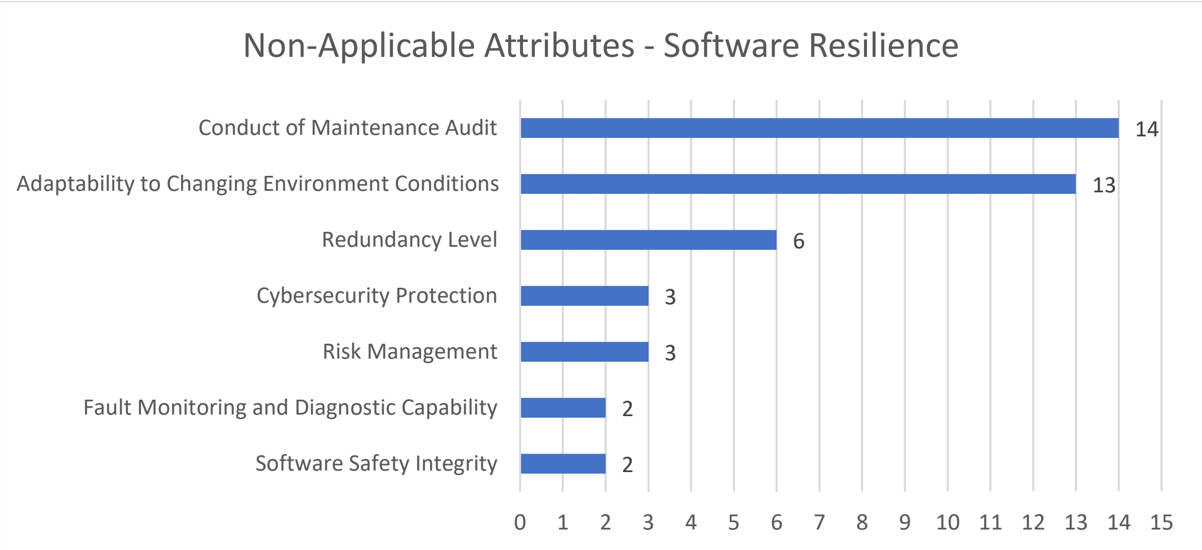

Figure 46: Results of applicability of software resilience attributes

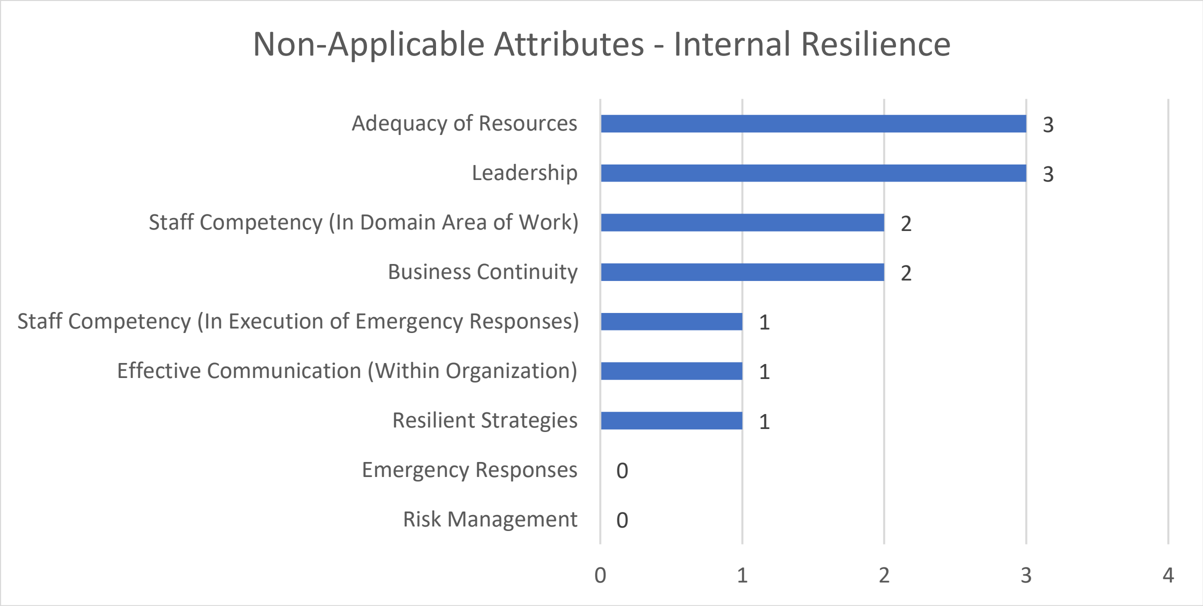

Figure 47: Results of applicability of internal resilience attributes

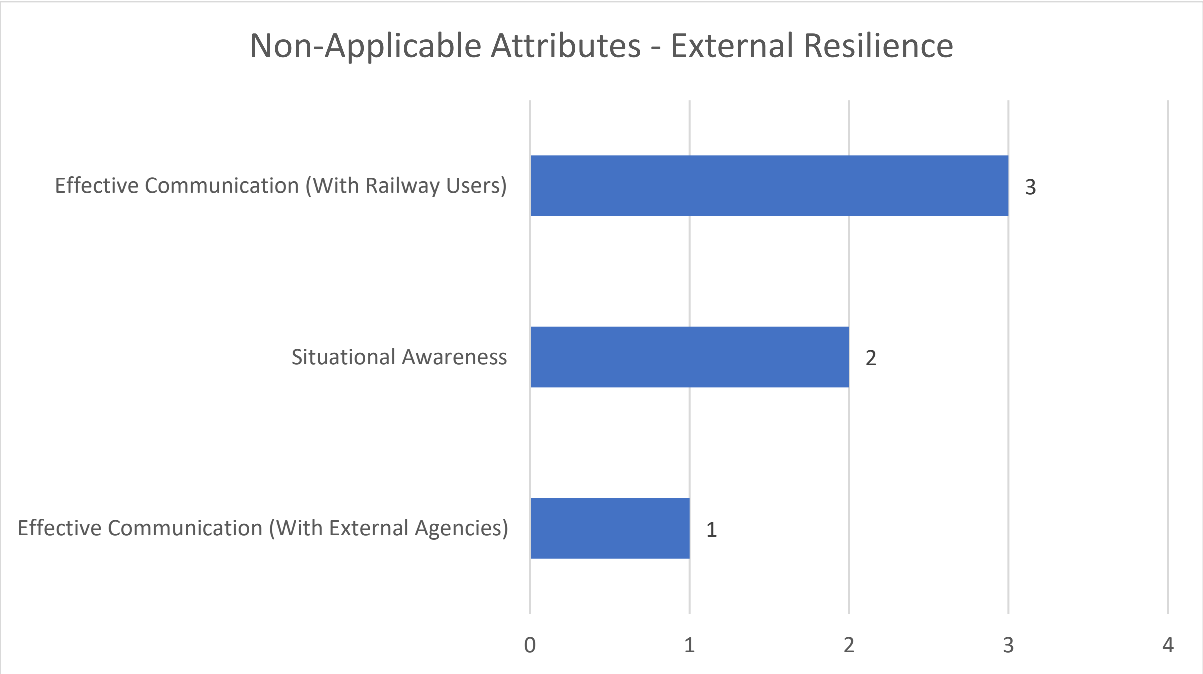

Figure 48: Results of applicability of external resilience attributes

E.2 Applicability of Evaluation Criteria

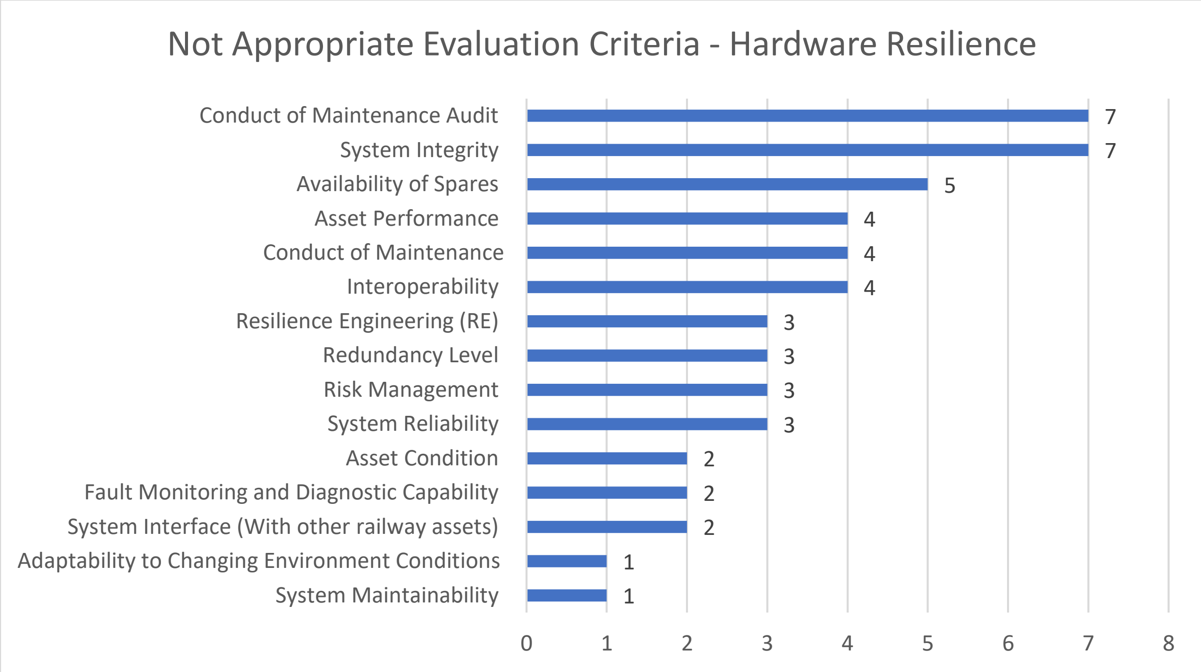

Figure 49: Results of applicability of evaluation criteria for hardware resilience attributes

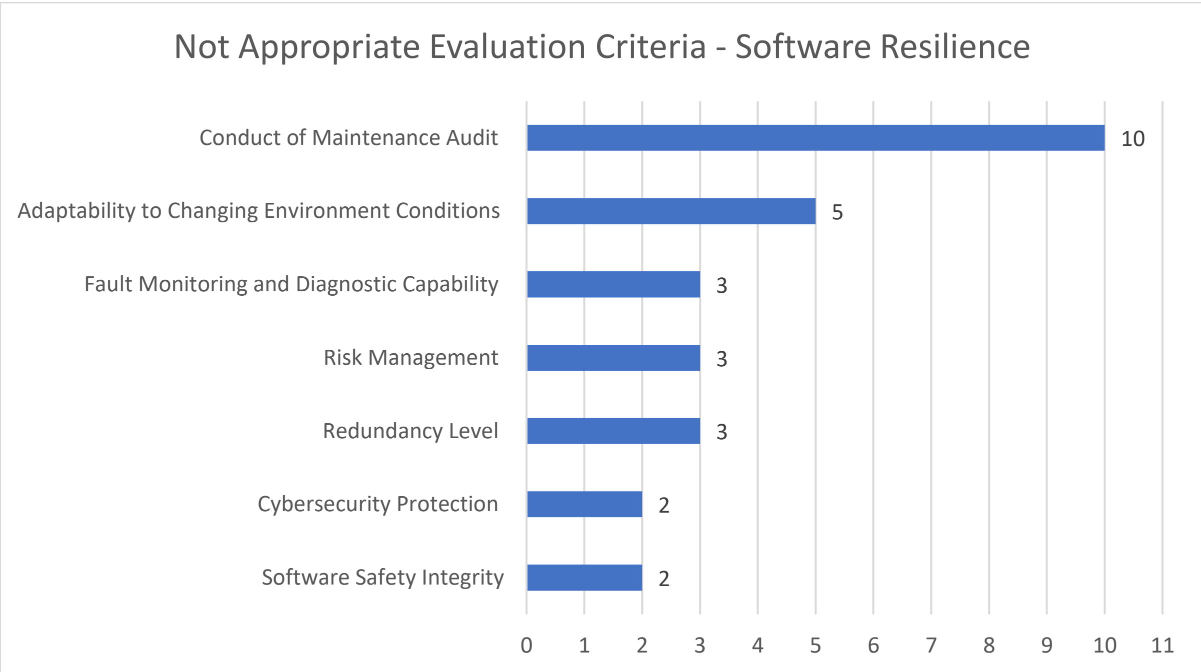

Figure 50: Results of applicability of evaluation criteria for software resilience attributes

Figure 51: Results of applicability of evaluation criteria for internal resilience attributes

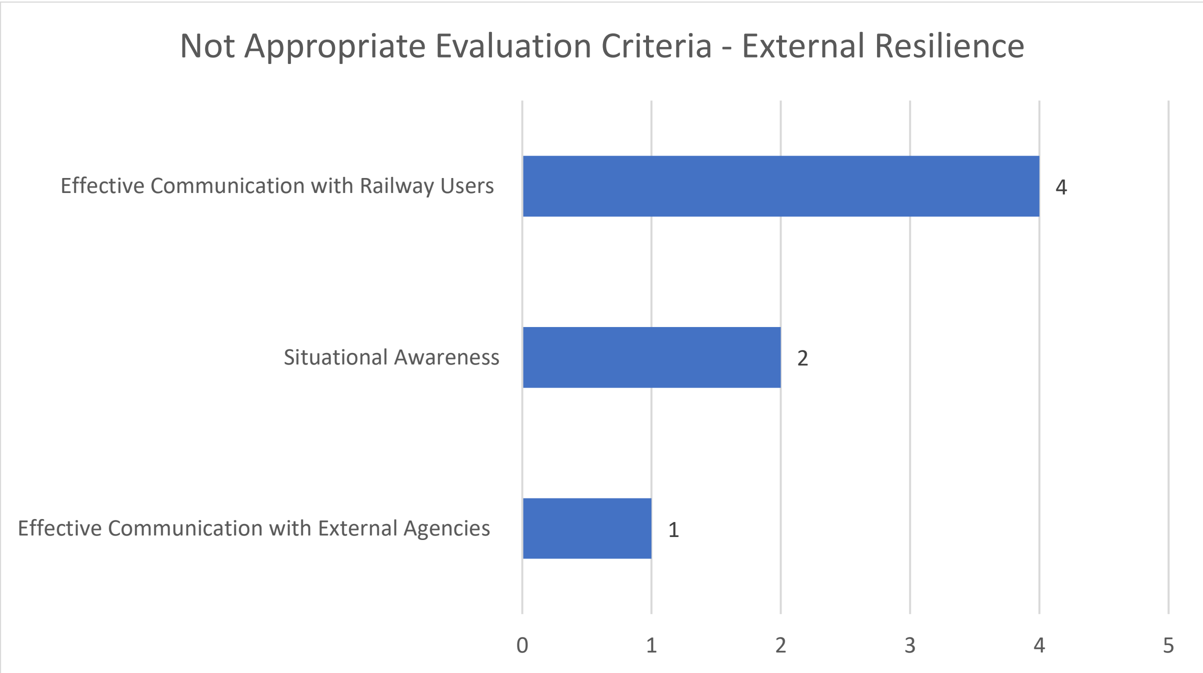

Figure 52: Results of applicability of evaluation criteria for external resilience attributes

APPENDIX F DISCUSSIONS ON QUALITATIVE SURVEY RESPONSES

F.1 Hardware Resilience Attributes

Table 29: Discussion on non-applicability of hardware resilience attributes

Hardware Resilience Attributes	Feedback Received	Discussion
System Reliability	Train bought should be reliable in the first place.	Yes, agree with this feedback. Rolling stocks are designed to meet a certain level of design reliability during the manufacturing phase. The intention to consider this attribute is to ensure that all rolling stocks are designed and validated to be reliable before being put into revenue service. If the trains are not able to achieve the specified level of reliability, but yet are being put into service, special attention will need to be paid to when facing the external events. Though the likelihood of such situation is low. In addition, the reliability of the rolling stock deteriorates over time. Thus, it is also possible to consider the attribute on Operational Reliability as a form to assess the Robustness of the asset.
Risk Management	Risk management is a tool to assess the system but does not directly contribute to the hardware resilience.	Yes, agree with this feedback. With the availability of such tool, the ways of how the rolling stock gets affected by the external events that can lead to system failure are being identified, so as to ensure that adequate mitigation measures are incorporated to the system design in the first place. If such systematic identification procedure is absent, there is no assurance that the rolling stock would be able to revert back to service as soon as possible, after facing the external events.
Redundancy Level	Redundancy level serves as an addition layer of protection.	Yes, agree with this feedback. Redundancy is to ensure that when the 'primary' layer of protection fails, the rolling stock can continue if coincidentally, system failure occurs during the occurrence of external events.
Resilience Engineering	Staff has to be sent overseas for training.	Training is essential. Upgrading the skill set of staff is a necessity so as to ensure their skills

		are updated, and with the change in operating environment, staff are well-prepared to face the different ways of how resilience engineering can be considered in the hardware operation.
Interoperability	1. Rolling Stock (RS) fleet operating in different network depends on its operating mode i.e., Automatic Mode, Coded Manual Mode, Restricted Mode. 2. Think this is independent as technology evolves over time so interoperability may not be achieved as desired.	1. This thesis opined that this comment is more relevant to the type of trainborne and trackside signalling system that the rolling stock is being equipped with. However, the attribute in this context refers to the rolling stock itself. Thus, if the design of the train is able to operate unanimously on different network, it serves as a form of infrastructure redundancy. Next consideration will then be on the type of signalling systems that are used on the different network itself, whether it allows different train type to operate on it. A good example is the standardisation of the European Rail Traffic Management System used in European railway networks. 2. Agree with feedback. This thesis opined that there needs to be a starting point, whereby interoperability can be considered for railway operation in the long term ahead.
System Interface (With other railway assets)	Isolate RS from rail network. Interface becomes less important.	In the railway network, it is difficult to isolate the rolling stock from the network as it is the main actor in the whole transportation system i.e., the people mover. Thus, interface between the different railway systems is very important.
Conduct of Maintenance	All maintenance tools should be tip top.	Aside to having maintenance tools in tip-top conditions, the rolling stocks have to adhere to the maintenance regimes as specified by the train manufacturer.
Conduct of Maintenance Audit	1. Not directly dependent on results from maintenance audit. Should adopt more predictive approach to maintain hardware resilience. 2. Audit is carried out to ensure proper documentation and records, and not directly	1. Predictive approach in terms of condition monitoring and diagnosis is considered as 1 of the attributes. 2. Audit ensures that the maintenance regimes and rectification work have been promptly carried out as required. In the event disruption occurred, there is a possibility that back-tracking of work history will be needed to review if

	contributing to the resilience of the hardware.	protocols have been adhered to and to identify if there are any lacking areas.
Adaptability to Changing Environment Conditions	1. Usually govern by specifications in relation to international standards, even with changing environment, it is often late and can be subjective and risk appetite. 2. Hardware cannot be designed for changing environments (conditions which are out of spec such as increased external temperature).	1. This thesis opined that it is not late to implement changes to improve the resilience such as via additional design provisions/reinforcement, the use of more condition monitoring tools, etc. The extent of risk appetite would be dependent on the railway organisation on how much risk the company is willing to bear, when the rolling stock encounters failure due to the external events. 2. Immediate assets that the organisation owns might not be able to be changed for the changing environment condition, however, it allows more stringent or better design specification to be specified for new trains to be procured. The intention of this attribute is allowing organisation to own a better sensing of how its existing stock will react, and thus able to take the necessary preventive measures for the operation of existing fleets as well as reviewing how the resilience for new fleets can be enhanced.
Availability of Spares	This is maintenance planning of part replacement - inventory control. Common parts in design will improve part replacement-interchangeability.	Yes, agree with this feedback. With more parts that are common in design among the different fleets of trains, it allows parts to be used interchangeably and seek to address the issue that certain fleet of trains fails to operate when encountering if encountering the external events.

F.2 Software Resilience Attributes

Table 30: Discussion on non-applicability of software resilience attributes

Software Resilience Attributes	Feedback Received	Discussion
Software Safety Integrity	Software system from signal should use a good software for the latest update.	This feedback is more applicable for the signalling system. For rolling stock itself, there could be subsystems that use software to execute safety functions. Thus, if there is, the robustness of the software development of these systems has to be ensured.
Redundancy Level	1. Depending on the hardware redundancy, software cannot control this. 2. Redundancy level serves as an addition layer of protection.	1. Hardware redundancy is 1 of the aspects to improve the level of resilience. This also applies for software. Software fault tolerance is 1 of the techniques that can be considered for redundancy. Similar to how it is done for hardware, critical software functions, data, components, etc. are duplicated. Thus, software redundancy is workable *(Jerome H. Saltzer & M. Frans Kaashoek, 2021)*. 2. Yes, agree with this feedback. Redundancy is to ensure that when the 'primary' layer of protection fails, the rolling stock can continue to operate in the event of external events.
Risk Management	1. Risk management is a tool to assess the system but does not directly contribute to the hardware resilience. 2. Software design architecture to be reviewed rather than from risk perspective.	Yes, agree with both feedback. With the availability of such tool, the ways of how the rolling stock gets affected by cyber-attacks and the consequences can be systematically identified, so as to ensure that adequate mitigation measures are incorporated such as to the software design architecture. This will help to enhance the robustness of the software used. If there is no such systematic procedure in place for risk identification, there is no assurance that the rolling stock would be able to revert back to service as soon as possible, after facing the external events; as well as the progressive release of security patches to protect the software.
Cybersecurity Protection	1. Rolling stock is more mechanical than software.	1. It is not absolutely true that rolling stock are more mechanical than software. Rolling stock today are installed with

	2. Such protection should be at the Command and Control.	onboard computers and communication systems, making them susceptible to remote exploitation. If attackers can gain unauthorized access to these systems, they may be able to take control of the train's functions or disrupt its operation. 2. Yes, agree with the feedback. Aside to the signalling system and the integrated supervisory and control system, rolling stock could also be installed with COTS, making third-party exploitation easy *(Bastow, 2014)*.
Conduct of Maintenance Audit	1. Rigorous testing during Testing & Commissioning (T&C) phase rather than checks performed in maintenance audit. 2. Maintenance audit will not cover software aspects, most of the items will be hardware. 3. not sure what is maintenance audit, if software self-test is part of this, then it is applicable.	1. It is part of the testing protocol to ensure that software is rigorously tested during T&C phase before they can be released for use. The purpose of software maintenance audit is to ensure that the necessary maintenance is adequately conducted to ensure no security lapse, no software bugs, etc. 2. Aside to hardware maintenance audit as mentioned in the previous table, there is another aspect on software maintenance audit. 3. Yes, software self-test is 1 of the methods.
Adaptability to Changing Environment Conditions	1. Software is codes. When environment change, doubt it can be easy to change the code and change the software. As the software development has to go through another round of assessment before it can be released for train operation. 2. Software Modification due to part replacement or change in supplier or model. Software development should already consider different operational needs during degraded conditions e.g., flooding, etc. 3. Robustness of software should not be environmental dependent. 4. Changing environment such as climate change, increase in	1. Whether changing of the code is necessary would depend on the software developer. The intent of this attribute is to enforce the need the ensure that rigorous coding and software development are progressively considered with the advancement of how cyber security can affect train operation. 2. Feedback noted. 3. Do not agree with the feedback that software should not be environmental dependent. It is necessary for software developer to keep abreast of the different and new ways of how change cyber-attacks can affect software used by rolling stock. 4. The aspect for software resilience is more on the cyber-attack external events and not from the climate change. 5. Adaptability of the hardware to the changing operating environment is already considered as 1 of the attributes.

	temperature, flooding, etc. would not affect the software nor what the software can help to mitigate it during. 5. More applicable for hardware.	From the software perspective, there is also a need for the improvement to be made.

F.3 Internal Resilience Attributes

Table 31: Other internal resilience related attributes

Possible Attributes (Internal Resilience)	Ways To Improve Resilience
- Monitoring and assessing level of preparedness and operational readiness. - Safety Culture. - Succession planning of key personnel and knowledge management.	- Proper and regular check & balance of various key attributes.

F.4 External Resilience Attributes

Table 32: Other external resilience related attributes

Possible Attributes (External Resilience)	Ways To Improve Resilience
- Effective communication with the community such as household located near railway tracks that are damaged. - Mental preparedness of the stakeholders of the railway organisation in terms of trust and confidence. - Relationship with suppliers, OEMs, resiliency of railway operator.	- Public education. - Proper and regular check & balance of various key attributes. - Objective review and consideration of feedback and lessons learnt. - Update knowledge from OEM, and awareness of available technology.

F.5 Hardware Resilience Evaluation Criteria

Table 33: Discussion on non-appropriateness for hardware resilience evaluation criteria

Hardware Resilience Attributes	Feedback Received	Discussion
System Integrity	1. System integrity of railways are not limited to rolling stock. Should include core systems that are essential for railway service. 2. 'Integrity' should mean no breakdown when disturbed? E.g., number of failed components a machine can take before having to be put out of service.	1. Yes, agree with feedback. However, in the scenario description of the questionnaire, the scope of the railway organisation refers to the entity that owns, design, operates and manages rolling stock only. 2. Feedback noted. This might need to further apply it at operational level of resilience assessment i.e., at component levels and for different subsystems.
System Reliability	1. System reliability should focus on actual reliability performance that is achieved during O&M. Need to track and monitor continuously, for early detection of deteriorating trends. 2. Reliability figure should consider period during revenue service, to avoid early failures.	1. Yes, agree with feedback. With actual monitoring of reliability performance during O&M, it can better reflect the performance of the rolling stock that have been in service. 2. Yes, agree with feedback.
Risk Management	This criterion is focused solely on availability of risk management protocols. Risk management will not be effective if the protocols are available but are not followed.	Yes, agree with feedback. Hence, the evaluation criteria proposed have focused on the extent of risk being mitigated by the organisation. If protocols are available yet not followed, this could mean a low resilience.
Redundancy Level	In addition to redundancy, should include diversity and segregation to avoid common cause failure. Should also consider change in system configuration during degraded mode,	Yes, agree with feedback. The suggestion seems to relate more to at operational level, whereby more in-depth ways to assess how the resilience can be improved in terms of how to improve the redundancy can be considered. At this moment, this thesis has

	when one of the redundant components has failed, the remaining component becomes a single point of failure.	considered only the Tier I resilience assessment approach.
Resilience Engineering (RE)	The rolling stock has many subsystems. At a deeper level, how the extent of incorporation of RE into the train design can be measured has to be reviewed.	Yes, agree with feedback. The suggestion seems to relate more to at operational level whereby more in-depth analysis can be considered.
Interoperability	1. Interoperability is also dependent on p-way, traction power supply system, signalling system, communications network, etc., and is not limited to rolling stock. 2. Current rolling stock fleets on different lines are not design for interoperability.	1. Yes, agree with feedback. 2. This comment is situation dependent. This attribute might be applicable to countries/networks whereby rolling stocks can interoperate on the various lines.
System Interface (With other railway assets)	Consideration of the passing rate of the test activities with interfacing contractor during testing phase.	Feedback is valid. This can be considered at operational level and as part of the inputs to the action plan that the evaluation criteria seek.
System Maintainability	Should emphasize on actual maintainability issues on site during O&M phase.	Yes, feedback is valid. The actual maintainability issues during O&M phase would show the resilience level of the rolling stock. However, this could be considered at the operational level i.e., Tier III of the resilience assessment approach.
Conduct of Maintenance	1. Should emphasize on the effectiveness of maintenance that is implemented during O&M phase. Operators should have competencies and abilities to review effectiveness of OEM's maintenance procedures and develop/modify/adapt	1. This feedback can be applied to the operational level whereby more in-depth measurement method or scale can be used. 2. Conducting extra and beyond of what have been recommended by the OEM is dependent on the capability and adequacy of resources that the Operator has. Benchmarking on the basic requirement would be the minimum level of maintenance required. Thus, the use of

	maintenance regimes for the actual system, when necessary. 2. OEM usually quote recommended maintenance regimes. Responsible an experienced operators should do more beyond the recommended instructions.	adherence to OEM recommendation as the evaluation criteria.
Conduct of Maintenance Audit	1. Frequency of maintenance audits does not ensure that the intended outcomes of the maintenance audits will be achieved. It's more important to address the purpose, resources, methods, criteria, etc., for the maintenance audits. 2. Predictive failure management might be more effective with tracking of failure trends rather than regular maintenance audit. 3. Should also include the scope and details of the maintenance audit.	1. The purpose, resources, methods, criteria, etc., for maintenance audits are to be defined at tactical or even operational level. If a railway organisation does not even see the importance to conduct maintenance audit, there is then no purpose to specify the different elements as mentioned above. 2. Feedback noted. This is considered under the fault monitoring and diagnostic capability attribute below. 3. The scope and details of maintenance audits would be at operational level.
Fault Monitoring and Diagnostic Capability	Should look at whether condition monitoring is effectively implemented for predictive maintenance.	Yes, agree with feedback. At strategic level, it is firstly necessary that the rolling stock are equipped with the diagnostic capability. Moving on to the next tier, the effectiveness of these tools in gathering the condition data of the rolling stock can be considered.
Asset Performance	1. In depth review and achievement of KPIs set. 2. 'Performance' should mean scorecard marked against supposed design on paper? E.g., a relay should last X number of cycles, else get low score. Carbody should last 30 years else the material or	1. The types of KPIs to be used will be dependent on the railway organisation at tactical level. At strategic level, this thesis opines that there must firstly have the initiative in place to review of technical asset performance. 2. Yes, the feedback would relate more to the operational level of how the performance of the assets at subsystem and even at Line Replaceable Unit level can be assessed.

	workmanship should get a low score.	
Availability of Spares	1. Stock/logistic management – more of planning process unless there is risk of supplier shortage issue. 2. Percentage of rolling stock components serving as spares	1. Yes, the feedback would relate more to the operational level of how the different level of spares of the assets at subsystem and even at Line Replaceable Unit level can be assessed. 2. Yes, the feedback would relate more to the operational level of how the different level of spares of the assets at subsystem and even at Line Replaceable Unit level can be assessed.

F.6 Software Resilience Evaluation Criteria

Table 34: Discussion on non-appropriateness for software resilience evaluation criteria

Software Resilience Attributes	Feedback Received	Discussion
Redundancy Level	1. In addition to redundancy, should include diversity and segregation to avoid common cause failure. Should also consider change in system configuration during degraded mode, when one of the redundant components has failed, the remaining component becomes a single point of failure. 2. Critical Components are hardware.	1. Yes, the feedback would relate more to hardware resilience than software resilience. 2. As per discussed Table 30, there is growing aware on the importance on the redundancy provision for critical software components.
Risk Management	This criterion is focused solely on availability of risk management protocols. Risk management will not be effective if the protocols are available but are not followed.	Yes, agree with feedback. Hence, the evaluation criteria focus on how much software-related risk are being mitigated by the organisation. If protocols are available yet not followed, this could mean a low resilience.
Cybersecurity Protection	Protection should be at Command and Control	This feedback is referring more to the trainborne signalling system, which is valid.

Fault Monitoring and Diagnostic Capability	Should look at whether condition monitoring is effectively implemented for predictive maintenance.	Yes, agree with feedback. At strategic level, it is firstly necessary that the software installed onboard the rolling stock are equipped with the diagnostic capability. Moving on to the next tier, the effectiveness of these tools in gathering the condition data of the rolling stock can be considered.
Conduct of Maintenance Audit	1. Frequency of maintenance audits does not ensure that the intended outcomes of the maintenance audits will be achieved. It's more important to address the purpose, resources, methods, criteria, etc., for the maintenance audits. 2. Minimal software maintenance. But to ensure proper software upgrade process due to asset renewal. 3. Should also include the scope and details of the maintenance audit.	1. The purpose, resources, methods, criteria, etc., for maintenance audits are to be defined at tactical or even operational level. If a railway organisation does not even see the importance to conduct maintenance audit, there is then no purpose to specify the different elements as mentioned above. 2. Asset renewal is also part of the resilience enhancement initiative. Old rolling stocks that are manufactured in the early years might not be able to withstand or have incorporated the necessary preventive measures to protect itself from the latest threats from cyber-security. Hence, this feedback can be related to tactical or operational level of resilience assessment. 3. The scope and details of maintenance audits would be at operational level.
Adaptability to Changing Environment Conditions	1. Potential threats should already be considered in their product design. 2. Should be number or % of software designed with adaptive system? E.g., setting of new UCL and LCL automatically by condition monitoring software	1. Consideration of potential threats during the product design would only covers threats that are uncovered at the point of design. However, as cyber threats are evolving and emerging, there is a need to progressively ensure that the existing software are able to withstand itself from cyber-attacks. Hence, leading to the need to ensure review of the software adaptability to changing environment conditions. 2. This feedback relates more to the assessment of the resilience at operational level.

APPENDIX G CRONBACH'S ALPHA CALCULATION

The formula to calculate the α-value is as follows *("Cronbach's Alpha," 2023)*:

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum {s^2}_y}{{s^2}_x}\right)$$

Whereby K = the total number of questions to be tested

$\sum {s^2}_y$ = the sum of the question variance

${s^2}_x$ = the variance of the total score

Table 35: Summary of data for Cronbach's Alpha calculation

Respondent #	Q27	Q30	Q31	Q33	Q35	Q38	Σ
1	5	5	5	3	4	4	26
2	4	4	4	4	4	3	23
3	4	5	4	4	4	5	26
4	3	2	4	3	3	4	19
5	4	4	4	4	4	4	24
6	4	5	2	3	4	4	22
7	4	5	5	4	4	4	26
8	4	5	5	4	4	4	26
9	4	4	4	3	3	4	22
10	4	4	4	4	4	4	24
11	4	4	4	4	4	4	24
12	4	5	5	4	4	4	26
13	4	4	4	3	2	3	20
14	4	5	3	3	3	3	21
15	5	5	5	5	5	5	30
16	4	4	3	4	4	4	23
17	3	5	5	5	5	5	28
18	4	4	4	3	3	3	21
19	5	5	5	5	5	5	30
20	5	5	5	5	4	5	29
21	4	4	4	4	4	4	24
22	4	5	4	4	4	5	26
23	5	5	5	5	5	5	30
24	1	5	4	4	4	4	22
25	2	4	3	3	3	3	18
26	4	4	4	4	3	3	22
27	3	4	4	3	3	3	20
28	3	4	4	3	3	3	20
29	4	5	4	4	4	4	25
30	4	4	4	4	4	4	24

31	2	3	3	3	3	3	17
32	5	5	5	4	4	5	28
33	3	4	4	3	3	3	20
34	4	4	4	4	4	4	24
35	5	5	5	4	4	4	27
36	3	4	4	4	4	4	23
37	4	5	5	4	4	4	26
38	2	3	4	3	3	3	18
39	3	4	3	3	3	3	19
40	4	5	4	4	4	4	25
41	4	4	4	4	4	3	23
42	3	4	2	5	3	3	20
43	3	4	3	3	3	3	19
44	4	4	4	4	4	4	24
45	4	4	5	4	4	4	25
46	4	4	3	3	2	2	18
47	5	5	5	5	5	5	30
48	4	4	4	4	4	4	24
49	4	4	4	4	4	4	24
50	4	4	4	4	4	4	24
51	4	5	5	4	4	4	26
52	4	4	4	4	4	4	24
53	4	5	5	4	4	4	26
54	3	4	4	3	3	2	19
55	4	5	5	4	4	4	26
56	3	5	5	3	4	4	24
57	3	5	3	4	4	4	23
58	4	3	3	4	4	4	22
59	4	4	4	3	3	3	21
60	3	4	4	4	4	3	22
61	5	4	4	4	4	4	25
62	3	4	4	4	4	4	23
63	3	4	4	3	3	3	20
64	5	4	5	5	5	5	29
65	3	4	4	4	4	4	23
66	4	5	5	5	5	5	29
67	4	4	4	3	3	3	21
68	4	4	4	3	3	3	21
69	3	4	4	3	4	4	22
70	2	2	2	1	1	1	9
71	3	4	4	3	3	3	20
72	3	4	4	3	3	3	20
73	3	4	4	4	3	4	22
74	4	4	4	4	4	4	24
75	3	4	4	4	4	3	22

76	3	4	4	3	3	4	21
77	3	4	4	4	4	4	23
78	3	4	4	3	3	3	20
79	2	3	2	3	3	3	16
80	4	4	4	3	3	3	21
81	3	4	3	3	3	3	19
82	4	4	4	4	4	4	24
83	3	4	4	3	3	4	21
84	3	4	4	4	4	4	23
85	2	4	4	3	3	3	19
86	3	5	4	3	3	3	21
87	4	4	4	3	3	4	22
88	3	4	4	3	3	4	21
89	3	4	4	2	3	3	19
90	3	4	4	3	3	3	20
91	4	4	4	3	3	4	22
92	3	4	4	3	4	3	21
93	4	4	4	2	3	3	20
94	4	4	4	3	4	4	23
95	3	4	4	3	3	3	20
96	2	4	4	3	3	3	19
97	3	5	4	3	4	4	23
98	4	3	4	3	3	3	20
99	5	5	5	5	5	5	30
	0.665034	0.38343	0.473829	0.543822	0.499133	0.558514	11.99633

Table 36: α-value calculated using MS Excel

Variables	**Values**
K	6
$\sum {s^2}_y$	3.123
${s^2}_x$	11.99
α	**0.924**

APPENDIX H LIST OF STRENGTHS AND WEAKNESSES OF TOOL

Table 37: List of strengths and weaknesses

Strengths	Weaknesses
Good stepping-stone in kicking start awareness and action to prepare for emergencies / unexpected occurrences.	Targeted users could have different levels of domain knowledge, process/situational integrity, and risk appetite, as well as different vested interests.
Useful to provide a qualitative assessment but may lack precision to definitively make a strong conclusion. It is also a challenge to try an attempt a quantitative way of assessment.	The assessment sheet might get too long when more assets are being considered.
The tool gives an overarching view of the resilience of the organisation, which can be a good thing. A consolidated platform for staff in the organisation, such as the top management to be aware of.	It requires a fair bit of time to understand the tool in the first place, as there are many parts to read in order to understand the meaning like the attributes and the evaluation criteria.
Critical attributes or factors are identified so that everyone is aware of the role of each attribute.	It is gets tedious at first as understanding of how the tool works is needed, before one can really fill in the blanks.
The tool addresses various factors and elements associated with system resilience.	The outcome from using the tool is dependent of subjective judgement and biases of individuals and may not provide a realistic representation of resilience of the railway organisation.
Able to identify deficient attributes easily.	Might be a bit difficult for first time user to understand, but good that there is a user guide, to explain in detail.
The tool may somehow aid in the assessment efficiently but still might get some hidden issue in it.	As it is more of a qualitative tool, it may somehow be subjective to the person assessing.
It provides a quick overview when someone needs to know the resilience, quick summary.	The tool can be converted using software, so that it makes the usage more intuitive. It takes a bit of time now to understand the different worksheets, before can use the assessment tool.
Provides an over-arching view.	Able to use the tool to identify the strong and weak areas for targeted focus, but drawback is that the assessment might be subjective (depending on individual).
Comprehensive tool to assess resilience of an organisation.	How people performed the assessment may be very subjective. Hence the rating might not reflect the real ground condition.
Identify and prioritise what is most important that would attribute to success.	Might be a bit confusing for first time users.

Strengths	Weaknesses
It adequately and effectively quantifies the resilience assessment for the user.	Provide indicative results however it is subjective to individual's personal experience and ranking.
It is a systematic way of assessment.	The weightage and risk severity setting could be subjective. Suggest referring to historical data (faults and defects encountered in the past) to finetune the weightage. In addition, different sub-systems will have different setting. For example, a bogie vs. electronic controller, the software reliability it is not applicable to the mechanical system while it is important for the latter.
Simple to apply.	Competency and wellness of applicants during tool applications may affect the outcomes.
Doable without large resource.	Not able to test until faced with adversity.
Facilitate staffs to identify what is the weak point in resilience.	Weakness as in unable to predict the actual failure according to the given MTBF, unable to fully utilise the money accordingly.
Strength in assessing the railway as one system and placing them in term of ranking and importance.	The weakness of the tool that it might be too much for layman to read.
The strength of the tools enables to identify the level of rigour.	The tool coverage is quite comprehensive; however, the arrangement of the tools can be more simplified.
1. Able to rank the attributes (similar to risk assessment) and to focus on the areas that need improvement. 2. Easy to understand and use.	Users have to be able to understand the concepts of a wide variety of the attributes to be able to use it effectively.
Prioritisation is clear and strainer efforts.	1. Need to expand to include other systems beside train to understand overall railway resiliency. 2. May not be able to provide a "score" for resiliency level so as to compare against other railway networks/international benchmark 3. Some of the attributes/criteria may need to be sharper so that it may reduce possibility of different interpretation by different person using the assessment
	It depends on personal prospective on the subject and may have variations depend on one experience.
	Could be quite subjective, depending on the user, might need a more detailed checklist to aid on the grading.
	Too much detailed measures for hardware assessment.

APPENDIX I FURTHER AREAS OF IMPROVEMENT FOR CONSIDERATION

Table 38: Suggested feedback on areas for improvement

Suggested feedback
Incident of varying impact levels and their trends where resilience on the subject matter is considered could be one other form of measurement to consider.
Instead of using excel, it is recommended to develop this by using some software to speed up the work.
When a company handles more than 1 rolling stock, who will define the attributes? For example, railway tracks do not involve software. And in term of hardware, how are the attributes to be identified for tracks? worth considering.
System resilience can be represented as a 2-dimensional graph of system performance versus time, to indicate how system performance is affected by a shock event. It is not clear how this tool is used to measure system resilience in relation to robustness, vulnerability, susceptibility, and recovery from the shock event.
Include cost as part of evaluation.
Lesson learnt and return of experience are important factors to be considered in order to improve the system reliability. In addition, besides "Maintenance", "Operation" is also an important factor in reliability. We have to understand the operational need and adjust the assessment accordingly. For example, the reliability requirement of saloon door system for inter-city train and city metro can be different. Inter-city train doors open close less frequently than the city metro in which the doors may open close every few minutes.
Substantiate it by referencing to real scenario applications will help.
The tool needs to be easily interpreted by users. It seems quite abstract now.
Can consider validating some of the attributes/criteria by applying it to some of the real-life cases.
To use in the tender phase? So that bidders are aware they must be at what level? Because RS and emergency exercise division are different, control ops, station ops, so it could be more than just rolling stock you are looking at. Other than competency, may also need to look at the emergency exercises conducted and frequency to grade.
There could be other systems that the company owns, should include too.

APPENDIX J DERIVATION OF OBJECTIVE WEIGHTS USING COMBINED ROC-TOPSIS METHOD

The Design category of Hardware Resilience sub-domain has been used as an example to derive the objective weights for each attribute as shown in Table 39. The ROC-TOPSIS has been executed using MS Excel and is 1 of the spreadsheets in the softcopy of the tool.

Table 39: Example illustration using design category of hardware resilience

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	1. Total votes	2. Rank	3. Calculate Subjective Weightage (ROC)	4. Calculate Objective Weightage (TOPSIS)
Hardware Resilience															
Design	System Integrity	1	1	1	1	1	0	1	0	1	1	8	2	0.26	0.318634954
	System Reliability	1	0	1	1	1	1	1	0	0	1	7	3	0.16	0.180058167
	Risk Management	1	1	0	1	1	1	1	1	1	1	9	1	0.46	0.378309557
	Redundancy Level	1	1	1	1	0	0	1	0	0	1	6	4	0.09	0.085980382
	Resilience Engineering	1	1	1	0	0	1	0	0	0	1	5	5	0.04	0.03701694
											Sum	35		1.00	1.00

1. **Total votes** – Determine vote-counts for each attribute.
2. **Rank** – Rank attributes base on vote-counts
3. **Calculate Subjective Weightage (ROC)** – Use the same ROC Technique formula (1.3) and shown below:

$$w_i = (1/m) \sum_{K=i}^{m} {}^{1}/_{K} \tag{1.3}$$

Where:

m represents the total number of attributes within a category, $i = 1,2, \dots, m$,

w_i *represents Attribute Weightage,*

K represents the ranking level of the i-th attribute within a category.

4. **Calculate Objective Weightage (TOPSIS)** – Use TOPSIS to convert subjective weights to objective weights. The steps and formulas are elaborated below:

Step 1: Establish Decision Matrix X, i.e., X_{ij}

The decision matrix is established by following the matrix structure shown below with *m* Attributes (A) and *n* number of Members (M).

	M_1	M_2	..	M_j	..	M_n
A_1	x_{11}	x_{12}	..	x_{1j}	..	x_{1n}
A_2	x_{21}	x_{22}	..	x_{2j}	..	x_{2n}
:	:	:	..	:	..	:
A_i	x_{i1}	x_{i2}	..	x_{ij}	..	x_{in}
:	:	:	..	:	..	:
A_m	x_{m1}	x_{m2}	..	x_{mj}	..	x_{mn}

Decision Matrix of Design Category

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}
A_1	1	1	1	1	1	0	1	0	1	1
A_2	1	0	1	1	1	1	1	0	0	1
A_3	1	1	0	1	1	1	1	1	1	1
A_4	1	1	1	1	0	0	1	0	0	1
A_5	1	1	1	0	0	1	0	0	0	1
SUM	**5**	**4**	**4**	**4**	**3**	**3**	**4**	**1**	**2**	**5**

Step 2: Normalize Decision Matrix

The normalization of the decision matrix is conducted using the following formula:

$$\bar{X}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{2.1}$$

Normalized Decision Matrix of Design Category

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}
A_1	0.20	0.25	0.25	0.25	0.33	0	0.25	0	0.50	0.20
A_2	0.20	0	0.25	0.25	0.33	0.33	0.25	0	0	0.20
A_3	0.20	0.25	0	0.25	0.33	0.33	0.25	0.20	0.50	0.20
A_4	0.20	0.25	0.25	0.25	0	0	0.25	0	0	0.20
A_5	0.20	0.25	0.25	0	0	0.33	0	0	0	0.20

Step 3: Establish Weighted Normalized Decision Matrix Y, i.e., Y_{ij} (Use subjective weights by ROC)

The weighted normalized decision matrix is established using the following formula:

$$Y_{ij} = \bar{X}_{ij} * w_i \tag{2.2}$$

W_i is the subjective weight calculated earlier using the ROC technique.

	A_1	A_2	A_3	A_4	A_5
W_i	0.26	0.16	0.46	0.09	0.04

Weighted Normalized Decision Matrix of Design Category

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}
A_1	0.05	0.06	0.06	0.06	0.09	0	0.06	0	0.13	0.05
A_2	0.03	0	0.04	0.04	0.05	0.05	0.04	0	0	0.03
A_3	0.09	0.06	0	0.06	0.09	0.09	0.064	0.05	0.13	0.05
A_4	0.02	0.02	0.02	0.02	0	0	0.02	0	0	0.02
A_5	0.01	0.01	0.01	0	0	0.01	0	0	0	0.02

Step 4: Determine Positive Ideal (A^+) and Negative Ideal (A^-) Solutions

The positive ideal solution (A^+) is determined and negative ideal solution (A^-) are determined by the followings:

$$A^+ = \{Y_1^+, Y_2^+, \ldots, Y_j^+, \ldots Y_n^+\} \tag{2.3}$$

$$A^{+} = \left\{\left(\max_{i} Y_{ij} \,\middle|\, j \in n\right)\right\} \quad (2.4)$$

$$A^{-} = \{Y_1^{-}, Y_2^{-}, \ldots, Y_j^{-}, \ldots Y_n^{-}\} \quad (2.5)$$

$$A^{-} = \left\{\left(\min_{i} Y_{ij} \,\middle|\, j \in n\right)\right\} \quad (2.6)$$

Calculated A^+ and A^-

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}
A^+	0.09	0.06	0.06	0.06	0.09	0.09	0.07	0.06	0.13	0.05
A^-	0.01	0	0	0	0	0	0	0	0	0.01

Step 5: Determine Euclidean Distance from A+ (d_i^+) and from A- (d_i^-), Performance Score (D_i)

a. The Euclidean distance from the positive ideal solution(d_i^+) and the negative ideal solution (d_i^-) is computed by using the following formula:

$$d_i^{+} = \sqrt{\sum_{j=1}^{n}\left(Y_{ij} - Y_j^{+}\right)^2} \quad (2.7)$$

$$d_i^{-} = \sqrt{\sum_{j=1}^{n}\left(Y_{ij} - Y_j^{-}\right)^2} \quad (2.8)$$

b. The performance score **(D_i)** is computed by using the following formula:

$$D_i = \frac{d_i^{-}}{d_i^{+} + d_i^{-}} \quad (2.9)$$

Step 6: Determine Objective Weight for each attribute (O_i)

The objective weight is computed by using the following formula:

$$O_i = \frac{D_i}{\sum_{i=1}^{m} D_i} \quad (2.10)$$

Computed O_i

	d_i^+	d_i^-	D_i	O_i
A_1	0.107494	0.209796	0.661213	0.318635
A_2	0.176972	0.105571	0.373646	0.180058
A_3	0.064167	0.234347	0.785046	0.37831
A_4	0.217204	0.04717	0.178421	0.08598
A_5	0.233592	0.019437	0.076815	0.037017
		Sum	2.075142	

This process is applied to all attributes within the assessment tool.

APPENDIX K IMPACTS OF VOTED CRITICALITY BY MEMBERS ON OBJECTIVE WEIGHTS

K.1 Scenario 1 – Extreme Case

The decision matrix considered in this scenario is shown below:

Table 40: Decision Matrix (1 pax voted not-critical for all attributes)

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	1. Total votes	2. Rank	3. Calculate Subjective Weightage (ROC)	4. Calculate Objective Weightage (TOPSIS)
Hardware Resilience															
Design	System Integrity	1	1	1	1	1	1	1	0	1	1	9	2	0.26	0.30439244
	System Reliability	1	1	1	1	1	1	1	0	1	1	9	3	0.16	0.179878
	Risk Management	1	1	1	1	1	1	1	0	1	1	9	1	0.46	0.43684657
	Redundancy Level	1	1	1	1	1	1	1	0	1	1	9	4	0.09	0.07888299
	Resilience Engineering	1	1	1	1	1	1	1	0	1	1	9	5	0.04	0
											Sum	45		1.00	1.00

The table below summarises the ***O$_i$*** *values for all attributes when the number of people who voted* ***not-critical*** *for all attributes increase.*

Table 41: Summary of Oi values

Attributes	1 pax	2 pax	3 pax	4 pax	5 pax	6 pax	7 pax	8 pax	9 pax
System Integrity	0.304392	0.313647	0.361111	0.361111	0.361111	0.361111	0.361111	0.361111	0.361111
System Reliability	0.179878	0.188053	0.194444	0.194444	0.194444	0.194444	0.194444	0.194444	0.194444
Risk Management	0.436847	0.416007	0.361111	0.361111	0.361111	0.361111	0.361111	0.361111	0.361111
Redundancy Level	0.078883	0.082293	0.083333	0.083333	0.083333	0.083333	0.083333	0.083333	0.083333
Resilience Engineering	0	0	0	0	0	0	0	0	0

K.2 Scenario 2 – Random Case

The decision matrix considered in this scenario is shown below:

Table 42: Decision Matrix (1 pax voted not-critical for all attributes)

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	1. Total votes	2. Rank	3. Calculate Subjective Weightage (ROC)	4. Calculate Objective Weightage (TOPSIS)
Hardware Resilience															
Design	System Integrity	0	1	1	1	1	0	1	0	1	1	7	2	0.26	0.30594545
	System Reliability	1	0	1	1	1	1	1	0	0	1	7	3	0.16	0.215282372
	Risk Management	0	1	0	1	1	1	1	0	1	1	7	1	0.46	0.324512479
	Redundancy Level	1	1	1	1	0	0	1	0	0	1	6	4	0.09	0.116355611
	Resilience Engineering	0	1	1	0	0	1	0	0	0	1	4	5	0.04	0.03790409
											Sum	31		1.00	1.00

The table below summarises the O_i values for all attributes when the number of people who voted ***not-critical*** for all attributes increase.

Table 43: Summary of O_i values

Attributes	1 pax	2 pax	3 pax	4 pax	5 pax	6 pax	7 pax	8 pax	9 pax
System Integrity	0.305945	0.329654	0.332044	0.475756	0.43123	0.432445	0.440015	0.449658	0.5
System Reliability	0.215282	0.184005	0.180794	0.099776	0.083078	0.080765	0.08822	0.063011	0
Risk Management	0.324512	0.358896	0.363011	0.353227	0.43123	0.432445	0.440015	0.449658	0.5
Redundancy Level	0.116356	0.088238	0.082248	0.05235	0.04162	0.041036	0.031749	0.037674	0
Resilience Engineering	0.037904	0.039207	0.041903	0.01889	0.012842	0.013308	0	0	0

K.3 Scenario 3 – Change in Numbers of Attributes

The decision matrix considered in the scenario with an increase in number of attributes is shown below:

Table 44: Decision Matrix (1 pax voted not-critical for all attributes) – Increase to 7

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	1. Total votes	2. Rank	3. Calculate Subjective Weightage (ROC)	4. Calculate Objective Weightage (TOPSIS)
Hardware Resilience															
Design	System Integrity	1	1	1	1	1	1	1	0	1	1	9	2	0.23	0.24166667
	System Reliability	1	1	1	1	1	1	1	0	1	1	9	3	0.16	0.15833333
	Risk Management	1	1	1	1	1	1	1	0	1	1	9	1	0.37	0.40833333
	Redundancy Level	1	1	1	1	1	1	1	0	1	1	9	4	0.11	0.10277778
	Resilience Engineering	1	1	1	1	1	1	1	0	1	1	9	5	0.07278912	0.06111111
	Attribute XX	1	1	1	1	1	1	1	0	1	1	9	6	0.04421769	0.02777778
	Attribute YY	1	1	1	1	1	1	1	0	1	1	9	7	0.02040816	0
											Sum	63		1.00	1.00

The table below summarises the O_i values for all attributes when the number of people who voted ***not-critical*** for all attributes increase.

Table 45: Summary of O_i values

Attributes	1 pax	2 pax	3 pax	4 pax	5 pax	6 pax
System Integrity	0.241667	0.241667	0.241667	0.241667	0.241667	0.241667
System Reliability	0.158333	0.158333	0.158333	0.158333	0.158333	0.158333
Risk Management	0.408333	0.408333	0.408333	0.408333	0.408333	0.408333
Redundancy Level	0.102778	0.102778	0.102778	0.102778	0.102778	0.102778
Resilience Engineering	0.061111	0.061111	0.061111	0.061111	0.061111	0.061111
Attribute XX	0.027778	0.027778	0.027778	0.027778	0.027778	0.027778
Attribute YY	0	0	0	0	0	0

The decision matrix considered in the scenario with a decrease in number of attributes is shown below:

Table 46: Decision Matrix (1 pax voted not-critical for all attributes) – Decrease to 2

	Resilience Attributes	Member #1	Member #2	Member #3	Member #4	Member #5	Member #6	Member #7	Member #8	Member #9	Member #10	1. Total votes	2. Rank	3. Calculate Subjective Weightage (ROC)	4. Calculate Objective Weightage (TOPSIS)
Hardware Resilience															
Design	System Integrity	1	1	1	1	1	1	1	0	1	1	9	1	0.75	1
	System Reliability	1	1	1	1	1	1	1	0	1	1	9	2	0.25	0
											Sum	18		1.00	1.00

The table below summarises the $\boldsymbol{O_i}$ values for all attributes when the number of people who voted ***not-critical*** for all attributes increase.

Table 47: Summary of O_i values

Attributes	1 pax	2 pax	3 pax	4 pax	5 pax	6 pax
System Integrity	1	1	1	1	1	1
System Reliability	0	0	0	0	0	0

APPENDIX L SIMULATED APPLICATION OF ASSESSMENT TOOL

1. Resilience Performance of Railway Organisation (Before Improvement)

Overall Resilience Score		**2.80**	
Resilience Domain	**Sub-Domains**	**Associated Attributes**	**Evaluated Attribute Score**
Technical (Rolling Stock)	**Hardware Resilience**		
	Design	System Integrity	2
		System Reliability	4
		Risk Management	3
		Redundancy Level	4
		Resilience Engineering	1
	Operation	Interoperability	2
		System Interface (With other railway assets)	4
	Maintenance	System Maintainability	4
		Conduct of Maintenance	3
		Conduct of Maintenance Audit	3
		Fault Monitoring and Diagnostic Capability	1
		Adaptability to Changing Environment Conditions	4
	Assets Renewal	Asset Performance	4
		Asset Conditions	4
		Availability of Spares	1
	Software Resilience		
	Design	Software Safety Integrity	4
		Redundancy Level	2
		Risk Management	4
		Cybersecurity Protection	4
	Maintenance	Fault Monitoring and Diagnostic Capability	1
		Conduct of Maintenance Audit	4
		Adaptability to Changing Environment Conditions	4
Organizational	**Internal Resilience**	Leadership	1
		Resilient Strategies	1
		Effective Communication (Within Organization)	4
		Risk Management	3
		Business Continuity	4
		Emergency Responses	4
		Staff Competency (In Execution of Emergency Responses)	2
		Staff Competency (In Domain Area of Work)	4
		Adequacy of Resources	4
	External Resilience	Situational Awareness	1
		Effective Communication (With External Agencies)	4
		Effective Communication (With Railway Users)	4

Figure 53: Resilience performance of railway organisation (before improvement)

2. Resilience Performance of Railway Organisation (After Improvement)

Overall Resilience Score		**2.98**	
Resilience Domain	**Sub-Domains**	**Associated Attributes**	**Evaluated Attribute Score**
Technical (Rolling Stock)	**Hardware Resilience**		
	Design	System Integrity	2
		System Reliability	4
		Risk Management	3
		Redundancy Level	4
		Resilience Engineering	2
	Operation	Interoperability	2
		System Interface (With other railway assets)	4
	Maintenance	System Maintainability	4
		Conduct of Maintenance	3
		Conduct of Maintenance Audit	3
		Fault Monitoring and Diagnostic Capability	2
		Adaptability to Changing Environment Conditions	4
	Assets Renewal	Asset Performance	4
		Asset Conditions	4
		Availability of Spares	1
	Software Resilience		
	Design	Software Safety Integrity	4
		Redundancy Level	2
		Risk Management	4
		Cybersecurity Protection	4
	Maintenance	Fault Monitoring and Diagnostic Capability	2
		Conduct of Maintenance Audit	4
		Adaptability to Changing Environment Conditions	4
Organizational	Internal Resilience	Leadership	2
		Resilient Strategies	2
		Effective Communication (Within Organization)	4
		Risk Management	3
		Business Continuity	4
		Emergency Responses	4
		Staff Competency (In Execution of Emergency Responses)	2
		Staff Competency (In Domain Area of Work)	4
		Adequacy of Resources	4
	External Resilience	Situational Awareness	2
		Effective Communication (With External Agencies)	4
		Effective Communication (With Railway Users)	4

Figure 54: Resilience performance of railway organisation (after improvement)