Resilient Railway Project Management by Means of System Dynamics Tools

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Executive Summary

Projects can be a collection of numerous interdependent subsystems, including activities, resources, information, etc. Complexity has been found to significantly impact the realisation of projects in terms of scope, time, and cost, and hence influences the discipline of project management. Studies confirm that most megaprojects do not meet their defined scope, time, and cost estimations and hence can be considered project failures. Despite many research studies considering these issues, projects still fail. This has been primarily due to a poor understanding of complexity, particularly the non-linear and dynamic interactions and interdependencies between project elements and the project and its surrounding environment. These issues can lead to deviations from defined objectives, delays, and cost overruns. Nonlinearity in complex projects causes unpredictability in the relationship between inputs and outputs. The behaviour of nonlinear systems can, on occasion, be predicted by employing some qualitative patterns, but complex systems are generally not responsive to conventional systems analysis. As modern projects are becoming more complex, new types of management approaches for projects are needed. Research is therefore needed to both: (i) understand complex issues within projects and (ii) decide how to manage complexity appropriately.

Railway infrastructure projects are particularly vulnerable to disruptive events caused by uncertainties and internal and external influences (such as scope change, change in design etc.) during their lifecycle. The adaptive capacity of systems refers to either the ability of the system to (i) return to its equilibrium point when disruption is encountered, using its programmed strategies, and planning methods, or (ii) adopt new approaches to respond to events that are outside of its preconfigured design and structure. The measure of the rapidness of a project to recover from disruption is referred to as resilience. The literature review highlighted a few of

future research avenues to achieve a reliable tool to assess project resilience : (i) apply methods in more advanced fields (i.e. applicable to megaprojects); (ii) identify a set of validated indicators that can assess a project's resilience, and hence its ability to manage disruptions; (iii) conduct structured experimental studies based on identified indicators that can evaluate proposed conceptual frameworks for assessing project resilience, and (iv) develop tools to be used by project stakeholders and managers to evaluate the impact of efforts required to enhance the resilience of the existing and future projects. Such a tool could be applied to measure a project's strengths and weaknesses and suggest action plans to improve its resilience. The tool would augment existing project risk management strategies and hence help projects to become more resilient when facing disruptive events or unexpected changes.

The scope of the research is to develop and apply an innovative methodology and analysis tool to railway project management. The approach considers project management as a system and utilises concepts and methods of system dynamics, to model the system (and its subsystems) and to evaluate its resilience. To evaluate the real-life application of the proposed method, the author applied his proposed method to measure the resilience of metro systems in response to disruptions or additional operating hours. The results are presented in Chapter 8.

The research aims to propose an innovative systematic, and reliable methodology to consider railway project management structure as a complex system and model its subsystems via Causal Loop Diagrams. To do so, the following objectives are defined:

- Generate a set of systematically developed causal loop diagrams for key subsystems of project management and conduct qualitative analysis to identify the resilience factors of each subsystem.

- Integrate and synthesise the modelled subsystems through developing innovative structured and formulated stock and flow diagrams (SFD) and studying the resilience of the proposed schematic project management structure. Qualitative analysis will be utilised to study interactions between developed subsystems
- Convert and propose the developed SFD into an innovative modelling tool, which can be adapted to any railway project and enable users to analyse trade-offs between different variables affecting project management resilience, as well as evaluate the impact of decisions on project performance.
- Develop a set of novel and unique CLDs and SFDs to model metro system operation management environment and analyse its resilience to be converted into 24-hour metro operation.

The proposed approach and platform of thinking are proposed to be applied as a complementary tool to measure the resilience of project management for railway infrastructure schemes and to add value to the existing project risk management approaches.

Project management was considered as a system with five main subsystems, namely, project governance, requirements management, configuration management, in-house engineering and change management. Multiple case study analysis was used to diagnose and identify the main components of the proposed subsystems that most affect the vulnerability and resilience of the system the most. To achieve this, questionnaires were designed to survey the key components and factors, to be finally used as the main variables for generating causal loop diagrams for each subsystem. Then CLDs were quantified to facilitate quantitative analysis in addition to the qualitative analysis. The full methodology is presented in Figure 1.5.

This thesis presents an innovative combination of qualitative and quantitative analysis approaches founded on system dynamics tools, to evaluate the resilience of the proposed schematic project management structure for railway. The main idea was to propose an innovative and practical approach to applying system thinking to conventional project management strategies to reinforce it and bridge the existing gaps to manage the growing complexity of modern projects., as highly recommended by previous researchers.

The proposed schematic project management structure and subsystems are modelled using the data derived from multiple case study analysis, causal loop diagrams (CLDs), and Vensim software. Generated CLDs were reviewed by a group of external experts and some from the studied projects to validate the realism of the CLDs. CLDs are simplified systematically to keep the reliability and at the same time applicability for analysis.

CLDs provide a set of cross-validation tools such as the Uses tree and Cause tree, which deliver traceability features of the generated CLDs. Uses trees can be used to trace the impact of any selected variable on the other components of the system., whilst the “Cause Tree” can be used to figure out the variables with an impact on any selected component. Employing these tools, provided a reliable qualitative analysis tool and allowed the author to bring out the causal feedback of each CLD and identify the key resilience indicators for each subsystem of the model (Qualitative analysis).

The qualitative analysis of CLDs highlighted the key resilience indicators affecting each subsystem and reflected the causal feedback of the loops. The traceability feature of the CLDs can be adopted as an applicable method to simulate the environment of complex projects and assist managers to visually trace the impact of their decisions on the performance of the project.

The research contribution can be briefly summarised as:

- Developed and proposed an innovative methodology combining multiple case study analysis and system dynamics tools, which can be followed by future researchers to visualise the complex environment of projects.

- Generated a set of reference CLDs to model the railway project management as a system. These models are developed for the first time and deliver a holistic overview of any similar railway project. Researchers can adapt these reference models and map their individual systems against the generated CLDs. Hence, the CLDs can be modified to reflect the true nature of any specific system (Qualitative analysis tool for complex railway projects).

- Designed, formulated, and proposed a novel SFD to analyse the resilience of the railway's proposed schematic project management structure, according to the resilience indicators identified via CLD analysis. The author designed a unique user interface for system analysis. This is the first-of-a-kind toolset, which allows managers and researchers to change the resilience indicators of the project management and analyse its impact on project performance and management resilience (A novel quantitative analysis tool applicable to all railway projects).

- Based on the findings from qualitative and quantitative analysis, the author developed a set of novel formulas and a conceptual two-dimensional model to enhance the understanding of project resilience. This creates a platform of thinking and proposes new research avenues for future researchers to focus on other dimensions with potential impact on resilience and achieve the optimum level of performance.

- Designed and proposed a unique system dynamic tool, formulated, and structured to assist managers and planners to analyse the resilience of metro operation environments. The tools can be sued to manage disruption in the metro system or in the case of converting metros to 24-hour metro operation and analyse its impact on metro system resilience.

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Finally, I am grateful to my dear friends and colleagues who became my family. Hats off to Dr Jenny Illingsworth, Joy grey, Charles, Stephen, Nadeen, Atkins and NCATI colleagues and all my friends of misery for their endless support.

Modestly and proudly, dedicated to:

All brave Iranian heroes, especially pioneer Iranian women, who influenced countless people around the world and selflessly fighting for:

Woman, Life, Liberty

#MahsaAmini

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LIST OF ABBREVIATIONS

APM	Association for Project Management
CLD	Causal Loop Diagram
DFT	Department for Transport
ECO	East Coast
HS2	High Speed Two
INCOSE	The International Council on Systems Engineering
KPI	Key Performance Indicator
MML	Midland Mainline
NAO	National Audit Office
NOE	North of England
NR	Network Rail
NY	Northern Yorkshire
ORR	Office of Rail and Road
SFD	Stock and Flow Diagram
SW	Southwest
WCRM	West coast Route Modernisation
WEC	World Economic Forum

GLOSSARY OF TERMINOLOGY

Causal Loop	Graphical diagrams bring out the causal interactions between components of a system and help in better understanding and anticipating the behaviour of the system.
causes Tree	A feature, which enables the user to choose any specific variable and map out the variables, which affect the selected variable.
Uses Tree	A feature, which enables the user to choose any specific variable and find the variables, which will influence by the selected variable.
Stock and Flow Diagram	Stock and flow (or Level and Rate) diagrams are ways of representing the structure of a system with more detailed information than is shown in a causal loop diagram. Stocks (Levels) are fundamental to generating behaviour in a system; flows (Rates) cause stocks to change.

Chapter 1

INTRODUCTION

1.1 Existing Challenges

Large systems, such as those found in the railway sector, are becoming increasingly complex in design, construction, and management. These systems are comprised of, and/or interface with, different subsystems that interact and exhibit outputs and behaviours that are commonly dynamic, nonlinear and unpredictable in nature (Maylor et al. 2008). This inherent diversity results in complex behaviour and creates emergent properties that render the systems' behaviour unpredictable (INCOSE 2015, pp.5-9).

Projects can be considered to be a collection of numerous interdependent subsystems including activities, resources, information, etc (Oughton et al. 2018). Complexity has been found to have a significant impact on the realisation of projects in terms of scope, time, and cost, and hence influences the discipline of project management.

Studies confirm that most megaprojects do not meet their defined scope, time, and cost estimations (Janssen et al. 2015). While some define megaprojects by their value (US$1 billion or more), duration (several years), or reach (multiple stakeholders), others state that complexity is a more important factor than the cost in defining megaprojects (Flyvbjerg 2014; Pitsis et al. 2018).

Despite many research studies considering these issues, projects still fail. This is primarily due to a poor understanding of complexity, in particular the non-linear and dynamic interactions and interdependencies between project elements (Baccarini 1996) and between the project and its surrounding environment (Rahi et al. 2019).

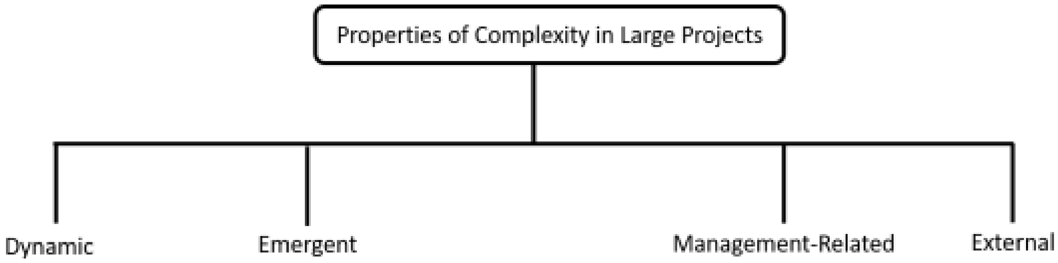


Figure 1-1. Types of complexity in large projects (Author)

These issues can lead to deviations from defined objectives, delays and cost overruns (Rahi et al. 2019). There are four main properties of complexity that affect large projects, namely dynamic, emergent, management-related, and external (Figure 1-1).

Dynamic complexity such as organisational changes (Schlick *et al.* 2013) is time-dependent and deals with the operational behaviour of a system (Zhu and Mostafavi 2017). Emergent properties arise from interactions and interdependencies between constituents in complex systems and greatly affect system-level behaviours and performance" (Johnson 2006).

Nonlinearity in complex projects causes unpredictability in the relationship between inputs and outputs (Richardson 2008). The behaviour of nonlinear systems can on occasion be predicted by employing some qualitative patterns, but complex systems are generally not responsive to conventional systems analysis (Hirsch et al. 2013). As modern projects are becoming more complex (Gatrell 2005; Tozan and Ompad 2015; Kermanshachi et al. 2016b), new types of management approaches for projects are needed (Gransberg et al. 2013; Bakhshi et al. 2016). Traditional project management tools and techniques, based on the assumptions that a set of tasks can be discrete, with well-defined information about time, cost, and resources, and with extensive preplanning and control, are often found inadequate (San Cristóbal et al. 2018, p.8).

Issues can also be caused by the financing and management structure of projects, for example, Grimsey and Lewis (2002) describe that the complexity of public, private, and partnership

(PPP) projects generates potential risks. The nature of the risks will change over time. Research is therefore needed to both: (i) understand complex issues within projects, and (ii) decide how to manage complexity appropriately.

1.2 Research Rationale

The challenges identified in the four properties of complexity highlight that the traditional use of conventional project management methods is not compatible with projects with growing complexity (Williams 2005, p.506). Railway infrastructure projects are particularly vulnerable to disruptive events caused by uncertainties and internal and external influences (such as scope change, change in design etc.) during their lifecycle (Han and Bogus 2020). The adaptive capacity of a system refers to either the ability of the system to (i) return to its equilibrium point when disruption is encountered, using its programmed strategies and planning methods (Woods and Wreathall 2008); or (ii) adopt new approaches to respond to events that are outside of its preconfigured design and structure (Vogus and Sutcliffe 2007). The measure of the rapidness of a project to recover from disruption is referred to as resilience (Armstrong *et al.* 2017; Han and Bogus 2020).

Integration of resilience management techniques with project management is novel, and studies suggest that resilience management and thinking are capable of supporting understanding and decision-making within projects particularly when they are faced with disruptive events (Rahi *et al.* 2019).

Different researchers, state that systems engineering can be used to analyse and describe complex systems and their project management (Keating et al. 2003; Gersh et al. 2005; Elliott 2014; Pickar 2015). Loosemore and Cheung (2015) have proposed that system thinking can support the understanding of complexity, but it is not widely adopted by project management practitioners in a recent study, Nachbagauer and Schirl-Boeck (2019) integrated system theory and resilience in the field of management of megaprojects and concluded that preceding project management research has neglected the risk of uncertainty and has focused on hierarchical planning and centralised control methods. Nachbagau and Schirl-Boeck conclude that uncertainty must be considered to realise a more resilient approach.

Figure 1-2 depicts a schematic overview of the systematic approach, adopted by the author to consider railway project management as a system and analyse its resilience via system dynamics tools. To bridge the existing gaps within the field of application of resilience thinking to project management, (Armstrong *et al.* 2017; Fraccascia *et al.* 2018; Rahi 2019b; Rahi *et al.* 2019)'s research defined future research avenues to achieve a reliable tool for assessing project resilience as follow: (i) apply methods in more advanced fields (i.e. applicable to megaprojects); (ii) identify a set of validated indicators that can assess a project's resilience, and hence its ability to manage disruptions; (iii) conduct structured experimental studies based on identified indicators that can evaluate proposed schematic project management structure for assessing project resilience, and (iv) develop tools to be used by project stakeholders and managers to evaluate the impact of efforts required to enhance the resilience of the existing and future projects. Such a tool could be applied to measure a project's strengths and weaknesses as well as suggest action plans to improve its resilience. The tool would augment existing project risk management strategies and hence help projects to become more resilient when facing disruptive events or unexpected changes (Rahi *et al.* 2014).

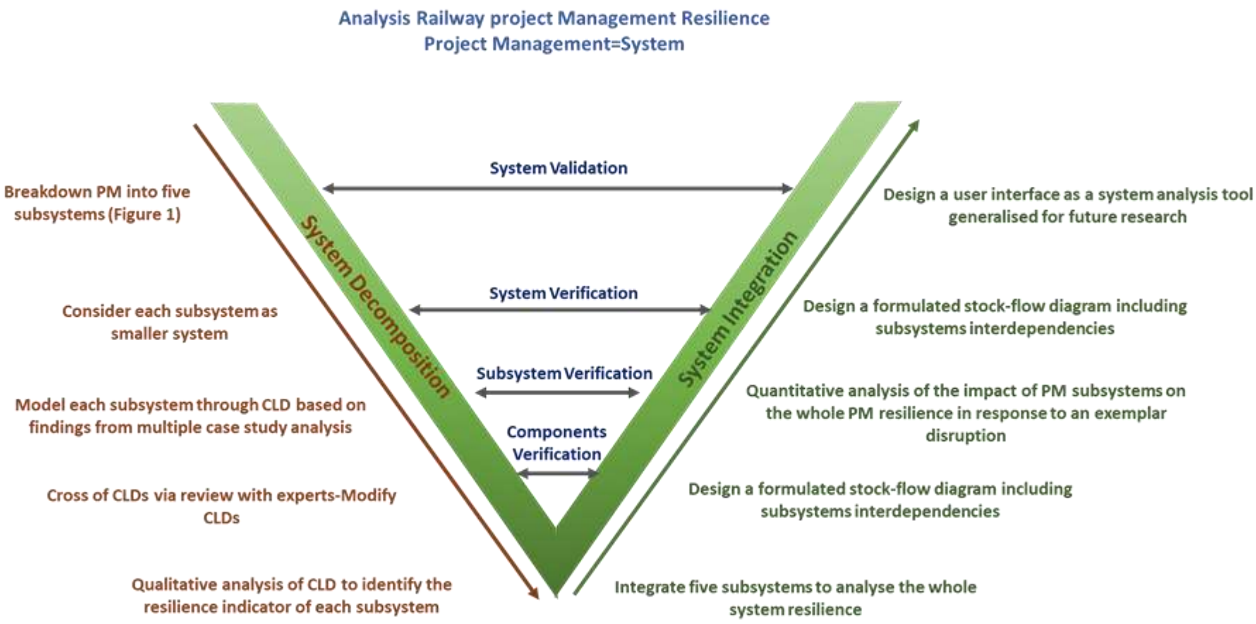


Figure 1-2 Schematic systematic process to consider PM as a system and analyse its resilience via system dynamics tools (Author)

1.3 Research Scope, Hypothesis & Objectives

1.3.1 Scope

The author’s research focussed on proposing and developing a schematic project management structure (i.e., considering project management as a complex system and breaking it down into smaller sub-systems) to create a platform to study its performance and resilience against disruptions (and to assess how application of system dynamics tools will optimise its performance). In other words, project management was considered an entity formed of some key components. Metaphorically, the model is a cog-wheel, which is formed of smaller cogwheels, affecting each other and their performance would affect the whole functionality of the system. The logic behind this proposed structure was to provide a platform to apply system thinking to project management. Hence, project management was considered as a system formed of five sub-systems and then those five sub-systems were modelled via system dynamics tools. Project management is a conceptual and non-tangible entity, and the proposed structure tries to visualise this entity. That is why the author calls the proposed model a schematic project management structure. To achieve this goal, the author utilised multiple case study analysis approaches to study UK tramway construction projects. Tramway projects were chosen as case studies as they have high levels of complexity and uncertainty. Additionally, as several construction projects were ongoing in the UK at the time of the research, the author had a chance to gather data from live projects and create a dialogue that allowed feedback to be provided to, and received from, experts in the field. The scope of the research is to develop and apply an innovative methodology and analysis tool to railway project management. The approach considers project management as a system and utilises concepts in system dynamics, which are used to model the system (and its subsystems) and evaluate its resilience.

1.3.2 Objectives

The research aims to propose an innovative systematic and reliable methodology to consider railway project management structure as a complex system and model its subsystems via Causal Loop Diagrams (CLDs). To do so, the following objectives are sought:

Objective 1: Consider railway project management as a system with five key subsystems to propose a schematic project management structure. This provides a platform to study the performance and resilience of the project management against disruptions. Then generate a set of systematically developed causal loop diagrams for key subsystems, which identify the resilience factors for each subsystem (Refer to Section 9.2).

Objective 2: Propose the generated CLDs as reference models to be used as the backbone to visually model and analyse any other railway projects. Models need to be modified and bespoke based on each project, which we need to study. (Refer to Section 9.2).

Objective 3: Conduct qualitative analysis for generated CLD models, to identify the existing gaps within the project management approach applied to the studied cases. Cross-validate the findings from multiple case study analysis with findings from real-life projects. This helps in assessing the capability of the proposed approach. (Refer to Section 9.2).

Objective 4: Introduce CLDs as a systematic decision-making tool. The traceability and impact analysis feature of the CLDs (qualitative analysis) can be applied to existing and future railway projects, to achieve a more reliable decision-making process. (Refer to Section 9.2).

Objective 5: Integrate and synthesise the modelled subsystems through innovative structured and formulated Stock and Flow diagrams (SFD) and study the resilience of the proposed schematic project management structure, by quantitative analysis of the interactions between developed subsystems. (Refer to Section 9.3).

Objective 6: Convert the developed SFD into an innovative modelling tool, which can be adapted to any railway project and enable users to analyse trade-offs between different variables affecting project management resilience, as well as evaluate the impact of decisions on project performance. (Refer to Section 9.3).

Objective 7: Propose the developed SFDs as a tool to apply system dynamics to railway project management. The proposed approach can assist in measuring the resilience of the adopted project management approaches in any specific project and the trade-off between different optimisation factors. This will assist project managers in making informed decisions, analysing the impact of their decisions on the project performance, and systematically optimising the project management strategies.

Objective 8: In parallel research, which is independent of the main topic of this thesis, the author will evaluate the applicability of his proposed approach to improve the resilience of metro systems operation. This will expand the applicability of the approach and identify further research avenues in this field of research. **(Refer to Section 9.4).**

1.3.3 Research Contributions

This research's contributions are listed below:

- As a pilot study, this research provides a holistic overview of railway project management resilience. Previous studies had focused on the resilience of projects from a specific point of view, such as the resilience of railway tracks, infrastructure, tunnels, passenger flow and diagnosing causes of accidents or risk analysis in general. This research considered railway project management as a system, formed from five main subsystems, and visualised using data derived systematically from multiple case study analysis and system dynamics tools. The outcome models can be used as a benchmark that can be adapted to other railway projects. Project managers and stakeholders can use the approach to improve decision-making processes and enhance the resilience of the proposed schematic project management structure.

- The proposed CLDs have been designed systematically and cross-validated by experts, hence they can be used as reference models. Modellers can use the author's CLDs and map them against the studied system.

- Two unique and innovative SFDs stand as the first implementation of formulated SFDs. They provide a toolset for future researchers, managers, and modellers to evaluate the impact of changes in the various factors affecting the resilience of the system and optimise the decision-making process. This work will potentially enhance the project management resilience of railway project management approaches, reduce change latency, and mitigate the impacts of unknowns in the project lifecycle.

1.4 Methodology

Project management was considered a system with five main subsystems, namely, project governance, requirements management, project governance, in-house engineering and change management. The proposed structure was reviewed, modified, and approved by a group of academic experts. The modified structure was cross-validated and modified against the results of the literature review. The modified version was reviewed by a group of project managers from the case study projects. 8 out of 10 project managers approved that structure presented in Figure 1-3 represents the main components of the project management adopted in the case study projects, hence the project management structure was simplified to facilitate the application of system dynamics tools.

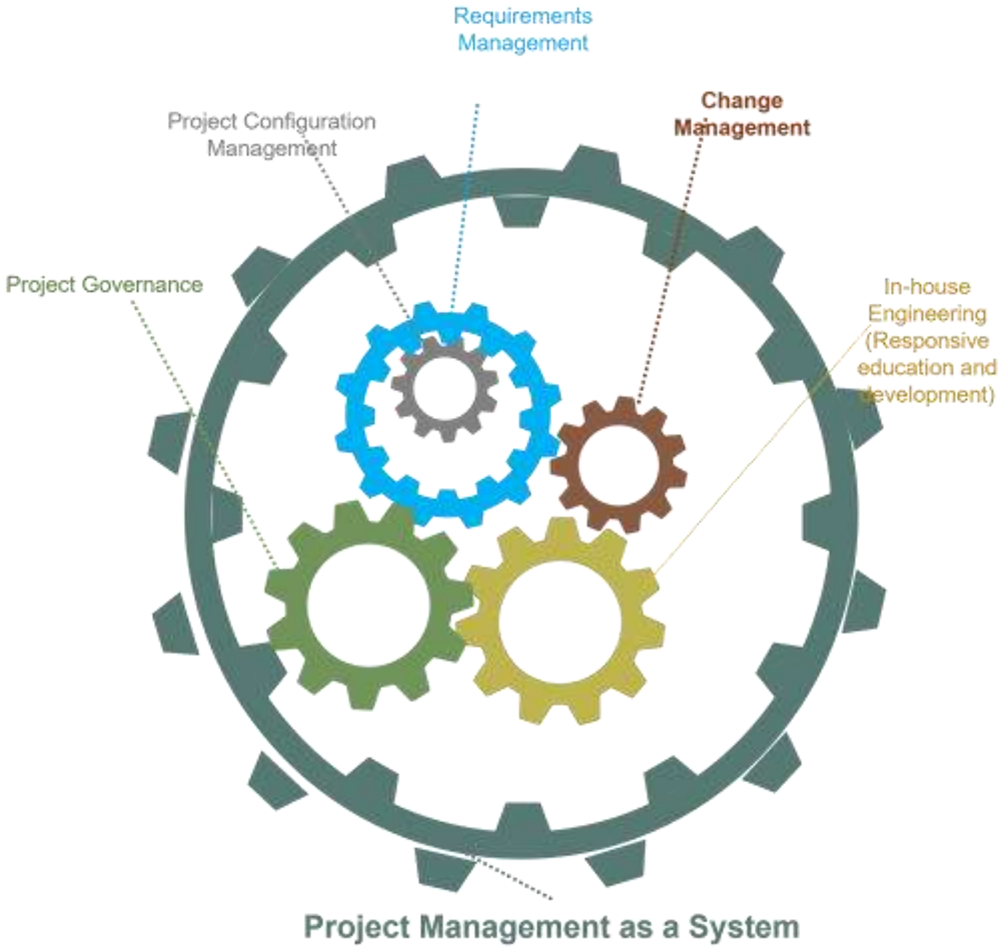


Figure 1-3 Proposed schematic structure for railway project management (Author)

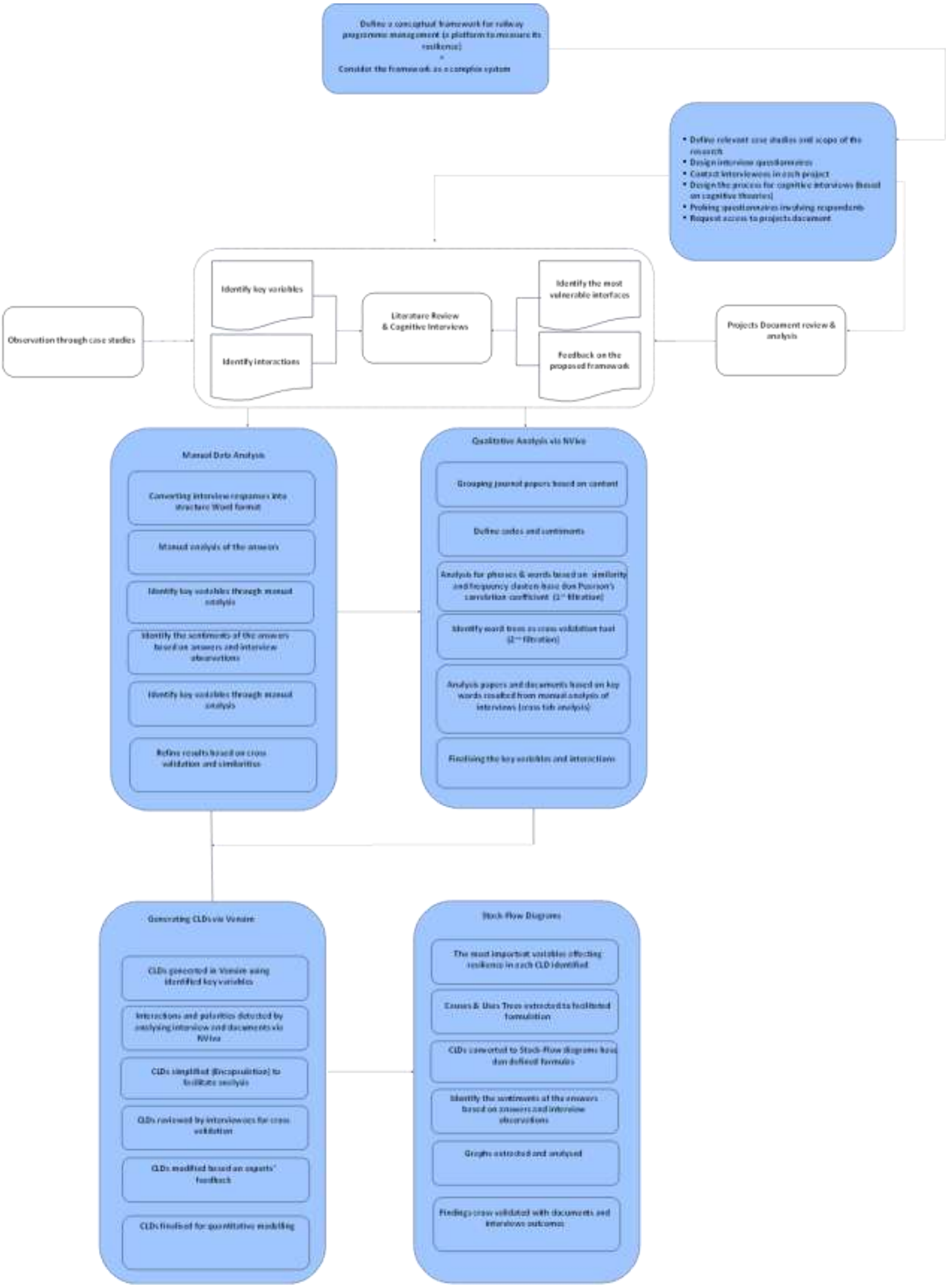


Figure 1-4 Research Methodology (Author)

Figure 1-4 illustrates the methodology, as an innovative combination of multiple case study analysis and system dynamics tools (qualitative and quantitative) to develop a novel systematic approach to model railway project management as a system and evaluate its resilience.

Multiple case studies were analysed to diagnose and identify the main components of the proposed subsystems that affect the vulnerability and resilience of the system the most. To achieve this, questionnaires were designed to survey the key components and factors, to be finally used as the main variables for generating causal loop diagrams.

More details on how to develop CLDs from data analysis are presented in the case studies chapter. Figure 1-5 and Figure 1-4 provide visual algorithms for future researchers. These algorithms recommend how the methodology proposed and developed in this thesis, can be utilised for any specific project, aiming at assessing and optimising project management resilience, employing system dynamics tools.

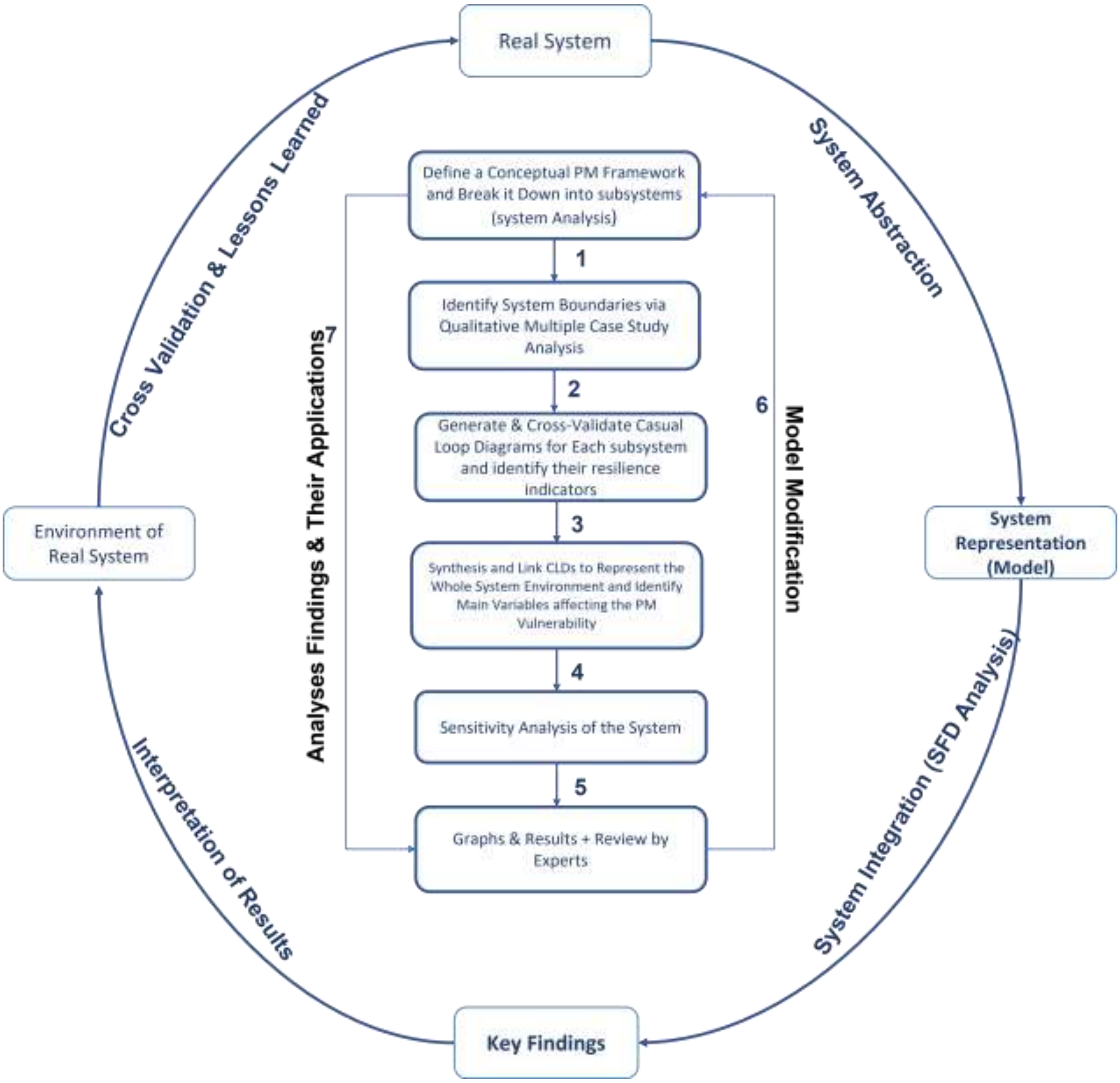


Figure 1-5 Proposed algorithm to develop SD tools to analyse the resilience of railway project management process (author)

1.5 Thesis Overview

This thesis is formed of 9 chapters as follows:

- **Chapter 1**: Introduction
- **Chapter 2:** State-of-the-Art of systematic project management (Literature review). This chapter summarises the author's findings resulting from a systematic literature review. The focus of the chapter is the state-of-the-art findings of the application of system thinking tools to project management aiming at reinforcing them to manage complexity.
- **Chapter 3:** Introduction to the concepts of Causal loop and stock-flow diagrams (system dynamics tools).
- **Chapter 4:** Review of the practical and academic application of system dynamics tools to the field of project management.
- **Chapter 5:** Case studies. This chapter presents details of the studied projects followed by a detailed explanation of the innovative approach proposed by the author to multiple case study analysis, utilising NVivo and system dynamics tool to achieve a reliable qualitative research analysis, as the foundation to generate causal loop diagrams.
- **Chapter 6:** Qualitative analysis of railway project management resilience. This chapter is the first chapter presenting the author's contributions and original work. The author's generated causal loop diagrams are presented followed by qualitative analysis and the author's interpretations.
- **Chapter 7:** Quantitative analysis of the railway project management resilience. This chapter explains the author's innovative approach to integrating the qualitative CLDs and presents the innovative stock and flow diagram, its formulation, and its functionality to

analyse the resilience of railway project management approaches. Graphs resulted from the quantitative analysis presented and analysed. A novel system analysis tool was developed and proposed to assist future researchers and managers in analysing and improving the resilience of the adopted project management approaches. The chapter wraps up with a new multi-dimensional model for project management resilience developed by the author. This will open a new research avenue for future researchers to achieve a comprehensive understanding of project management resilience.

- Chapter 8: Presents findings from parallel research to evaluate the application of system dynamics tools and the innovative proposed approach to metro systems operation management.
- Chapter 9: Conclusion, recommendations, and future work.

The next chapter will provide the author's findings from the literature review.

Chapter 2

LITERATURE REVIEW

State-of-the-Art of Systematic Project Management

Approaches to Apply System Thinking to Improve Project Management Response to Complexity

2.1 Introduction

Chapter 2 presents the author's findings from the literature review. The adopted approach, scope and findings are described in the following sections.

2.2 The Literature Review Methodology

This chapter is written based on conducting a systematic literature review approach inspired by work undertaken by (Yunofri and Kurniawan; Maylor and Turner 2017; Yunofri and Kurniawan 2018; Yang *et al.* 2019). Figure 2-1 explains the methodology followed.

The approach for the review is based on using a precise question to underpin a piece of research (Robinson and Lowe 2015). Rather than finding papers through a random process, the search was performed via numerous databases using exact terminologies and keywords, as recommended by (Yang et al. 2019). Papers were selected according to defined inclusion and exclusion criteria to enhance accuracy.

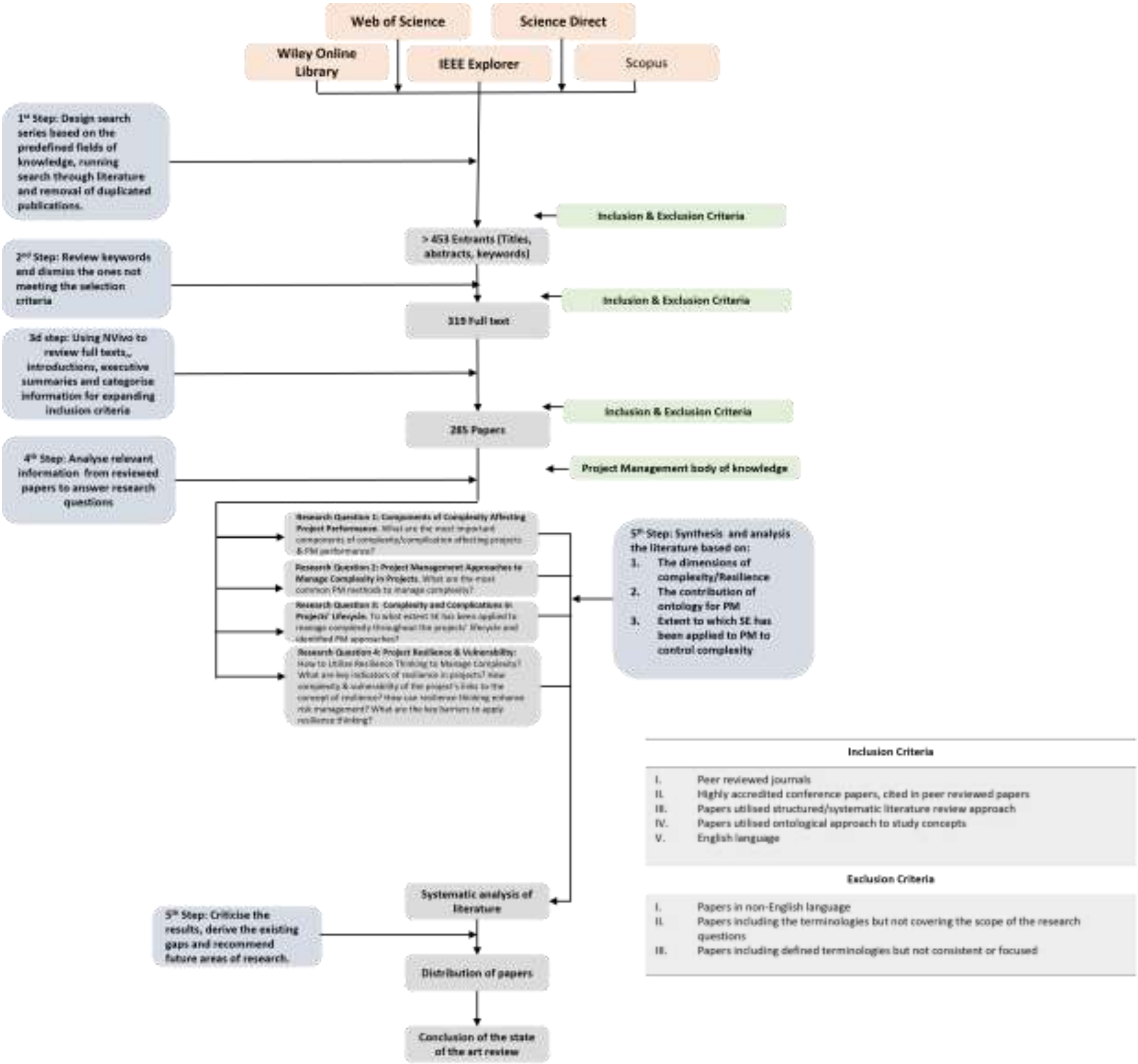


Figure 2-1 Systematic literature review methodology, by Author

Figure 2-1 summarises the systematic literature review approach adopted by the author to write this chapter. Following the adopted approach assists in systematic choice of papers. To reduce the role of human errors in the literature review and findings analysis, the author utilised a computer-aided qualitative data analysis using software called “NVivo”. NVivo provides a series of features which assist researchers in analysing dependency, correlation, frequency, and validity of the findings from the literature review. For all themes and topics covered in the literature review, the following features were utilised to ensure high-quality and accurate data were used in the literature review chapter: word frequency search, cross-tab analysis and comparative analysis of references. NVivo software, its nature and its features are explained in detail in Chapter 5.

2.3 Components of Complexity Affecting Project Performance

This section summarises the key findings around question 1 in Figure 2-2. The definition and dimensions of complexity, which affect projects' performance and may cause failures, are presented in this section.

Complexity is growing within projects, and reports highlight many infrastructure projects facing failures and struggling to meet their defined scopes (Flyvbjerg 2007c; Cantarelli and Flyvbjerg 2010; Brandão 2015; Schneider et al. 2016). The Project Management Institute (PMI) defines a project as "a temporary endeavour undertaken to create a unique product, service or result" (PMI 2013).

A project fails if it cannot meet the defined deadline, overruns the estimated budget, fails to deliver agreed deliverables or leads to a benefits shortfall (dörner 2002; mišić and radujković 2015). Project failure: including delay, cost overrun, benefit shortfall or underperformance, has been prevalent in recent decades, and hence, project failures have been at the centre of much research (Pinto and Mantel 1990; Dörner 2002; Flyvbjerg et al. 2003; Han et al. 2009). There have been many identified reasons affecting cost and time overruns. Flyvbjerg(2014) states that "the cost overrun of some European, North American and Canadian railway construction and upgrade projects is between 60-300%." Table 2-1 summarises the key findings from

Flyvbjerg's research. 44 urban and 214 other infrastructure projects reviewed by (Flyvbjerg et al. 2003; Flyvbjerg 2007b) reveal that:

- 75% of the projects experienced a cost escalation of a minimum of 24%.
- 25% of the projects experienced a minimum of 60% cost escalation.
- The average cost escalation that projects experienced was 44.7%.
- 9 out of 10 transport infrastructure projects encounter cost escalation. (Flyvbjerg et al. 2003) Suggests that for any selected project, there is an 86% possibility that the actual cost will overrun the estimated cost.
- In general, actual costs overrun the estimated cost by an average of 28%.

The EU developed a holistic research project called the Evaluation of Investment for Transport and Energy Networks in Europe (EVA-TREN). The findings of (EVA-TREN 2008) demonstrated that the cost overrun for a significant number of railway construction projects in Europe fluctuated between 8% and 116%. Some key figures are accessible in Figure 2-1

TABLE 2-1 COST OVERRUNS IN DIFFERENT RAILWAY PROJECTS
ADOPTED FROM (FLYVBJERG 2014)

Country	**Project**	**Cost Overrun**
Switzerland	Furka Base Rail Tunnel	300%
Denmark	Copenhagen Metro	150%
Denmark	Great Belt Rail Tunnel	120%
UK	London Jubilee Line extension	80%
UK, France	Channel Tunnel	80%
Germany	Karlsruhe - Bretten Light Rail	80%
Netherland	High-Speed Rail Line South	60%
USA	Troy and Greenfield Railroad	900%

USA	Minneapolis Hiawatha light rail	190%
Canada	Montreal Metro Laval	160%

TABLE 2-2 COST OVERRUNS OF RAILWAY CONSTRUCTION PROJECTS IN EUROPE (EVA-TREN 2008)

Project	**Estimated Budget (Million £)**	**Actual Cost (Million £)**	**Overrun (%)**
Cologne ICE	2,192	3,172	116
Eurotunnel	2,128	3,597	69
Oeresund Fixed	1,413	2,302	63
Paris - Lille	2,099	2,625	25

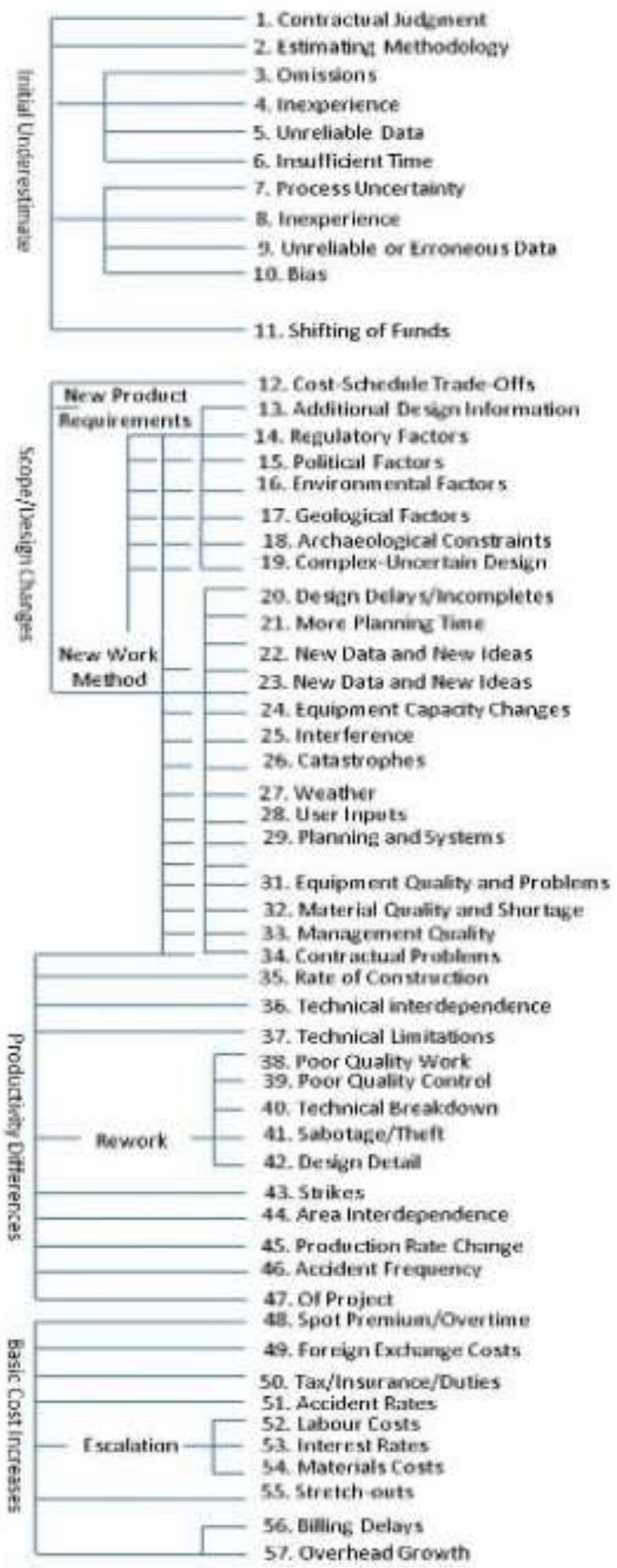


Figure 2-2 Causes affecting construction projects' success, by author after (Avots 1983)

(Avots 1983) identified a series of drivers for failures in projects as depicted in Figure 2-2**Error! Reference source not found.**. Based on official reports, projects repeatedly suffer from failure caused by: delays, cost overruns or benefit shortfalls (Love *et al.* 2012) despite remarkable progress in management studies and developed handbooks, and there are still gaps within the body of knowledge and practice of project management (Love *et al.* 2012; Turner *et al.* 2013; Ackermann and Alexander 2016; Ahiaga-Dagbui *et al.* 2017). Researchers suggest that new approaches to research are required to bridge the existing gap (Cicmil *et al.* 2006; Smyth and Morris 2007; Turner *et al.* 2013). As modern projects are becoming more complex (Gatrell 2005; Tozan and Ompad 2015; Kermanshachi *et al.* 2016a), the need for new types of management approaches for complex projects has become inevitable (Granberg *et al.* 2013; Bakhshi *et al.* 2016). The absence of a unified agreement on the definition of complexity is evident in project management studies (Vidal *et al.* 2011; Brady and Davies 2014; Padalkar and Gopinath 2016). Project managers use a broad, and different set of definitions of complexity (Maylor *et al.* 2008; Whitty and Maylor 2009). For this research, complexity is considered as *"the property of a system, which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given complete information about the project system"* (Vidal *et al.* 2011).

In complex systems, different subsystems interact to deliver outputs and behaviours which are nonlinear and unpredictable (Maylor *et al.* 2008). Nonlinearity in complex systems causes unpredictability in the relationship between inputs and outputs (Richardson 2008). The behaviour of nonlinear systems can be predicted by employing some qualitative patterns, but complex systems are not responsive to conventional systems analysis (Hirsch *et al.* 2013; Zhang *et al.* 2014).

A few researchers propose different models for project complexity, which add value to this study. Williams and Hillson (2002) propose that on top of the two dimensions of complexity (number of elements and interdependencies), there is another dimension called ‘uncertainty’ (Figure 2-3)

Kahane (2004) looked at complexity from a social environment point of view and distinguished complexity into three aspects. Dynamic complexity results from cause and effects that make it difficult to anticipate the project behaviour (Kahane 2004; Olaleye *et al.* 2014). Generative complexity, or emergent complexity is a combination of uncertainty and dynamics within the project (Maylor and Turner 2017). The theory of emergence relates to holism, which considers complex systems as a collection of subsystems that interact and deliver an unexpected system-level output, behaviour or function (Sage and Rouse 2009; Fernandez-Recio and Verma 2012). Social complexity links to people involved who may have different opinions and interests, which all affect the decision-making process (Sophie HASIAK 2012).

Uncertainty and complexity used to be considered the same entities in project management (Luoma, 2006), but recent studies look at these two concepts as two different but interwoven entities (Mišić and Radujković, 2015). From a holistic point of view, uncertainty is a state of unknowns, meaning that, managers do not have adequate information about a specific situation (Perminova et al., 2008). Unknowns in projects can be categorised into four main types (Brockmeier, 2017, Pawson et al., 2011) described in Table 2-3. Because of their important role in projects’ failure, Unknown-Unknowns (Unk-Unks) can be divided into two categories (Ramasesh and Browning, 2014).

TABLE 2-3 TYPES OF KNOWNS & UNKNOWNS MATRIX
(RAMASESH AND BROWNING 2014; BROCKMEIER 2017)

	Knowns	**Unknowns**
Knowns	**Known Knowns** (Things we know that we know) Uncertainties, which managers are informed of and know the methods to mitigate the associated risks.	**Known Unknowns** (Things we know and do not Know) Facts that we are not aware we know them.
Unknowns	**Unknown Knowns** (Assumptions and Changes) Facts that we know that we are not aware of but can list and manage how to mitigate the associated risks.	**Unknown Unknowns** (Facts we do not know and are not aware of) Obscure uncertainties of which managers are unaware. This can lead to unpredictable and disastrous outcomes.

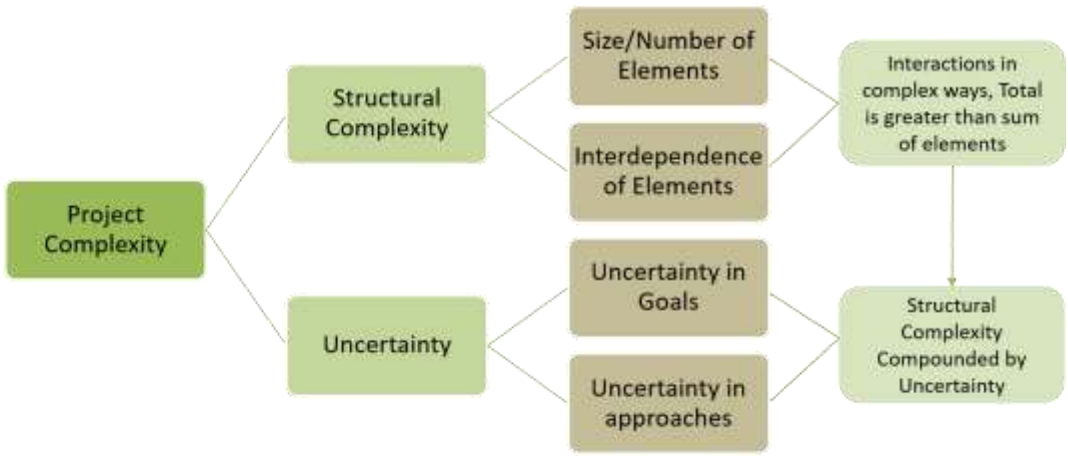


Figure 2-3 William's model for project complexity, by author after(Williams and Hillson 2002)

I. Knowable Unknown Unknowns

project managers can potentially identify this type of Ukn-Ukns but usually being neglected due to cognitive barriers the human brain has in understanding complexity (Zhang et al., 2014).

II. Unknowable Unknown Unknowns

This group of Unk-Unks are categorised as unexpected inputs to the project and cannot be anticipated by project managers (Russo et al. 2017; Singh et al. 2017).

The project management literature differentiates between risk (known unknowns) and uncertainty (unknown unknowns). both concepts provide a challenge to project implementation, but uncertainty adds even more unknowns to the project world (Kvalnes, 2016, p.102).

2.3.1 Complications in Projects

The other concept which plays an essential role in studying project management from a non-deterministic point of view is 'complication'. In some literature, complication and complexity are considered the same entity (Luoma 2006). However, Poli (2013) defines a golden rule to distinguish complexity from complication:

"Complicated problems originate from causes that can be individually distinguished; they can be addressed piece-by-piece; for each input to the system, there is a proportionate output; the relevant systems can be controlled, and the problems they present admit permanent solutions. On the other hand, complex problems and systems result from networks of multiple interacting causes that cannot be individually distinguished; and, therefore, must be addressed as entire

systems. That is, they cannot be addressed in a piecemeal way; they are such that small inputs may result in disproportionate effects".

From a project point of view, complexity and complication are separate but overlapping concepts. The target subject of this thesis is the railway system.

2.4 Project Management Approaches to Manage Complexity in Projects

This section provides findings around question 2 in Figure 2-2 and reviews the most recent project management approaches adopted to manage the growing complexity of the project.

The Project Management Institute (2013) defines project management as: "the application of knowledge, skills, tools, and techniques to project activities to meet the stakeholder's project requirements".

Further, risk management is an integral part of project management (Rosen 2003). Zou *et al.* (2007) identify poor project management as one of project's most important risks. Existing risk management tools lack the predictive capability to determine potential risks before the beginning of the project (Yim *et al.* 2015).

Conventionally project managers improve their predictive theory-building skills based on their learning from their previous experience with projects. When a failure occurs, it provides an opportunity to learn new skills; complexity within projects makes this learning challenge, and project managers risk making incorrect assertions about specific issues (Ivory and Alderman 2005; EVA-TREN 2008; Adoko *et al.* 2015).

In recent decades, researchers have disputed the relevance of project management theories to management practices (Blomquist *et al.* 2010). Williams (2005) highlights a challenge to recognise what makes projects complex to manage and develop a framework that can be shared among a project's actors to understand and respond to the complexity.

Maylor and Turner (2017) highlight some key challenges in trying to apply insights from complexity science to assist the effective management of complexity: a) the concept of complexity is not well perceived in the context of projects, especially in distinguishing issues of complexity and complication (Geyer and Davies 2000; Styhre 2002); b) the analogies used are borrowed from various fields of science, such as weather systems and biological systems, and this makes the insights far from the practice of project management (Dörner 2002; Maylor and Turner 2017).

Analysing existing literature reveals that, although the essentiality of new management approaches has been well perceived, the conceptual theories of methodologies and models for project management have stayed rather stagnant (Koskela and Howell 2002) and profoundly controlled by rationalistic perspectives over recent years (Morris et al. 2011). Researchers have begun to criticise the ability of conventional project management approaches to address challenges inherent in modern projects, such as unpredictability and understanding the impact of making changes (Shenhar 2001; Zidane et al. 2013).

To address these challenges, researchers have explored various different techniques (Morris et al. 2011; Guyot et al. 2016). This new thinking around project management has led to the assessment of novel approaches in the last decade, such as moving from the conventional 'project as a tool' method to thinking of the 'project as a temporary organisation' (Karrbom Gustavsson and Hallin 2014; Svejvig and Andersen 2015). Project management is also now considered a holistic discipline to attain organisational innovation, effectiveness and efficiency

(Jugdev et al. 2001). The resultant of this holistic and pluralistic understanding of project management led to 'Rethinking Project Management' (RPM) (Winter et al. 2006a; Prieto 2015; Svejvig and Andersen 2015).

The UK's Engineering and Physical Sciences Research Council (EPSRC) funded a research network in 2003 called 'Rethinking Project Management. The main goal was to consider current and future research scope in project management (Winter et al. 2006b). By comparing different management practices and identifying gaps in approaches, five main areas of focus were defined (i) project complexity, (ii) social processes; (iii) value creation; (iv) project conceptualisation; and (v) practitioner development (Maylor 2006).

Modern project management originated from research in operation management (Slack 2005). However, the two areas diverged over time, and several new paradigms were conceived. Söderlund (2002) conducted an extensive literature review and categorised project management theories into seven schools of thought.

It is accepted that systems thinking has the potential to assist in managing complexity and uncertainty by providing flexibility in managerial activities (HV Haraldsson 2004; Wu and Xu 2008). System thinking improves project management in several ways, including a) enhancing the realisation of time and cost estimates by recognising the fact that projects are not deterministic anymore, b) increasing the integration at interfaces through forecasting potential challenges, and c) optimising the understanding of the stakeholders' requirements during the whole life cycle of the projects.

System thinking can promote the culture of thinking about how projects can effectively meet the stakeholders' needs and consider a wider range of project benefits outside of the defined system boundary (Conforto 2013; Locatelli et al. 2014; Grösser 2017).

Developing concepts of system thinking usually includes two main steps: (i) identifying the types of systems; and (ii) identifying the corresponding project management approaches, which can accommodate system thinking (Sheffield et al. 2012a).

Recent studies argue that it is appropriate to distinguish between optimisation and modelling schools of thought, to mirror the modelling of multiple parameters and the application of soft systems modelling, and hence, at least nine schools of thought for project management can be considered to exist (Turner et al. 2013), as depicted in Figure 2-4.

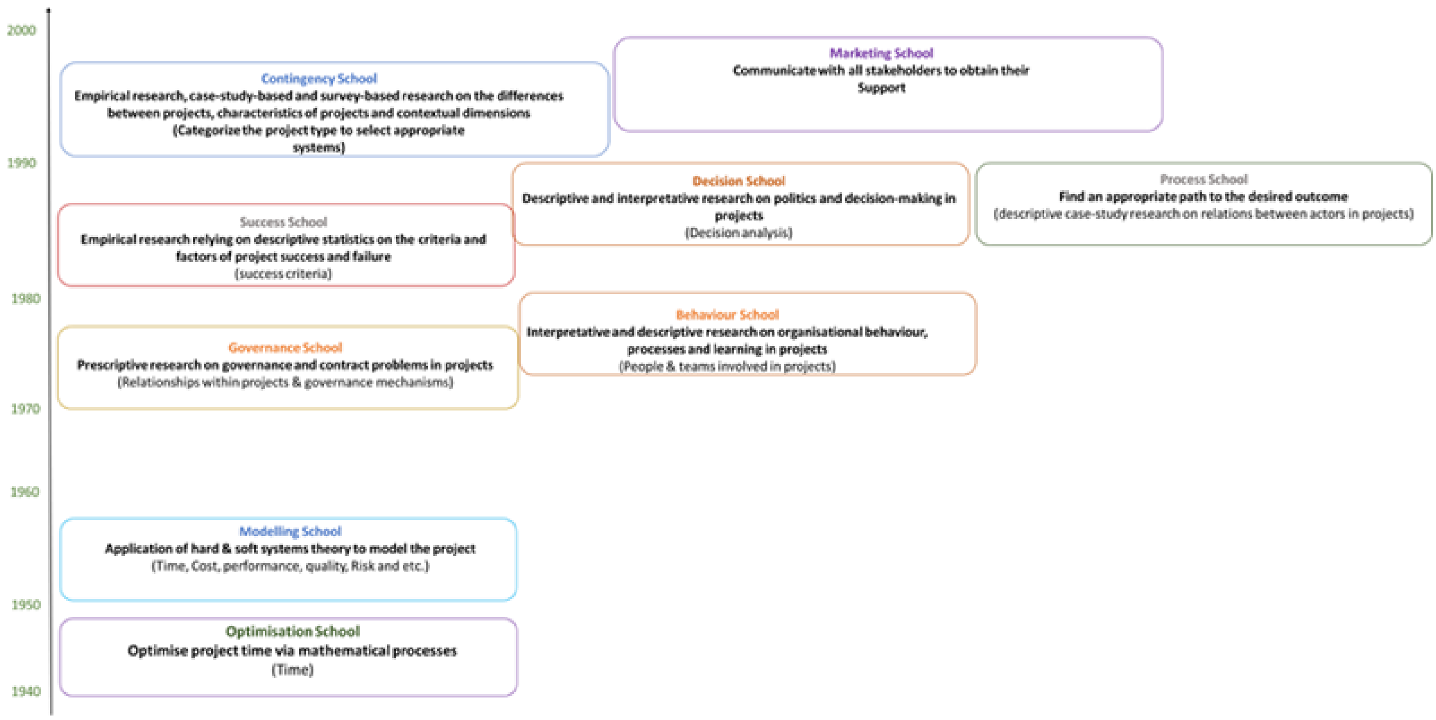


Figure 2-4 Project management schools of thought

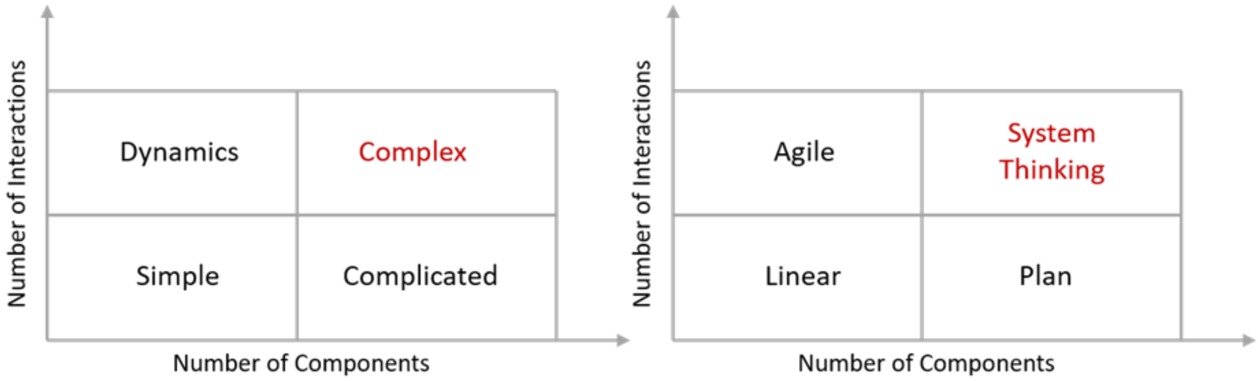


Figure 2-5 types of systems/projects and project management, Author after (Sheffield et al. 2012b)

Figure 2-4 and Figure 2-5 depict the identified project management schools of thought and different types of systems and project management strategies, respectively. In order to choose a suitable set of management methods and strategies for complex projects, it is important to recognise the different types of project complexity that exist (Poveda-Bautista *et al.* 2018). Different authors have identified four types of complexity, which need to be considered in analysing project management tools (Williams 1999; Williams and Hillson 2002; KAYE REMINGTON and Pollakc 2016).

Structural complexity: This is most common in large-scale projects and originates from the difficulties in tracing and managing the enormous number of interrelated activities (Eriksson *et al.* 2017). The primary approach to managing such projects is to decompose outcomes and deliverables into smaller units, which can be managed and, in the end, be integrated to deliver the whole project outcome (Cooke-Davies 2011).

Technical complexity: This category usually occurs within projects with design or technical problems, specifically targeting products or outcomes, which have not been achieved before, and hence there is no precedence (Gregoriades 2001; Bosch-Rekveldt *et al.* 2011). In such projects, the origin of complexity is the interaction between several solution options (KAYE

REMINGTON and Pollakc 2016)and ; hence, project managers will face difficulties in managing contracts, critical paths, and stakeholders' requirements (Flyvbjerg *et al.* 2005; Flyvbjerg 2007a).

Directional complexity: This category of complexity potentially forms in projects with unshared goals; hence, the complexity arises from the vagueness of different interpretations of objectives (Thiry 2002; Zhang *et al.* 2015).

Temporal complexity appears in projects where the environment and strategies are prone to change and those changes are out of the project team's control (Kelly *et al.* 2013). In these kinds of projects, complexity originates from the uncertainty in future restrictions or the future existence of projects. Changes in governmental decisions or changes in the public sector can be potential factors (Flyvbjerg *et al.* 2003; Flyvbjerg 2009). Temporal complexity can potentially arise in any phase of the project life cycle, in projects with unexpected delays originating from external factors (Majoor 2018).

In megaprojects, there is commonly found a combination of all four types of complexity (Rodriguez-Toro *et al.* 2003). Recognising how project managers manage different types of complexity and the nature of their response to complexity can assist in avoiding project failure (San Cristóbal *et al.* 2018). Classification can be a useful tool, as it helps project managers to understand the nature and source of the project's complexity. Table 2-4 summarises some of the existing tools which project managers use to deal with different types of complexity.

Many researchers have identified the application of system thinking as a reliable tool to better manage the growing complexity of projects. The system approach, or so-called system thinking, has been considered when developing management theories by early researchers and followed by innovative concepts such as soft systems analysis (Churchman 1963; Mingers and White 2010).

System thinking improves project management in many ways, including a) enhancing the realisation of time and cost estimates by recognising the fact that projects are not deterministic anymore, b) increasing the integration at interfaces through forecasting potential challenges, and c) optimising the understanding of the stakeholders' requirements during the whole life cycle of the projects.

Developing concepts of system thinking usually includes two main steps: (i) identifying the types of systems; and (ii) identifying the corresponding project management approaches, which can accommodate system thinking (Sheffield *et al.* 2012a).

Change is a common phenomenon in mega projects and is prone to occur in any phase of the project life cycle (Aramo-Immonen and Vanharanta 2009). Soft system methodology (SSM) aims to improve the decision-making process and helps managers realise which changes are feasible by explaining the interactions within the projects (Song 2012; Eigbe *et al.* 2015). The most popular element of the systemic approach, which can be applied to project management, is the concept of a 'rich picture. Walker and Steinfort (2013) explain that SSM can be used to visualise complex problems and as a tool to understand the projects' situational context to improve action project planning and implementation phases. Accordingly, the rich picture is a component of SSM that adds layers of meaning to better understand the problem (Walker and Steinfort 2013; Berg *et al.* 2019). A project would be better to be studied as a programme formed of integrated projects to understand its context and interactions better, as postulated by (Walker and Steinfort 2013).

TABLE 2-4 EXISTING TOOLS FOR MANAGING COMPLEXITY
CREATED AND MODIFIED BY AUTHOR INSPIRED BY (COOKE-DAVIES 2011; KAYE REMINGTON AND POLLAKC 2016)

Type of Complexity	Origin of Complexity	Existing Tools
Structural	High level of interdependencies between project components	• Programme management tools. • High-level monitoring & control tools (earned value management, procurement via partnership) (Colin *et al.* 2015; Chen *et al.* 2016) • Complex systems-based risk analysis tools (Haimes 2009; Bjerga *et al.* 2016)
Technical	Design or technical challenges and conflict between different solutions	• Value management • Transparent role definition (Verboom *et al.* 2004; Anantatmula 2010) • Hands-off control approaches (Nagahara *et al.* 2016; Challapalli *et al.* 2017) • Creative thinking tools • Integrating tools via rich communication
Directional	Vagueness in different interpretations of objectives, unclear/unshared objectives	• Soft system thinking tools • Value management • Problem structuring tools (Rosenhead 2006; Gregory *et al.* 2013)
Temporal	Uncertainty in future restrictions or future existence of projects, unexpected changes in scope, changes in project environment through its lifecycle	• Environmental scanning (Fabbe-Costes *et al.* 2014; Wilburn *et al.* 2016) • Problem structuring and problem analysis tools • Change management tools • Parallel processing tools

2.5 Complexity and Complications in Projects' Lifecycle

This section summarises findings around question 3 of Figure 2-2. This section tends to highlight to what extent the systems engineering approaches have been applied throughout the projects' lifecycle to manage complexity and complication. A project lifecycle is a management tool focusing on resource management, integration of activities, decision-making and risk reduction through governance and control mechanisms (Setsobhonkul *et al.* 2017). Lifecycle is an integral component of the project management concept as it defines the process, flow, dynamics and boundaries of projects, considered systems (Carvalho *et al.* 2015).

Complexity and complication exist in all the phases of the project lifecycle, with the most impact on costs rising from decisions on concept, design and implementation phases (Emes *et al.* 2010; INCOSE 2010). Flyvbjerg *et al.* (2004) state that a one-year delay in the project implementation phase could potentially increase cost overrun by 4.64%. The INCOSE Handbook claims that the cost of eliminating errors is lower where they are identified earlier in the project and debates that systems engineering would decrease cost by providing information that supports better earlier decisions.

Elliott (2014) proposes that system engineering can deliver benefits to a project in three different respects:

a. The control of complexity; for highly complex systems, SE is essential for understanding and defining the system and its requirements.

b. Entire system optimisation, where SE, is a tool to optimise the.

c. Left Shift effect, meaning the effort and SE activities in the. Projects' early stages will lead to later investment savings (Honour 2013).

The first step in applying system thinking to project management is understanding the problem-solving procedure (Yaghootkar and Gil 2012; Kopczyński and Brzozowski 2015). To apply system thinking to project management, Sheffield *et al.* (2012b) advise a technique widely accepted by the Association for Project Management (APM), illustrated in Figure 2-6.

The proposed tools can be used in different phases of the project life cycle. System archetypes, which are revealed patterns via causal loop diagrams, will be described in Chapter 4. It was mentioned earlier that complex projects could be considered temporary organisations. Thus, adopting the mindset of system thinking can improve the internal function of the organisations, and this can be generalised to projects using five key principles (Brønn and Brønn 2017):

I. Considering the big picture and holism project managers must think of the impact of their decisions and beyond the limit of their responsibilities.
II. Creating a balance between short and long-term outlooks.
III. Understanding the dynamic, complex, and interdependent nature of projects (as systems). This requires moving away from traditional project management frames of thinking.
IV. Focus on both measurable and non-measurable variables.
V. Impact analysis means to realise the fact that we are all part of the system we are part of its function.

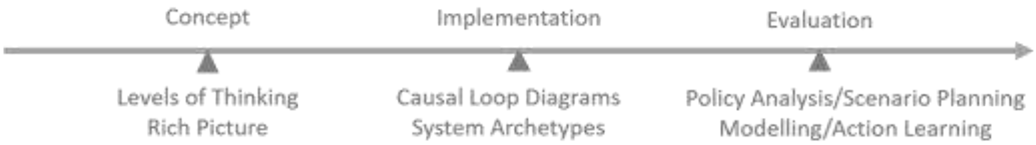


Figure 2-6 Application of system thinking to system development lifecycle, Author after (Sheffield et al. 2012b; Emes and Griffiths 2018)

From (Maani and Cavana 2007)'s point of view, system thinking methodology includes five phases (Table 2-5). The Association for Project Management (APM) and the International Council on Systems Engineering (INCOSE) conducted joint research to identify how system thinking can help the project, programme, and portfolio management. They identified some of the main current system thinking tools, briefly explained in Table 2-6.

TABLE 2-5 STEPS OF SYSTEM THINKING AND ASSOCIATED TOOLS
AUTHOR, INSPIRED BY (MAANI AND CAVANA 2007; EMES AND GRIFFITHS 2018)

System Thinking Methodology Steps	Associated System Thinking Tools
1. Problem Structuring	• Affinity diagrams (Miura *et al.* 2011; Widjaja *et al.* 2013) • Hexagon clustering (Hodgson 1992; Raposo 2013)
2. Causal Loop diagrams	• Causal Loop Diagrams
3. Dynamic Modelling	• Rich picture • Stock & flow diagrams (Wheat 2008; Kasada *et al.* 2015) • Software packages such Dynamo & Stella
4. Scenario Planning & Modelling	• Scenario planning (Graetz 2002; Amer *et al.* 2013)
5. Implementation & Organisational Learning	• Management flight simulator (Computer simulation game) • (Papageorgiou *et al.* 2008)

TABLE 2-6 CURRENT SYSTEM THINKING TOOLS IDENTIFIED
BY (APM AND INCOSE JULY 2018)

System Thinking Tools	Comments
Context diagrams	it helps to understand problems and define the system within its surrounding environment.

Fishbone diagrams	Assists in structuring thoughts and distinguishing soft and hard variables affecting the project.
Actor maps	Represent the main organisations and roles forming them and are affected by the system.
Concept maps	A tool to break down the problem into smaller components and their interactions.
Trend maps	This tool studies the trends which impact the system. Trends are usually concluded from experts' expertise.
Causal Loop Diagrams	Brings out the causal interactions and feedback of the system and assists in understanding the behaviour of complex systems.

Conceptual modelling, as exemplified by the tools in Table 2.7, is the process of abstracting a model from a real or proposed system (Robinson 2008a). Conceptual modelling is about transferring from the problem island via model requirements toward recognising what will be modelled and how we need to create the model (Morris *et al.* 2011). Reliable conceptual modelling is recommended to follow the following steps; a) recognising the problem situational context, b) defining the objectives of the model and the actual project, c) detecting the outputs of the model (responses), and d) identifying the model inputs (experimental factors), e)deciding about the model content (scope and level of details) and e) defining assumptions and level of simplification (Robinson 2008a; Too and Weaver 2014).

Diagrammatic representations of the model have been suggested by a few authors as a set of practical and beneficial tools. The list below presents a brief introduction to some examples of such tools:

- Activity cycle diagrams
- PETRI nets
- Event graphs

- UML (the unified modelling language)
- Object models
- Process flow diagram

This is not possible to create a definite suitable conceptual model since the model is a function of the perceptions and preferences of the people who are involved in the project simulation and analysis (Davies *et al.* 2006; Robinson 2008b). Different researchers conclude that despite understanding the importance of conceptual modelling in the field of project management, there is still a large-scale gap in research in the realm of conceptual modelling (Robinson 2008a; Robinson 2008b; Morris *et al.* 2011; Carvalho *et al.* 2015).

One of the main reasons for such a gap is that conventional project management cannot cope with increased diversity and complexity (Maylor *et al.* 2008). Cooke-Davies (2011) and

One of the most productive approaches for managing complex projects is 'Systemic Pluralism', which was developed as a branch of critical system thinking, focusing on methodological and theoretical pluralism (Cooke-Davies 2011). (Söderlund 2011; Söderlund and Geraldi 2012) identified the differences between schools of thought in project management to highlight the range of benefits the combination of schools of thought can bring to projects from a pluralistic point of view., Complex projects can be considered as complex adaptive systems. Thus it would be more beneficial to apply approaches founded on both system thinking and multidimensional methods (Holland 2006; Oughton *et al.* 2018; Sage *et al.* 2014; Cape *et al.* 2018; Grabowski *et al.* 2019). The concept of systemic pluralism enables project managers to (i) appreciate the systemic nature of complex projects; and (ii) adopt and apply various combinations of tools and methods whilst being adaptable to changes in tools to deal with specific complexity in the projects (Cape *et al.* 2018; Grabowski *et al.* 2019).

In 2010, the Rail Value for Money (RVfM) study identified that "such improvements are likely to come principally from getting all parts of the rail system to work together more effectively within a whole system perspective" (Risk-Solutions and Steer February 2011).

In October 2011, the McNulty Rail Value for Money (RVM) report (McNulty 2011) aimed to promote the whole system programme management. The report identified potential cost savings in three main areas: (i) increased efficiency by focusing on output rather than process; (ii) increased early efforts that concentrate on the transparency of the objectives; and (iii) reduced overspends, utilising optimised planning and delivery approaches (Halcrow 2012).

The National Audit Office published a report about lessons from major rail infrastructure programmes to better advise the nation on managing budgets (NAO 2014).

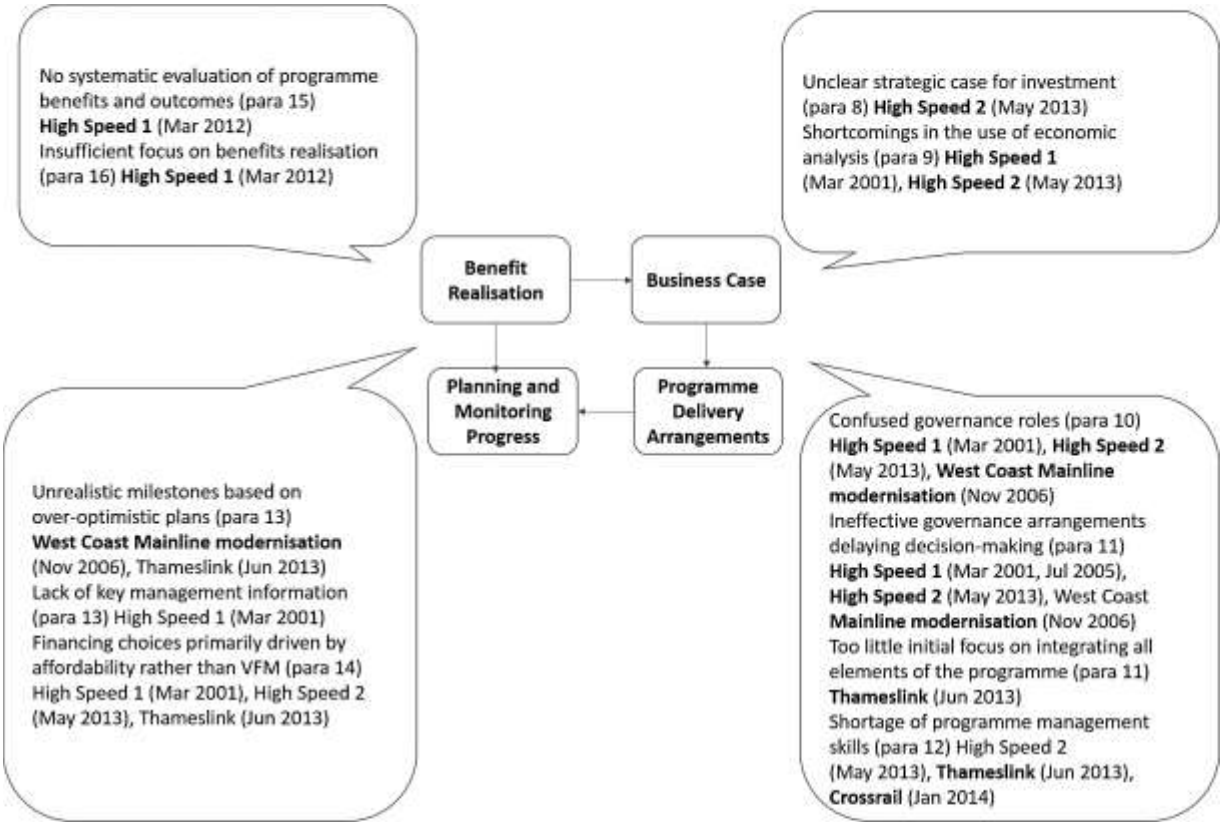


Figure 2-7 Issues DFT dealt within its programme management strategies, Author after(NAO 2014)

It confirmed that DFT's sponsorship has improved the approaches to major rail programmes but there are still tangible gaps that must be bridged to avoid causing cost overruns and delays in major rail programmes. Some of the most important problems within DFT's programme management strategies are demonstrated in Figure 2-7.

The Nichols Group (2015) identified that:

"Major cross-industry rail programmes like West Coast Route Modernisation (WCRM), Thameslink and Great Western Modernisation (GWRM) have all needed mid-programme review, re- configuration, and re-baselining because the complexity of these upgrades was underestimated. his has sometimes led to significant cost escalation, programme delay and reputational damage to the industry."

Slightly later, a brief strategic report was issued to Network Rail's Infrastructure Strategy Group and underlined a set of important facts. According to the report:

"Network Rail missed 16 of 44 (36%) GRIP 3 regulated outputs and 14 out of 40 (35%) GRIP 6 regulated outputs in 2014-15. Our analysis has shown that 30 missed milestones (36% of all milestones) in 2014-15 relate to projects that vary by size, type, location, and complexity."

Figure 2-8 shows the components of a complex railway programme and their interactions, which can cause major changes in the timetable (Nichols Group 2017). The authors highlighted four main concerns by ORR about NR's programme management capabilities as follows:

1. The poor setting of project and programme requirements and change control.
2. Accountabilities of the client, sponsor and deliverer blurred through the project lifecycle.
3. Lack of programme integration with other industry stakeholders, and.

4. Lack of capability to model timetable performance during and after construction to inform integrated design and development decisions.

Table 2-7 (taken from (ORR, 2015)) identified many gaps within Network Rail's major programmes. Most importantly, the ORR concluded that, according to their nature and diverse range, the detected Network Rail's problems "are systemic, rather than the result of individual project failings or adverse circumstances. This is also evidenced by the wide range of causes and the scale of the required long-term improvements that Network Rail requires to develop and embed into the business". Figure 2-8 shows the components of a complex railway programme and their interactions, which can cause major changes in the timetable (Nichols Group 2017). The next section will cover findings around the impact of complexity on project vulnerability and how this can be related to the concept of resilience.

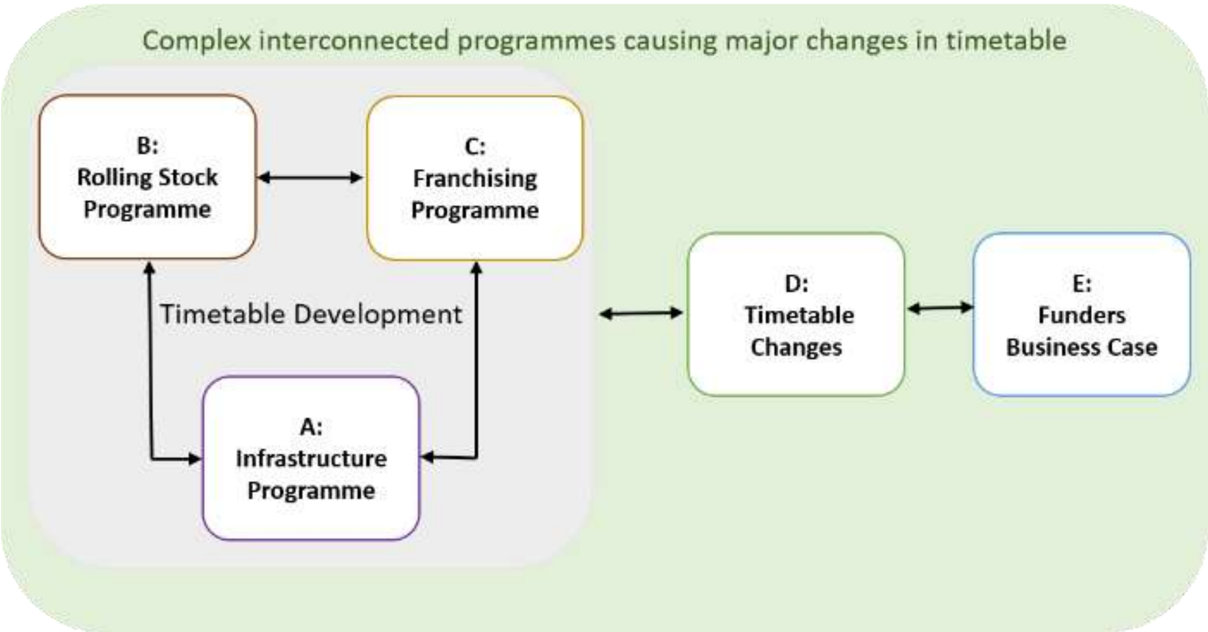


Figure 2-8 Rail industry (Tier 1) level integration of the major elements of a complex rail programme, Author after (NicholsGroup 2017)

TABLE 2-7 IDENTIFIED GAPS IN NETWORK RAIL MAJOR PROGRAMMES

AUTHOR AFTER (NICHOLSGROUP 2015)

No	Gaps within Network Rail Programme Integration
1	No formal approach was instructed to Network Rail, but elements of systems integration are evident.
2	A formal systems integration function is actively under consideration.
3	A formal systems integration function in existence
4	Infrastructure programmes may often require early initiation about the franchise and rolling stock development
5	Franchises may be awarded at different timings throughout the delivery of the infrastructure programme.
6	Franchise agreements ultimately define the end-state timetable.
7	Rolling stock procurement under franchise agreements encourages innovation but places infrastructure programme assumptions at risk.
8	During programme delivery, the quality of integration is variable.

2.6 Project Resilience and Vulnerability: How to Utilise Resilience Thinking to Manage Complexity

This section provides findings from question 4 Figures 2-2. The concepts of resilience, vulnerability and how resilience thinking has been used to manage complexity and risks within projects and the main associated barriers are explained in this section. Infrastructure project delivery processes are vulnerable to uncertainties and disruptions throughout the process, which can affect "everything from technical feasibility to cost, market timing, financial performance, and strategic objectives" (Thamhain 2013, p.4; Han and Bogus 2020). The interactions between project components and surrounding environments are dynamic and non-linear. Hence any change within the project might affect the other components and interactions, creating a new set of unpredictable risks (Vidal et al. 2011; Chen *et al.* 2012; Zhang et al. 2014;

Rahi 2019b). Uncertainty can be explained by the inability to assess the project's objectives and features and the consequences of actions and decisions on the entire project environment (Geraldi *et* al. 2011). Current project risk management approaches depend on a source of known disruptive events to reduce the vulnerability (Teller 2013) against known disruptions. To manage uncertainty, we need to manage unknowns (NyBlom 2020).

Figure 2-9 depicts a generic overview of the resilience components in railway systems. Resilience is a comprehensive system measure covering the following building characteristics, representing distinct system states: vulnerability, survivability, response and recovery (Bešinović 2020). Some researchers consider resilience as a function of a system's vulnerability and adaptive capacity to recover from disruption and deliver a reasonable level of service within a reasonable period (Ferranti *et al.* 2016; Bababeik *et al.* 2018; Saadat *et al.* 2018; Diab and Shalaby 2020).

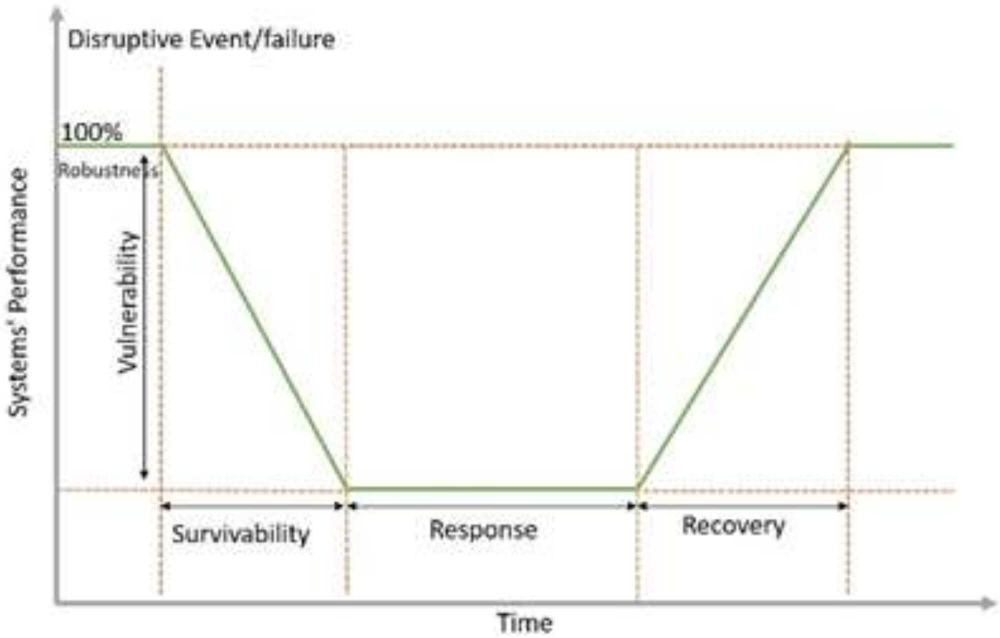


Figure 2-9 Resilience components for railway systems, Author after (Bešinović 2020)

Vulnerability is a measure of how a system's level of performance is affected by disruption'(Khaled *et al.* 2014). The response is the set of decisions and actions required to bring the system back from a disrupted steady-state to an operational level (Zhu *et al.* 2020). Survivability is the capability of a system to transfer from a regular operation to a disrupted mode reasonably (Bešinović 2020). Recovery reflects the system's capacity to be restored from disrupted to ordinary operation mode (Saadat *et al.* 2018). Vulnerability is an integrated component of resilience and is required to analyse the resilience of the transport systems, as presented in Figure.

Complex Network Theories are one of the common tools adopted in infrastructure megaprojects to identify vulnerable components (Taylor and D'Este 2007; Ouyang *et al.* 2014). Most of the studies considered vulnerability as an inherent flaw of the system and created a theoretical safety insurance mechanism. However, they focused on analysing the vulnerability of the transport system against attacks from a systematic point of view (Laporte *et al.* 2010; Han and Cheng 2012).

Researchers have presented similar definitions for project resilience. Schroeder and Hatton (2012) defined resilience as the capacity of project to recover from the consequences of unexpected risks, which are unknown in the planning phase of the project. Geambasu (2011) defined resilience as the capability of a project to reinstate its capacity and, continuously adapting to changes and fulfilling its objectives even in disruptive circumstances.

Giezen (2013) identified that project managers of megaprojects tend to simplify the process and scope of the projects, which has led to complexity and unexpected disruptions being neglected; hence he introduced the concepts of strategic and adaptive capacity to optimise planning in megaprojects. Seville and McManus (2008) proposed that the system's resilience can be improved by increasing its adaptive capacity. This can be achieved by optimising the system design to ensure adequate redundancy of the system so that it can be rapidly recover from disruptive situations to normal functionality (Fraccascia *et al.* 2018). Rahi *et al.* (2019, p.11) add that:

"Project system resilience can be linked to two aspects, namely, awareness (a continuous understanding of the project systems' elements, vulnerabilities, and successive monitoring of the changes within the project environment) and adaptive capacity (the capacity of the project system to transform itself to cope with disruptive events".

The concept of resilience in project management is new, and recently a group of researchers have focused on applying resilience thinking to the management field of complex projects (Babick 2009). Resilience in complex systems has become an important concern for managers dealing with complex systems (Fraccascia *et al.* 2018).

Resilience is complex and cannot be measured based on a single indicator. Hence it needs to be measured based on a system's performance (McDaniels *et al.* 2008). Figure 2-10 shows a conceptual visualisation that illustrates the impact of decision-making on systems resilience. They investigated the impact of decision-making one infrastructure resilience after an incident such as an earthquake using flow diagrams. McDaniels et al. (2008) considered the two main components of resilience as robustness (the ability of the system to sustain its function after a disruption) and rapidity (required time for the system to return to its full functionality), referred to earlier as 'response'.

Table 2-8 presents some of the most recent and relevant papers covering railway resilience, considering system thinking approaches. Most, papers covered specific themes within railway systems, and only a few utilised the actual system dynamics tools and CLDs. Nevertheless, some authors have focused on a more holistic investigation of resilience to measure its impact on planning and decision-making but still limited their scope to the resilience of the railway network and sustainability, with the most minor focus on resilient project management.

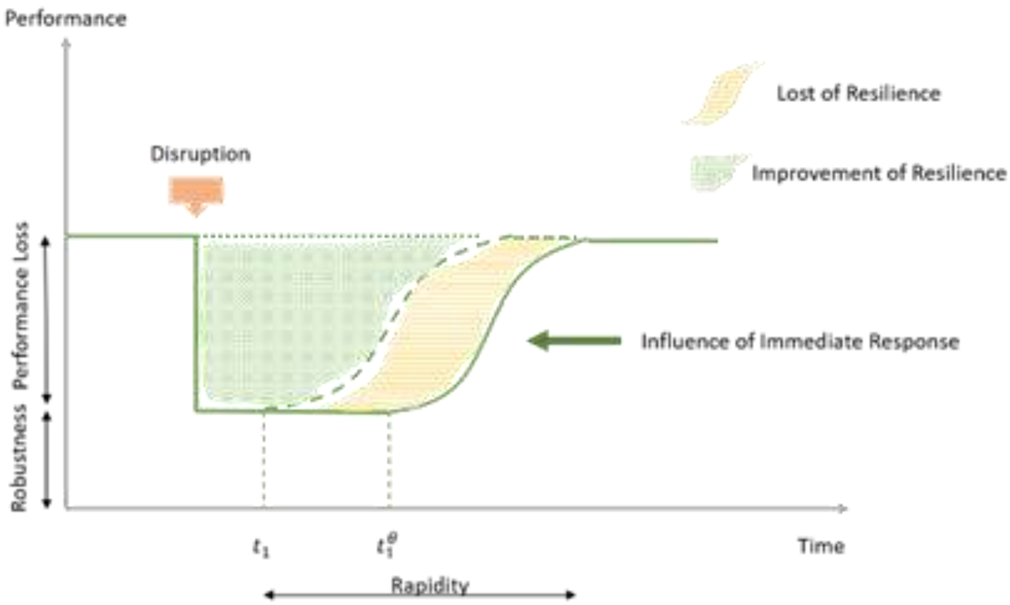


Figure 2-10 Impact of decision-making on systems' resilience, Author

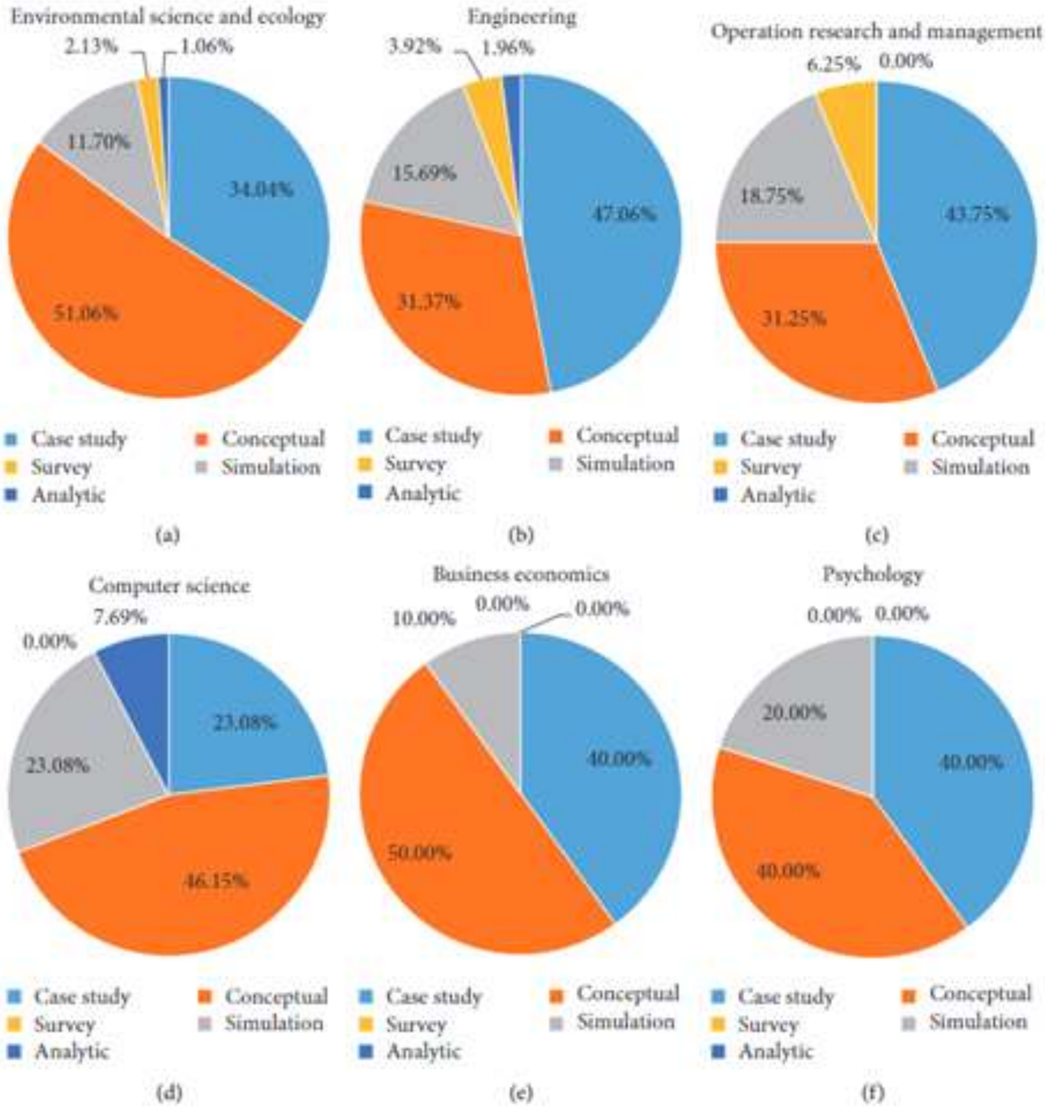


Figure 2-11. Research approaches to study resilience in different fields (Fraccascia et al. 2018) reproduced by the author inspired by (McDaniels *et al.* 2008)

TABLE 2-8 RECENT PAPERS COVERED RESILIENCE IN RAILWAY

FROM THE SYSTEM THINKING POINT OF VIEW (AUTHOR)

Theme	**Researchers**
Explained how enhanced data collection and analysis techniques have enabled the UK railway network to optimise whole-industry costs at the wheel–rail interface, maximise system capability by use of spare capacity and analyse implications of climatic conditions	(Doherty *et al.* 2012)
Developed a numerical model to quantify the resilience of mass railway transportation systems.	(Adjetey-Bahun *et al.* 2016)
Reviewed the assessments of the likely effects of climate change on infrastructures in general and on Britain's railway.	(Armstrong *et al.* 2017)
Combined four key variables, namely health, safety, ergonomics, and resilience engineering, to assess the performance of a railway transportation system.	(Azadeh *et al.* 2018)
Examined the location of relief trains aiming at enhancing the network resilience using bi-objective programming.	(Bababeik *et al.* 2018)
Examined whether the different topological measures the of resilience (stability) or robustness(failure) are more appropriate for understanding poor railway performance	(Pagani *et al.* 2019)
Conducted a systematic literature review to set up an afield-specific definition of resilience in railway transport and have a comprehensive, up-to-date review of railway resilience papers with a focus on quantitative approaches.	(Bešinović 2020)
Compared to the concepts of resilience and vulnerability of the railway infrastructures	(Hoterová 2020)
Modelled the dynamic resilience of rail passenger transport networks affected by large-scale disruptive events whose impacts deteriorate the network's planned infrastructural, operational, economic, and social-economic performances	(Sun *et al.* 2020)
Analysed the Structural Resilience of the Doha Metro due to climate change impact	(Nikolis *et al.* 2020)
Developed a Fuzzy Bayesian Reasoning (FBR) model to analyse the effect of climate change on rail systems for adaptation planning	(Wang *et al.* 2020)
Proposed a conceptual Framework for the Incorporation of economic Resilience into Transportation Decision Making	(Chacon-Hurtado *et al.* 2020)

One of the most recent studies, which is not in the railway context, considered the Beijing megacity as a case study and developed system dynamics tools to analyse urban resilience (Li *et al.* 2020). Other authors used systems dynamic tools and CLDs to "discuss how changes in dynamics can influence the critical performance indicators of a project throughout its lifecycle" (Shafieezadeh *et al.* 2019). Their work did not consider the resilience of project management; it used a few of the existing CLDs from the literature and was not focused on railway systems but was notable since it highlighted the applicability of system dynamics to improve project performance, which is aligned with the author's research.

Equally relevant, Yildiz *et al.* (2020) developed system dynamics modelling (qualitative & quantitative) in collaboration with a specific construction company to measure project performance and to address some barriers with existing static methods.

Within the scope of railway projects, Boateng (2014) combined the application of system dynamics tools and analytic network processes to assess risks in megaprojects, using the Edinburgh tram as a case study. While similar in scope to this research, three main differences are observed. First, the focus of this thesis is broader, considering four case studies. Second, it covers risks as a general concept, whilst this thesis focuses on assessing the resilience of project management approaches by identifying the vulnerable components. Finally, Boateng (2014) utilised a series of complex numerical models, whilst this work promotes a more practicable approach using systems dynamics tools.

2.7 Conclusion

Numerous reports and studies have recorded projects that have failed, delayed, or run over budget. Complexity, a growing and endemic characteristic of projects, has been identified as one of the main reasons for projects' failure. Managing project complexity and how managers respond to complexity have been researched during the last two decades. Complexity, uncertainty, and non-linearity are interwoven features in projects.

Chapter 2 of this thesis – as explained earlier – focuses on identifying the concept of complexity in projects and how these impacts project failures. Modern project management approaches to manage complexity were reviewed. The concepts of resilience thinking and how it can be utilised to manage complexity and its associated risks were then studied. The most important findings of this chapter can be listed below:

I. Uncertainty is an endemic feature within complex projects. Emergent complexity enhances the uncertainty of projects. This is mainly because and the interrelations between components and sub-systems in complex projects (systems) arenon-linear. This means that it is not straightforward to trace, analyse, and measure the impact of changes and unexpected inputs using the existing project management and analysis tools, mostly based on linear concepts. Research findings suggest that conventional project management theories, which are founded on linear approaches, are not capable of identifying and analysing the non-linear interactions within the project environment, or managing growing complexity, and hence will cause project failures.

II. Previous research studies have considered introducing new approaches and ideas to manage projects' complexity and mitigate the risk of failures. This led the research streams to shift from traditional to the modern field of (RPM), which recommends that project management researchers and practitioners have a holistic overview and utilise pluralistic approaches to reinforce project management's body of knowledge. RPM includes suggestions and research avenues to enable the project management body of knowledge to manage unknowns and uncertainties. RPM findings recommend the importance of innovating and adopting new pluralistic project management approaches combined with system thinking concepts. Such approaches are necessary to manage the non-linearity and complexity of modern projects via informed decision-making and systemic change management processes.

III. Most of the previous studies have focused on investigating the efficacy of system thinking to improve project management performance on a specific topic in a silo. In the field of railway engineering, most of the research studies have concentrated on mitigating the risks of accidents, failure of the tracks, bridges or other structures, financial risks, operational risks, etc. There has been limited attention paid to applying system thinking to optimise the whole project lifecycle, considering a holistic approach. The literature review suggests the application of system thinking to a wider domain of management practices, considering the whole railway system's functionality and performance.

IV. The literature review highlighted that many researchers who focused on optimising project management have predominantly focused on optimising a specific phase of the projects rather than optimising the project management entity and its processes. However, a few researchers have proposed the necessity of adopting innovative approaches to study multiple complex projects based on practical surveys from real-life projects. This will assist researchers in studying project management efficiency in dealing with complexity and disruptions in a more realistic and practical way.

V. Most of the previous project management research studies have focused on hierarchical planning and control-focused methods. This has affected the quality of understanding uncertainty and its associated risks within complex projects. To achieve a reasonable understanding of uncertainty within projects, research recommends that it is necessary to adopt more resilient approaches to project management practices to encompass elements of self-organising systems (Nachbagauer and Schirl-Boeck 2019). This is addressed as the complex adaptive system in this thesis.

VI. Despite advancements in broadening project management approaches to address complexity, complex projects still suffer from poor management practices, leading to failure in meeting key objectives. To bridge this gap, resilience thinking needs to be integrated with project management to increase the adaptive capacity of the management approaches when facing disruptive events or changes.

VII. Most existing research projects have had less focus on, and at some level, underestimated analysing the resilience of project management as an entity. Most studies have focused on evaluating the resilience of the actual projects. Future research must be focused on finding systematic solutions to provide practitioners with systematic impact analysis tools. This will assist them in making informed decisions and accordingly enhance the resilience of the project management approaches when facing disruption or change. This is linked to the concept of change latency in this thesis.

VIII. Railway infrastructure projects can be considered *complex adaptive systems*, and accordingly, the project environment would be the convertor and receiver of the project inputs and outputs. The dynamic and nonlinear interactions between project components and between the project and its changing surrounding environment generate unknown risks; this area would benefit from more focus by researchers working in project management.

IX. System thinking has been adopted within project management, and conceptual modelling methods are becoming popular. However, they are not widely practised within the industry, especially within the construction and rail sectors.

X. System dynamics tools, including CLDs and SFD, are reliable tools which have been proposed by researchers to understand the dynamics of complex systems. The non-linear behaviour of complex projects (as systems) can be studied over time, utilising system dynamics tools, as will be described later in this thesis.

XI. Causal loop diagrams have been applied to the railway industry, but mostly for risk analysis purposes and to investigate specific cases such as accident analysis. They are not currently well perceived and are not being used to support the optimisation of railway project management processes and strategies.

XII. System dynamics tools require a series of complicated tasks to be followed, from data collection and interpretation to modelling and analysis. This creates a level of cumbersomeness, which might be translated as the main factor why system dynamics tools are not widely used within the engineering industry. Novel utilisation of system dynamics approaches is required to be developed to facilitate their application to the real-life project and benefit from its advantages.

XIII. "System dynamics modelling (SDM) is an operative approach for helping reveal temporal behaviour of complex systems considering their non-linearity, time-delay and multi-loop structure" (Assumma *et al.* 2019).

Table 2-9 summarises the gaps identified from the literature review and explains how the defined research objectives have addressed them accordingly.

Table 2-9 How Objectives Address Identified Gaps (Author)

Findings from Literature Review (Section 2.7)	Research objectives	How They Link to the Identified Research Objectives
I & II	1 & 2	These findings highlight the gaps within the conventional project management approaches and their lack of compatibility to manage the growing compatibility within modern projects. Finding II specifies the importance of shifting from traditional project management towards (PRM). RPM findings recommend the importance of innovating and adopting new pluralistic project management approaches, combined with system thinking. Such approaches are necessary to manage the non-linearity and complexity of modern projects, via informed decision-making and systemic change management processes. Hence, Objectives 1 & 2 were defined to address these gaps. Considering project management structure as a system (Figure 1.4) and a combination of system dynamics tools and multiple case study analysis to model and analyse the system's resilience provide a pluralistic and innovative method to optimise project management using system thinking tools.
III & VI	2 to 6	Findings II explains that most of the previous studies have focused on investigating the efficacy of system thinking to improve project management performance on a specific topic in a silo and specifies that there has been very limited attention to applying system thinking to optimise the whole project lifecycle, considering a holistic approach. Finding VI confirms Findings III and additionally recommends that a few researchers proposed the necessity of adopting innovative approaches to study multiple complex projects based on practical surveys from real-life projects. This will assist researchers ing studying project management efficiency in dealing with complexity and disruptions. That is why multiple case study analysis was adopted to facilitate real-life surveys from real-life projects. Objectives 2 to 6 cover the author's intention to proposed approaches to collect, analyse and utilise qualitative data to generate visual model for the proposed project management structure (via CLDs and SFDs). Objectives 5 and 6 provides a platform to integrate all generated CLDs (sub-systems) and hence assess the whole project management performance, rather than the actual project.
V & VI	2 to 7	Findings V describes that Most of the previous project management research studies have focused on hierarchical planning and control-focused methods and an appreciation of uncertainty is necessary to adopt more resilient approaches to project management. Findings VI states that despite advancements in broadening project management approaches to address complexity, complex projects still suffer from poor management practices. To bridge this gap, resilience thinking

		needs to be integrated with project management to increase the adaptive capacity of the management approaches when facing disruptive events or changes. Findings 2 to 7 provide a platform to apply pluralistic approaches to apply resilience thinking to project management and bridge this gap.
VII & VIII	6,7 & 8	Finding VII indicates that Future research must be focused on finding systematic solutions to help practitioners analyse the impact of their decisions and accordingly enhance the resilience of the project management approaches when facing disruption or change. Finding VIII states that Railway infrastructure projects can be considered *complex adaptive systems* and the project environment is the convertor and receiver of the project inputs and outputs. Objectives 6,7 and 8 are defined to bridge these gaps. The produced CLDs and SFDs provide an innovative platform to consider railway PM as a system, model it via system dynamics tools and improve the process of decision-making for practitioners and researchers.
IX & X	2 to 8	These findings show that IX. System thinking has been adopted within project management and conceptual modelling methods are becoming popular, but they are not widely practised within the industry, especially within the construction and rail sectors. System dynamics tools are proposed by researchers to understand the dynamics of complex systems. The non-linear behaviour of the complex projects (as systems) can be studied over time.
XI, X1II and XIII	2 to 8	These findings suggested that CLDs have been used in the railway industry, but mostly for risk analysis purposes and to investigate specific cases such as accident route analysis. They are not currently well perceived and are not being used to support the optimisation of railway project management processes and strategies. System dynamics tools are complex, and this might create reluctance and hinder their wide use within the industry. System dynamic modelling can assist in the understanding of complex systems' behaviour over time and when dealing with multi-loop structures. Objectives 2 to 8 cover all these gaps. The research will provide a series of reference CLDs and two innovative SFDs, which can be used by future researchers and managers as a point of departure and be modified based on individual projects.

The next chapter introduces the concept of system dynamics tools and their components. Since this thesis is founded on system dynamics tools, this is important to explain the key definitions, concepts, and processes.

Chapter 3

INTRODUCTION TO SYSTEM DYNAMICS TOOLS

3.1 Introduction

The logic behind this chapter is to provide future researchers with an insight into the key methodology and concepts applied in this thesis to generate causal loop diagrams and stock and flow diagrams. Building conceptual models from theory based on qualitative data derived from multiple case study analysis requires a proper understanding of the components of the system thinking approach (i.e., system analysis and system dynamics, as depicted in Figure 3-1). This chapter provides a summary of the key required concepts and techniques for creating, simplifying, validating, and converting CLDs to stock and flow diagrams.

These provided instructions will assist future researchers to take essential steps to generate CLDs systematically. To make CLDs usable and reliable for developing hypotheses, they need to be simplified without scarifying the key variables and interactions. The author utilised Vensim software to develop and simplify the CLDs, but this is important to understand the logic behind simplification because part of the simplification process will rely on the modeller's judgment. Without following the provided steps, the CLDs will not reflect the true nature of the modelled system and hence, do not deliver an accurate understating of the system behaviour.

System Thinking embeds two other concepts, System Analysis (SA) and System Dynamics (SD). In general terms, system thinking is the mental modelling and science of structuring the logic and asking the relevant questions, but it also has practical applications through System Analysis and System Dynamics (HV Haraldsson 2004). System dynamics is a combination of methodological and complex tools founded on system thinking (Lane and Sterman 2011).

System thinking methods have been developed to help deal with complexity, which is a result of changes over time (dynamics), nonlinear relationships, bidirectional relationships (feedback loops), time-delayed effects, and emergent properties of the system (phenomena that are observed at the system level but cannot be causally linked to a specific individual component of the system (Mabry et al. 2010)).

System dynamics (SD) is a modelling and representation method, which expands the horizon for systems' behaviour investigation. Systems modelled employing system dynamics include dynamically changing components based on various influences (Mykoniatis and Angelopoulou 2017). The principal attribute of a system is that we can only understand its dynamic behaviour and interaction by viewing it. When applying systems thinking, one observes the dynamic relationships between all the parts within a system. To grasp the behaviour of a system, it is necessary to understand the feedbacks that steer it within its boundaries (HV Haraldsson 2004). Figure 3-1 is a schematic view to show the relationship between system analysis and system dynamics within the realms of systems thinking. All investigations into the properties and function of a system can be described through system thinking, which involves a mental model representation (system analysis) of the problem. System dynamics is a mathematical recreation of the problem to explain the past and understand the future. Created by author after (HV Haraldsson 2004).

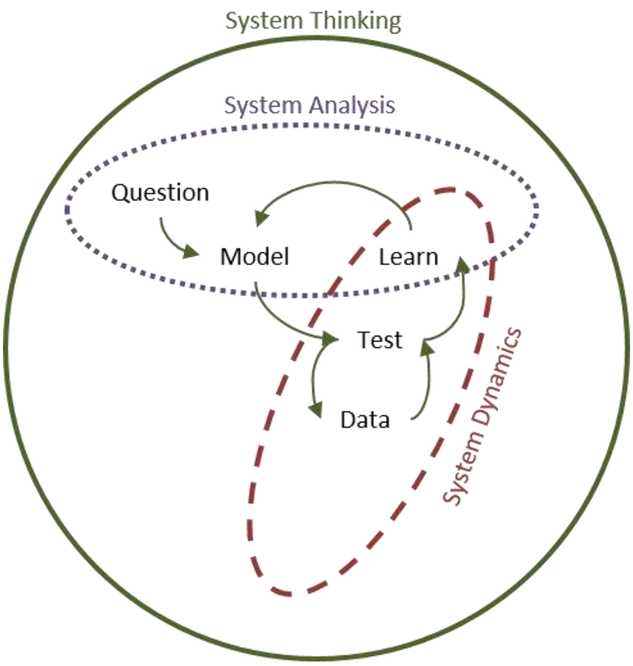


Figure 3-1 System Thinking Components

3.2 Causal Loop Diagrams

An important factor that must be considered is the “system boundary” of CLDs. The outcome of the modelling process can take the form of diagrams, mostly stock-and-flow diagrams, or causal loop diagrams. The former enables quantitative simulation, and the latter offers visually grounded logic models being the main topic of this study.

CLDs are developed to capture a shared understanding of complex problems and provide a visual tool to guide interventions (McGlashan *et al.* 2016). Creating CLDs is all about understanding the causes and the effects. Table 3-1 lists the steps of the logical stage and to development of causal loop diagrams. CLDs are generated mainly through qualitative analysis methods such as literature review, observations, and interviews with stakeholders. Generated CLDs need to be reviewed, modified, and verified by expert' feedback and cross-validation; this will lead to a more accurate level of reality.

Table 3-2 and Table 3-3 introduce the basic components of causal loop diagrams, followed by some basic examples to assist readers in better understanding the process.

During the development of CLDs, it is appropriate to consider which stakeholders should be engaged, which variables should be selected, and what to do when stakeholders perceive aspects differently (Dhirasasna and Sahin 2019). Within the modelling process, it is required to identify other variables, on which the selected variable depends. Specifically, it is needed to understand how the causal interactions between the variables in a system work together in that system.

TABLE 3-1 RECOMMENDED STEPS TO GENERATE CAUSAL LOOP DIAGRAMS
CREATED BY AUTHOR AFTER ADOPTION FROM(HV HARALDSSON 2004; T. TOOLE 2005)

Stage	Process
1. Define the Problem	Problem definition/System Boundaries
2. Questioning	Define the exact question to be answered
3. Identify and arrange main variables	Make a list of 8-10 main variables associated with the question and rank them based on hierarchical order.
4. Create a simple CLD	Draw the links between selected variables, making sure there is a link back to create feedback loops. Repeating the next loops to create an initial CLD.
5. Create a Basic Behaviour Pattern (BRP)	Utilise BRP to describe the model behaviour and compare it with Observed Behaviour Pattern (OBP) to diagnose the differences.
6. Test the CLD model	When you have finished the first version of the CLD check if it is reasonable; do the “Norwegian” laughing test. If you find yourself laughing at the result, then clearly something is wrong with your assumptions. Ask others to give feedback on your CLD; test your understanding of them or use the literature. Use the RBP to explain to them how the variables are behaving in the model.
7. Learn and Revise	This is essential to repeat the iterative process of modifying the CLDs based on a revision to make them more accurate.
8. Conclude	It can take many iterations to be content with the final version of the CLD. When we make conclusions, we are answering our initial question. We should check if our conclusions change the initial question. It often does. The initial question is changed because the iteration process with the CLD changed the definition of the problem and thus shifted the focus of the question.

To make the CLD understandable by all stakeholders it is important to carefully consider the terms used and to ensure arrow polarities are correct and consistent with the relationship being correct when ‘read’ in either direction. CLDs are mental representations of our understanding of processes and feedback of systems in the real world. Generating models begins with the definition of the problem first, identifying the causalities and then simplification of causalities. One of the most common mistakes is to assume that models are required to be highly complex (Haraldsson and Sverdrup 2004; Bureš 2017b). *“When we create mental models, we do not* *intend to capture the whole reality in one model. Such models are as complex as reality itself. We want to map part of the reality in such a way that it gives us a basic understanding of a complex problem"* (Haraldsson and Sverdrup 2004). The main tendency of system thinking is to simplify the understanding of key relationships in complicated circumstances. The main intention of the application of system dynamics in research is to deliver more thoughtful insights aiming at optimising the situation (Reynolds and Holwell 2010).

TABLE 3-2 COMPONENTS OF CLDS, CREATED AND MODIFIED BY AUTHOR AFTER ADOPTION FROM (HV HARALDSSON 2004)

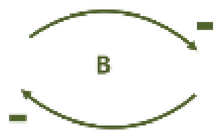
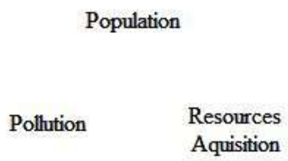
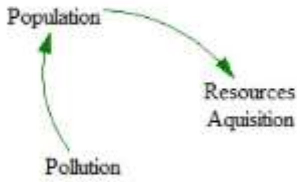
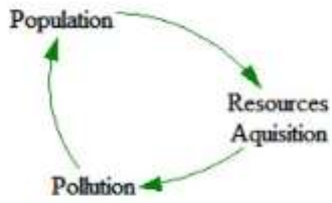
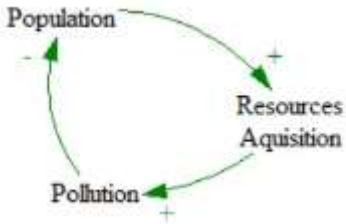
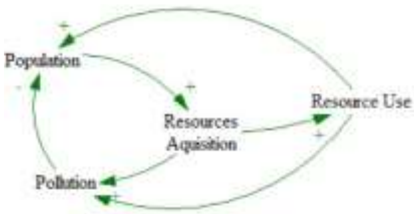
 The arrow illustrates causality. The variable on the tail causes a change to the variable at the head of the arrow. The plus sign on the head of the arrow indicates that the variable on the tail of the arrow and the variable on the end of the arrow, change in the same direction: If the variable on the tail increases, the head increases. If the variable in the tail decreases, the head decreases.	 Feedback loops come about when arrows connect a variable to itself through a series of other variables. There are two main types of feedback loops that can be expressed using CLDs (Rwashana *et al.* 2014). Loops with all plus signs or even several negative signs have positive polarity. These kinds of loops are called 'Reinforcing Loops' and hence labelled with an (R). This shows a systematic exponential growth or decline. This behaviour is moving away from an equilibrium state.
 The minus sign on the head of the arrow explains that the variable on the tail and the variable on the head of the arrow change in opposite directions: If the variable in the tail increases, the labelled decreases. If the variable in the tail decreases, the head increases.	 Feedback loops with odd number of minus signs have negative polarity and are labelled with a (B). This behaviour transfers systems into the equilibrium or a fluctuation around an equilibrium state.

TABLE 3-3 COMPONENTS OF CLDS

Step 1: Locate variables 	Step 2: Determine causality 	Step 3: Is there a link back? 
Step 4: Identify polarities 	Step 5: Locate variables of the second loop 	Step 6: Identify loops' behaviours, if possible

3.3 Model Simplification and Validation

One of the most common activities when carrying out problem-solving is seeking guidance and advice from experts; however, when it comes to more complex systems, even experts cannot provide solutions (Vermaak 2019). It has been suggested that system dynamics should represent problems and not actual systems. Modellers should not focus on expanding their models' boundaries too broadly and should instead develop their models around a specific purpose (Schwaninger and Groesser 2011). It is suggested that issues or problems can be considered as a 'system' and models can be generated to address specific issues (Hospers and Rapoport 1961). Referring back to the above table, a CLD is an abstract representation of perceived reality and CLD simulation tends to deliver insight into the real complex system (Schwaninger and Groesser 2011).

The causal loop modelling process is carried out by sorting the causalities according to their importance in answering specific questions. Afterwards, they need to be sorted based on their role in performance, meaning that causalities with strong relationships would have the highest performance. Then the next variables and arrows are identified to shape the system boundary. After a certain stage, the performance of the model would level out, even if we add more variables and causalities. This occurs because adding every single causality brings extra uncertainty and, at some point, that level of uncertainty will affect the functionality of the model to achieve a better understanding of its behaviour. In other words, we can expand the model to add more accurate details from the real world, but the imposed uncertainty would affect the functionality of the model. From that point, there would be no improvement in the model functionality and it “is characterised as the point where more complexity cost more in extra inputs and added inaccuracies than the extra complexity can improve performance.” (Haraldsson and Sverdrup 2004; Bureš 2017b)

CLDs are developed based on sub-systems and their forming components. Hence when the number of components of a model increase, the number of interactions increases. This will make the model more difficult to be observed. Each individual model could consist of components on various system levels. It is critical to select the level of the system required to understand the interactions between specific variables we want to study (Haraldsson and Sverdrup 2004; Bureš 2017b). The tendency to generate complex CLDs by adding more variables aimed at enhanced accuracy would make CLDs difficult to understand. Hence it is important to simplify complex CLDs (Bureš 2017b). Saysel and Barlas (2006) recommended that, to finalise the modelling cycle, to achieve a simpler and core model, an additional step requires to be taken, called model simplification. There are a set of terminologies related to the modelling process, which is summarised in Table 3-4.

TABLE 3-4 CLD MODELLING TERMINOLOGY
CREATED
BY AUTHOR AFTER ADOPTION FROM (SCHWANINGER AND GROESSER 2011)

Terminology	Description
Model	A model is a simplified representation of a real system.
Validity	Validity is the primary criterion of model quality and is the trait of the model to sufficiently reflect the modelled system.
Purpose	The model's purpose is the aim that the model is developed. That is related to the model owner and hence the model is the criterion to define the range of the model boundary and its design.
Modelling Process	The process involving phases such as problem articulation, boundary selection, development of a dynamic hypothesis, model formulation, model testing, policy formulation and policy evaluation (Sterman 2000).
Validation Process	Validation is the process by which model validity is improved systematically. It steadily builds up confidence in the effectiveness of a model by applying validation.

The main goal of system dynamics modelling for modellers is to use it as a communication tool with stakeholders, hence models must be sensible. Modellers usually depict cause/effect connections that are intuitive to them but not to others.

Therefore, to achieve a functional and fit-for-purpose model, causal loop diagrams must be simplified to avoid excessive uncertainty, which affects the performance of the model, but at the same time, models are required to be validated to ensure the level of quality of how they embody the real system. Jay Forrester, the father of system dynamics stated that system dynamics and CLDs are getting far from their dynamic nature and becoming more dependent on the human brain, which is proven to be inadequate to solve high-level dynamic feedback systems. He proposed that simplification processes of CLDs always suffer from a lack of clarity (Forrester 2007). Hence, it is important to understand the core concept of simplification and then find out the most valid research studies dealing with this important problem.

"Model simplification purifies the fundamental model structures causing selected problems and enhances the quality and understanding of models. Simplification is a process, which produces the main dynamics of a model. Beyond increasing the quality and understanding of the existing models, the commitment of the system dynamics field to the idea of creating integrative theories of seemingly separate, case-specific management problems motivates simplification practice. Through simplification, a case-specific, large and parameterized model of a dynamic problem can be reduced to a generic representation of the same problem, suitable for transferring knowledge in the same domain and useful for disseminating the essential structures responsible for the problematic behaviour and mismanagement" (Saysel and Barlas 2006).

One of the challenges system dynamics modellers face is that some models might be criticised as unrealistically simple, which generally leads to creating models that are too complex, unrealistic and difficult to understand (Saysel and Barlas 2006; Bureš 2017b). Bureš (2017b) highlights the fact that most of the existing methods are not adequate to manage the current level of complexity without sacrificing the quality of the models. An approach is then suggested:

1. Systems dynamics is founded on system-as-a-cause thinking and hence, the model structure must describe system behaviour (T. Binder *et al.* 2004; Saysel and Barlas 2006);

2. The proposed simplification method assumes no issues exist with regards to the suitability of reducing the number of model variables. As mentioned earlier, adding more details adds to the accuracy, but likewise, the complexity of the model grows and vice versa. There is a point that excessive complexity affects model performance, and we need to achieve that point of balance. That is the goal of simplification.

3. Capturing the whole picture is more important than the very specific details. It is assumed that multiple-input and multiple-output (MIMO) variables are the factors forming the main backbone of the models and affect the system behaviour.

The method proposed by Bureš (2017b) is based on three activities, which must be applied iteratively during specific steps. The three activities are:

1. Endogenization; The process of eliminating exogenous variables which do not reflect the true nature of the system in a CLD.
2. Encapsulation: The process of eliminating simple local feedback loops, in which only two variables are included; and.
3. Order-oriented reduction.

The method focuses on MIMO variables of the model and suppresses in-degree, out-degree and mediator variables (Saysel and Barlas 2006). Three phases are recommended in order and are sorted based on the range of their damage to the nature of the model. In other words, where it is possible, Endogenization is preferred to be applied rather than encapsulation, and encapsulation is recommended to be applied as much as possible prior to reduction. Complexity can be mostly managed via iterative approaches (Roubos and Setnes 2001), hence the method contains numerous reiterations concerning the level of simplicity or complexity of the CLDs.

This approach of simplification applies to qualitative models with no considerations for quantification. Concentrating on the qualitative model is supported by Coyle's notion that "the risks associated with attempting to quantify multiple and poorly understood soft relationships are likely to outweigh whatever potential benefit there might be"(Coyle 2001). This is aligned with Forrester's (2007) idea that small models are powerful. System dynamics modelling, and specifically, CLD modelling has become popular for analysing complex systems such as politics, economics, and management. The effectiveness of these models is grounded in their aptitude to link patterns of behaviour of a system to the underlying structures of the system. Table 3-5 provides the Burns and Musa (2001) simplification process for causal loop diagrams. This approach was adopted by the author to simplify the CLDs used in this thesis. Vensim software has some features to facilitate such an approach.

Despite these facts, the reception of the model by stakeholders and decision-makers is restricted (Qudrat-Ullah 2012). The model validation process is vital to establish the foundation for the prediction competence of the models (Oko and Wang 2014). As a communication tool, experts must scrutinise and examine CLDs before being presented to the other stakeholders for decision-making (Burns and Musa 2001).

To build theories from CLDs, there should be more proper scrutiny in validating CLDs. They should be assessed from two different aspects, namely Epistemological and Methodological (Figure 3-2). Degrees of resolution breaks down the model into smaller sections to enhance the quality of the assessment. Micro includes the smallest components such as links or small variables, Meso embraces the blocks forming the model and Macro looks at the model. Epistemological and technical validation as depicted in Figure 3-2 and their associated concepts are discussed in the methodology chapter in detail. There are some potential defined criteria, on which CLDs might be assessed, which are listed in Table 3-6. The author used these criteria to validate the CLDs with experts.

TABLE 3-5 PHASES FOR CLD SIMPLIFICATION (INDIGENISATION, ENCAPSULATION & REDUCTION) BY AUTHOR AFTER (Bureš 2017b)

Phase	**Activity**
1	Generate the diagram and draw duplicate variables as ghost variables. Ghost variables are considered just as an input to the other variables. This will enhance the readability of CLDs.
2	Identify the required complexity of the model. CLDs are graphical and that makes them complex and impossible to follow all links. However, the author utilised the Causes and Uses Tree features of the Vensim software to deal with the issue. The number of variables can be used as a measure to identify the required complexity.
3	List all exogenous variables (model inputs and outputs). Exogenous variables often represent a fairly significant portion of model variables. They should be listed due to the valuable information that will be lost during the simplification procedure. It can be used later for a better understanding of the simplified model.
4	The spot and mark technique can be used to identify inputs and outputs and their associated blind branches. All exogenous variables should be marked prior to elimination. This is recommended to remove all variables in one step to avoid disorientation caused by the occurrence of the new exogenous variable that may be created because of this step. Blind branches help to speed up this step as well. Blind branches are represented by the cause-and-effect relationship among exogenous variables (leaf of the branch) and other consequent variables without feedback. Every blind branch end in a variable that is a part of any feedback loop.
5	Remove selected variables (**Endogenisation**).
6	Mark SISO variables—when exogenous variables are removed, the system behaviour is completely explained by its structure. SISO variables represent only transformation elements that help to get the system dynamics from one point to another without any contribution, or better to say with a contribution that can be substituted by a structural change. Again, it is recommended to mark all SISO variables and remove them simultaneously.
	Bridge SISO variables (**Encapsulation**)—during this step, two issues need to be considered. First, it is necessary to define the polarity of a new link. For these purposes, the same principle used for the definition of the feedback loop polarity can be used. The new polarity can be determined based on the number of links with negative polarities. The signum

7	function is used for this purpose, as it returns two values only—0 or 1—which clearly define the link polarity. Second, this procedure results in the elimination of simple local feedback in which only two variables are included. However, this is in concordance with the assumption about the preference of the global picture to details
8	Perform Steps 2–5 unless the model is fully endogenous again—in the following Steps 8–10, the main principle is applied. After the removal of local feedbacks, new exogenous variables may appear.
9	Perform Steps 6–7 unless the model has no SISO variables again.
10	Repeat Steps 8–9 unless all exogenous variables and SISO variables disappear.
11	Mark all SIDO and DISO variables.
12	Erase SIDO and DISO variables (**Order-Oriented Reduction**)
13	Perform Steps 2–5 unless the model is fully endogenous again.
14	Perform Steps 6–7 unless the model is fully endogenous again.
15	Repeat Steps 8–9 unless all exogenous variables and SISO variables disappear.
16	Repeat Steps 11–15 with DIDO variables, triple variables (SITO, TISO, and TITO), etc., unless the required complexity is obtained.

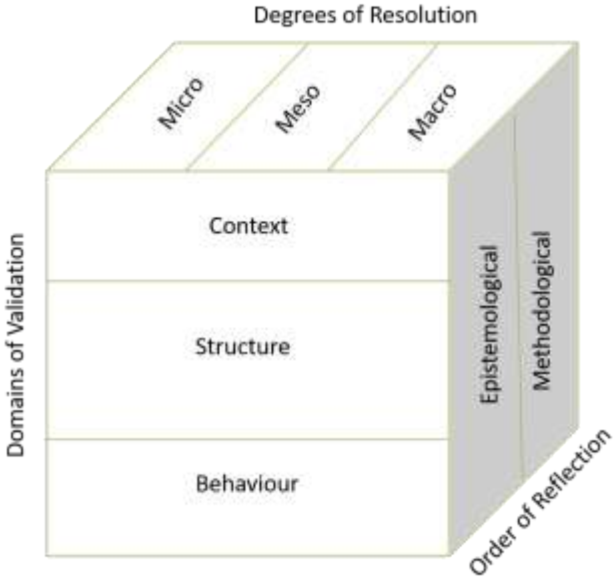


Figure 3-2 Validation cube- Three dimensions for validation to assure CLD quality, by author after (Schwaninger and Groesser 2011)

TABLE 3-6 POTENTIAL CRITERIA THAT CLDS' COMPETENCY MIGHT BE ASSESSED BASED ON. AUTHOR AFTER(BURNS AND MUSA 2001)

Criteria	Description
Clarity	The level of ability of the model on how it communicates the implied causalities. To achieve clarity, the following questions are recommended to be raised: a. Are all causes and their effects understandable or some verbal changes are required? b. Is the link between cause and effect convincing? c. Is there any middle variable missing in causal links?
Quantity Existence and Units Associated Therewith	The entity of each variable and its immediate existence can be criticised. If the variable does not exist now but will provide a view of an issue of interest, still can be valid.
Causality Existence	The realism and originality of the link between the two variables can be questioned.
Cause Inadequacy	The objective of the causal relationship would be investigated. The question is “can the causal link, create the effect we are expecting in the target quantity on its own?” If the answer is NO, the cause inadequacy exists. Then the next question is, “are there any significant cause factors missing?” Taking the perspective of the effect variable and looking back to all its immediate cause antecedents, we ask, “are the exhibited cause variables sufficient to produce the stated effect?” If our answer is no, we haven’t been thorough in our inclusion of all the possible causal factors.
Additional Cause	In some cases, it could be discussed whether the identified cause-effect is unique or whether other interactions will independently create the same effect.
Cause-Effect Reversal	Sometimes, in assessing CLDs, it might be realised that the cause-effect relation could be reversed.
Expected Effect existence	If an identified variable with a valid cause exists, what can be its other associated effects?
Tautology	A statement that is factual. In CLDs many effects might be presented as a rationale for the existence of the cause; but these are the same. Thus, tautologous statements of causality are circular in terms of their reasoning.

3.4 Stock-Flow Diagram

"The stock and flow modelling (SF) is formed of stock (state) and flow (rate) variables. Stock variables are the accumulations within the system. The flow variables represent the flows in the system, which result from the decision-making process. The behaviour of a system is obtained by the evolution of state variables. Although delays exist in all flow variables, only the significant ones (compared with the simulation time step) are included in the model because they impact the system's behaviour" (Samara *et al.* 2012, p.628). Causal loop diagrams are an appropriate point to start system modelling, but converting them into stock and flow diagrams is not a straightforward process (Hördur Haraldsson 2004). Binder *et al.* (2004) proposed a model to develop stock-flow diagrams from CLDs using the following key steps:

a) Decide which variables on the CLD are stock, which one flows and identify which links represent flow dependencies and which information dependencies.

b) Manually controlled steps to transform CLDs to the stock-flow diagram to make it fit-for-purpose associated with the content of the CLD.

c) Utilise automatic transformation of CLDs to SFDs (in this research the Vensim tool was utilised).

d) Quantify the developed SFD. Define initial values and formulas for the labelled dependencies. Depending on the nature of the research, step 'c' can be skipped and the actual CLD can be quantified instead of the SFD (T. Binder *et al.* 2004, p.2).

Figure 3-3 depicts the steps towards SD simulation, inspired by (Boateng 2014). The system dynamics approach involves a series of differential and algebraic equations developed from a broad spectrum of relevant measured and experiential data (Cavana and Mares 2004). Since system dynamics simulation is an iterative process, it involves recurring efforts to identify scope, generate a hypothesis, validate CLDs, quantification and verification (Qudrat-Ullah 2012; Lin *et al.* 2020). The process needs to be selectively repeated until the model can generate useful insights and meet certain criteria, such as its realism, robustness, and flexibility (Homer and Hirsch 2006; Lin *et al.* 2020). System dynamics modelling provides a holistic overview of complex systems and facilitates studying the whole system behaviour, hence SD can deliver a model to understand the complexity, change and evaluation sustainability of policies and decisions (Cavana and Mares 2004; Videira *et al.* 2017; Lin *et al.* 2020; Roubík *et al.* 2020). The process to develop a stock and flow diagram from CLD is depicted in Figure 3-3 and will be expanded in Chapter 7.

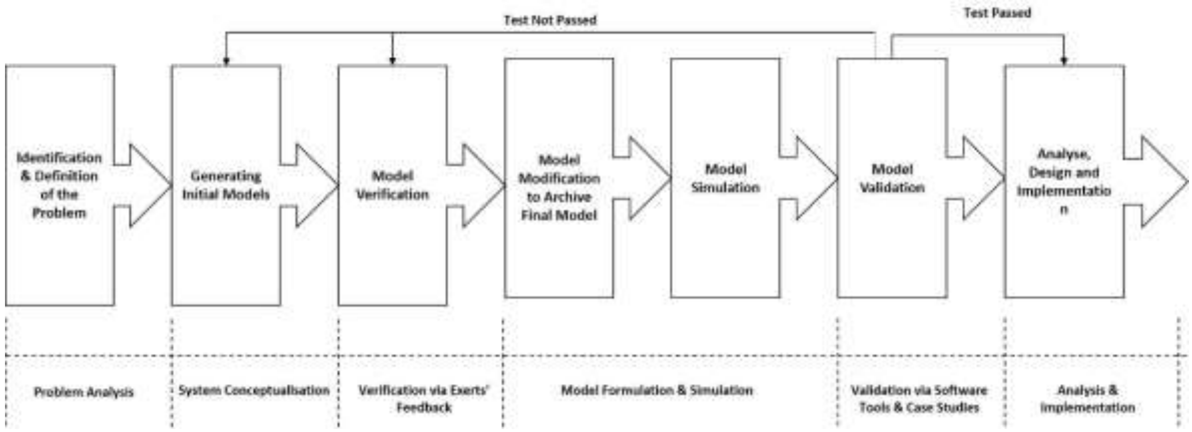


Figure 3-3 Process of SD simulation, Author after (Boateng 2014)

3.5 Conclusion

The purpose of modelling project systems via system dynamics tools is to represent the inherent complexity, so making models overcomplicated would not add any value to understanding the project systems' behaviour. On the other hand, oversimplification of the models will lead to neglecting key components and a lack of accuracy when analysing the models. Hence, this is important to follow the systematic steps in the process of creating conceptual models from qualitative data.

The section below explains how the content of this chapter has been used to contribute to shaping the overall focus of the research:

Section 3.1 & 3.2 Causal Loop Diagram; the concepts have been used to create, read, and interpret the CLDs, which contributes to qualitative analysis.

Section 3.3 model Simplification & Validation; this is an important section as provides an approved methodology to simplify the generated causal loop diagrams. CLDs need to be systematically simplified to make them acceptable for qualitative analysis.

Section 3.4 Stock & Flow Diagrams; This section provides a basic Introduction to the concept of SFDs and how to convert CLDs to SFDs to enable conducting a quantitative analysis.

Chapter 4 provides a summary of key previous research studies focused on the application of system dynamics tools to the field of project management. Chapter 4 tends to summarise the most recent advancements in the application of system thinking tools to the field of project management and explains how the body of knowledge for project management has been improved.

Chapter 4

APPLICATION OF SYSTEM DYNAMICS TOOLS TO PROJECT MANAGEMENT

4.1 Logic & Introduction

4.1.1 The logic of the Chapter

This chapter is provided based on a systematic literature review and NVivo analysis (as described in Chapter 2) to identify and classify the different fields of application of system dynamics tools in the realm of project management. This chapter is deliberately presented separately from the literature review chapter. One of the key areas focused on in this thesis is the application of system dynamics tools to optimise railway project management strategies. Hence, it was important to understand all previous research avenues, their strength and drawbacks and their scope. Analysis of the previous works delivered a series of benefits as follows:

- Provided the author with a holistic insight into the existing gaps within the body of knowledge and applicable methodologies.
- Assisted the author in defining a rational research avenue and a suitable methodology to bridge the identified gaps.
- Provided the author with a holistic overview and learning from the previously applied methods to a wide range of engineering and management disciplines. This helped the author to choose the best applicable approach, being capable of addressing the problems within the rail industry.
- This chapter provides readers with a holistic review of the previous projects reinforced via system dynamics tools. This will be beneficial to all future researchers who are interested to work on similar research streams.

4.1.2 Introduction

As investigated in Chapter 2, traditional project management techniques are not compatible with the dynamic and changing environment of modern complex projects. In Chapter 2, it was mentioned that the application of SD concepts and analytical methods is capable of improving quite a lot of imperfections of the conventional project management analytical tools (T. Toole 2005). SD tools are recommended to profoundly improve the understanding of projects (as complex systems) as a whole (Wang and Yuan 2017). Some researchers such as Reason (1990), have mentioned the role of 'pathogens' as hidden conditions within a system until an error comes to light. Busby and Hughes (2004) define these pathogens by a few characteristics:

1. They are relatively stable phenomena that have been in existence for a substantial time before the error occurs.
2. Before the error occurs, they would not have been seen as obvious stages in an identifiable sequence failure.
3. They are strongly connected to the error and are identifiable as the principal causes of the error once it occurs.

Before the pathogens emerge, project participants are usually uninformed of the impacts of the pathogens on the decision-making process and project performance. The pathogens can potentially emerge because of strategic decisions taken at the top management level by main decision-makers. Such decisions may be erroneous, but they need not be. Latent conditions can stay silent within a system for a remarkable period and thus will potentially become an inherent component of everyday work practices. When these pathogens combine with other active failures, errors will occur and their consequences will be noteworthy (Reason 2000; Busby and Hughes 2004).

Reviewing the papers mentioned in the above table shows that most of the researchers have focused on understanding the main variables creating risks in projects and modelling their interactions to enable managers to employ more effective decision-making methods. Risk as a single factor is the centre of almost all the listed publications. A pure focus on deadlines and project deliverables will lead to unexpected and undesirable outcomes and underperformance. CLDs are capable of assisting managers in analysing the impact and consequences of their decisions and actions originating from feedback loops (T. Toole 2005). The APM and INCOSE joint report published in 2018 promotes the application of system thinking to project management and states that CLDs can assist project teams to develop a shared understanding of the problems and understand their roles to avoid a blame culture.

Figure 4-1 shows the key principles for a successful application of system thinking to project management. SD in general and CLDs particularly are recommended to be applied to projects, programme, and portfolio management. Accordingly, the main recommended areas of CLD application are (APM and INCOSE July 2018):

- ***Phase and stage scope definition and requirements:*** CLDs could be useful for lifecycle analysis.
- ***Risk management:*** systems thinking highlights interactions between different interfaces of portfolio, programme and project components, stakeholders, the environment, and associated risks.
- ***Dependency management:*** systems thinking approaches are founded on the identification of dependencies, but it is important to ensure that this will be applied throughout all stages of projects, programmes, and portfolios. CLDs could be useful tools to facilitate this.

The following section will briefly summarise the most important areas of application of CLDs to projects. TABLE 4-1 provides a list of the most recent journal papers focused on the application of stock and flow diagrams to the field of project management. These papers have considered the impact of SFD models on system optimisation, improving the decision-making process and analysing systems' behaviour.

Figure 4-1 presents the key principles of applying system thinking to projects. According to the figure, as the first step to applying system thinking to projects, the big picture needs to be considered. The next step is to appreciate that, in addition to external factors, the causality and non-linear interactions of the project components play a significant role in defining project system behaviour. Defining the system boundary-as stated earlier- is essential. Each model should be designed based on its limited, defined capability and to serve the defined research questions and hypothesis.

To analyse the behaviour of the system over time, CLDs need to be converted into stock and flow diagrams and quantified. Additionally, CLDs need to be updated regularly and consider the dynamic nature of the projects to ensure reflecting a realistic picture of the projects' environment. As explained earlier, Figure 4-1 presents the key principles of applying system thinking to projects.

TABLE 4-1 EXAMPLES OF SD APPLICATION TO PROJECT MANAGEMENT 2010–2020 (AUTHOR)

Fields of SD Application	**Authors**
Strategic project management	Lyneis et al. (2001); Lee et al. (2006); Ecem Yildiz et al. (2020)
Logistics and supply chain	Rashid and Weston (2012); Tako and Robinson (2012); Cedillo-Campos and Sánchez-Ramírez (2013); Iannone et al. (2015)
Determining the concession period in build–operate–transfer (BOT) projects	Zhang et al. (2002); Nasirzadeh et al. (2014); Song et al. (2015)
Establishing a decision-making system to anticipate organisational behaviour	Spector et al. (2001); Macmillan et al. (2016); Raj et al. (2020); Roubík et al. (2020)
Understanding the causation of the constriction staff unsafe behaviours	Spector et al. (2001); Han et al. (2014); Jiang et al. (2014); Guo et al. (2015); Raj et al. (2020)
Selection of sustainable construction methods for highway projects	Rehan et al. (2014); Orji and Wei (2015); Ozcan-Deniz and Zhu (2016); Kotir et al. (2017); Perrone et al. (2020); Wu et al. (2020)

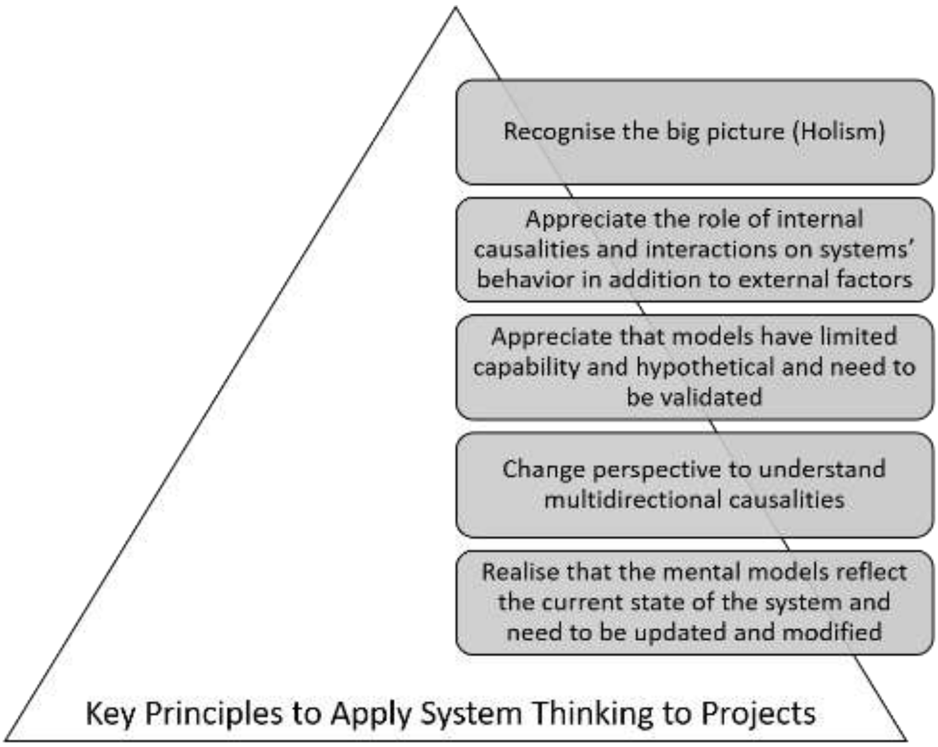


Figure 4-1 Key principles to applying system thinking to projects (author, inspired by Grösser (2017) and APM and INCOSE (2018))

4.2 Causal Loop Diagrams Applied to Project Risk Evaluation and Prioritisation

Table 4-2 presents some of the most important publications between 2010 and 2020. Listing all publications is out of the scope of this thesis, but the list below was chosen based on the variety of nature and thematic subjects to highlight the categories of CLD application to project risk. The listed research publications used a combination of solely CLDs and quantified SFDs.

Analysing the existing publications shows that the main domain of CLD application to projects, both academically and practically, is risk evaluation and management in complex projects. CLDs have been applied from the early stages of projects through the whole lifecycle but are mostly considered the implementation and operation phases of the projects. Conventional methods are not competent to assess project risks and consider project integrity (Fan and Gao 2019).

There are different approaches and tools in place to manage risks in projects, such as risk registers (Patterson and Neailey 2002; Kuchta and Ptaszyńska 2017), critical path analysis (Chen and Hsueh 2008; Zareei 2018), Monte Carlo simulation (Arnold and Yildiz 2015; Jiang et al. 2015), decision trees (Tan et al. 2010; Rasool et al. 2012), risk breakdown structures (Holzmann and Spiegler 2011; Rasool et al. 2012), and probability and impact matrices (Karantininis 2002; Usuda et al. 2016). Risk registers are the most commonly used approach in projects (O'Har et al. 2017).

However, classic risk registers do not reflect the interactions between different potential risks, specifically when the combination of risks (for example in portfolios) will be much more destructive than individual risks (Cagliano et al. 2011).

TABLE 4-2 KEY PUBLICATIONS FOCUSING ON THE APPLICATION OF SD TO MANAGE RISKS (AUTHOR)

Area of Application	**Author(s)**	**Key Points**
Causal loop-based change propagation and risk assessment	Wollan et al. (2010)	Application of CLDs in the initial phase to describe the principle, recommending application of CLDs to the projects' whole lifecycle.
Probabilistic risk analysis and terrorism risk	Ezell et al. (2010)	Analysing terrorism attacks and the risk of occurrence.
Applying systems thinking concepts in the analysis of major incidents and safety culture	Goh et al. (2010)	Application of CLDs to identify the systemic structure supporting a safety culture.
System dynamic methodological approach for design and analysis of risk in supply chain	Mei and Hehua (2011)	Evaluating the level of risk in the food supply industry.
System dynamics investigation of information technology in small and medium enterprise supply chains	Sidola and Kumar (2012)	Utilising CLDs to analyse the impact of IT capability on organisational performance.
Systems approach for modelling supply chain risks	Ghadge et al. (2013)	Analysing supply chain management risks in the comparative market.
Post-seismic supply chain risk management: a system dynamic disruption analysis approach for inventory and logistics planning	Peng et al. (2014)	Analysing the behaviours of disrupted disaster relief supply chain by simulating the uncertainties.
Applying a systems model to enterprise risk management	Bharathy and McShane (2014)	Assessing enterprise risk and its management.
When does operational risk cause supply chain enterprises to tip? A simulation of intra-organisational dynamics	Guertler and Spinler (2015)	Studying the interactions and feedback loops between different enterprises in a supply chain.
System-focused risk identification and assessment for disaster preparedness: Dynamic threat analysis	Powell et al. (2016)	Risk identification and assessment of systems in the early stages of development.
Renewable energy investment risk evaluation model based on system dynamics	Liu and Zeng (2017)	Evaluating the impact of risk policy on renewable energy investment.
Conceptual model of failure risk control on raw materials inventory system	Suwandi et al. (2018)	Using CLDs to create a conceptual model for risk control of failure in raw materials warehousing.
Scenario analysis and disaster preparedness for port and maritime logistics risk management	Kwesi-Buor et al. (2019)	Identifying the risk-generating cause and effect of a policy change.
Risk evaluation and prioritisation in bridge construction projects using system dynamics approach	Mortazavi et al. (2020)	Risk evaluation and prioritisation for bridge construction projects.

This imposes the inevitability of considering the concept of 'risk systematicity' and utilising system dynamic tools to assess and manage risks in modern complex projects (Ackermann et al. 2007). The application of SD and CLDs assists managers to achieve a comprehensive understanding of risks and the interactions between different types of risk in a project environment dealing with too many stakeholders (Ackermann et al. 2014).

4.3 Application of Systems Dynamics and Causal Loop Diagrams to Analyse and Engage Stakeholders

SD tends to solve problems and, in this field, stakeholders can be considered as 'problem owners'; it is recommended that they are engaged in causal loop modelling and the project simulation process (Videira et al. 2017). Stakeholder dynamics is a concept that was initially proposed by Freeman and McVea (1984) and Alkhafaji (1989). Stakeholder dynamics considers changes in stakeholders' combination over time, new stakeholders joining a group and others existing, and changes in stakeholders' requirements and desired deliverables (Elias et al. 2000).

To achieve a sustainable management strategy, we need to establish a decision-making process that takes into account the dynamic interactions between socio-environmental systems and enables stakeholder feedback and information based on a scientific method (Stave 2010). This is essential to improve stakeholders' relationships and to enable managers to cope with change in projects (Boddy and Paton 2004). CLDs are practical and useful tools that can assist stakeholders in raising awareness and shared understanding of the interactions between system components (Inam et al. 2015). Project management strategies suffer from a lack of engagement of participants and stakeholders (Eskerod and Lund 2013) and CLDs can be utilised to enhance their engagement in the project scoping stage (Ravesteijn et al. 2014) and, most importantly, used as a validation tool for project outcomes (Aikenhead et al. 2015). CLDs can potentially introduce new areas for the collection of data from stakeholders and accumulate their different perspectives (Alladi and Vadari 2011; Kotir et al. 2017). Some researchers like Pagano et al. (2019) and Heijkoop and Cunningham (2007) proposed employing CLDs and SD to the model realisation of a project's benefits, involving the combination of conflicting stakeholders' requirements. Requirements engineering is defined as the key to success for the project (Love et al. 2002).

SD and CLDs have been applied as stakeholder analysis tools to analyse dynamic complex scenarios related to conflicts in requirements (Stave 2003; Voinov and Bousquet 2010; Elias 2012). SD is capable of capturing and managing the dynamics of stakeholders in three aspects (Elias et al. 2000):

I. Group model building utilising SD can help to understand the existing dynamics of stakeholders and their different perspectives.

II. Stakeholders can experience different scenarios and a combination of situations using a management flight simulator. This will help to recognise the future dynamics of stakeholders.

III. Project managers can use SD to engage stakeholders and understand their interactions, specifically when there are a large group of stakeholders in projects (collaborative requirements engineering).

Table 4-3 summarises some of the key examples of the application of SD and CLDs to manage the complexity of stakeholder management in projects.

TABLE 4-3 IMPORTANT PUBLICATIONS FOCUSED ON UTILISNG CLDS FOR STAKEHOLDER MANAGEMENT (AUTHOR)

Area of Application	**Author(s)**	**Key Points**
System dynamics modelling and simulation of collaborative requirements engineering	Stallinger and Grünbacher (2001)	Developed a SD model to facilitate easy win-win requirements negotiations.
Stakeholder theory and dynamics in supply chain collaboration	Co and Barro (2009)	Application of SD to evaluate the impact of mutual interactions with stakeholders on the aggressive vs cooperative strategies in managing stakeholder relationships.
Dynamic stakeholder interaction analysis: innovative smart living design cases	Solaimani et al. (2013)	Application of a quantitative SD model to move from static and conceptual stakeholder analysis to dynamic understanding of their relationships (smart homes and smart living).
Engaging stakeholders for collaborative decision-making in humanitarian logistics using system dynamics	Guo and Kapucu (2019)	SD model that captures the complexity of humanitarian logistics systems and facilitates stakeholder engagement for efficient and effective humanitarian relief.
System dynamics-based stakeholders' impact analysis of highway maintenance systems	H. Zhang et al. (2019)	Utilising SD to model complex interactions between numerous stakeholders in highway projects.
Simulating opinion dynamics on stakeholders' networks through agent-based modelling for collective transport decisions	Le Pira et al. (2015)	Developing an agent-based model to analyse the interaction of a group of stakeholders to decide the priorities of a prefixed set of alternatives to be implemented in transport planning.
Engaging stakeholders in environmental and sustainability decisions with participatory system dynamics modelling	Videira et al. (2017)	Application of a participatory SD model to engage stakeholders in collaborative decision-making for humanitarian logistic situations.
A system dynamics model to facilitate public understanding of water management options	Stave (2003)	Utilising a strategic-level SD model for water management to simulate the interactivity feature of the model to stimulate stakeholders' interest.
Modelling with stakeholders	Voinov and Bousquet (2010)	Comparison of different types of modelling with stakeholders with a touch on SD.
Engaging stakeholders in the assessment of NBS effectiveness in flood risk reduction: a participatory system dynamics model for benefits evaluation	Powell et al. (2016); Pagano et al. (2019)	Generating a quantitative SFD using stakeholders' perception of the project as inputs to enhance the benefits realisation.
Engaging stakeholders in engineering systems representation and modelling	Mostashari and Sussman (2020)	Evaluating the impact of risk policy on renewable energy investment.

The papers listed in Table 4-3 were selected from 63 journal papers, based on the relevance of their scope for the application of SD and CLDs to project stakeholder management; the author has tried to consider the different industrial fields of application. From the analysis of the literature review and the previous work done in this field, the following conclusions can be drawn:

- any of the research papers focused on the application of SD to deal with the complexity and dynamics of stakeholders, aiming to enhance stakeholder engagement in defining the scope of the projects. The desired goal for most of those papers is to involve stakeholders in modelling the complex environment of the projects as an incentive and as a tool to improve the realisation of the project benefits.
- A smaller portion of the published papers focused on simulating the complex interactions between stakeholders. They mostly utilised CLDs to model stakeholder dynamics and then moved to SFDs and model quantification to analyse specific situations in specific projects as listed in Table 4-3;
- Despite the importance of collaborative requirements, engineering being highlighted, and the benefits of SD tools being emphasised in the literature, only a few shreds of evidence exist to show the practical application of CLDs in real projects. In other words, although some researchers have used real-life case studies to apply SD to improve stakeholder management, the realm of this subject has remained in the academic environment.

4.4 Causal Loop Diagrams to Model the Complexity of Projects and Analyse the Impact of Changes

One of the fields for the application of SD and CLDs to project management is modelling the complex interactions of project components to analyse the impact of changes, errors, or decision-making. One of the most significant and complicated elements of simulating complex systems is to discover the impact of changes over time (Flores and Ambrósio 2010). The industrial application of CLDs in this field varies from analysing the impact of policies, investments, innovation, or managerial changes on project benefits to supply chain productivity, success etc.

A group of researchers recommend the application of SD models and CLDs to study the complex interactions between the different components of a collaborative supply chain market, to enhance the effectiveness of the change management process (Reddi and Moon 2011; Jaradat et al. 2017).

Construction project environments are complex and dynamic (Ozcan-Deniz and Zhu 2016) and, accordingly, they encounter dynamic and sometimes iterative errors leading to remarkable time and cost overruns (Flyvbjerg et al. 2002). SD and CLDs are recommended to be used for identifying those iterative errors by analysing the mechanism associated with errors and changes (Lee and Peña-Mora 2007). A great example of those iterative errors is 'rework' in projects. SD modelling has been used by a few researchers such as Love et al. (2002) and Han et al. (2013) who applied CLDs and mathematical computer modelling to measure the impact of changes (design errors, rework, change in resources etc.) on construction project success.

Precisely speaking, "the rework cycle is at the heart of modelling projects, one of the major research and application areas in system dynamics. The current formulations for the rework cycle assume each task is either defective or not. Yet in many projects, multiple defects can occur in one task" (Rahmandad and Hu 2010). TABLE 4-4 summarises the most important research publications emphasising the application of CLDs and SD to analyse the behaviour of complex projects and analyse the impact of change in such environments.

Analysis of the themes and approaches adopted by the above-mentioned researchers reveals that most of those research papers emphasise specific problems or changes within the project's components. Then, they tried to model the environment of the projects to assist them in better understanding its nature and measure the impact of change on the whole system's behaviour, project cost, time, and benefits. In other words, most of the projects focused on analysing the known changes within the projects.

TABLE 4-4 IMPORTANT PUBLICATIONS COVERING THE APPLICATION OF SD AND CLDS TO ANALYSE THE IMPACT OF CHANGES IN PROJECTS (AUTHOR)

Area of Application	**Author(s)**	**Key Points**
Evaluation of labour hiring policies in construction project performance using system dynamics	Abbaspour and Dabirian (2019)	Utilising SD to evaluate how labour recruitment policies would impact construction project performance and future investment.
Evaluation of the impact of rework through a system dynamics approach in an overlapping product development schedule	Marujo (2009)	Application of a numerical SD model to establish an innovative framework to analyse the project planning concepts to avoid rework in product production.
System dynamics model for assessing the impacts of design errors in construction projects	Han et al. (2013)	Using an SD model to measure the impact of design errors on a university building project delay and cost overrun.
System dynamics simulation model to evaluate project planning policies	Shafieezadeh et al. 2019)	Analysing the hierarchical complexities of projects and analysing how changes in dynamics would impact project performance.
System dynamics approach for change management in new product development	Rodrigues et al. (2006)	Utilising CLDs and SFDs to facilitate effective change management for new product development.
Impact of innovation policies on the performance of national innovation systems: a system dynamics analysis	Samara et al. (2012)	Modelling a national innovative system using SD tools to provide a holistic analysis of its components.
System dynamics modelling for estimating municipal water demand in an urban region under uncertain economic impacts	Qi and Chang (2011)	Generating an SD model to anticipate the demand for water in urban areas affected by changes in the economic situation.
System dynamics models of the environment, energy, and climate change	Bharathy and McShane (2014); Ford (2020)	CLD modelling to analyse the changing patterns in climate and its impact on the environment and energy.
System dynamics modelling of engineering change management in a collaborative environment	Reddi and Moon (2011); Guertler and Spinler (2015)	SD modelling to understand the complex interactions in the competitive market of the supply chain to achieve effective change management.
Scenario-derived planning with system dynamics	Georgantzas (2020)	Comprehend the cause and effect of relationships in complex systems, which affect the decision-making process.

4.5 Application of Causal Loop Diagrams to Railway Projects

Railway systems, as one of the most safety-critical modes of transportation, are complex and complicated, and researchers like Abbas and Bell (1994) pioneered the application of SD and CLDs to the transportation area. They identified 12 advantages of SD applied to the transportation industry compared to the conventional modelling approaches and emphasised that SD tools are competent for strategic policy analysis and as a support tool for decision-making. SD tools and CLDs have been applied to the transportation field mainly in five areas (Shepherd 2014):

- Modelling the uptake of alternate fuel vehicles.
- Supply chain management with transportation.
- Highway maintenance/construction.
- Strategic policy at urban, regional, and national levels.
- Airlines and airports.

The literature review shows that most research projects applying SD to railway projects have focused on risk assessment and risk management.T. The author’s research highlighted two outstanding PhD projects focusing on the application of SD as a risk analysis tool in railway projects. The research performed by Kawakami (2014) applied SD to analyse the inherent risks of high-speed rail project management in the United States. Kawakami proposed that, apart from focusing on the physical complexity of a project, a holistic approach is required to study the institutional levels of the project to achieve a realistic risk analysis. SD can contribute to risk management by identifying the key variables affecting safety, meaning that comprehensive feedback from the controlled process provides the controller with a process model of the system dynamism, which bridges the system development and system operations (Kawakami 2014). The second important research identified was performed by Boateng et al. (2015), who utilised

SD tools as a complementary tool combined with an analytical network process to evaluate the impact of Edinburgh Tramways project risks (cost overrun, delay etc.) on the profitability phase of the project. In other words, the impact of megaproject risks on the economic risks was measured using quantified CLDs.

TABLE 4-5 APPLICATION OF SD IN PROJECT MANAGEMENT (AUTHOR)

Area of Application	Author(s)	Key Points
System dynamics for railway infrastructure protection	De Maggio and Setola (2013); Abbaspour and Dabirian (2019)	Application of SD to model how different factors influence railway station target attractiveness, fragility, and vulnerability.
System dynamics of railway vehicles and track	Popp et al. (2003); Marujo (2009)	Application of a numerical SD model to understand the interaction between high-speed trains and track.
A system dynamics-based method for demand forecasting in infrastructure projects – a case of PPP projects	Alasad et al. (2013)	Creating an SD model to establish the causal structure of the demand system, which assists in representing and defining the impacts of different factors on-demand volume.
Research on management information station of railway construction projects	Zhou et al. (2014)	Analysing the hierarchical complexities of projects and analysing how changes in dynamics would impact projects' performance.
A project risk management framework for railway construction projects	Johnson (2008)	Utilising CLDs and SFDs to facilitate effective change management for new product development.
An accident causation model for the railway industry: application of the model to 80 rail accident investigation reports from the UK	Kim and Yoon (2013)	Generating a causation accident model for the railway industry.
Demand risk management of private high-speed rail operators: a review of experiences in Japan and Taiwan	Bugalia et al. (2019)	Application of causal loops to evaluate the demand risks and their impact on private sector involvement in the rail industry.
Improving the management of innovation risks: R&D risk assessment for large technology projects	Dillerup et al. (2018)	Application of CLDs and SD as an innovative technique for multi-dimensional risk management.
Impact of transportation disruptions on supply chain performance	Wilson (2007)	Investigating the impact of a transportation disruption on supply chain performance using SD simulation.

4.6 Conclusion

From analysing the content and methodologies of the above-mentioned research papers, the following conclusions can be drawn:

- SD tools, including CLDs, have been utilised in project management, mainly in the fields of supply chain and operation management. The main areas of application of CLDs are project risk evaluation and prioritisation, stakeholder analysis and change impact analysis.

- CLDs are mostly used as the foundation for SFDs to enable quantification of the models, specifically to measure the impact of risks on the safety, costs, benefits, and lifecycle of projects. In most projects, the whole modelling process is shaped around a single or one group of main variables to analyse their interactions and impact on the whole system's behaviour.

- SD and CLDs have previously been used to optimise some components of projects such as project governance and project risk management, as recommended by APM, but there is little evidence to show their application for modelling and the whole project management process.

- The application of SD has been mostly based on heavy numerical modelling and required in-depth technical skills, which has led to some generic reluctance amongst managers and management practitioners to adopt SD and CLDs as optimisation tools.

- System dynamics tools are not well perceived as reliable toolsets to manage the resilience of systems, specifically in railways. Despite it having been used in a limited number of research studies, again, the scope of research has been mostly on risks or resilience of a specific element of railway, such as tracks or bridges.

4.6.1 Recommended Future Work by Researchers

Analysis of the literature review highlights some key areas for future research to manage project complexities. These recommendations focus on developing innovative techniques to enable conventional management methods and combining system thinking techniques to bridge the existing gaps within the body of knowledge of management:

- "There is a growing recognition within the project management community of the need for pluralism of approaches to create broader-ranging perspectives on projects and thus improve our understandings of them. While the CLD technique is emerging within project management, the paper has suggested further avenues for research in which the technique could offer additional insights for both project theory and practice. These included the practitioner-led application of the technique, longitudinal analysis of projects and mixing of the technique with more typical methods such as the survey design. Causal mapping is collaborative, engaged, draw on multiple perspectives and enables application" (Ackermann and Alexander 2016);

- "The understand–reduce–respond approach does not yet have comprehensive empirical data on whether it is effective (i.e., improves project performance) as part of regular project work. Many anecdotal accounts demonstrate this, but the collation of empirical data would be helpful in both building evidence for it as well as contributing to the nuance of the approach. Secondly, the responses to emergent complexities appear to be the biggest gap between the OM and PM literature and the practices are seen thus far. Exploring the recursive nature of complexity and response appears to open up many possibilities" (Maylor and Turner 2017).

"The new complex and dynamic environments require project managers to rethink the traditional definition of a project and the ways to manage it. Project managers must be able to make decisions in these dynamic yet unstable systems that are continuously changing and evolving randomly and are hard to predict, very different from the linear, predictable systems traditionally studied. To achieve this objective, more integrated approaches for managing projects in complex environments and new methods of planning, scheduling, executing, and controlling projects must be investigated" (San Cristóbal et al. 2018). Chapter 4 identified and classified the main areas of application of system dynamics tools to project management.

Chapter 5 introduces the multiple case study analysis approach, its components, features and limitations.

Chapter 5

UTILISING CASE STUDIES:

MULTIPLE CASE STUDY ANALYSIS

5.1 Introduction

Chapter 5 introduces the author's adopted approach to developing his hypothesis from real-life projects and via multiple case study analysis. Methodologies to design cognitive questionnaires and conduct in-depth interviews, utilising NVivo for qualitative data analysis, utilising Vensim to create CLDs, limitations imposed by circumstances and the ethical framework adopted by this research will be presented. In the end, the author presents a diagram to assist future researchers to utilise his proposed approach for similar projects (Replication of Approach).

To comprehend the subject of the research and achieve an unbiased, systematic, and reliable data-gathering approach, some modern British tramway development schemes have been selected as case studies for this thesis. Observations, interviews, and document revisions were utilised to gather information. The results were filtered and utilised to generate the CLDs defined within the research framework. As described in the introduction chapter of the thesis, a schematic project management structure was proposed to create a platform to visualise the project management entity. This was generated to provide a platform to visualise the proposed PM model via causal loop diagrams.

The consideration of case studies is commonly considered in research to provide a platform for qualitative analysis within evolving fields of science which have not been broadly studied (Yin 2003). Case study research facilitates "an in-depth review of the emerging or blurred phenomena, whilst retaining the holistic and meaningful characteristics of real-life events" (Phelan 2011). This method "explores multiple bounded systems (cases) over time, through detailed, in-depth data collection involving multiple sources of information and reports a case description and case themes" (J.W. Creswell 2013). In this approach, the findings of each project were analysed independently. Then the similarities or differences were identified in terms of the nature, size, time and cost of the projects (Stave 2003).

TABLE 5-1 BUILDING THEORY FROM THE CASE STUDY BY MULTIPLE CASE STUDY ANALYSIS APPROACH AUTHOR AFTER (EISENHARDT, 1989)

Step	**Action**	**Logic**
Getting Started	Definition of the research question Possibly a priori constructs	Focuses efforts Provides better grounding of construct measures
Selecting Cases	Neither theory nor hypotheses (specified population) Theoretical, not random, sampling	Retains theoretical flexibility Constrains extraneous variation and sharpens external validity Focuses efforts on theoretically useful cases, i.e., those that replicate or extend
Crafting Instruments and Protocols	Multiple data collection methods Qualitative and quantitative data combined with multiple investigations	Strengthens grounding of theory by triangulation of evidence Synergistic view of the evidence Fosters divergent perspectives and strengthens grounding
Entering the Field	Overlap data collection and analysis, including field notes Flexible and opportunistic data collection methods	Speeds analysis and reveals helpful adjustments to data collection Allows investigators to take advantage of emergent themes and unique case features
Analysing Data	Within-case analysis Cross-case pattern search using divergent techniques	Gains familiarity with data and preliminary theory generation Forces investigators to look beyond initial impressions and see evidence through multiple lenses
Shaping Hypotheses	Iterative tabulation of evidence for each construct Replication, not sampling, logic across cases Search evidence for ‘why’ behind	Sharpens construct definition, validity, and measurability Confirms extends and sharpens the theory Builds internal validity
Enclosing Literature	Comparison with conflicting literature Comparison with similar literature	Builds internal validity, raises the theoretical level, and sharpens construct definitions Sharpens generalisability improves construct definition and raises the theoretical level
Reaching Closure	Theoretical saturation when possible	Ends process when marginal improvement becomes small

(Yin, 1994) identified key components to designing a reliable case study as; (a) the study's questions, (b) the study's propositions, (c) the unit of analysis, (d) the logic linking the data to propositions, and (e) the criteria for interpreting the findings.

(Eisenhardt 1989) then proposed an approach adopted by the author as a highly credible method which is broadly approved by academics. A summary of the process is tabulated in Table 5-1. Case studies should afford multiple sources of data, including; interviews, documentation, archival records, direct observations, participant observation, and physical artefacts (Alpi and Evans 2019). Interviews are the key source of data for case study analysis (Yin 2009; J. Creswell 2013). Additionally, analysing documents and literature can be used to validate and increase the credibility of the interview findings (Patnaik and Pandey 2019).

5.2 Case Studies

Summarising the findings from the literature review and learning from real-life projects, the author proposed a schematic structure as the foundation of his research, depicted in Figure 5-1. The authors' conceptual approach considers the whole railway programme management as an entity (system of systems) formed of different subsystems. This schematic structure supported the author in decomposing the programme into components that could be included within a CLD. TABLE 5-2 shows the selected case studies for this research and the associated data collection approaches. TABLE 5-3 shows the number of interviewees and their roles in each studied project.

TABLE 5-2 CASE STUDIES

Project	**Duration/Delay**	**Cost (Overrun)**
Birmingham Metro Extension Phase One (Broad Street Extension)	11 field visits between April-October 2020	9 Interviews, Observations & Documents/Literature Revision
Birmingham Metro Extension Phase One (Centenary Square Extension)	12 field visits between July-Dec 2019	11 Interviews, Observations & Documents/Literature Revision
Birmingham Metro Extension Phase One	25 field visits from April 2014 to March 2016	32 Interviews, Observations & Documents/Literature Revision Corporation with infrastructure owner
Nottingham (Beeston) Express Transit	10 field visits (Jul 2014 - Aug 2015)	7 Interviews, Observations & Documents/Literature Revision
Manchester Metrolink and Beeston	3 field visits (Jun 2014 - Dec 2015)	17 Interviews, Observations, clients' experiences evaluation
London Trams & DLR	3 field visits (Jun 2014 - Mar 2015)	Joint research project between BCRRE and London Trams

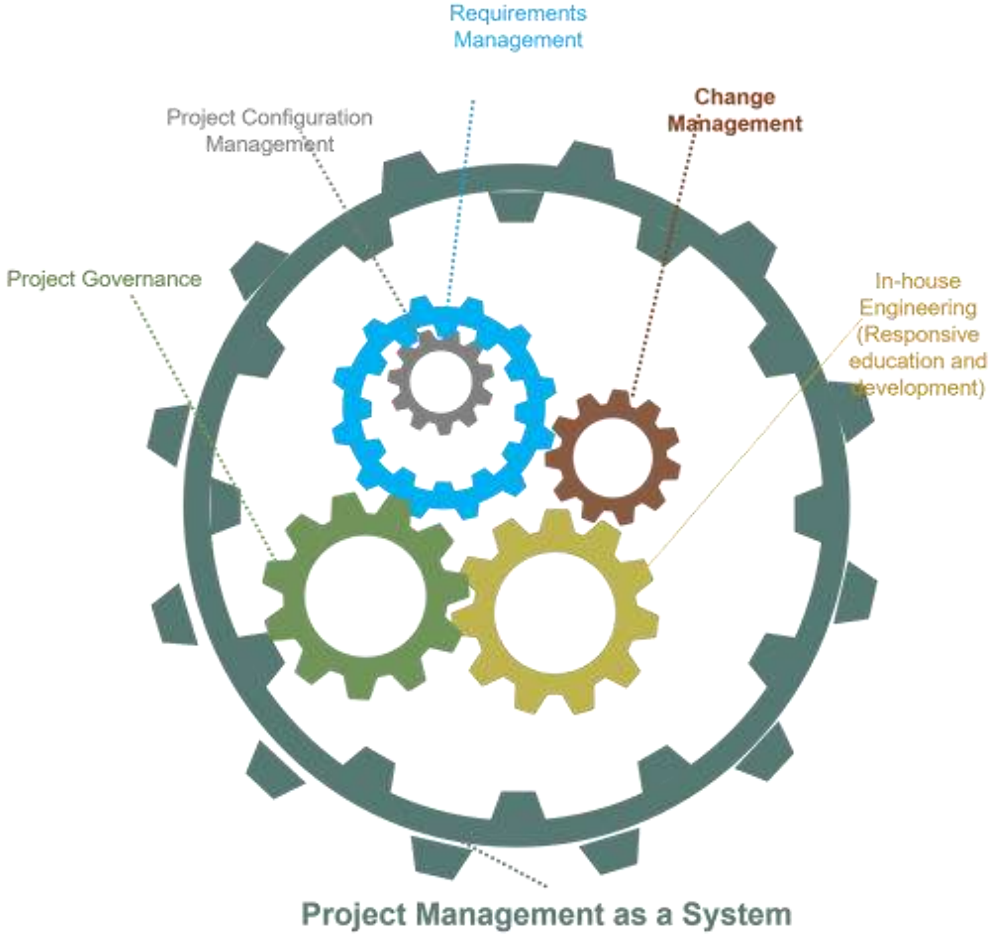


Figure 5-1 Proposed conceptual model to visualise project management as a system (Author)

TABLE 5-3 ROLES AND NUMBER OF INTERVIEWEES IN EACH PROJECT (AUTHOR)

	Birmingham Metro Extension	Nottingham Express Transit	Manchester Metrolink & Beeston	London Trams & DLR
Construction contractor liaison managers	3	2	2	1
City council representative	2	1	1	1
Traffic diversion officer	5	2	2	2
Project managers	9	4	2	2
System engineer (or similar roles)	7	2	1	1
Safety manager	4	3	1	1
Track engineer	6	1	2	1
Construction site manager	9	2	3	1
Legal director	5	3	-	-
Utilities diversion liaison manager	7	4	-	1
Construction site coordinator	5	2	1	-
Client's representative	6	3	1	-
Customer experience manager	-		-	1
Construction site manager	5	2	1	1
Resources manager	2	-	1	1
Liaison manager	3	1	1	1
Project planner in construction contractor companies	8	4	1	1
Delivery manager	3	1	1	1
System safety assurance engineer	2	-	1	1
Community engagement manager	1	1	-	-
The delivery manager from project owner companies	2	1	1	-
System integrator (or similar roles)	3	1	-	-
Financial/commercial manager	4	1	-	-
Contract office	2	-	-	-
Stakeholders' manager	2	1	-	-
Requirements management team (or similar)	2	1	-	-
Construction labour	27	15	12	7
Local business owners	15	2	2	-

Time, availability of resources and legal restrictions were the main barriers to covering an equal and diverse range of data across the projects and promoting the message that the research will benefit companies for their future projects. The author created a link between the university and involved companies to conduct his research, interviews and observations within a collaborative framework and meet the ethical criteria requested by projects and research ethos.

Figure 5-2 depicts a schematic view of the thematic data collected from case studies.

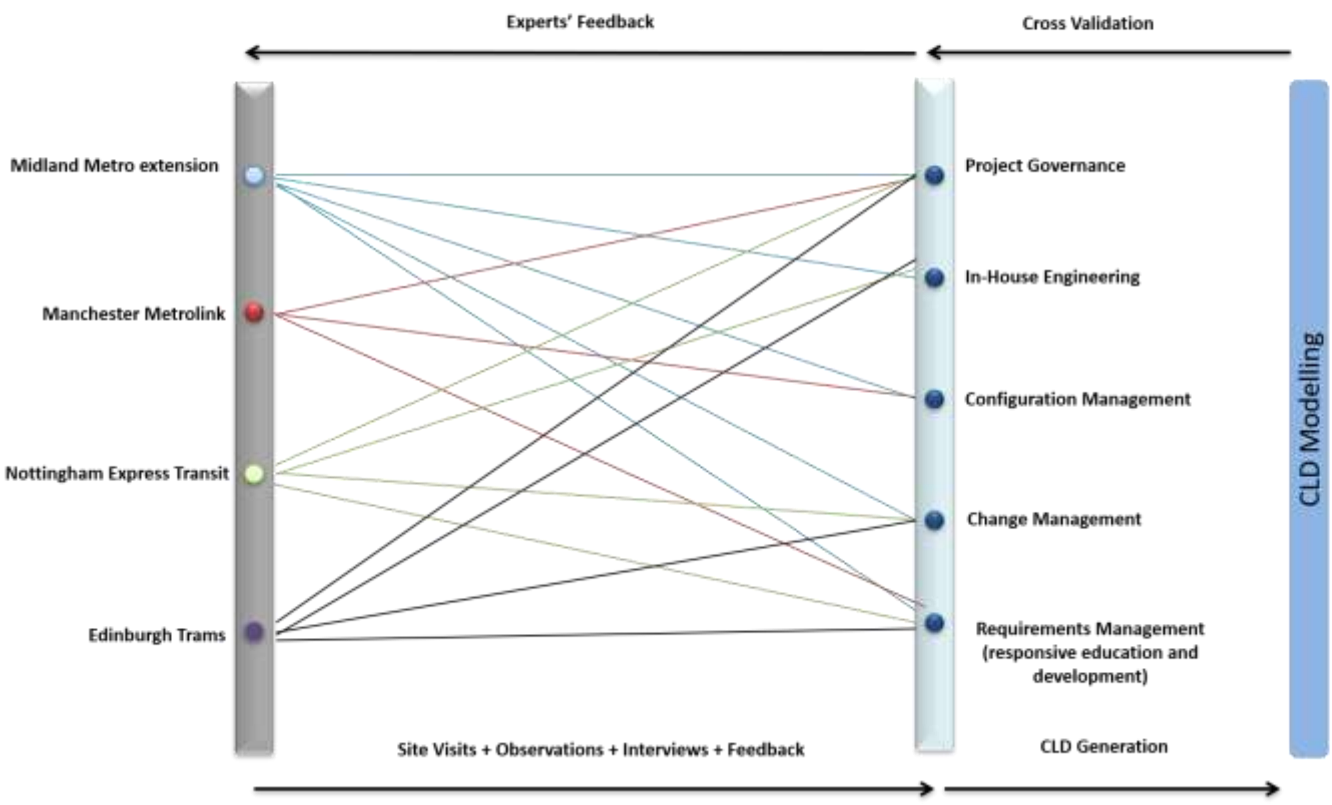


Figure 5-2 Schematic view of thematic data collection from each project (author)

5.3 Design of the Case Study

(Benbasat *et al.* 1987) detected a few drawbacks within the case study research method and recommended some solutions to bridge the gaps. (Benbasat *et al.* 1987) recommended the application of multiple data collection methods, clarifying the scope of the research and utilising in-depth interviews. To achieve this goal, the author designed a case study protocol to enhance the reliability of the approach inspired by (Bandara *et al.* 2005). A qualitative data-gathering approach was composed of in-depth interviews, document review and literature review aiming to obtain rich data and evidence. Cross-validation through observation and discussions was used as an additional layer of control to ensure the validity of collected data, as proposed by (Tsamardinos *et al.* 2015; Roberts *et al.* 2016). The author undertook formal and informal interviews with multiple stakeholders and experts where available. Informal interviews were generally used on construction sites where time or permission restrictions did not allow a formal interview process to be applied (Archard 2020). Interviews were designed to be in either structured or semi-structured formats (Crocker *et al.* 2014). Structured interviews were generally completed within 45-60 minutes, while semi-structured interviews lasted between 15-30 minutes. Interviews followed the same format, beginning with an open discussion around the success or failure factors of the studied project, the key variables, and their interactions. Individual opinions about the main variables and their interactions were recorded, followed by a period where the interviewee was guided through a designed questionnaire. To achieve higher reliability and validity, obtained data were recorded in Excel sheets to achieve a structured format, as recommended by (Yin 1994).

The author utilised computer-Assisted Qualitative Data Analysis (CAQDA) to reduce the risks associated with the complexity of qualitative data analysis and biased interpretation. The NVivo software, as proposed by (Bringer et al. 2006; Zamawe 2015), was employed for qualitative data analysis. "NVivo saves researchers from 'time-consuming' transcription and boosts the accuracy and speed of the analysis process" (Zamawe 2015, p.15).It was important to keep consistency in terminology, data analysis techniques and data interpretation methods. Choosing the final variables to generate causal loop diagrams was based on cross-validation and convincingness. “Convincingness in this type of study comes from the researcher’s ability to describe the process, contingency and context while at the same time being clear that the research does not ‘prove’ a particular point. The multi-case method enables specifics to be kept ‘in the frame’ while moving steadily towards higher levels of abstraction in the identification of factors” (Stewart 2012, p.75). To enhance the reliability and convincingness of data, developed causal loop diagrams were reviewed by interviewees and experts from the rail industry. The advantage of requesting interviewees to review CLDs rather than raw data and variables was that CLDs allowed reviewers to evaluate the relationship and underlying meaning represented in the CLD.

The following steps were followed to convert interview recordings into a structured format that could be utilised with the NVivo software:

1. The conversation conducted during interviews were typed up in Microsoft Word so that the text could be imported into the NVivo software.

2. Initial categorisation of data (to choose key variables for CLDs) and interpretation of sentiments were performed manually, based on the approach proposed by (Eisenhardt 1989) in line with the categories shown in Table 5-1;

3. Data were uploaded to the NVivo software to relevant categories.

4. Journal papers, project documents and relevant web pages are also uploaded to the NVivo software.

5. NVivo cluster analysis was utilised to cross-validate the author’s manual findings with the automated data analysis.

6. NVivo coding statements, which guide searches within the dataset, were developed. This was essential to ensure that the NVivo software would identify all similar sentiments.

7. Based on the NVivo cluster analysis, the frequency of sentiments was quantified were cross-validated with the initially identified vital variables.

8. NVivo analysis added value to the research not only by cross-validating the data but also by improving the phraseology used within the CLDs. Moreover, analysis of the data within each category revealed some variables that were not identified during the interview process. Analysing the documents and literature associated with each category identified additional factors.

This approach provided multiple data analysis sources in line with the recommendation outlined in previous research (Yin 2003; Bandara *et al.* 2005; Yin 2009; Stewart 2012).

5.4 Questionnaires and Interview Process

The design of questionnaires, and interview processes were founded on the concepts and techniques of the cognitive interview approach to enhance the reliability and comprehensiveness of the process(Beatty and Willis 2007, p.57). "Questionnaire design should involve developing wording that is clear, unambiguous and permits respondents successfully to answer the question that is asked" (Drennan 2003, p.57; Rowley 2012). Cognitive interviews exploit the cognitive theory to understand human information processing, which includes attention span, word recognition, action, memory, language processing, problem-solving and reasoning, as well as the exploration of how knowledge is organised in memory and how memory is retrieved concerning completing questionnaires"(Drennan 2003, p.59).

To elicit the interviewees' understanding of questions, two methods are recommended by researchers such as (Conrad *et al.* 1999; Morrison *et al.* 2004; Beatty and Willis 2007; Knafl *et al.* 2007; Fowler *et al.* 2016). The first method is probing, which involves asking interviewees to paraphrase the questions and wording of the designed questionnaire to identify the areas creating confusion or lack of understanding among the respondents. The second approach is observing the interviewees' behaviour during the interview process. Observing factors such as the reluctance of interviewees to go into depth answers for some questions, or skipping a question, can help the interviewer (researcher) to record more accurate sentiment for a respondents' answers (Drennan 2003).

Cognitive interviews produce a series of long narratives, which are mostly qualitative. Analysing the findings from cognitive interviews is usually subjective (Desimone and Le Floch 2004). Many researchers have proposed methods to ensure that the analysis process will be more objective rather than subjective (Morrison *et al.* 2004).

The author considered the key ethical issues related to the research interview process, identified by (Dicicco-Bloom and Crabtree 2006; Hewitt 2007). The key ethical issues defined by (Dicicco-Bloom and Crabtree 2006, p.319) were: "

a) Reducing unanticipated harm.

b) Protecting the respondent's information and anonymity.

c) Providing effective and adequate information to the interviewees about the nature and scope of the research.

d) Reducing the risk of exploitation.

The author adopted Hewitt's recommended ethical framework, applicable to qualitative interview procedures, including cognitive interviews. TABLE 5-4 is provided based on recommendations. form (Hewitt 2007, p.1155).

Before the interviews, the interviewees were informed about the generic topic of the questionnaire to allow them time to prepare any documents they believed might add value to their responses. All the respondents were briefed about the ethical framework adopted by the author, the study's intention, the research's scope, data protection, anonymity, and their right to skip any questions they may find irrelevant or against the associated organisations' principles.

The general cognitive interview approach was to ask respondents to think out loud as they go through a survey questionnaire and tell them everything they are thinking. This allows the understanding of the questionnaire from the respondents' perspective rather than that of the researchers" (Drennan 2003, p.57). The respondents were allowed to paraphrase the questions or change the order of the questions. For the questions that the interviewees required time to investigate, they were given the option to provide the author with a short narrative about their general feeling and understanding of the questions, followed by providing the author with a detailed answer by email or through a phone call. Interview scripts were sent to respondents to be checked and modified to ensure that an author's perception of the answers was not biased. Respondents were informed that the outcome of the interviews would be used to create causal loop diagrams, and accordingly, they would receive CLDs to be reviewed.

the author kept a consistent data-gathering and note-taking approach for the informal interviews, specifically on construction sites and with local stakeholders. Interviewees were briefed about the nature of the research and provided with the author's student ID as proof of identity. The results from informal interviews helped the author capture external factors affecting the success of programme management from people whose businesses and daily lives were affected by the associated construction projects. The review of answers from respondents in the project team revealed that many of the factors identified by local stakeholders were neglected or not covered by the project teams.

TABLE 5-4 ETHICAL FRAMEWORKS FOR THE QUALITATIVE RESEARCH INTERVIEW (HEWITT 2007, P.1155)

Ethical Framework for Qualitative Research	
Acknowledgement of bias	• Closer examination of the personal qualities that researchers bring to interviews, including personal presence, values, and beliefs. • Explicit acknowledgement that research findings do not represent objective reality, but the construction of knowledge is influenced by context and the belief systems of the researcher and participant.
Rigour	• Factors influencing the research relationship should be addressed in the construction and reporting of research (e.g., age, appearance, social class, culture, inequalities of knowledge and power, environment, and gender). • Reflexivity is necessary for researchers to critically examine their prior assumptions and actions by being self-conscious and self-aware. • Examples from transcripts should be sufficient to give a representative presentation of responses and processes. Misinterpretation of participants' experiences might be reduced through respondent validation. • Changes to grammar and punctuation and simplification or loss of tone, pace, or volume during the transcription of interviews should be minimised.
Rapport	• Factors of influence include the level of formality or informality, perceptions of professional boundaries, the capacity for intimacy, and the personal qualities projected by the researcher. • Ideal research relationships are characterised by genuine rapport, honesty and emotional closeness while recognising the potential abuses of power, which might be increased by the facilitation of deeper levels of rapport.
Respect for autonomy	• Informed consent is given by participants without threat or inducement, after receiving and comprehending information regarding the nature of the research. Participants must have the mental competence to give consent, which might alter during the research and requires that the researcher is continually sensitive to changes in the voluntariness of participants. • The power imbalance between researchers and participants should be reduced through the promotion of egalitarian relationships, grounded in reciprocity and a sense of mutuality.

	• Participants should be involved and consulted by ethics approval committees. Vulnerable groups, such as those with mental illness, should not automatically be prevented from participating in research.
Avoidance of exploitation	• Anxiety, distress, guilt, and damage to participants' self-esteem might occur because of exploitation through an overly intrusive interview. The remit of the research interview should be clearly defined to avoid confusion with therapeutic aims, particularly when the researcher has clinical responsibilities. When sensitive issues are explored, consideration should be given to the availability of further support mechanisms and debriefing for participants and researchers. • Research should be worth doing, in the sense that the results are likely to lead to a tangible benefit for participants. Inconvenience and costs should be minimised.
Confidentiality	• Ground rules should be established, particularly when there is a risk that participants' disclosures might reveal potentially significant harm to self or others, which would require that confidentiality be overridden, or when political control over the dissemination of findings might not be within the researcher's control. Interview transcripts should not provide information that could lead to the identification of participants.

5.5 Interview Process Limitations

5.5.1 Limitations Imposed by Circumstances

The nature and circumstances of this research imposed a set of problems and limitations in utilisation of the cognitive interview techniques and affected the design and content of the questionnaires and the process of interviews over time. These limitations are identified and listed in this section. A systematic approach has been followed to mitigate and minimise these limitations' risks, however, some of these limitations have identified and remained to be addressed in the future works.

At the early stages of this work, the potential impact of these limitations on the process, quality, and outcome of this research have been investigated, as follows:

5.5.1.1 The Complex and Evolving Scope of the Research

Due to the complex nature of the topic at the early stages of the project, and the consequent learning curves, defining a baselined scope was not straightforward. This limitation was not only a function of the nature of the research, but also a function of the complications and restrictions imposed by the case study projects. The availability of information, the progress of the case study projects, and legal restrictions were the other factors affecting the data collection, and hence the scope of this research. As a result, the earlier questionnaires are focused on a narrower scope, neglecting some broader factors.

Gradually, the domain and depth of the scopes required to be revisited and baselined. Hence, the questionnaires evolved over time to cover different factors and aspects of the evolving process, and to provide a more holistic overview of the problem statement. This limitation is categorised as the "overall limitation" and can be experienced in other similar research topics, which utilise cognitive questionnaires and interviews as the foundation of qualitative research.

5.5.1.2 Data Inconsistency, Imposed by Evolving Questionnaires

By expanding the scope of the research, and adding more cognitive factors to the newer questionaries, the size and complexity of questionnaires were increased. Hence, it was a challenge to design a concise questionnaire and conduct an in-depth interview to cover the growing aspects of the case study. As the result, the author had to prioritise the questionnaires and interviewees, based on the availability of resources and the nature of the questionnaires. This could potentially create inconsistency in data, which is tried to be mitigated in the next section. However, it is important that future researchers be aware of the possible impact of this limitation on the accuracy and consistency of the data. This limitation is highly dependent on the nature, governance and organisational culture of the case study projects, so can be considered as an external limiting factor, which researchers have a limited ability to control or mitigate. This limitation is categorised as a "limitation imposed by circumstances".

5.5.1.3 Data Integrity, Imposed by Interviewees Availability Over Time

On the other hand, considering the completion period of the case study projects, access to the same respondents on the same projects was reduced over time. As mentioned earlier, the approached utilised in this research requires to cross-validate the findings with interviewees. In some specific cases, it was not possible, or it was a challenge to approach or find the same interviewees, as they may have left the project or moved around. Consequently, some data could not be correlated, verified and cross-validated. Consequently, some interviews were repeated with new interviewees. Researchers should consider the impact of this limitation, as in timebound research projects, this can significantly affect the timeline. Additionally, this might create a rework cycle, which might affect the integrity of the data extracted from the interview over time. This limitation is categorised as the "overall limitation" and can be experienced in other similar research topics

5.5.1.4 Archive Migration Loss

Software packages used in this research (e.g., NVivo and Vensim) were under educational/student licence, hosted on university computer. Also, all the copies of the questionnaires and interview manuscripts were located on the same university computer. The university office moved to a new building during the COVID-19 pandemic, followed by an un-attended IT migration. Unfortunately, some of the original archives, including some of the questionnaires and manuscripts were lost, during this migration. Due to this unexpected situation, the different versions of the questionnaires are not attached to his thesis.

However, the derived data and analysis were restored from the cloud copies. This includes the data analysis and modelling exports, including CLDs, SFDs and analytics from qualitative data analysis (NVivo graphs). Although, this problem did not significantly impact the research outcome, but the absence of the questionnaires is a gap in the Appendix and thesis flow. This limitation is categorised as a "limitation imposed by circumstances”.

5.5.2 Methods to Mitigate Risks Resulting from Limitations and Enhance the Reliability of the Approach

The above-mentioned limitations could potentially affect the quality, integrity and consistency of the data concluded from interviews, and consequently affect cross-validation and correlation of the derived end-results. Hence, it was crucial to design and apply a mechanism to mitigate the impact of these limitations and assist evolving process to deliver a quality set of results. To mitigate the identified risks, an innovative approach was designed and adopted, which will be described in the following section. Mitigation techniques were then considered and applied accordingly.

Although these mitigation techniques could not fully eliminate all the limitations, they were designed in a way to ensure that the interview process and multiple case study analysis elicited sufficient quality-data required for the later steps of this research.

5.5.2.1 Overlapping Techniques

This method introduces content overlap between different versions of the questionnaires to investigate each criterion from a different point of view. This technique also accommodates respondents overlap, meaning that different sets of questionnaires, targeting different criteria, were exposed to overlapping society of respondents from different range of expertise and experience, in different projects. This method helps to protect the integrity of the questionnaires and extracted data. Figure 5-3 shows the overlap of content and criteria between different versions of the questionnaires.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Learning legacy & Optimisation	X	X		X			
Configuration Management	X	X		X	X	X	X
Change Management/Impact Analysis		X	X	X	X	X	X
Project Governance			X	X	X		X
Requirements Management	X	X	X	X		X	
In-House Engineering /R&D	X	X	X			X	X
Resilience Thinking			X	X	X	X	X

Figure 5-3 Overlap of contents and criteria between different versions of questionnaires (Author)

5.5.2.2 Computer-Aided Qualitative Data and Visual Analysis

NVivo software is utilised for this proposed method to find, create, and enhance the correlation between data and improve the accuracy of data analysis. NVivo provides a platform to cross-validate and verify findings and questionnaires data against the data extracted from the literature review, based on different correlation factors. NVivo is an academically approved software and recommended by many researchers such as (Zamawe 2015, Brandão 2015 and Alyahmady 2013). NVivo and its features will be described in the following sections of this chapter. NVivo was utilised for two main purposes:

1. To add additional layers of data verification and cross-validation between data extracted from interviews and literature review (to assess the validity of identified variables and their interactions).
2. To find the correlation between results extracted from a different set of questionnaires, including different criteria, and from respondents with different ranges of expertise and background, over time.

Error! Reference source not found. shows how NVivo provides a systematic approach and a reliable toolset to collect, analyse, validate, and verify data from multiple case study analysis, before converting them into Casual Loop Diagrams (CLD). The proposed approach is a gradual and seamless approach to establish correlations between questions, content, and criteria over time. Figure shows the evolution process of the questionaries.

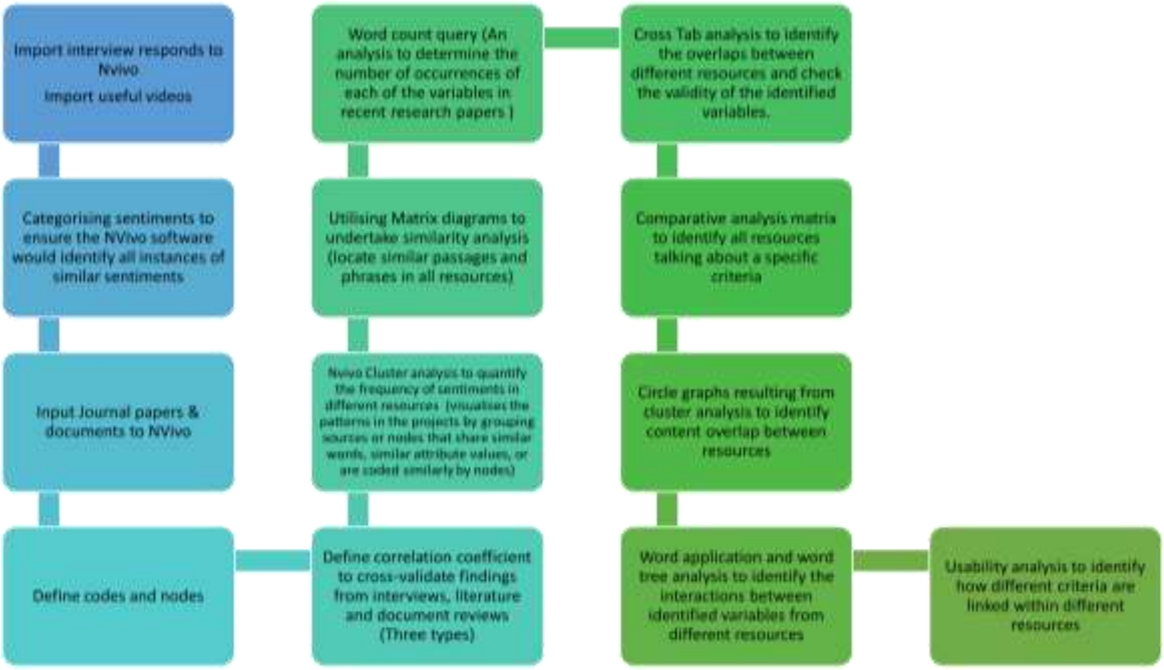


Figure 5-4 NVivo Features for Qualitative Data Analysis (Author)

5.5.2.3 Manual Cross-Validation of Findings with Interviewees

All identified variables to generate CLDs and their interactions, both from manual analysis and NVivo, were cross-checked with most of the interviewees to ensure credibility. Initial CLDs were generated via Vensim PLE software, and the author printed the generated CLDs in A3 paper and met with the respondents from formal interviews for the cross-validation of the data. Respondents were asked to review the CLDs, their variables and interactions. Interviewees were asked to suggest the modification of the variables or connections if required. The author analysed the whole reviewed models and accordingly modified all generated CLDs.

Error! Reference source not found. depicts the evolution process of the questionnaires and p resents a typical nature- and structure of the questionaries.

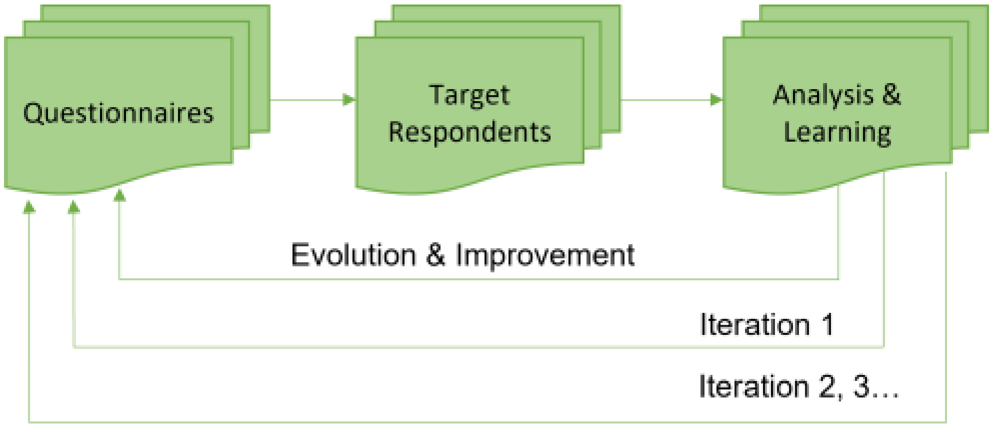


Figure 5-5 Questionnaires Evolution Process (Author)

5.5.2.4 A Systematic Approach

Based on the findings from qualitative data analysis, some of the generated CLDs were required to be cross-validated to ensure credibility of the variables and their interactions. However, as mentioned, some of the archives were lost during an IT migration.

To mitigate this risk, a few extra meetings were set with two previous interviewees and one new interviewee from West Midlands Metro. These meetings provided the opportunity to review the CLDs and update some variables and relationships accordingly. Additionally, the proposed SFD was reviewed by the interviewees to enhance its accuracy.

In addition, to reduce this problem's impact on the thesis flow and for future researchers benefit, the systematic proposed approach and methodology of designing questionnaires, interview process, adoption of ethical frameworks, computer-aided qualitative data analysis, and the questionnaire evolution process are extensively elaborated in the thesis, alongside with the advantages and limitations.

5.5.3 Residual Limitations on the Interview Process

The adoption of above-mentioned mitigations could successfully reduce the impact of limitations around the interview and data collection process at an acceptable level, required to validate the result of this research.

However, this research acknowledges that these limitations are not fully waived. The key limitations remained are briefly explained below to assist future researchers to understand the inherent limitations and their potential impact on the outcome of the research:

5.5.3.1 Cognitive Process Limitations

The design process and conducting of the interviews are founded on the cognitive process. Interviewees, as individuals, have different cognitive domains. Hence, not only the questionnaires must be designed cognitively, but sometimes they are required to be modified, paraphrased, and asked considering the individual's characteristics as far as possible. Since this is not feasible to design bespoke questionnaires for each interviewee, hence the interview process, data collection, quality and accuracy of the data, comprehensiveness and depth of the answers will vary for different individuals. Therefore, always, an additional layer of data verification is required to be undertaken by researchers to ensure consistency and convergence of obtained data.

5.5.3.2 Research Deviations

The progression of the different versions of the questionnaires could become dependent on the case studies, their construction progress, legal restrictions to accessing information and the nature of the problem they face. Hence, researchers must take due-diligence considerations into account to ensure the developed questionnaires and interviews align with the research objectives and questions. Depending on the nature of the research and its objectives, the information required might need to be collected from another or additional sources. Correlation between data and consistency of approach might be challenging.

5.5.3.3 Cross-Validation Limitations

The results derived from cognitive interviews (e.g., scripts and CLDs in this study) must be validated by interviewees to enhance reliability and accuracy. This creates two types of limitations. First, the quality of data analysis and communicating this with respondents will significantly affect the accuracy and reliability of the findings. On the other hand, access to the same group of interviewees might not be always feasible. Rotational jobs, retirements, legal restrictions, and many other factors will affect the availability of the same respondents to verify their answers based on the researcher's interpretation.

The impact of the above-mentioned limitations might be mitigated but cannot be fully eliminated. Hence, it is important for future researchers to consider all these limitations before adopting the proposed approach and keep updating the risks, limitations, and mitigation techniques, to ensure the competency of the approach for their research.

5.6 Justification of the Approach

Multiple case study analyses and in-depth cognitive interviews have been adopted in this research to answer the research questions. This section provides a brief justification to explain why multiple case study analysis and in-depth interview approaches were utilised amongst the other alternatives. This will provide future researchers with an overview of the best available approaches and their applicability to their research.

5.6.1 Multiple Case Study Vs In-Depth Single Case

Case study analyses can be categorised into an a) single pilot (in-depth) case study and b) Multiple case study analysis (Banadra et. al 2005). Multiple case study approaches are particularly valuable when relationships between organisational structures, management processes and outcomes are under investigation (Stewart, 2011). Multiple data collections may also take place to obtain maximum insight into sensitive topics (Hammarberg1, 2015).

Table 5-5 provides the soundness criteria for the case study method (both multiple and single). In this thesis-as mentioned earlier- the author utilised a systematic approach to gathering information from various resources, followed by the application of NVivo software to ensure systematic and smart data interpretation. The choice between multiple or single case study analysis depends on the context and objectives of the research but Table 5-6 summarises some of the key strengths and limitations of each technique.

TABLE 5-5 SOUNDNESS OF CASE STUDY METHOD - AUTHOR AFTER (TEEGAVARAPU ET AL., 2008)

Criteria for Soundness	Case Study Techniques	Occurrence
Construct Validity	• Use of multiple sources of evidence • Establish a chain of evidence • Let key informants review the case study output	Data collection Data collection Creating reports and narratives
Internal Validity	• Do pattern matching • Do explanation building • Address rival explanations • Use logic models	Data analysis
External Validity	• Use theory in single-case studies • Use replication logic in multiple case studies	Research Design
Reliability	• Use case study protocol (Ethical and systematic approach)	Data collection

TABLE 5-6 MULTIPLE VS SINGLE CASE STUDY- AUTHOR INSPIRED BY (GUSTAFSSON, 2017)

Case Study Approach	Strengths	Limitations
Multiple	• It helps to understand the similarities and differences • between the cases and, therefore can provide the literature with important influences from its differences and similarities. • The evidence generated from multiple case studies is strong and reliable and the writer can clarify if the findings from the results are valuable or not. It also allows a wider discovery of theoretical evaluation and research questions. • When the suggestions are more intensely grounded in different empirical evidence, this type of case study then creates a more convincing theory	• Time-consuming • Data collection, classification, and analysis, should be through multiple sources to achieve the highest accuracy • The researcher must know how to filter data and categorise the differences and similarities between cases
Single	• Is not as expensive and time-consuming as multiple case studies • Provides a deeper understanding of the subject explored. • single case studies can richly describe the existence of a phenomenon and it is better to make a single case study than a multiple case study when the writer wants to study, for example, a person or a group of people.	• Not accurate for studying multiple cases, when the researcher needs to compare various source of information. • Does not provide a holistic overview of the developing theory, instead, this will provide researchers with an in-depth insight into a specific case.

The author's research intended to propose a schematic structure for railway project management, which will be used as a platform to analyse its performance and resilience for all similar railway projects. Accordingly, all generated CLDs, stock and flow diagrams and decision-making tools designed to be reference models. Hence, the models required be developed based on multiple case studies to reflect a wide range of facts, causes and effects affecting project failures. Apart from this critical reason, the following causes can be listed. Table 5-5 summarises some of the key strengths and limitations of each technique. The author chose multiple case study analyses over an in-depth single case study because:

- The context and nature of the research required the research methodology to be established based on data collection from multiple resources. Tramway development schemes are one of the most complex types of railway projects, occurring within the heart of city centres. So, they could be the most suitable cases. Luckily, the author had this opportunity to get involved with different real-life tramway development projects in the UK, as listed earlier in Chapter 5.
- Tramway construction projects are subject to a high level of confidentiality and security. This imposed a set of restrictions and limitations for the author in terms of access to resources, information, and documents. So, utilising an in-depth case study analysis was not practically feasible, apart from the associated limitations of the approach.

The context of the research methodology required a systematic comparison (NVivo) between data collected from studied cases, literature, and project documents. Hence, multiple case study analysis was the best choice to achieve this goal and create the most possible realistic models.

The following section provides details around the author’s reasons for choosing in-depth cognitive interviews over focused group method. This will assist future researchers to make informed decision and trade-off between different options to conduct interview for case study analysis.

5.7 In-Depth Cognitive Interviews vs Focused Group Interviews

The other alternative approach to an in-depth interview, which could be adopted by the author, was focus group interviews. This section explains the author's reasons for choosing the first option as his methodology.

"In recent years, focus-group interviews, as a means of qualitative data collection, have gained popularity amongst professionals within the health and social care arena" (Rabiee, 2014 P.655). "A focus group interview is an unstructured, free-flowing, and relaxed group interview taking between one and three hours to complete. This interview is conducted by a moderator who works based on a structured script to ensure all topics are covered and manages conversation flow." (Hyman et al. 2016). Compared to individual cognitive interviews, in focused group interviews, individuals' ideas might trigger others to come up with new ideas and comments. Similarly, some people feel more co comfortable speaking in a group (Tagart et al. 2013).

On the other hand, "individual cognitive interviews provide flexibility in exploring topics that are appropriate in local situations. The early detection of survey problems will increase instrument quality by reducing or eliminating confusing language, inadequacy in adaptation, poor item format, or any contextual inappropriateness" (Lee, 2014). Cognitive interviews allow the understanding of the questionnaire from the respondents' perspective rather than that of the researchers" (Drennan 2003, p.57). Considering the facts stated in the last few paragraphs, the author adopted the individual in-depth cognitive interview (using cognitive questionnaires) over the focus group interview technique because:

- The author utilised multiple case study analyses to develop his research according to the reasons provided earlier. The author utilised multiple case study analyses to develop his research according to the reasons provided earlier. This required involvement with different stakeholders in charge of the design and construction of the studied projects. Because of confidentiality, data protection and limited accessibility to information, it was not feasible to conduct a focus group interview workshop.

- During the individual interview process (which was designed based on an ethical framework), the author could convince the interviewees about anonymity and data protection. This was not achievable in the focus group interview format. In other words, individual interviews provided a platform for the researcher to obtain in-depth information around specific questions. This could provide a higher level of confidence for respondents to provide their honest and accurate answers.
- Based on the scope and methodology of this thesis, modified interview narratives and accordingly generated CLDs need to be reviewed and cross-validated by the interviewees to enhance the reliability and accuracy of the models. Individual interviews were the best approach to facilitate this process.

For future researchers who tend to utilise the author's proposed methodology and analyse specific project management strategy resilience, an in-depth single case study combined with focus group interviews would be ideal, if possible. Because this will allow researchers to obtain in-depth information for that specific project and accordingly update the adopted CLD and SFD models. The next section provides a summary of the process for generating causal loop diagrams from qualitative analysis of data gathered from case studies.

5.8 Generating Causal Loop Diagrams from Qualitative Data Analysis

This section summarises the author's approach to conducting qualitative data analysis and extracting data from multiple case study approach. The key variables to construct each CLD were derived from qualitative data analysis and filtering. Qualitative research interview analysis always results in a complex and wide range of words and phrases, and this will become problematic when it comes to creating CLDs. Constructing models aids to understand the feedback loops, delays, nonlinearities, or gathering of variables that all together reflect the relationships between systems components (Groesser and Schaffernicht 2012).

One of the common problems with CLDs identified by researchers is that the models are unrealistically simple. This has led to the tendency of model developers to generate complex and extremely detailed models, which creates problems. Large models are too complex to study and do not necessarily provide a more representative view of the systems under consideration (Groesser and Schaffernicht 2012). Hence to make a balance between the model's complexity and simplicity, the modellers shall identify the boundaries of the system (Li *et al.* 2014). To deal with this problem and to ensure the CLDs reflect the real nature of the system, (Saysel and Barlas 2006) recommend that there should be an additional step in CLD modelling called 'model simplification'. The supporting reason for simplification is that the whole picture of the system is more important than specific details and the model should be able to help researchers to understand the overall behaviour of the system (Bureš 2017a, p.5).

The author utilised the following approaches to follow the above-mentioned instructions and avoid associated problems with developed CLDs:

1. Data collection and analysis were carried out based on a systematic approach derived from academically approved techniques.

2. The design process of the questionnaires and interview process considered capturing interviewees' opinions around the key variables of the models, which could help in defining the system boundaries.

3. Interview scripts were reviewed by respondents and external experts to ensure the defined system boundaries were as realistic as possible. Undoubtedly, it was not feasible to reach a cooperative agreement on system boundaries, but qualitative analysis of the interviews and cross-validation against findings from academic papers and project documents helped to increase the confidence in the validity and accuracy of the defined boundaries.

4. As discussed earlier, the NVivo software was utilised to conduct qualitative data analysis and verify the manual data analysis processes.

5. CLDs were created based on the variable filtered by the built-in NVivo analysis approaches.

6. As described in Chapter 4 the simplification method proposed by (Bureš 2017b) was adopted by the author to simplify the complex CLDs;

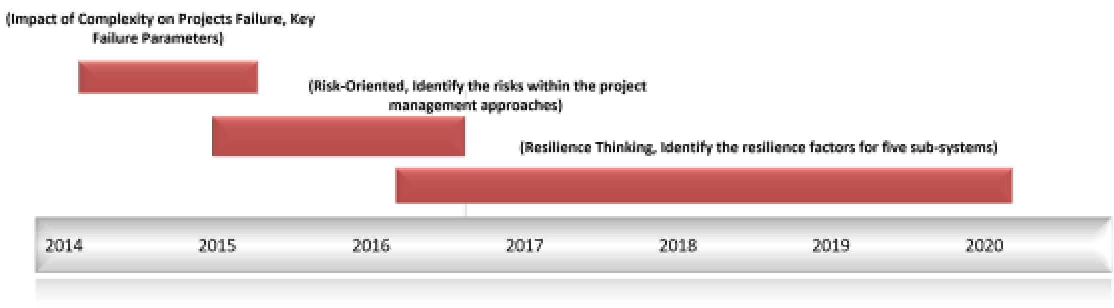
7. Simplified CLDs were reviewed by experts to provide a final layer of validation.

Within the NVivo software word similarities were considered by creating clusters based on Pearson's correlation factor; this resulted in finding new phraseology, and hence relevant text segments in papers. The author used the identified phrases in the thematic codes for additional analysis. The analysis via NVivo generated graphs, text documents and charts; a few examples are presented below to help describe the process.

The matrix diagrams (Figure 5-8 and Figure 5-9) have been generated by undertaking a similarity analysis. The figures show the categorisation of the references against selected phrases. By clicking on each cell and/or colour-coded section a user can ascertain the percentage of resources (e.g., interviews or academic papers) that mention a particular parameter. This helps to validate the process of determining the categorisation phrases (known as codes), which in turn inform the selection of variables for the CLDs.

By querying the matrixes, a user can locate similar passages and phrases in all resources. In addition to the categorisation of resources, analysis of the matrixes can also help to identify the overlaps between different resources. (Houghton *et al.* 2013) developed a methodology for combined analysis of interviews and literature review material which has been followed in this paper.

The cluster analysis feature of the NVivo software is an exploratory method, which visualises the patterns in the projects by grouping sources or nodes that share similar words, similar attribute values, or are coded similarly by nodes. This feature reveals the similarities and differences between different sources or codes. NVivo uses three different correlation coefficients to measure the similarities. Figures 5.5 and 5.6 are created based on the Pearson factor. Codes were determined through analysis of the interview transcripts. These were used by a series of cluster analysis routines that measured the similarities of the identified variables amongst existing resources (interviews, documents, and literature). This method helps to filter and validate the identified variables and define the categories and subcategories for each causal loop diagram. Cluster analysis provides a systematic assessment method to increase the dependability and confirmability of the results (Houghton *et al.* 2013).



Typical Nature of the Questions (2015-2016):

Considering the project as a complex adaptive system and referring to the cogwheel model, how do you define the key risks which might affect the functionality of the whole system?

How do you define vulnerability within project management? Can you provide me with a conceptual figure or description?

Referring to the proposed cogwheel model, what key sub-systems can you define for each component (configuration management, project governance, etc.)?

Amongst the identified variables, which will be the most vulnerable ones, which can lead a project management strategy to fail? You can use pen and paper to draw graphs if required.

To what extent does your project suffer from the identified vulnerabilities?

How do you prioritize the importance of the vulnerable variables?

How do the resilience factors of each sub-system interact (feedback loops)?

Referring to your drawings or notes, how do you believe the vulnerable components of each sub-system will affect the other sub-systems?

How do you reckon we can enhance the performance of the project management entity by learning from identified vulnerable components? What systematic tools do you believe we can use to mitigate the risks?

For this specific project, to what extent do you believe these vulnerable variables are considered in the planning phase of the project?

Typical Nature of the Questions (2016-2020):

How do you describe project resilience? Explain your perception.

Referring to the proposed cogwheel model, what are the key resilience factors for each sub-system? You may use pen and pencil to explain your ideas utilising graphics.

How do the resilience factors of each sub-system interact (feedback loops)?

Based on the given definition, how do you link the project's adaptive capacity to these identified factors? Which items can affect the capacity the most, you may prioritise them using a numbering system?

What are the monitoring tools in this project to ensure changes can be tracked and analysed? Tio, to what extent are they effective?

How do you define awareness as a component of resilience? Referring to the identified factors, how they will contribute to enhancing project awareness?

What is your project approach in managing unplanned disruptions or changes within the process of the project? How do you analyse the impact of those changes on the duration and outcome of the projects?

If you had modern tools to enhance project resilience, which was your priority; financial, environmental, performance or any other criteria?

Given the provided definition, to what extent your project is successful to mitigate the impacts of change and reduce change latency?

How the resilience thinking can improve the decision-making process, both in identifying the changes and reducing the changed latency? Can you highlight the key factors affecting the effectiveness of decision-making, if you apply this in your project?

What skills your team members will need to enhance the resilience of the project, considering the identified factors?

Let’s say you are recruited as a system analyst to improve the project management resilience of your organisation. You have defined key resilience factors for five sub-systems. How do you integrate those five components? How do these five sub-system links to each other from a resilience point of view?

How can the resilience thinking improve the decision-making process, both in identifying the changes and reducing the change latency? Can you highlight the key factors affecting the effectiveness of decision-making, if you apply this in your project?

What skills your team members will need to enhance the resilience of the project, considering the identified factors?

Figure 5-6 Schematic view of the questionnaire’s evolution & typical nature of questionnaires

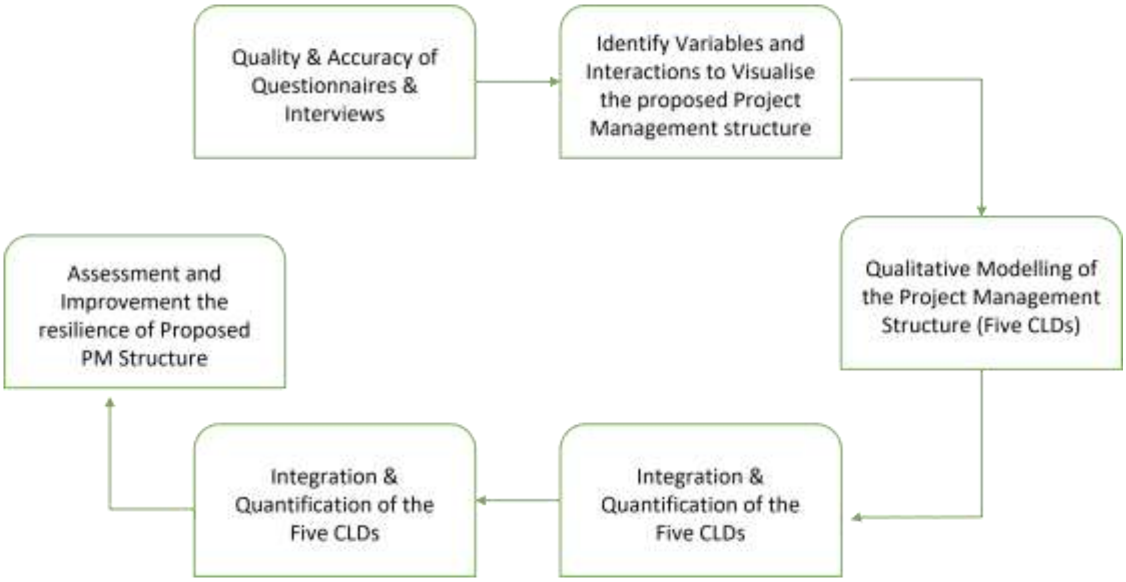


Figure 5-7 Assessment and Improvement of Questionnaires and its impact on the final objectives of the research (Author)

Figure 5-10 and Figure 5-11 show examples of cluster analysis for attribute similarity between 67 academic papers and results from interviews for factors identified around complex interactions between stakeholders and their impact on project failure and project governance, respectively. This feature could assist to check the transferability of the results derived from qualitative data analysis, as recommended by (Houghton *et al.* 2013).

Word count query was another NVivo feature used in this study. For each thematic subject, many variables were identified via the interviews and literature review analysis. An analysis to determine the number of occurrences of each of the variables in recent research papers was undertaken. Figure 5-12 represents an example of the word count query for the 'impact of project governance on project success' analysing 97 journal papers published between 2014-2020. The papers were already categorised using NVivo analysis. Figure 5-9 shows an example outcome of a cross-tab analysis for "project systematic failures" in 121 papers categorised and grouped based on systematic coding. This feature helps to identify the overlaps between different resources and check the validity of the identified variables.

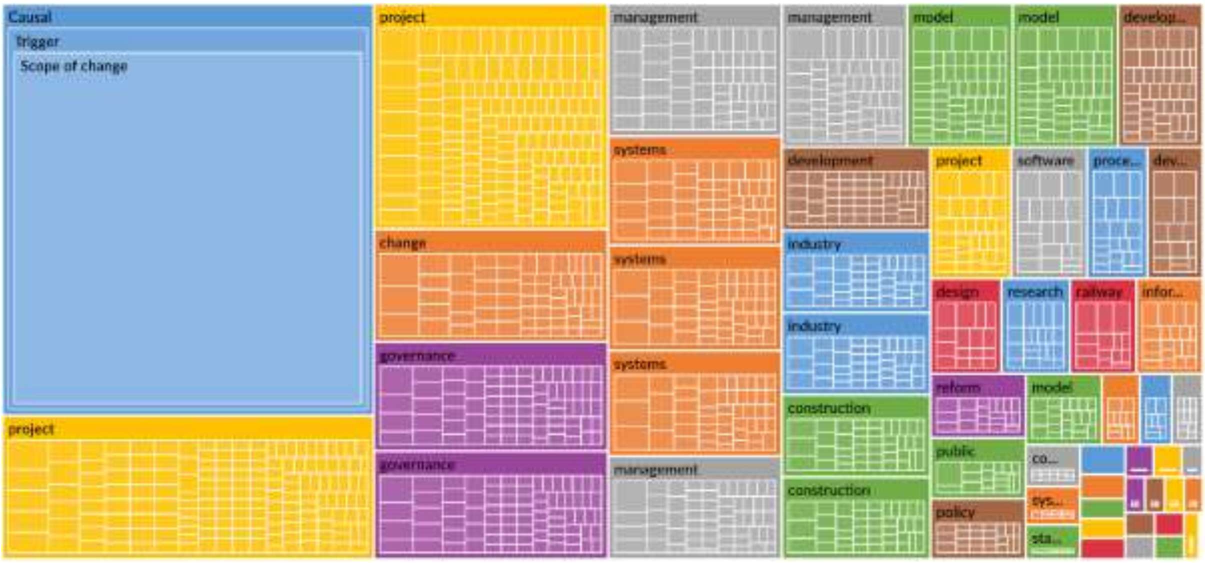


Figure 5-8 Comparative analysis matrix based on the number of coding references for project governance. Blocks and colours represent different themes, and each cell will guide you through a specific paper or interview reference (NVivo)

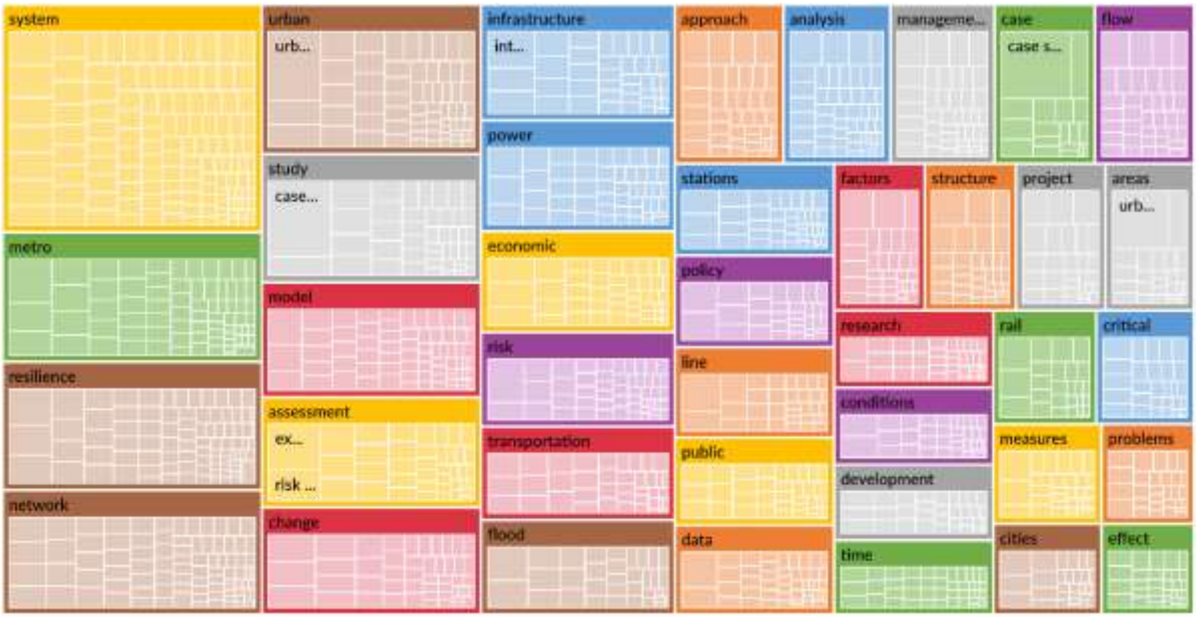


Figure 5-9 Crosstab (comparative analysis matrix) to identify areas of research covering resilience

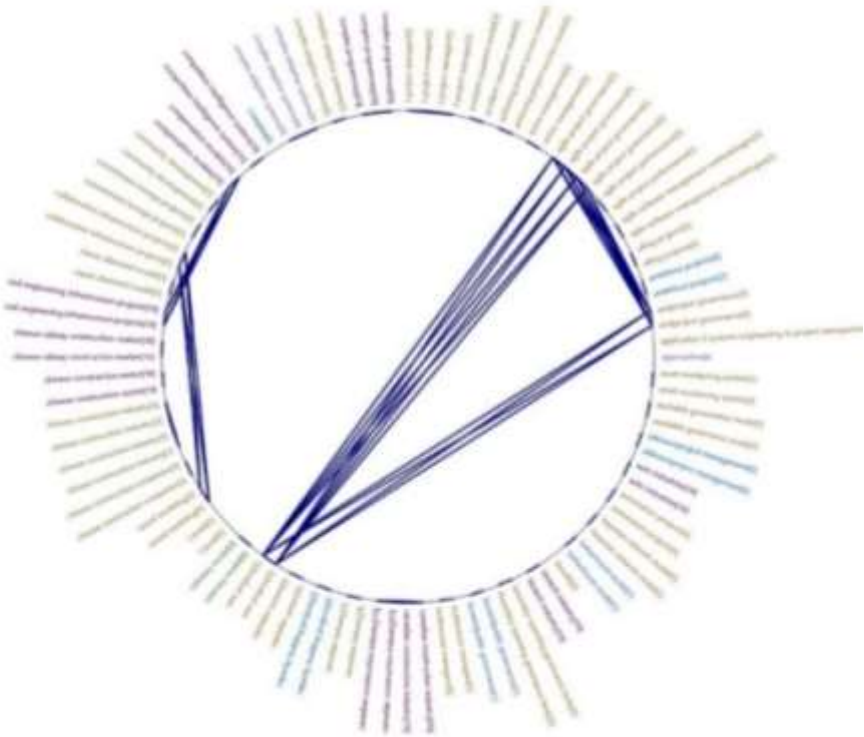


Figure 5-10 Circle graph resulting from cluster analysis for cross-validating findings from interviews and the literature review

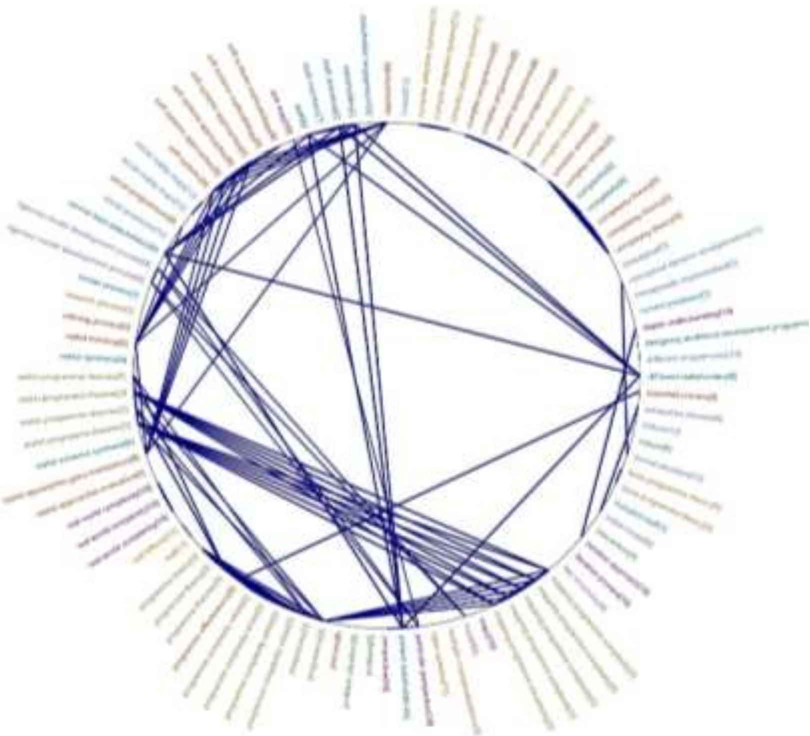


Figure 5-11 Circle graph resulting from cluster analysis of codes covering project governance (word similarity)

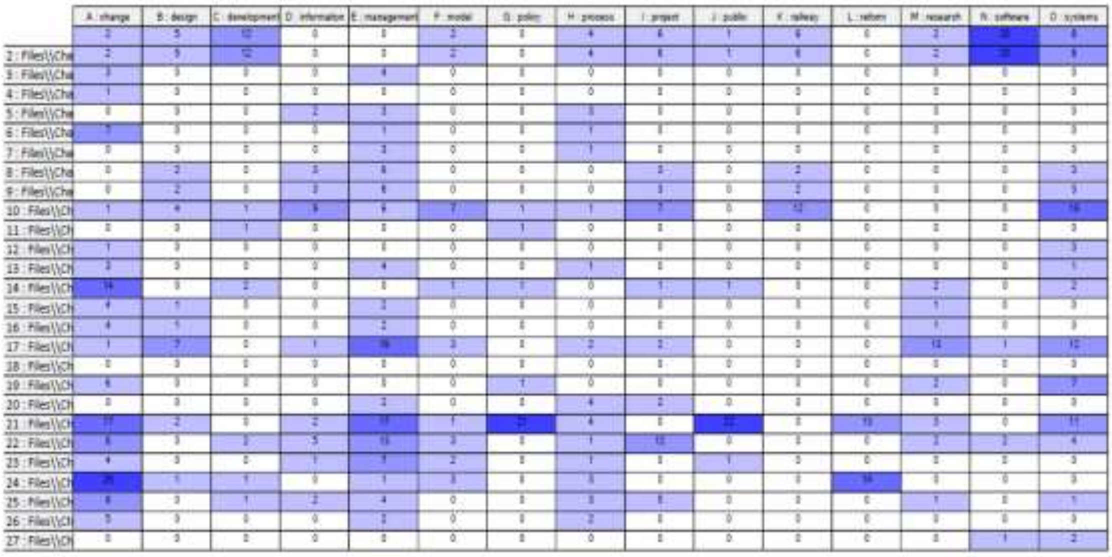


Figure 5-12 Word frequency analysis

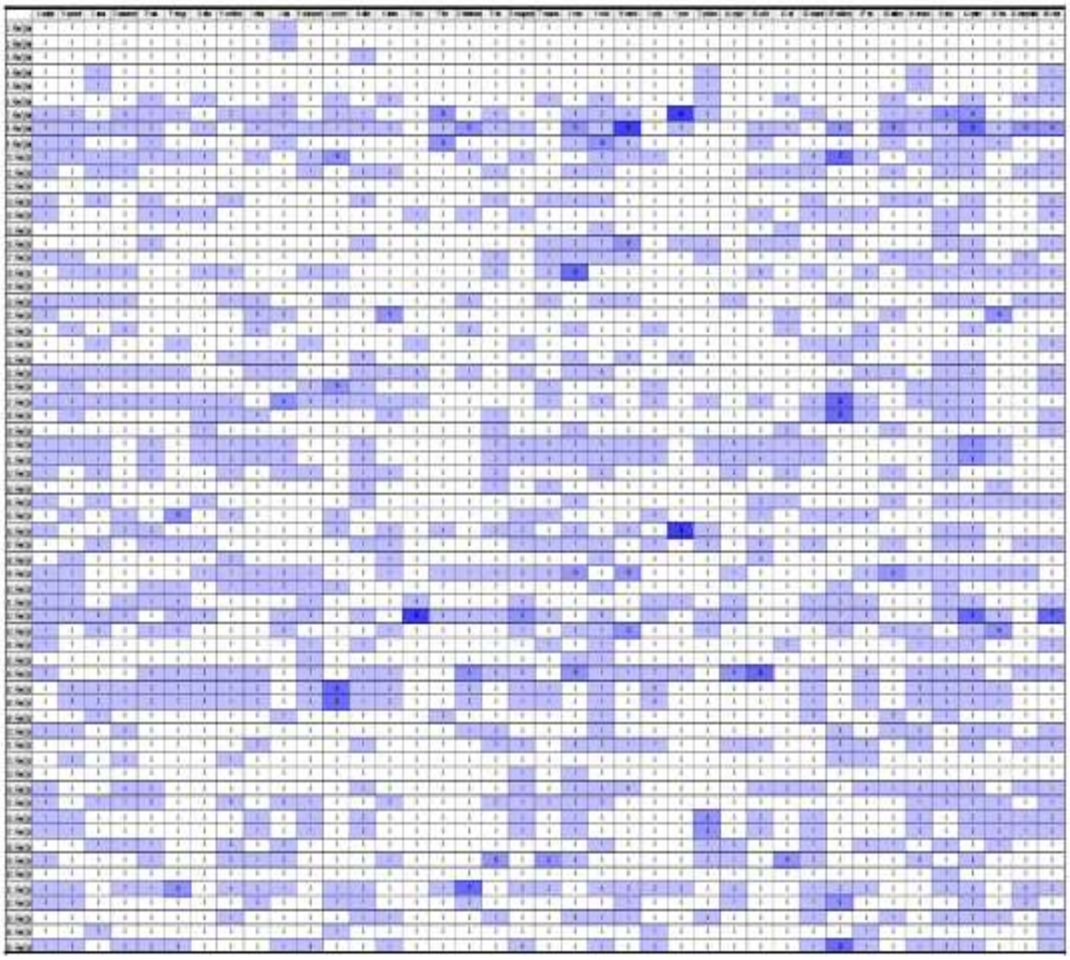


Figure 5-13 Word frequency comparative analysis

Word count query and -cross-tab analysis enhanced the quality of the qualitative data analysis by assessing the credibility of the identified variables and filtering them by their frequency of use in the focused research papers and repeating the process assisted the author in systematically filtering the variables for each category and increasing the relevance of the chosen variables, as suggested by (Abdulkareem 2018). Figure 5-12 ad Figure 5-13 show two examples of word frequency and word frequency comparative analysis generated by NVivo. Figure 5-14, Figure 5-15 and Figure 5-16 show examples of the generated 'word application hierarchy' resulting from analysis using NVivo. This feature added value to the findings from word frequency analysis and highlighted the hierarchy of world usability in different journal papers from various fields. Analysis enhanced the quality of identifying the interactions between identified variables from interviews and judging their validity against literature findings.

Word Trees are the other ,helpful feature of NVivo, which can assist in systematically analysing interdependencies between elements and variables. Once the key variables are determined through the previously mentioned steps, one can define different sets of relationships between elements and categories. According to the defined relationships, a s word tree analysis can explore specific words or phrases. This tool provided the dependability feature as proposed by (Houghton *et al.* 2013) to enhance the validity of qualitative data analysis. Word tree analysis reveals additional layers of dependencies between different resources and is a useful tool to cross-validate findings from data analysis and narrow them down to create CLDs.

The word trees could help a researcher to identify some interactions between variables and their causal links and accordingly increase the accuracy of the identified variables and interactions to generate causal loop diagrams.

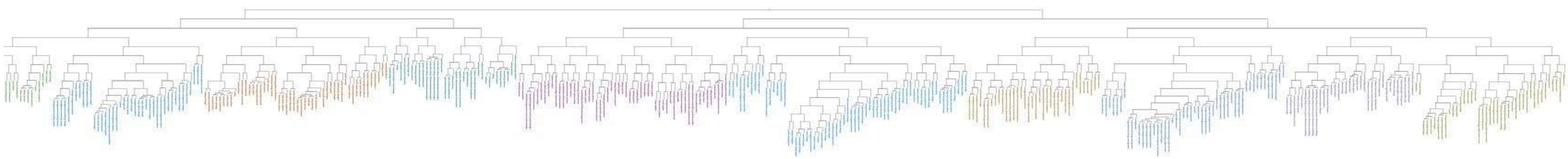


Figure 5-14 Word application hierarchy for Change management

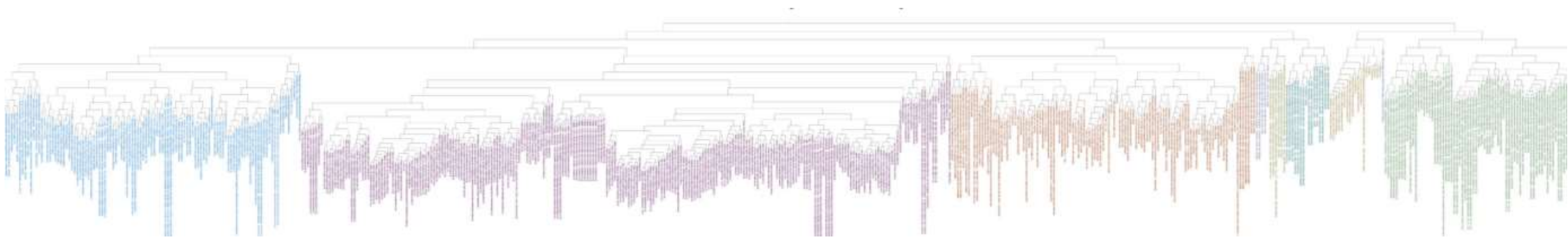


Figure 5-15 Word application hierarchy for project governance

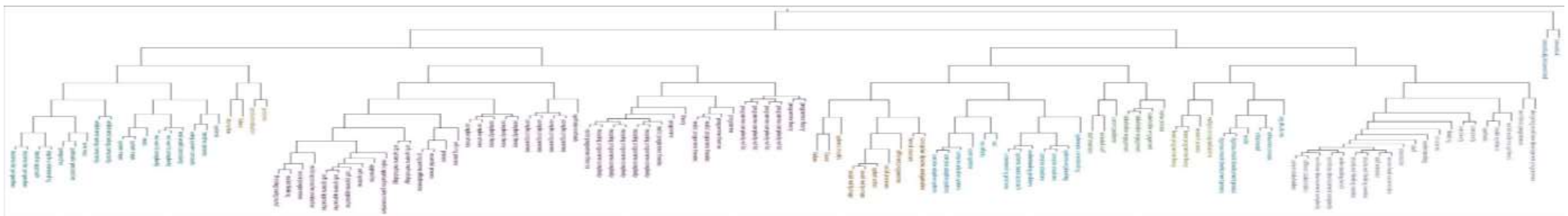


Figure 5-16 Word application hierarchy for system dynamics

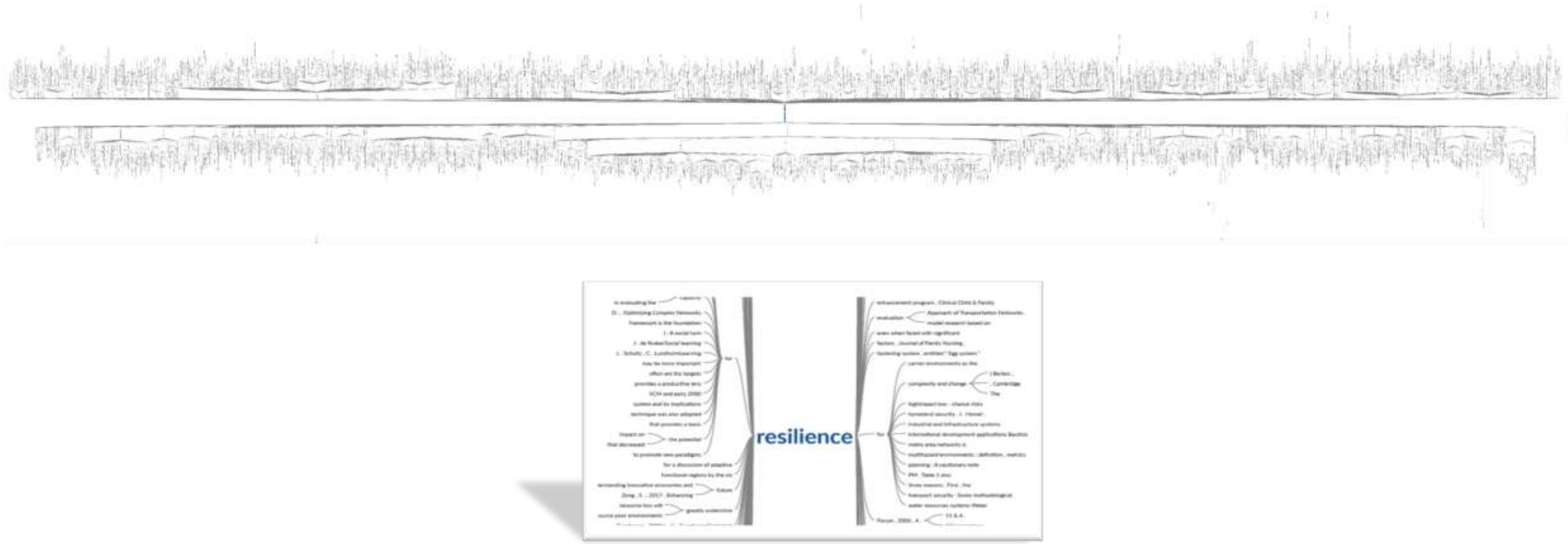


Figure 5-17 Word tree analysis for resilience

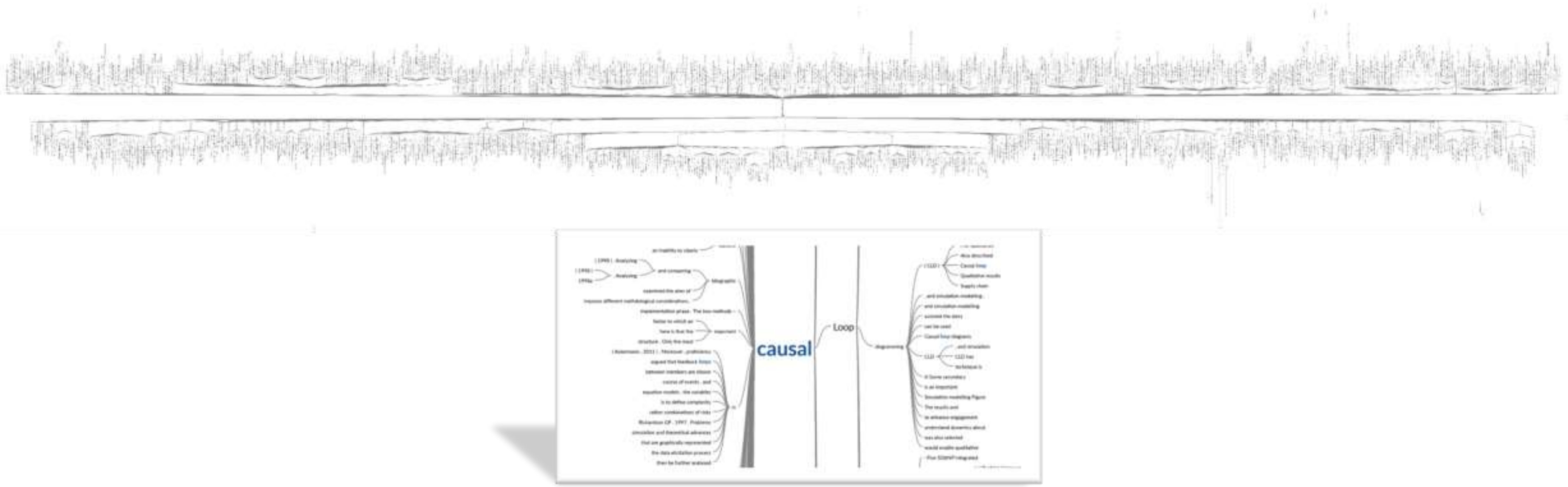


Figure 5-18 Word tree analysis for causal modelling

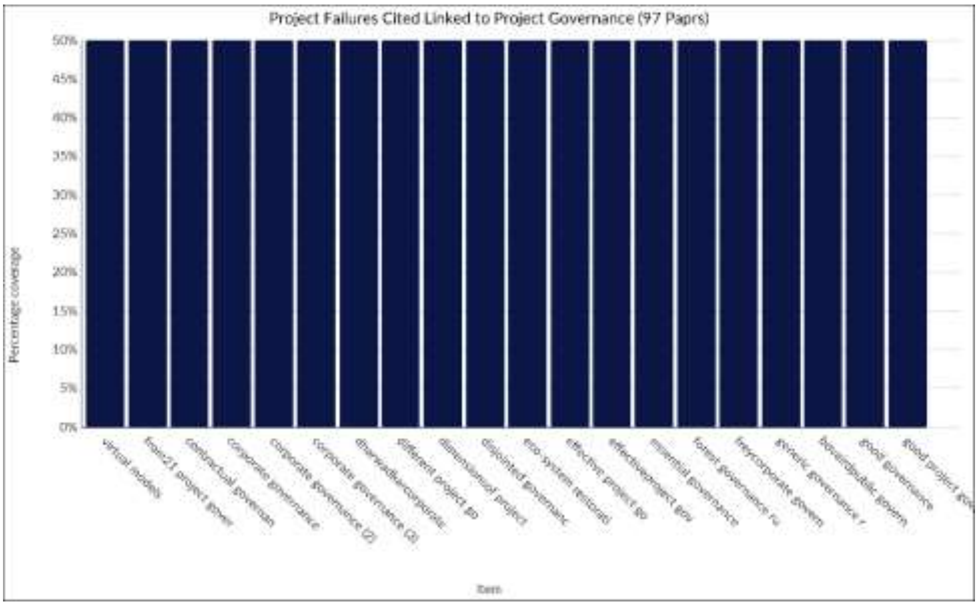


Figure 5-19 Usability analysis

Figure 5-20 provides a step-by-step guideline for future researchers interested in utilising NVivo for their research. The presented graph, in addition to the process and examples of the author's approach provided in Sections 5-5 and 5-6, can be used by researchers to conduct qualitative analysis, which can enhance the reliability of the research in similar fields.

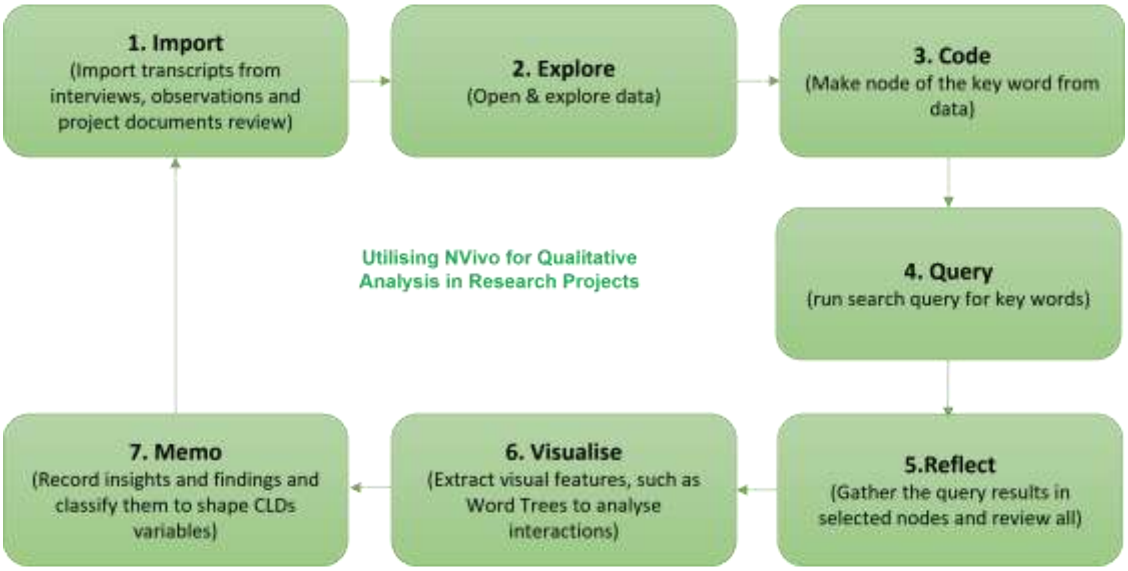


Figure 5-20 Step-by-Step guidelines to utilise NVivo in research projects

5.9 Replication of Method for Future Researchers

This section provides future researchers with a summary of the author's proposed methodology to develop system dynamics models from multiple case study analysis. The provided chart presents a systematic and reliable method, not only for railway projects but for all relevant fields of science. Figure 5-21 provides a schematic step-by-step instruction for future researcher. The limitations of the overall methodology will be explained in Chapter 9.

Chapter 6, as one of the key chapters, provides the author's proposed innovative approach to utilising system dynamics tools to analyse and improve railway project management resilience. In this chapter, the author presents a series of his developed Causal Loop Diagrams to visually model his proposed schematic project management structure. This chapter is focused on the qualitative analysis of project management resilience via features provided by CLD modelling. Chapter 6 reflects the qualitative part of the research, where CLDs are interpreted to study the behaviour of the system. The developed CLDs are the key resilience factors for the proposed project management structure, hence, they need to be analysed from different aspects. This will shape the foundation to formulate and integrate generated CLDs utilising SFDs in Chapter 7.

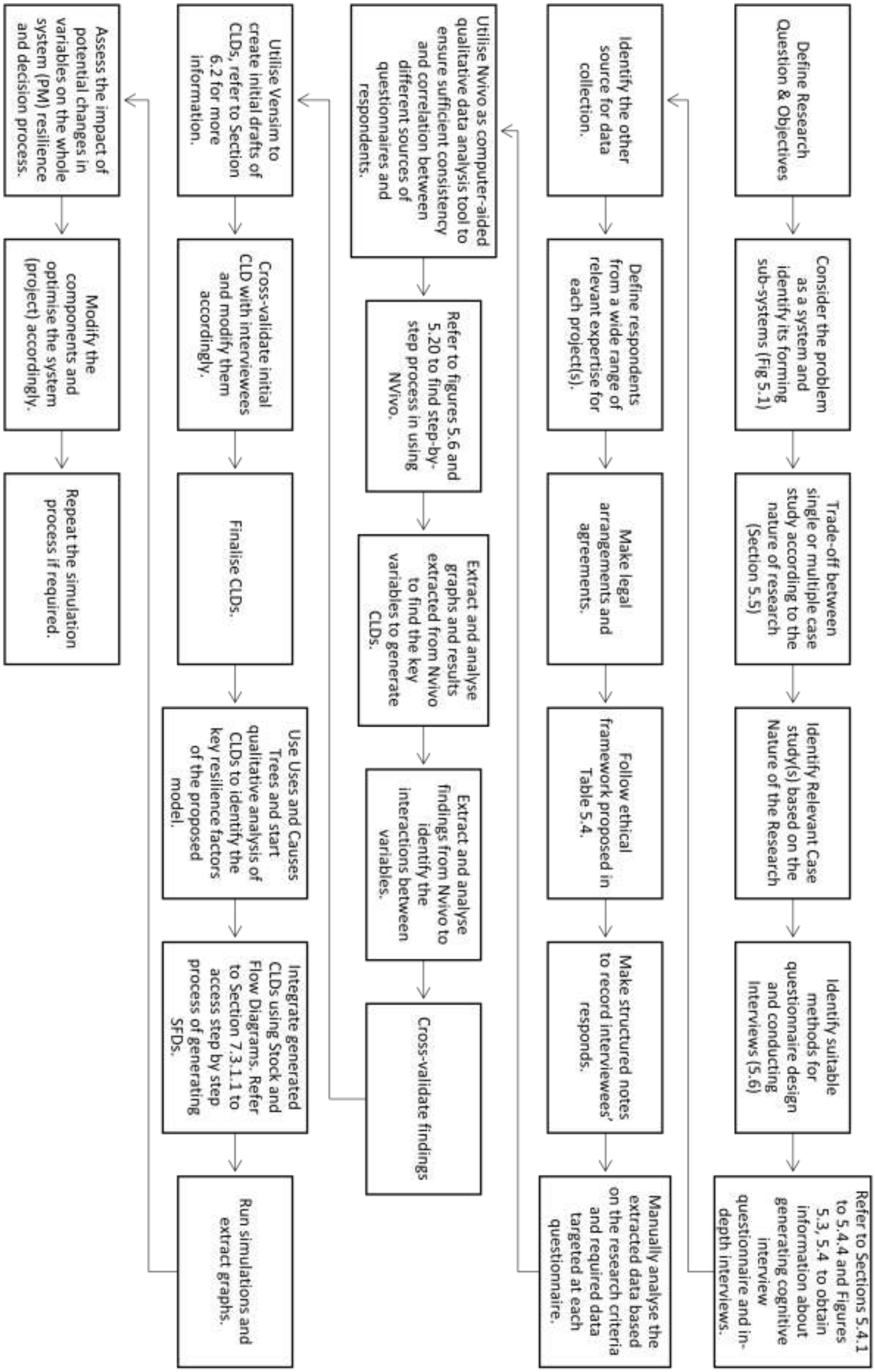


Figure 5-21 Step by Step guideline for future researchers- Develop System Dynamic Modelling from Multiple Case study Analysis (Author)

Chapter 6

APPLICATION OF SYSTEM DYNAMICS TOOLS TO IMPROVE RAILWAY PROJECT MANAGEMENT RESILIENCE

(Causal Loop Diagrams- Qualitative Research Analysis)

6.1 Introduction and Logic of the Chapter

The main hindrance to the application of system dynamics tools as a common method in the rail (and other) industries is that those approaches are complicated and require a reasonable level of training. Particularly, when it comes to the modelling approaches, those working in the industry generally express reluctance to learn related software packages.

To develop the hypothesis of this research and integrate resilience thinking with project management, the author considered railway project management as a system formed of five key subsystems, as demonstrated in Proposed algorithm to develop SD tools to analyse the resilience of railway project management process (author)

This provided a schematic structure and allowed the researcher to utilise system dynamics tools to visually model the entity of project management and analyse its performance and resilience.

This chapter presents the generated causal loop diagrams, followed by a summary of their qualitative analysis, which was used as a foundation to develop the stock and flow diagram.

6.2 Generated Causal Loop Diagrams (Qualitative Research & Analysis)

In this section, the author presents the developed CLDs derived from multiple case study analysis and using Vensim software. Figure 6-1 illustrates the proposed model to model project management and the steps towards creating a hypothesis from multiple case study analysis.

The author has deliberately illustrated his proposed model as a cogwheel model. This is to emphasise the interactions between the identified subsystems and their impact on each other and most importantly, on the whole system (project management). This facilitates establishing a logical flow between sections 6-1 to 6-5 of this chapter. The section below briefly explains the approach to generating CLD utilising Vensim software.

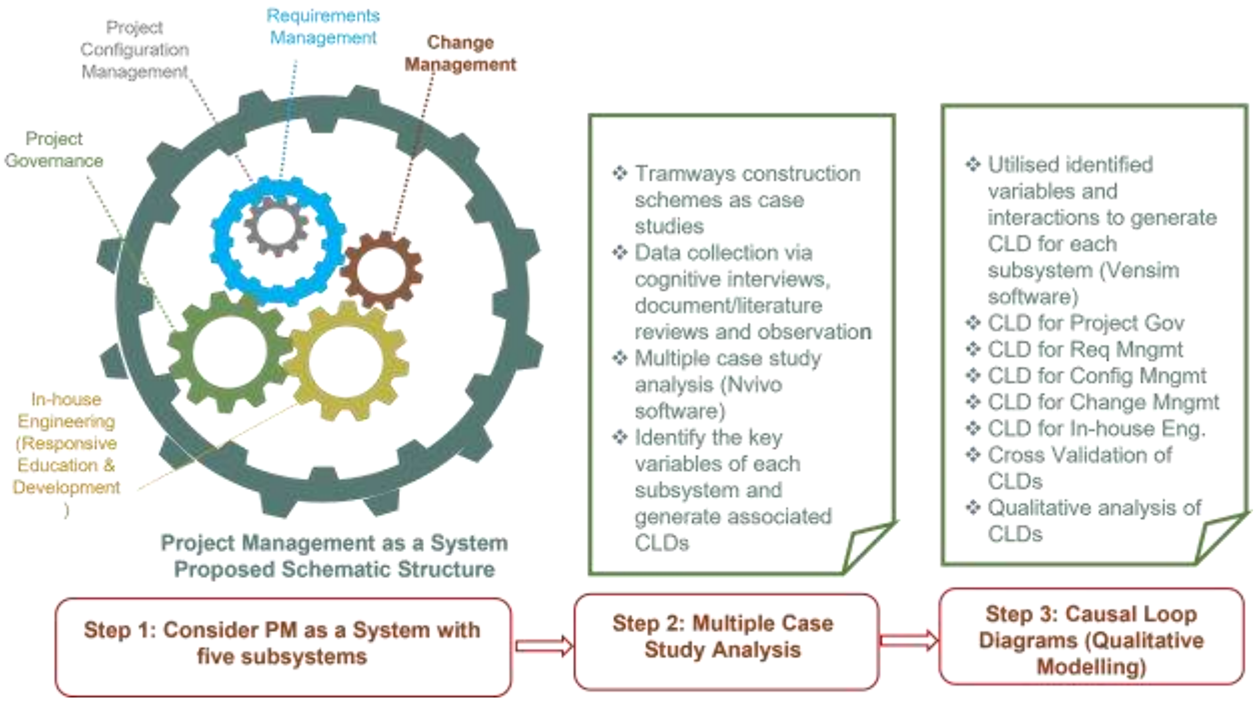


Figure 6-1 Proposed schematic structure and steps toward developing the hypothesis (author)

- Referring to the top level of the chart, first, we need to identify the relevant case studies that reflect our research scope's nature. Then identify the multiple sources of data collection, such as interviews, documents and literature reviews and observations. Data will be collected via those multiple sources of information. The data will be categorised and filtered manually. Then the filtered data needs to be qualitatively analysed using NVivo software. The trade-off between different types of interviews and case study analysis in addition to a guideline on how to utilise NVivo for qualitative case study analysis are presented in Chapter 5. Figure 5-20 can be used by researchers as a framework to develop qualitative case study analysis in NVivo (Verifying the findings against literature review and manual analysis).

- Once the qualitative analysis was done and variables and their interactions were identified via Nvivo, we need to cross-validate them against reality and get them reviewed by experts. At this stage, basic CLDs, even hand-drawn versions are recommended. Initial CLDs shall be annotated and modified by interviewed experts (additional layer of data validation).
- Modified CLDs can now be modelled within the Vensim environment. In the software, we open a new model. The units and time limit then will be defined. From the toolbar, we chose variables and add the boxes to the model. In the boxes, we can write the name of the variables. It is recommended to add variables based on the feedback loops they are shaping. Then, from the toolbar, we choose arrows, click on the variable, and drag the arrow to the variable affected by the variable on the tail of the arrow. Right-clicking on the arrows gives us the option to add polarity to the arrows (as explained in Chapter 3).
- After adding all variables, arrows, and polarities, we need to ensure that loops are completed. Hence from the toolbar, we need to check the validity of the model. We need to keep editing the diagram until the validity check is completed.
- Referring to the concepts explained in Chapter 3 (CLD simplification), the Vensim software provides a feature to simplify the CLDs. At this level, the level of abstraction and simplification depends on the modeller's judgment. We need to make a balance between the complexity and usability of the CLDs. Throughout all the previous processes, we need to ensure the model reflects the true nature of the system, without being over complicated or scarifying the key variables and interactions.

- We can use Causes and Uses Trees and validation tools and extract the relationship trees to ensure we have identified the right interactions.
- Finalised CLDs shall be sent back to the experts for final review. Changes will be applied and CLDs will; be ready for analysis and converted to SFD.

The chapter begins with a brief introduction to the context of the subsystem modelled via CLD, followed by a brief model interpretation, cross-validation with real-life projects (to show how the author analysed the models) and a brief suggestion on the applicability of the approach to improve the performance and resilience of each subsystem. Exemplar Uses and Cause Trees are presented to showcase the causal tracing feature to identify the resilience factor of each subsystem. The author did not go through an in-depth analysis of each CLD, a sit was out of the scope of this thesis. But the findings from the qualitative analysis of CLDs identified the resilience factors for each subsystem and contributed to formulating the CLDs and converting them into stock and flow diagrams. At the end of each section, the author briefly explained how each subsystem is causally interrelated with the other ones.

6.2.1 Project Governance

Despite project governance has been the topic of many research projects during the last decade, the actual project management concept and its origins remain somewhat ambiguous in the context of organisations and projects. Project governance can be defined as a structure that delivers a framework for ethical decision-making and managerial activities within an organisation, taking into account decision transparency, accountability, and defined roles (Muller 2011).

The choice of governance structure is influenced by the necessity to manage the mutual dependency between stakeholders, clients and the project team, between phases of the project or programme, and between different human resources and project supply chain factors (Turner and Keegan 2001). For the studied projects, whilst interviewing experts, the respondents were asked to explain the gaps they believed existed within the project governance of the project at the time. They were also asked to consider the positive aspects of the adopted governance. Results were cross-validated with literature findings using NVivo, and the following CLD was subsequently generated to visually model the generic components of project governance, which can affect the resilience and functionality of a project.

During the research and interviews, the author identified a few findings in project governance common among all studied projects. Apart from the project management team, it was common for other project staff to only have limited or unclear knowledge of a project's governance structure. Respondents generally thought that they had a clear understanding of project roles, but there were several cases where respondents were unable to provide clear answers when asked who in the project was responsible for collecting near-miss reports or managing unplanned changes.

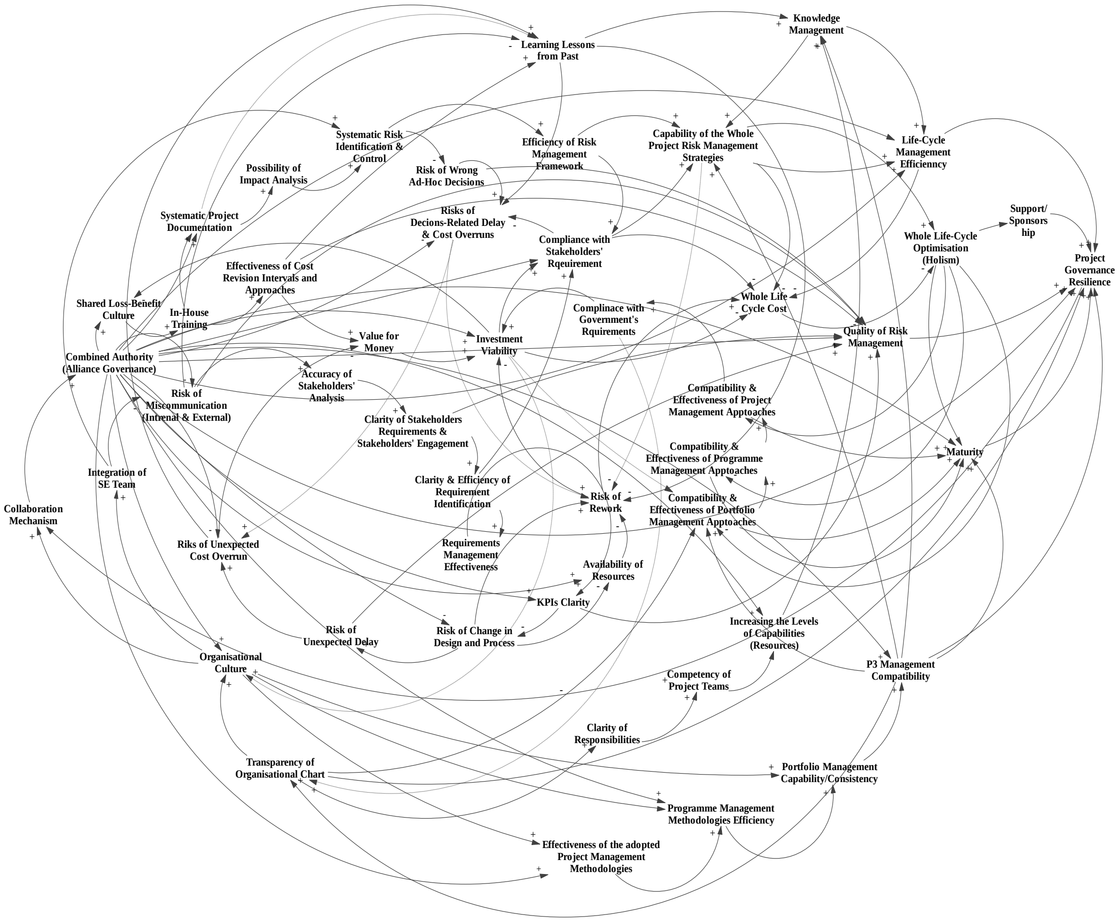


Figure 6-2 CLD generated for project governance resilience (author)

A variable understanding of a project's governance was diagnosed as one of the key factors affecting the communication between project teams and external stakeholders. In one of the case studies, it was mentioned that lessons from the Edinburgh Tram project, had been applied to the project governance, however, the author could not find any documented proof to confirm this. In other case studies, it was mentioned that the structure of the project differed from previous similar projects and hence the governance structure was untested.

The author's studies showed reasonable similarities between projects in the benefits that could be gained from learning from the mistakes of previous projects. However, it was found that there were limited formal processes to capture and disseminate learning. No projects were developing a documented and meaningful learning legacy.

Further, the lack of a unified understanding of the purpose and coverage of documents was identified as an issue through analysis of interview responses and the author's observations. It was found that there were often a set of documents summarising the overview of targets for a particular phase, but very limited documentation relating the current phase of the project to future phases and interaction between different project phases was often overlooked or underestimated in the project governance.

There were some signs that senior management teams had begun to think about how to systematically link the scopes and benefits of different phases of the projects and consider them as a programme. This approach enhances system thinking within the project, enabling planners to apply lessons learned from previous projects. Additionally, the integration of specific tramway construction projects with other transportation programmes, such as HS2 and systematic portfolio, programme, and project (P3) management was briefly outlined in the documents, but the author's research found that the integration and analysis of the benefits and KPIs are very limited with much more action being required to result in more reliable project governance processes that are based on system thinking.

The other important finding from the review process was that the project governance structure plays a significant role in the risk assessment of a project. The quality of the project risk identification, which has potential impacts on the cost, time, and benefits of the projects, was highly dependent on the project governance structure, clarity of roles, systematic documentation, communication skills and choosing compatible project management approaches. The Birmingham Midland Metro Extension project was a great exemplar in this area. Centro was the initial owner of the project, which contracted the construction to the infrastructure contractors. Approaching the end of the first phase of the project, the Midland Metro Alliance (MMA) was formed. "The MMA consists of the West Midlands Combined

Authority, which owns West Midlands Metro; a consortium of design experts from Egis, Tony Gee and Pell Frischmann; and rail construction specialists Colas Rail – with Colas' sub-alliance partners Colas Ltd, Barhale, Bouygues UK and Actus Management Group" (Metro Alliance).

One of the key positive factors was the promotion of a culture of shared loss and shared benefit, which motivated project teams to consider the quality and risk management of the project and encourage systems thinking. During the project, the author developed a close collaboration with the MMA (and Centro, who led the project before 2014The recommendations and associated report were based on: (i) casual table 6-1 which shows the results of the literature review focusing on the impact of alliance project governance on projects risk management; (ii) the CLD shown in Figure 6-2; and (iii) a set of guidelines which were developed to support the establishment of the MMA.

CASUAL TABLE 6-1 BENEFITS OF ALLIANCE PROJECT GOVERNANCE FOR PROJECT RISK MANAGEMENT (AUTHOR AFTER GUO ET AL. (2014))

Elements of Risk Management	Advantages of Alliance Governance
Time and Quality	• Pain-share and gain-share mechanisms created an incentive to complete works ahead of time and defect-free • 'Defect-free on an opening day, as one of the KPIs of the alliance, had derived decisions towards regular quality review and control
Cost	• Monthly cost review within the alliance • The budget was divided into different disciplines and different teams, with each team manager in charge of monitoring and reporting risks
Availability of Human Resources	• An independent costing estimator • Cost savings were shared by the alliance as a whole • Availability of labour • In-house skills training within the alliance • The alliance team aimed to leave a legacy of training in the regional construction industry

Environmental & Social Measures	• Environmental monitoring was a part of the consent process • Incentives in the alliance agreement encouraged healthy competition and innovative solutions • All inductions, pre-start workshops and toolbox meetings had integrated the agreed sustainability and environmental achievements • Contractors were trained to continuously address environmental and social concerns • A communications plan was in place, including regular newsletters and monthly meetings with a community reference group
Collaborative Mechanism	• The alliance was regarded by interviewees of this research as a truly collaborative model • Value for money was manifested in the contractual arrangement between the client and alliance participants • The pain-share and gain-share principle provided the formal basis for alliance governance

Figure 6-3 Uses tree for the impact of alliance project governance, derived from CLD (author)

Figure 6-3 is a Uses Tree Diagram derived from the CLD generated by the author. Uses and Causes Tree diagrams can be used to cross-validate the findings and better understanding the causal behaviours of the CLDs. The presented Uses Tree brings out the key variables that can be affected if we invest in alliance project governance. This delivers a systematic and reliable impact analysis approach, which contributes toward informed decision-making.

6.2.2 Requirements Management

According to (INCOSE 2010), when following a systems engineering approach, it is important that:"

- Requirements are thoroughly defined, refined, and allocated to lower-level system elements, assigned to suppliers and subcontractors, and tracked, through the testing and verification phase of the work.
- The product is viewed from a system perspective: links between requirements are identified so that changes to any one area can be analysed for impacts on the requirements for the system.
- The entire product lifecycle is considered from the start of the project, including the disposal of the final product.

The INCOSE Infrastructure Working Group report on the application of systems engineering to infrastructure projects. The group recommends that requirements management should be considered as a process, that "collects input from authorised sources to produce managed baselines of validated and traceable requirements. The process gathers evidence that requirements were met" (INCOSE 2016).

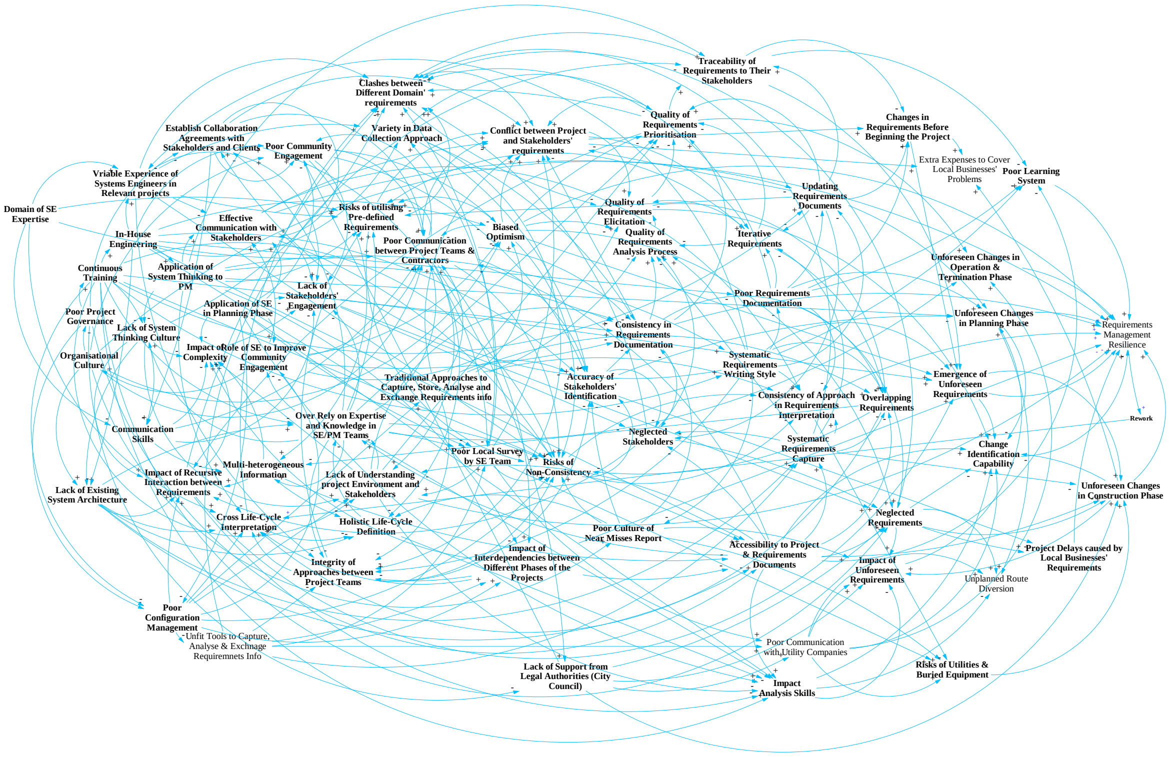


Figure 6-4 CLD generated to model requirements management resilience, derived from multiple case study analyses (author)

All the projects considered as case studies were cited as suffering in the planning and design phases from poor requirements identification, stakeholder management and requirements prioritisation. The developed CLD provides the key variables affecting the resilience of requirements management. The model was reviewed and confirmed by experts from studied projects and cross-validated with literature review findings. One of the most important problems common in all projects was miscommunication with external stakeholders (such as utility companies), leading to significant reworks, delays, and cost overruns. This formed the bases and was used as an example to develop stock and flow diagrams in Chapter 7.

Respondents also highlighted issues involving external stakeholders, noting inefficient communication with local communities and lack of community engagement as impacting the effectiveness of the requirement management processes. project's planning phase

Respondents also raised the poor interactions from a systems perspective between project teams and City Councils, local communities, and utility companies. As an example, in one of the projects, the track was supposed to pass by a shopping centre, and this affected the routes used by delivery trucks. Ignoring the complex nature of the project, the project team had assumed that they could divert the delivery trucks to the parallel back street for 3 months and continue construction work. Two problems were identified one week after beginning construction. First, the City Council was not fully informed of the diversion and diversion hours, hence there was a miscommunication between the City Council's plan to collect bins and undertake maintenance, and the infrastructure contractor's construction plan. The City Council requested to charge the company for access and potential damages to the alternative route.

The second problem identified was the lack of knowledge of existing underground utilities; in this case, the project team had not been given access to a plan of existing utility routes. The local investigation identified buried cables and a gas pipe, which needed to be diverted. These miscommunications and poor requirements management resulted in a 3-month delay and around a 15% cost overrun in that specific section of the project.

The Causes Tree derived from the CLD presented in Figure 6-5 shows the main variable identified as affecting the resilience of requirements management, based on findings from the case studies.

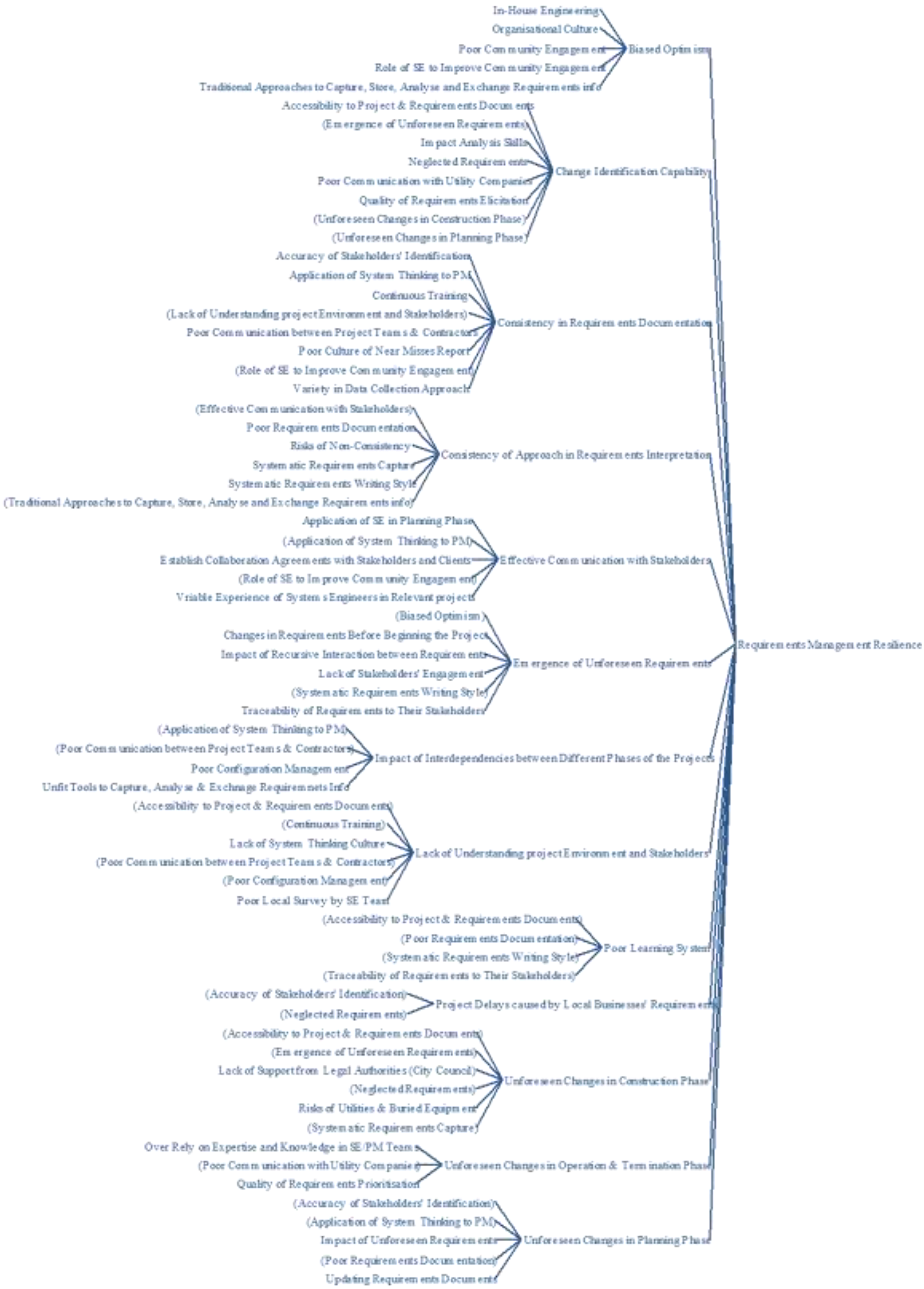


Figure 6-5 Causes tree to show the resilience indicators for requirements management (author)

Figure 6-6 Uses tree to show how poor project governance impacts requirements management resilience (author)

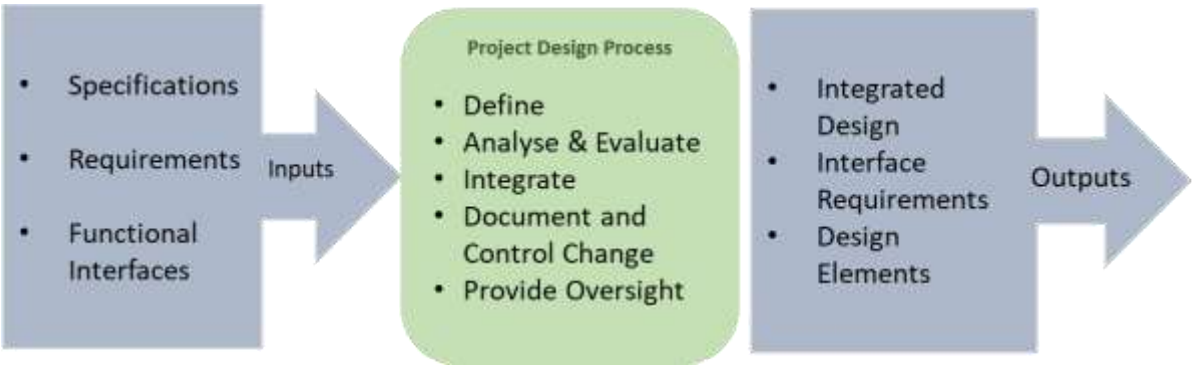


Figure 6-7 Requirements management as a process (author after INCOSE (2016))

Figure 6-7 shows the key aspects of the INCOSE recommended framework for requirements management. The proposed CLD and associated tools can support managers and planners in following the INCOSE framework. Project requirements and their associated specifications can be considered as systems and be modelled via CLDs (1st step). In complex and dynamically changing projects, requirements keep changing. Hence, Requirements Change Management (RCM) has become an inevitable process within modern requirements management approaches (Akbar et al., 2019). The author's proposed approach provides a reliable and traceable approach to assist the RCM process, as suggested by (Lai & Jayatilleke, 2018). as depicted in Figure 6-8, , RCM requires key factors such as impact analysis, monitoring of the change and constant verification and validation, which are all embedded within the CLD approach.

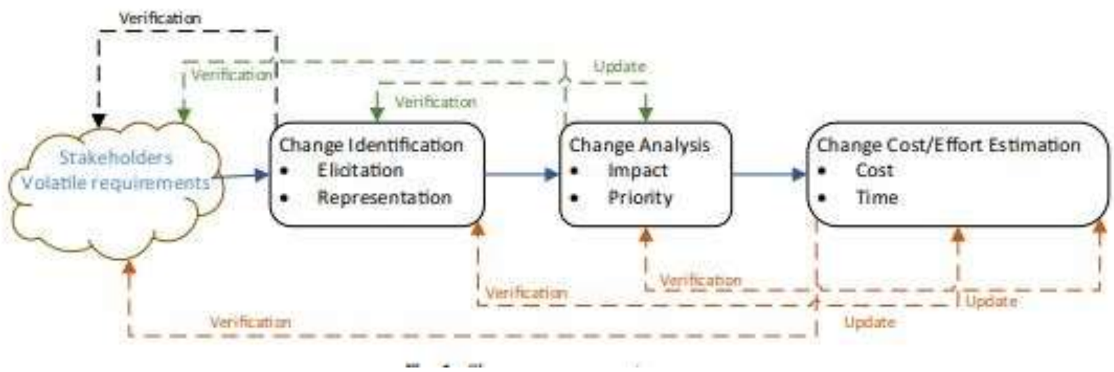


Figure 6-8 Requirements Change Management Process (Lai & Jayatilleke, 2018)

Figure 6-6 shows the Uses Tree derived from the requirements CLD. Referring to the cogwheel model in Figure 6-1, the qualitative analysis of the causal loop diagram identifies the key variables affected by poor project governance. This assists in studying the behaviour of the system and its resilience.

6.2.3 Project Configuration Management

"Configuration management ensures that accurate information, consistent with the physical and operational characteristics of the project, is available at any point in time. The ability to rapidly identify and retrieve this information is vital to achieve cost-effective construction, to maintain the configuration of the plant, and to support future upgrades" (Chichi et al. 2007, p.549). Configuration management plays an important role during the whole lifecycle of a project (Lindkvist et al. 2013) as it can be considered a hub to store, maintain and analyse project data (Morant et al. 2012).

The APM defines configuration management as "encompass[ing] the technical and administrative activities concerned with the creation, maintenance, controlled change, and quality control of the scope of work. A configuration is the functional and physical characteristics of a product as defined in its specification and achieved through the deployment of project management plans". In the context of the rail industry, the scope of configuration management is a function of a system's characteristics and includes documentation and system deliverables (Morant et al. 2012). Configuration management can be considered as an approach based on systems engineering to maintain the integrity of information in all phases of the project lifecycle and to facilitate control of changes in complex projects (Whyte et al. 2016).

Figure 6-9 depicts the CLD derived from the case studies and reflects the key resilience indicators of project configuration management.

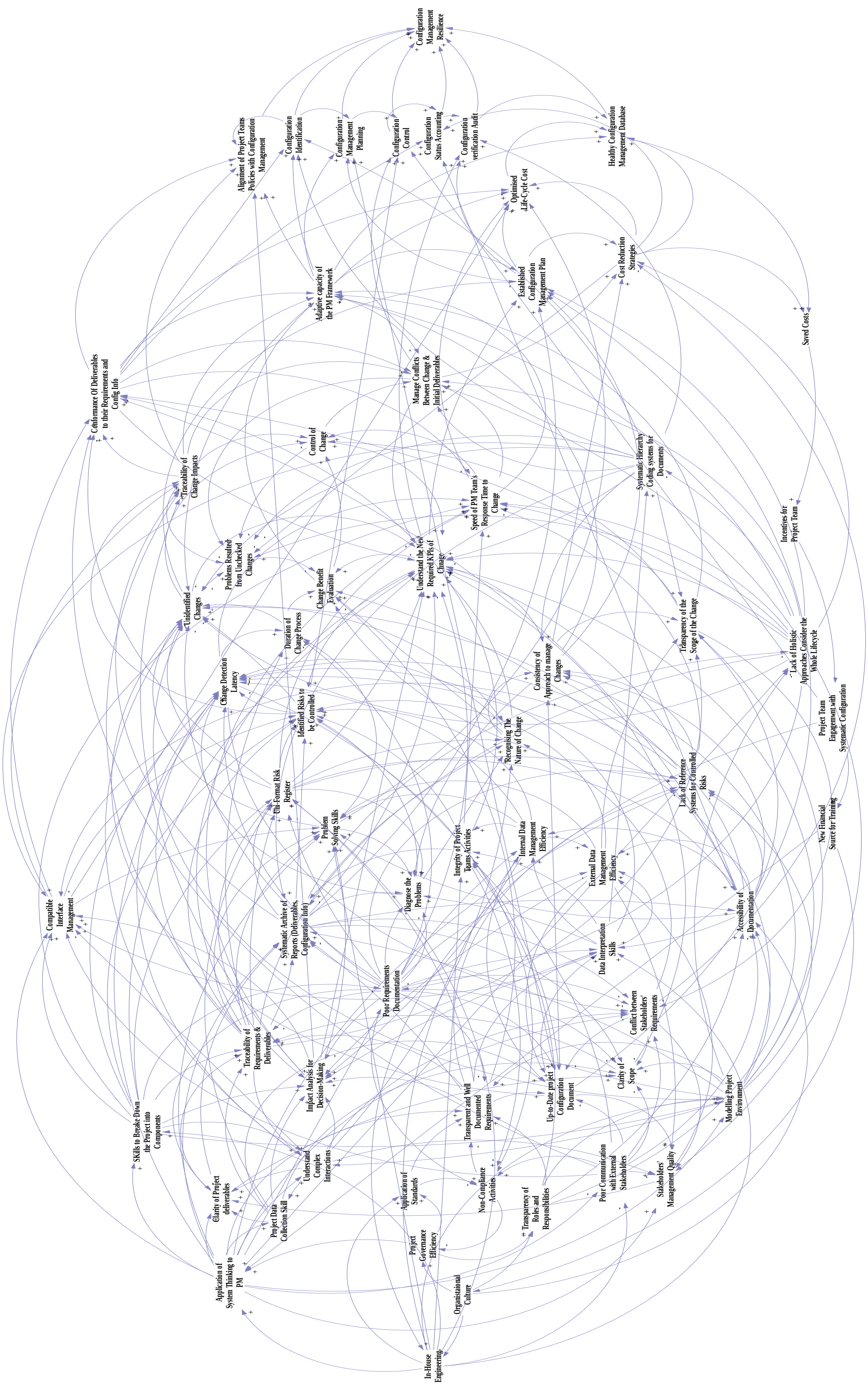


Figure 6-9 CLD for identifying key resilience indicators of project configuration management (author)

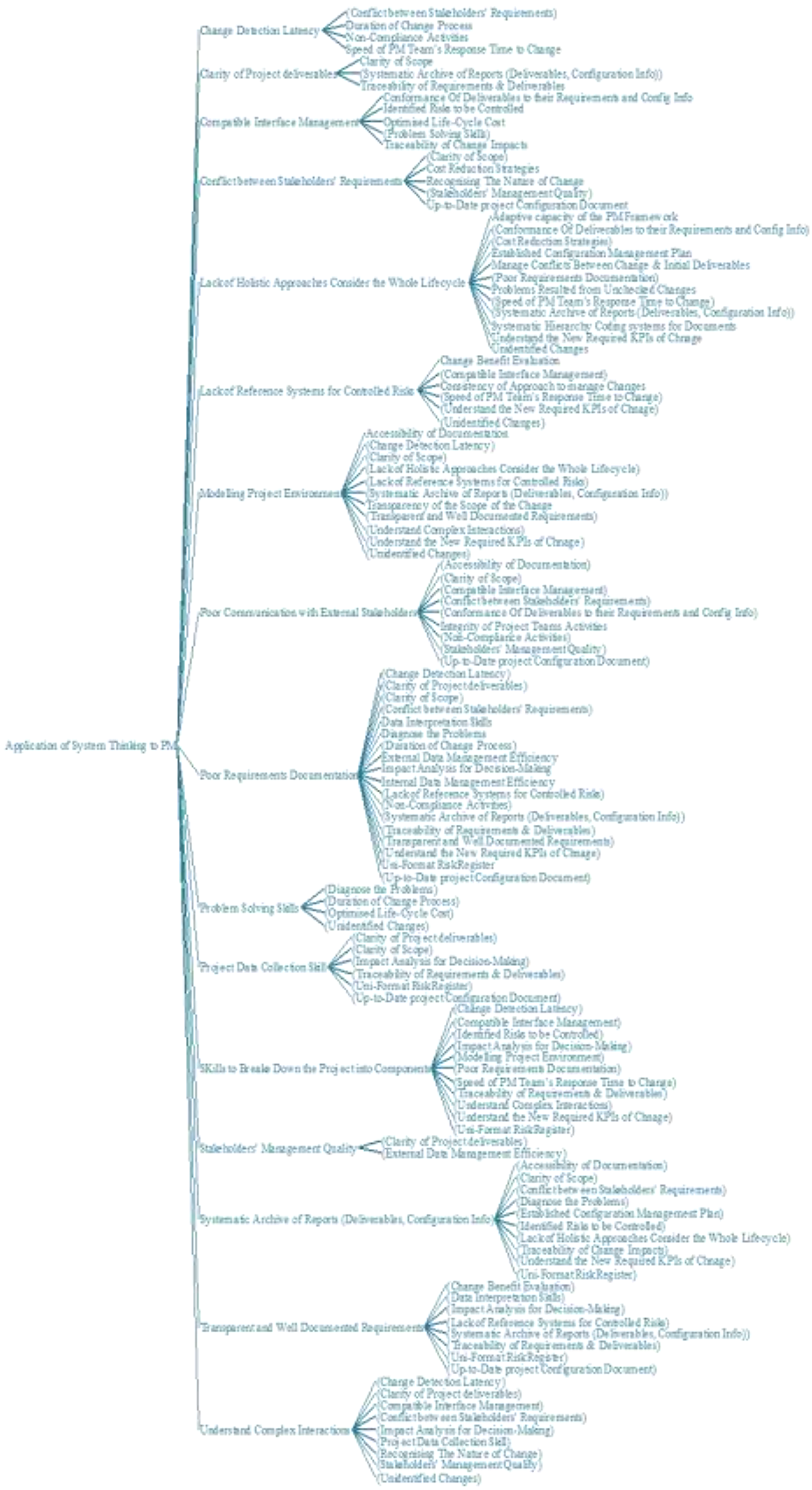


Figure 6-10 Uses Tree showing the causal impact of system thinking tools on project configuration resilience (author)

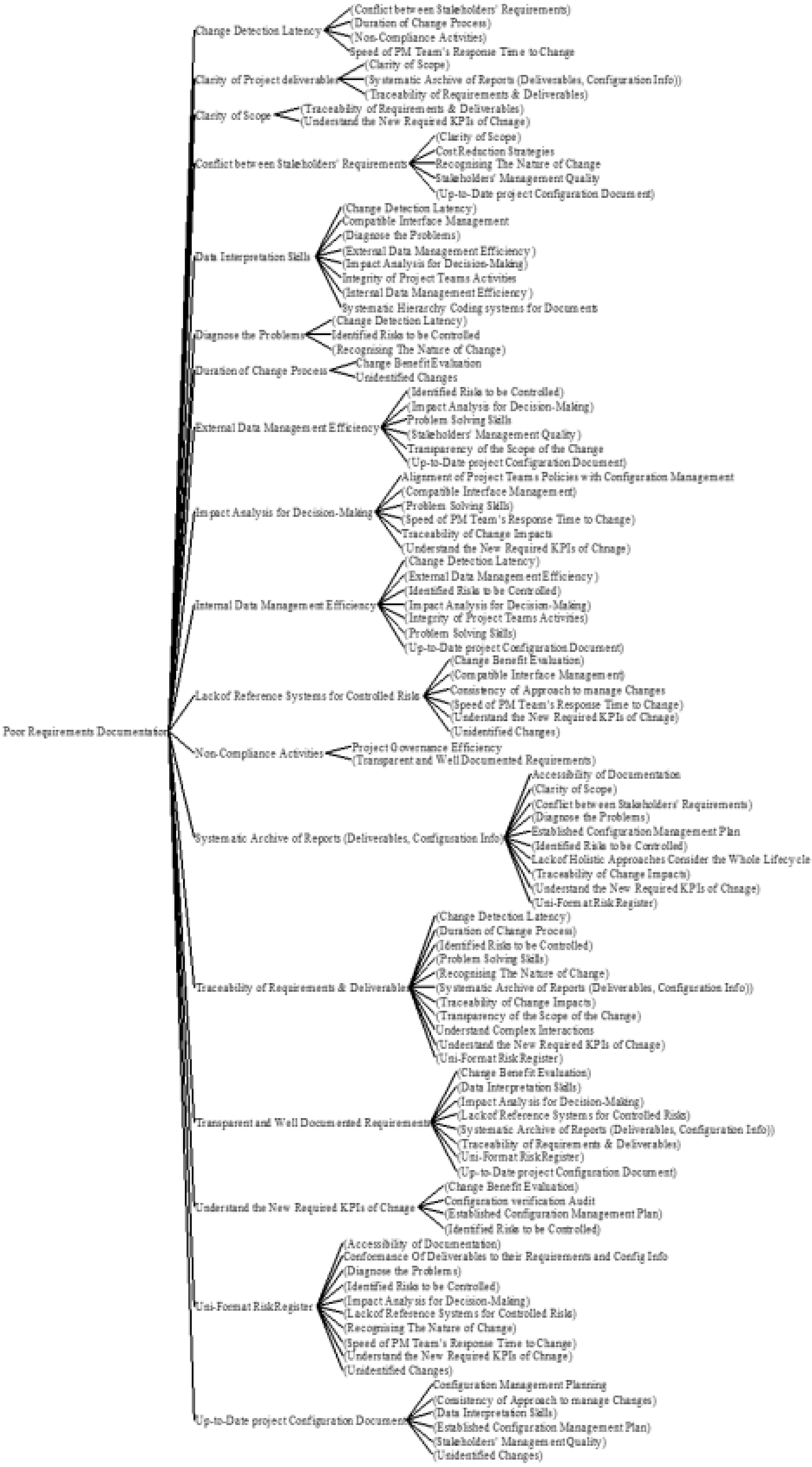


Figure 6-11 Uses tree to trace the causal effect of poor requirements documentation on configuration management resilience (author)

As mentioned earlier, configuration management requires the availability of data throughout the whole lifecycle of a project. In other words, configuration management means systematic information management. This is not achievable without a reliable documentation approach. Developing CLDs can contribute to the configuration management process through the following steps:

- Provides a visual model, identifying the key variables and interactions. This will facilitate understanding the directions and patterns of information flow.
- Identifies vulnerable variables (interfaces), which might embed high levels of risks. This allows configuration managers to monitor the state of equilibrium of a project's system through the whole lifecycle. Please note that CLDs need to be updated based on the lessons learnt and based on the updated information.
- Assists in improving decision-making accuracy via impact analysis. Refer to Figure 6-10. This diagram extracts all the variables interrelated to the system thinking procedures in the project. In other words, a modeller can refer to this diagram and realise what aspects of the project will benefit from applying system thinking approaches (or would fail in the absence of system thinking).

Providing a repository of CLDs for a specific project can provide a platform to integrate system thinking into the project, which consequently feeds into the project's configuration management. As we keep updating CLDs, the previous versions can be referenced as a reliable source of the project's state documentation. Figure 6-10 and Figure 6-11 are extracted from the CLD and identify the causal impact of applying systems engineering (or a lack of systems engineering culture) and the causal effect of poor requirements documentation (resulting from poor requirements management and project configuration management resilience, respectively). This provides a traceability feature that assists researchers and managers in diagnosing the origins of problems and the potential interfaces to improve them.

6.2.4 Change Management Resilience

The APM defines change management as "the overarching approach taken in an organisation to move from the current to a desirable future state using a coordinated and structured approach in collaboration with stakeholders." Change is an integrated component of organisational strategy and an everlasting entity within projects (Rieley and Clarkson 2001).

In 2017, ORR conducted research and suggested that metros and tramways are vulnerable to a lack of resources and the capability to apply reliable and rigorous change management approaches, hence they need to learn from heavy rail projects. ORR clearly stated that "Investigating the change management in tramways projects, ORR found evidence of some weaknesses in works and systems that were subject to safety verification in some projects.

A focus on the lack of a whole-system approach to system safety and the use of inappropriate heavy-rail technology in the design of the new British tramways may have led to unnecessary risk needing to be managed through operational controls instead of being designed out" (ORR 2017, p.10). Interestingly, the author's research and interview analysis strongly confirmed this statement. The interviews revealed that the design framework adopted for the modern tramway mostly uses design concepts from heavy rails; however, in the case of Birmingham Metro, there was evidence that the design team have considered innovative design practices, especially for tracks and drainage systems.

Figure 6-12 visualises the key variables and their interactions that affect the resilience and efficiency of project change management, based on the case study analysis. Figure 6-13 is a uses tree concluded from the CLD, which explains the causal impact of system thinking on the variables of change management resilience.

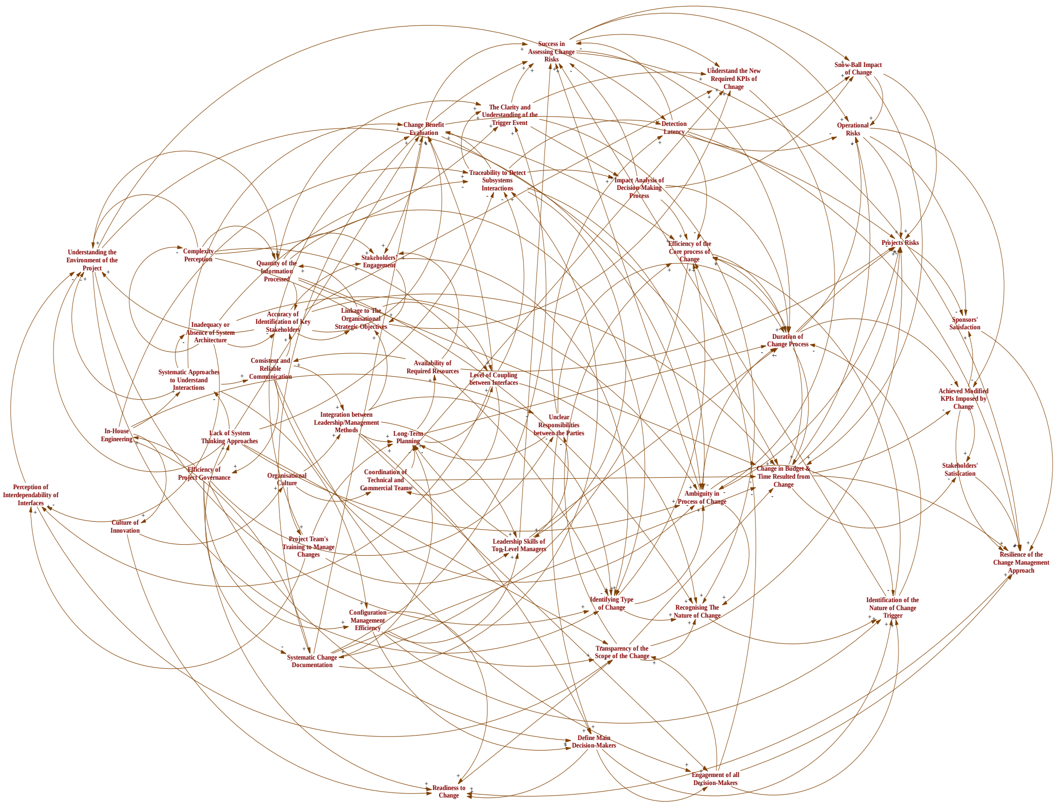


Figure 6-12 CLD derived from multiple case study analysis to model the resilience indicators of change management (author)

Figure 6-13 Uses tree to study the causal effect of a lack of system thinking approaches on change management resilience (author)

From the analysis of the causal feedback of the CLD, it can be concluded that the key problem within the studied projects, which led to inefficient change management, originates from the lack of an effective and established systematic approach to identifying the triggers and scope of change and, accordingly, incompetence of the existing decision-making tools to analyse the impact of decisions on system behaviour (due to system complexity and non-linear interactions). This was causally proved in the CLD developed for configuration management.

Figure 6-13 identifies the impact of systems engineering approaches on the resilience of change management. Considering the cogwheel model and causal impacts, analysing the provided Uses Tree highlights that, poor systems engineering approaches will causally affect the quality of configuration management and this will have a knock-on impact on data analysis of the project and reduce the capability of the project team to detect unexpected changes in advance or to detect their origins after they occur.

A change to one part of a system can led to many changes to the other parts of the system. This phenomenon is known as the 'snowball effect' (Elliott 2014). It means that the impact of change on a project is a function of time, and the cost and impact of the change will increase over time. According to (Elliott 2014):

$$\textit{Change Latency} = \textit{Detection Latency} + \textit{Decision Latency}$$

The proposed approach (CLD modelling) provides a practical toolset (combined with quantitative analysis via SFD) for managers and modellers to constantly monitor the changes and behaviour of the system over time, analyse the impact of their decisions on the whole project's performance and assess the impact of any optimisation activity on the system's resilience.

6.2.5 In-House Engineering (Responsive Research, Education, and Innovation)

The term in-house refers to the culture of an organisation to conduct activities within their team and use internal staff by upskilling them, according to the project's needs, instead of relying on outsourcing. The concept of in-house engineering in this research is mainly focused on improving organisational culture to promote continuous education, research, and development, aiming to upskill the staff of project teams. Due to the high level of complexity in the studied projects, outsourcing construction jobs to external contractors seems reasonable as the project owners might not have the technical capability and equipment; additionally, outsourcing would be cost-saving (Aitzaz et al. 2016).

On the other hand, responsible research and innovation are required for sustainable improvement to meet the project teams' requirements (Ravesteijn et al. 2014). Studies show that in complex projects, knowledge sharing and system integration are two key challenges within complex projects and this area has not been covered properly in research (Gurca et al. 2020). Pich et al. (2002) looked at projects and their required management strategies from the viewpoint of the degree of information accessible to the project team before the project.

Tramway construction projects and railway projects, in general, can be categorised as learning projects. The complexity and variability of multiple stakeholders require project teams to consider of continuous research, education, and development. This need was identified in the author's research. The research demonstrated that the innovation culture must originate from project governance as the heart and be pumped through the other components of the project. The CLD presented in Figure 6-14 was produced based on an analysis of the interviews; the most important variables need to be included in continuous education and development to respond effectively to project complexity impacts and mitigate unexpected causal effects.

The main idea is to highlight the key points on which to focus when project teams are planning their staff education, according to the findings from the case studies.

TABLE 6-2 TYPES OF PROJECTS BASED ON THE AVAILABILITY OF INFORMATION AND SUITABLE MANAGEMENT STRATEGY (AUTHOR AFTER SHENHAR (2001); PICH ET AL. (2002))

Type of Project	Characteristics	Management Strategy
Insstructionist Project	Most of the information needed for planning is available, and the project team has a good understanding of the 'best policy that must be implemented.	Planning an instructional project mainly involves optimisation that is focused on the critical path and risk management. An Insstructionist project primarily exploits known information and does not need to deal with high levels of uncertainty.

Selectionist Project	There is not enough information to define an optimal policy; the project team is faced with a higher level of uncertainty, and it cannot accurately anticipate the results of its actions.	Rather than exploiting existing knowledge, the team is encouraged to explore; plan multiple trials and prototypes, while executing them simultaneously; and then select the best performing solution. From this point on, the project could be managed as an Insstructionist project.
Learning Project	Susceptible to unforeseen events that might influence its course.	In this environment, there is little benefit in detailed planning of the entire project, because the unforeseen might alter its course and force the team to learn and continuously readjust the plan. While each project needs a clear vision, detailed planning can only be done for the nearest tasks and must be updated with progress.

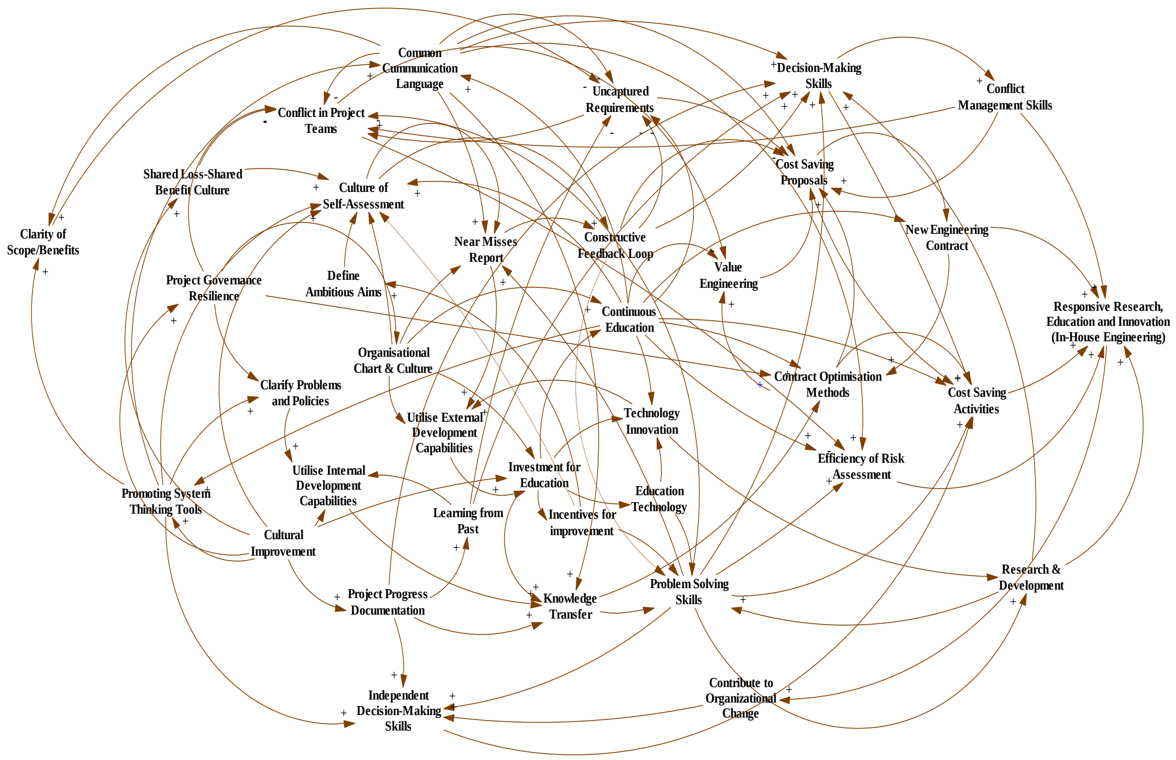


Figure 6-14 CLD produced based on case study analysis to reflect the key requirements for responsive education and development (author)

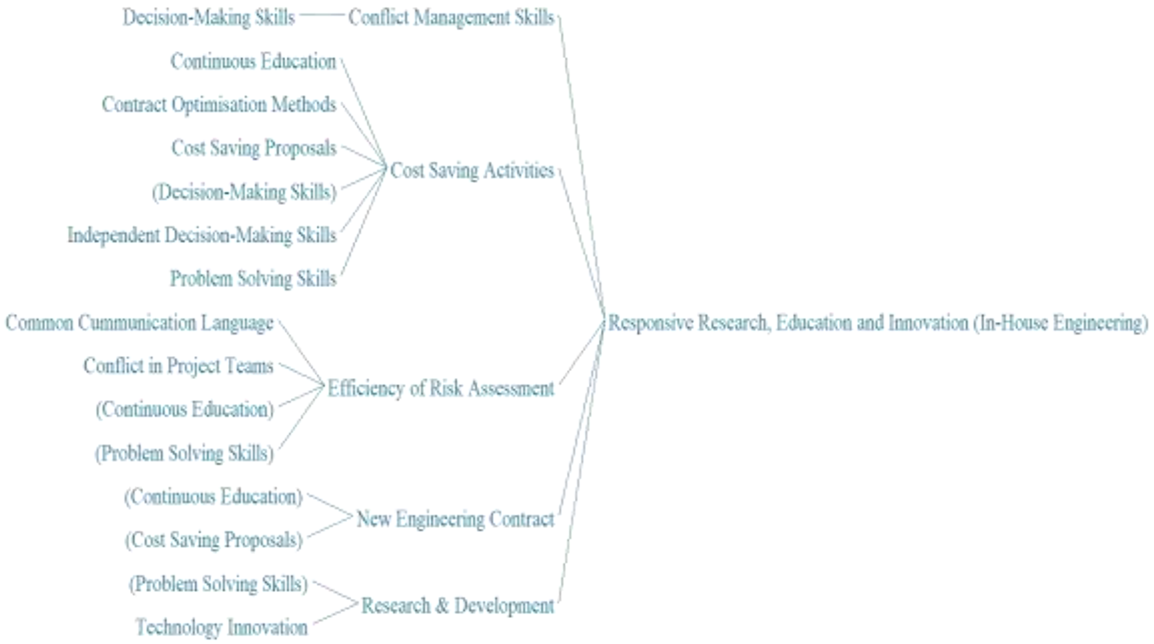


Figure 6-15 Causes tree for responsive education (author)

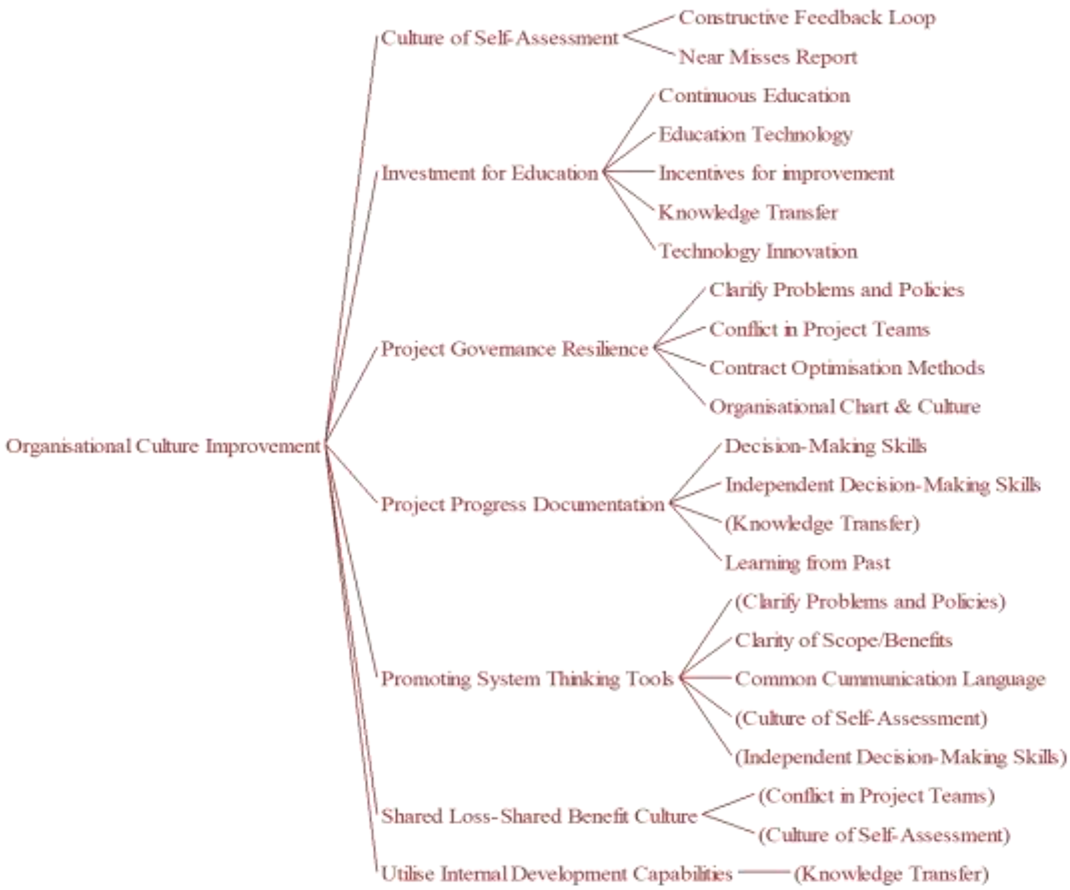


Figure 6-16 Uses tree to show the impact of cultural improvement on the components of responsive education (author)

The identified factors based on analysing the causal feedback of the produced CLD and cross-validation with experts are as follows:

- Decision-making skill was diagnosed as the most important factor. Project staff, even in non-managerial roles, need to be competent to make an independent decision in an emergency or contribute to group decision-making, especially when it comes to disruption or change. The author's observations provided a series of evidence to prove that in most the projects, communication between the construction team (in case of change) and the management team to authorise a solution was a time-consuming process that affected project performance. The author realised that in many cases, the construction team could make independent decisions. The other problem common in all projects was the lack of existing systematic impact analysis tools, even at high managerial levels. The most common tool was system architecture or Excel-based process plans, which provided linear impact analysis and are not capable of managing complex interactions.

- Risk assessment skill was the second most important problem identified. Risks can include project risks and health and safety risks. Most of the projects had reasonable performance and medium-highly skilled staff to manage health and safety risks. Surprisingly, project teams, especially construction teams, suffered from a lack of skills to systematically analyse project risks (affecting cost, time, and benefits). This had a knock-on impact on independent decision-making skills.

- Cost-saving skills and skills to understand the new engineering contracts need to be improved. In-house engineering to enable construction engineers and workers to come up with innovative solutions to reduce the cost needs to be at the centre of attention for future projects.

- Application of systems engineering, and promotion of system thinking is getting attention from managers but, in practice, all projects had an evident shortage of skills. The common language of communication and the lack of an existing systematic documentation process, storage, and analysis; the level of authorisation required to access project documentation and the application of old-fashion IT tools were the other important problems identified.

Shenhar (2001) studied Boeing's project management strategies based on complexity and proposed a graph. The author developed a bespoke diagram inspired by Shenhar, to depict suitable project management strategies for the studied projects, as depicted in Figure . The author's research and qualitative analysis of findings show that in the current tramway development schemes in the UK, the level of novelty adopted by project teams is at a derivative level. The author's qualitative research recommends that tramway construction projects could be considered as first-of-a-kind complex projects because of their three unique characteristics:

I. The project environment (urban area) is super complex. The determinants of complexity are unique for each project. Underground utilities are dispersed based on totally different patterns, which are sometimes even unknown to the utility companies. City councils are complex stakeholders with unique requirements, varying from one city to another. Local communities and their requirements vary.

II. The traffic pattern, street layouts, governance of the projects and the funding schemes vary in each project.

III. The social culture of each city differs, and this will affect the construction process and rework.

The combination of the above-mentioned factors is adequate to classify tramway projects as a unique entity in each city. This means that tramway projects can learn from each other, but solutions and management strategies must be designed to be fit for the purpose of each project. The current projects are being constructed with medium-level technologies, as are similar projects around the world. It is essential to move towards modern construction technologies, which accordingly require bespoke education and upskilling programmes. The level of systems engineering tools adopted in projects is more suitable for medium-complexity projects. However, considering the unique features of tramway projects, they can be classified as highly complex (system of systems).

The pace of tramway projects is fast but needs to be moved towards time-critical, due to its socio-political considerations. The identified gaps for which it would be suitable to propose a more reliable and systematic project management strategy are depicted in green in Figure 6-17.

The author's research will provide a platform and systematic tool to move from the current to the modern proposed framework.

Figure 1-2 shows a schematic V-diagram, which summarises the approach toward developing the author's hypothesis. Chapter 6 provided an insight into the qualitative part of the author's hypothesis (left wing of the V-diagram). The proposed schematic project management structure has already been modelled and analysed qualitatively through causal loop modelling. The causal interactions between five subsystems have been identified through causal feedback analysis. Now, there is a need for focus on the system integration aspect to validate the functionality and assess the resilience of the proposed model as defined in the research objectives.

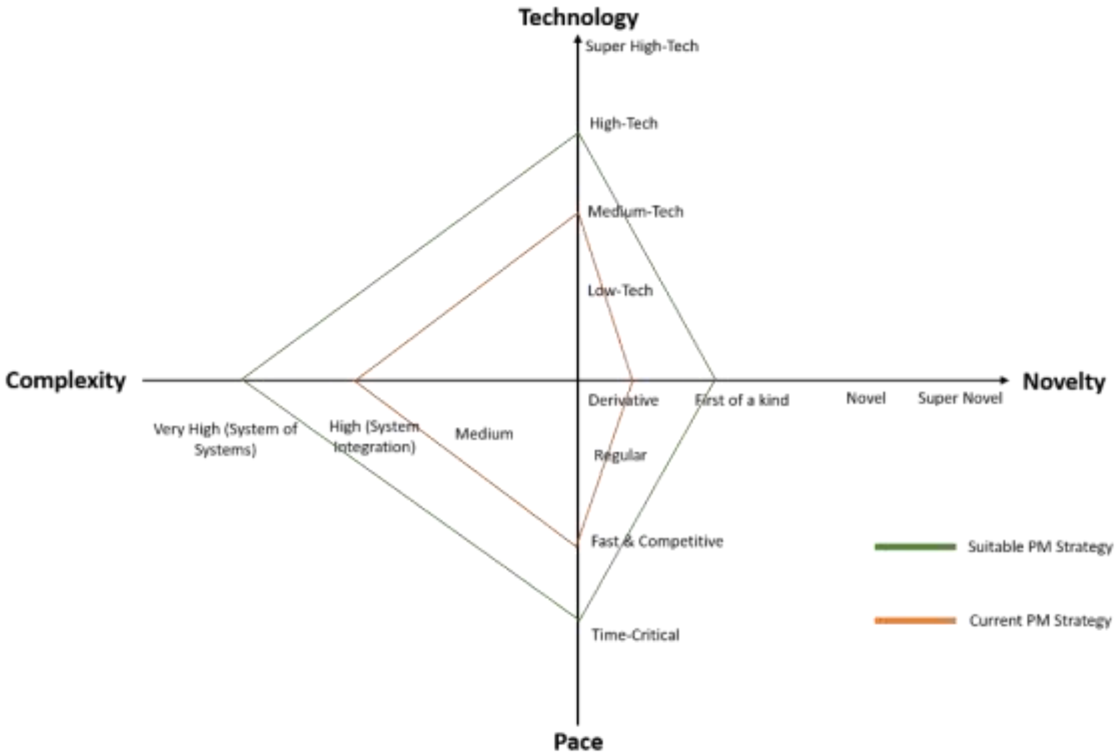


Figure 6-17 Current vs suitable project management strategy for current tramway projects (author, inspired by Shenhar (2001))

Qualitative analysis and CLDs provide the state of a system at the time and cannot analyse the system's behaviour over time. System dynamic and Vensim software let modellers quantify the causal loop diagrams based on stock and flow diagrams, and hence study the system's behaviour over time. Chapter 7 presented the author's proposed approach, findings, and contributions.

Chapter 6 presented the author's methodology to create CLDs in addition to five generated CLDs as part of the qualitative modelling of the proposed project management structure. The author presented a summary of his analysis- extracted from CLDs. This provided a platform to bring out the systematic feedback of the system and understand the structure of each sub-system in more depth. In fact, CLDs reflected the resilience factors of the railway project management, which affect the decision-making process and can improve project management performance and resilience if managed properly and systematically. The findings from this chapter will be used to identify stock and flows and to determine the relationship and formulation between variables to generate stock and flow diagrams.

Chapter 7 presents the author's proposed novel approach to combine qualitative and quantitative analysis of railway project management resilience. The developed CLDs were analysed in Chapter 6 and accordingly, the findings were utilised to generate a stock and flow diagram as a platform to quantify the developed CLDs. The quantified model was analysed, the graphs were extracted and interpreted.

Chapter 7

STOCK AND FLOW DIAGRAMS

(QUANTITATIVE RESEARCH & ANALYSIS)

7.1 Introduction

Chapter 7 utilises findings from Chapter 6 to create a platform to quantify the developed CLDs. Referring to the proposed schematic project management structure, causal loop diagrams were utilised to model the defined subsystems of the structure, whereas a novel Stock and Flow diagram was developed to integrate the five identified subsystems. This will assist in analysing the integration between five subsystems and, accordingly, analyse the behaviour of the project management (as a system) over time and analyse its resilience against disruption or change. In the author's proposed conceptual model, the resilience of project management is a combination of the resilience of each subsystem, as modelled by CLDs.

The project management structure is a qualitative concept, and it is not easy to quantify its resilience. As a novel approach, the author designed an innovative SFD which allows modellers, researchers, and managers to oose a specific failure, change or disruption in the project and analyse the project performance and resilience against that change.

To enhance the accuracy and practicality of the proposed approach, the presented SFD is formulated based on a real disruption observed by the author during the construction phase of one of the studied projects. The name of the project is not mentioned due to active confidentiality agreements that are in place.

7.2 Statement of the Problem

In the first construction phase of one of the studied tramway projects in the UK, it was planned to construct a piece of straight track (with no curvature) in one of the busiest city centre areas, with an initial estimated completion time of 3 months. The estimated time had considered

Bank Holidays and contingency plans to fulfil the requirements of the main local business stakeholders affected by the excavation and delivery of materials.

In the sixth month of the whole project (the end of the first month of that specific phase of the project), an unexpected disruption occurred. During excavation for the alignment of the track, an unidentified buried gas pipe was discovered. Luckily, the pipe was not damaged, but because of the safety-critical situation, the project's progress was put on hold. Further investigation revealed that the communication between the project team and the utility company had been minimal and only based on limited email exchanges.

The utility company claimed that the project team did not inform them about the actual alignment of the track, hence the permission was issued based on a wrong assumption. On the other hand, the project team claimed that the exact location of the gas pipe was not highlighted correctly in the urban maps provided by the utility company. The complaints process took about 45 days.

The author identified the main factors as a lack of an established documentation and communication process and poor requirements management in the design phase of the project. The project team had two options. The first was to redirect the track, which required them to construct an additional curved piece of track, as a torsional point, to avoid removing the pipe.

It took about a month to realise that this option was not feasible, as to meet the technical criteria of curved track and its associated safety clearance, a bookshop located on the corner of a junction would have had to be partially demolished. After 3 weeks, this option was rejected, and negotiations began with the utility company to redirect the pipe. It was a safety-critical process and required community engagement to inform local businesses, as they would experience a gas outage for a few hours. Finally, and after more than 3 months' delay, the pipe redirection was performed.

The project cost for that piece of the track increased significantly due to unexpected delay, penalties, access charges, changes in material rate, etc. The author could not access the exact cost figures due to confidentiality. However, the impact of poor requirements identification, poor documentation, inefficient governance, a slow decision-making process, no established change management approach to reduce the time taken to respond to the change, and an obvious difference between organisational cultures, generated a significant causal impact on the project performance.

7.3 Stock and Flow Diagram Model – Analysis of Project Management Resilience to Respond to Disruptive Events

The key objective of establishing a project management model is to enhance project performance by meeting the estimated budget and time, achieving defined targets, and satisfying stakeholders. According to the definition of resilience, successful project management is a combination of decisions to a) keep the project performance at its desired level and b), in case of disruption, deliver a responsive change management strategy to recover from disaster and bring the performance back to normal.

7.3.1 Proposed Stock and Flow Diagram

As described earlier 'Vensim' software was utilised (as one of the most reliable systems dynamics simulation toolsets) to CLDs and then stock and flow diagrams.

The scope of this thesis and the nature, size and domain of the presented causal loop diagrams is to optimise the resilience of the whole project management strategy as a system. Hence, this is not feasible to convert the whole CLDs into stock and flow diagrams. Additionally, there will be no benefit in converting all five developed CLDs to SFDs. The author applied an innovative approach to making a bespoke model responsive to his research objectives.

In the proposed qualitative schematic model (Figure 1-3), project management resilience originates from its defined subsystems, namely, project governance, requirements management, configuration management, change management and responsive education and innovation. Hence a schematic causal loop can be defined, connecting the five subsystems as depicted in Figure 7-1. This provides a platform for achieving the following objectives:

- The final objective of this thesis was to consider railway project management as a schematic structure, formed of five key subsystems. The model each subsystem using the causal loop diagram to identify the key resilience factors of that subsystem. Then Integrate these five subsystems (system integration) to investigate how they interact and deliver a system-level (project management) functionality. This can provide a systematic impact analysis tool, which assists managers to analyse the efficacy of the adopted project management strategies for each project.
- Extract the key variables affecting the resilience of each key subsystem of the project management structure in Figure 4-1.

7.3.1.1 A Brief Methodology to Develop Stock and Flow Diagrams

In this section, the author provides a brief step-by-step process to show how the presented SFD was developed. The full details cannot be presented as a narrative, as software menus are utilised but, the following description gives an overview of the approach. Please refer to the diagrams provided in **Appendix VII.**

i. Define Stock and Flows:

"Stock and flow (or Level and Rate) diagrams are the way of representing the structure of a system with more detailed information than is shown in a causal loop diagram. Stocks (Levels) are fundamental to generating behaviour in a system; flows (Rates) cause stocks to change. Stock and flow diagrams are the most common first step in building a simulation model because they help define types of variables that are important in causing the behaviour" (Vensim Manual).

ii. Define Levels & Rates

Levels are also known as stocks, accumulations, or state variables. Levels change their values by accumulating or integrating rates. This means that the values of levels change continuously over time, even when the rates are changing discontinuously. Rates, also known as flows, change the value of levels. The value of a rate is not dependent on previous values of that rate; instead, the levels in a system, along with exogenous influences, determine the values of rates. Intermediate concepts or calculations are known as auxiliaries and, like rates, can change immediately in response to changes in levels of exogenous influences.

When constructing a Level and Rate diagram, consider what variables accumulate over some time. Another way to think about this: if Time slowed down to zero for your system, what variables would still be nonzero? For example, in the system where you pour water into a glass, the water contained in the glass is the Level. If you froze time, the pouring (a Rate) would stop, but you would still see a quantity of water in the glass (a Level). Once you know what levels you need, enter the first and then connect the rates and auxiliaries. Model building tends to be iterative. (Vensim Manual).

The agent of all these factors affecting project performance is 'decision-making'. Hence, the designed SFD considers the proportion of impacts project management component has on decision-making efficiency and similarly embeds the causal interaction between the subsystems. Decision-making efficiency affects project performance as an input, whilst the impact of unexpected changes triggered by the utility problem is considered an outcome flow, reducing the performance.

From the toolbar and via the Rate tab, we can generate rate arrows. The Rate has a single arrowhead, indicating the direction the material can flow (the Rate can only increase the Level). This is only a diagram; in a simulation model, the equation governs the direction that material can flow. However, we can use the diagram to indicate whether the flow is intended to be one-way or two-way (Vensim Manual). We can choose one-way or two-way flow arrows, depending on the nature of our stock and flow. In Figure 7-1, the author has defined two one-way arrows, one; decision-making efficiency (as input flow feeding project performance) and the second; the impact of unplanned changes (as output flow draining performance tank).

Using the 'Variable' tool, a curved arrow will join the Level and the Rate valve. Vensim allows you to connect arrows to either the Rate name or the Rate valve. The Rate name and valve are structurally the same (Vensim Manual). Vensim can include different types of variables based on their content. The figure provided in Appendix VI provides more details about different types of variables.

iii. Define the Time Limit and Units of the Model Variables

After creating the basic CLD for five subsystems of the project management structure and defining stock and flows (inflows and outflows), we can start quantifying the model. To begin, we need to choose the time limit of the simulation based on the context. For this simulation, the duration of 5 years was chosen to analyse the behaviour of the system over five years. The cloud icon in the model represents the boundary of the model. This defines the area, for which its flow is considered.

iv. Define Equations (Consider Appropriate units & consistency)

The variables defined in the model developed in Figure 7-1 are five key subsystems and the project performance as the key stock variable. The scope of this thesis was to create a systematic tool to Assist managers in informed decision-making and analysing the resilience of the project systems. Hence, the author had to formulate the model based on an exemplary model (derived from multiple case study analyses) to narrow down the realm of the formulation. Variables in Vensim are classified as either exogenous or endogenous. The former being are those variables, which are not part of the feedback loop, while the latter are part of the created feedback loop. Equations are then written using the Equations tab in Vensim PLE. Proper modelling requires that its equations be written with unified units. Otherwise, the simulation process will fail. Dimensional consistency is important as a formal check of the correct model structure (Vensim Manual). Units allow us to check for dimensional consistency among all the equations. The process of formulating the presented SFD design is based on the facts and figures of the exemplar disruption, but the model can be generalised for similar changes. The proposed SFD provides a holistic-systematic platform to quantitatively analyse the impact of project management on project performance over time and affected by the disruption.

v. Review model, Check Units & Run Simulation

The modelling process starts with sketching a model, then writing equations and specifying numerical quantities. Next, the model is simulated with simulation output automatically saved as a dataset. Finally, the simulation data can be examined with Analysis tools to discover the dynamic behaviour of variables in the model (Vensim Manual).

Normal model construction follows a pattern of creating, examining, recreating, and iterating until your model meets your requirements. Debugging (making a model simulate properly) and model analysis (investigating output behaviour) both play a part in refining the model.

After finalising the equation writing, we need to check the validity of the model and units. Reality Check is another technology to aid in the construction and refinement of models. At this stage, we can run the simulation. The simulation's output can be autogenerated diagrams and graphs as presented in Figure 7-2.

This section presents the SFD developed for the exemplar disruption, followed by the author's interpretation of graphs and their applicability. Figure 7-1 presents the author's proposed innovative SFD and the novel user interface as a toolbox that facilitates the application of SD tools to assess the impact of a specific disruption on project performance and evaluate project management resilience. The SFD requires a set of initial inputs derived from qualitative analysis of the generated CLDs. According to the analysis of CLDs, as depicted in Figure 7-2, a control panel is provided on top, allowing the modeller to change the model's specification as presented in Table 7-1.

Once the SFD's structure, components, interaction, inputs, and outputs were designed, it was formulated. Referring to the author's analysis of the exemplar disruption and its origins concluded from CLDs, the results were discussed with experts in systems engineering and project management. That helped the author to come up with a holistic understanding of the interactions and formulise the model as a reference model, which can be generalised and modified for any other similar change or disruption.

The initial state of the project management subsystems was rated using scores (functionality of each subsystem at the time of disruption) and weights (the proportion of the impact of each subsystem on the generated disruption). The model simulation was performed, and the requested graphs were extracted as presented in Figure 7-2. The following section summarises the graphs' interpretation and explains their applicability to future research and practical management practices.

TABLE 7-1 CONTROL PANEL OPTIONS AND THEIR USABILITY (AUTHOR)

Control Panel Option (%)	**Functionality**
Subsystem Impact Weight	The impact weight indicates the proportion of the impact of each subsystem on disruption or change. The initial value should originate from CLD analysis and a project documentation review and includes a judgement about the impact of each factor. The control panel provides the flexibility to trade-off between different impact weights and quantitatively analyse their impact on project performance.
Subsystem Score	The initial score of each subsystem is derived from CLD analysis and a review of the functionality of the existing project management components by the modeller and project experts' opinion. The score will allow the modeller to rate the current ability of each subsystem's functionality to respond to the disruption. The second set of scores will be based on the project management team's decisions on how to prioritise investments in each subsystem to improve the project management performance.
Subsystem Enhancement	This variable comes into play when it comes to improving project management resilience. This option will let the modeller decide how the enhancement of each subsystem would affect the whole project's performance.

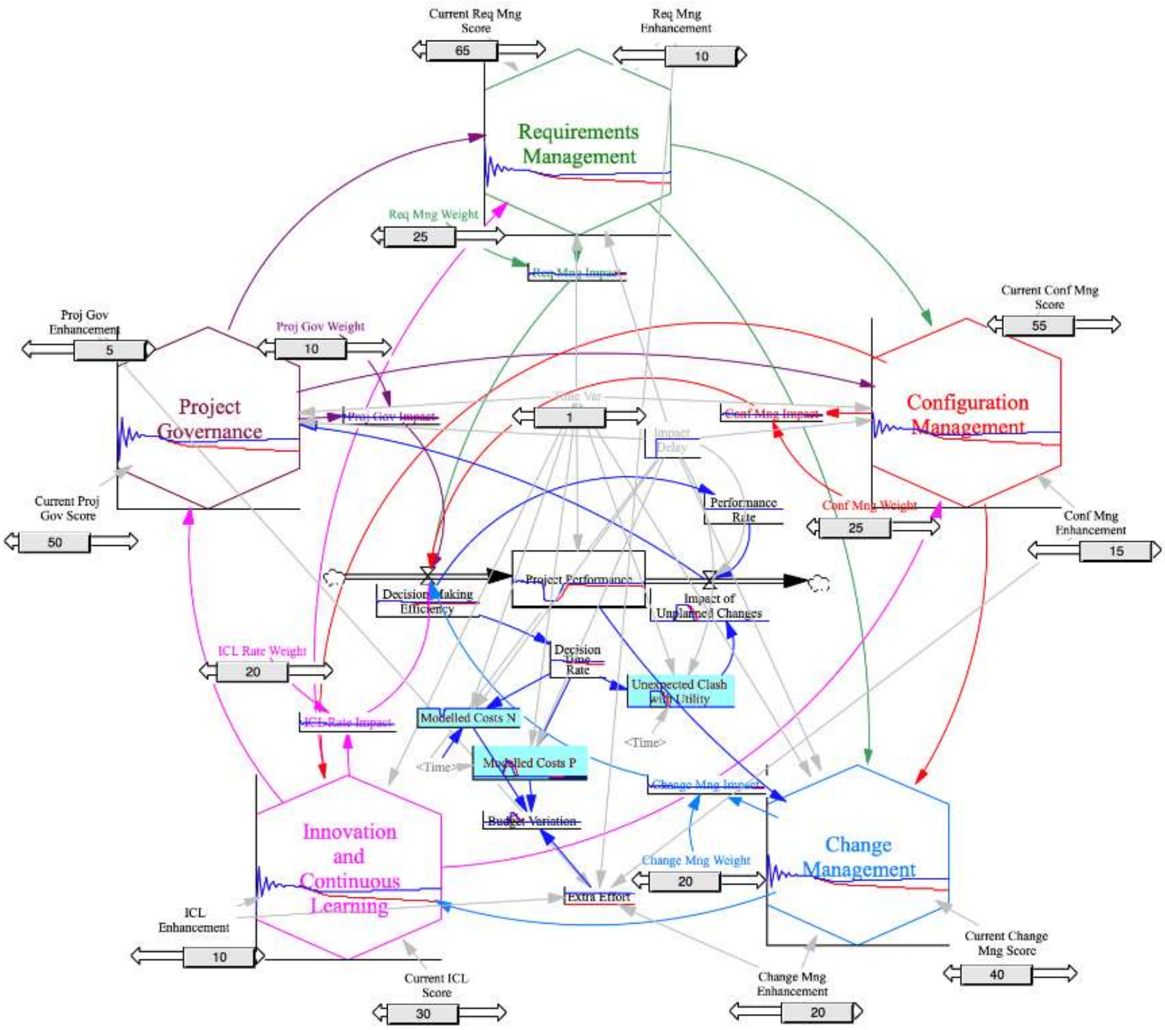


Figure 7-1 Formulated SFD model, designed to analyse the project management resilience against disruption (author)

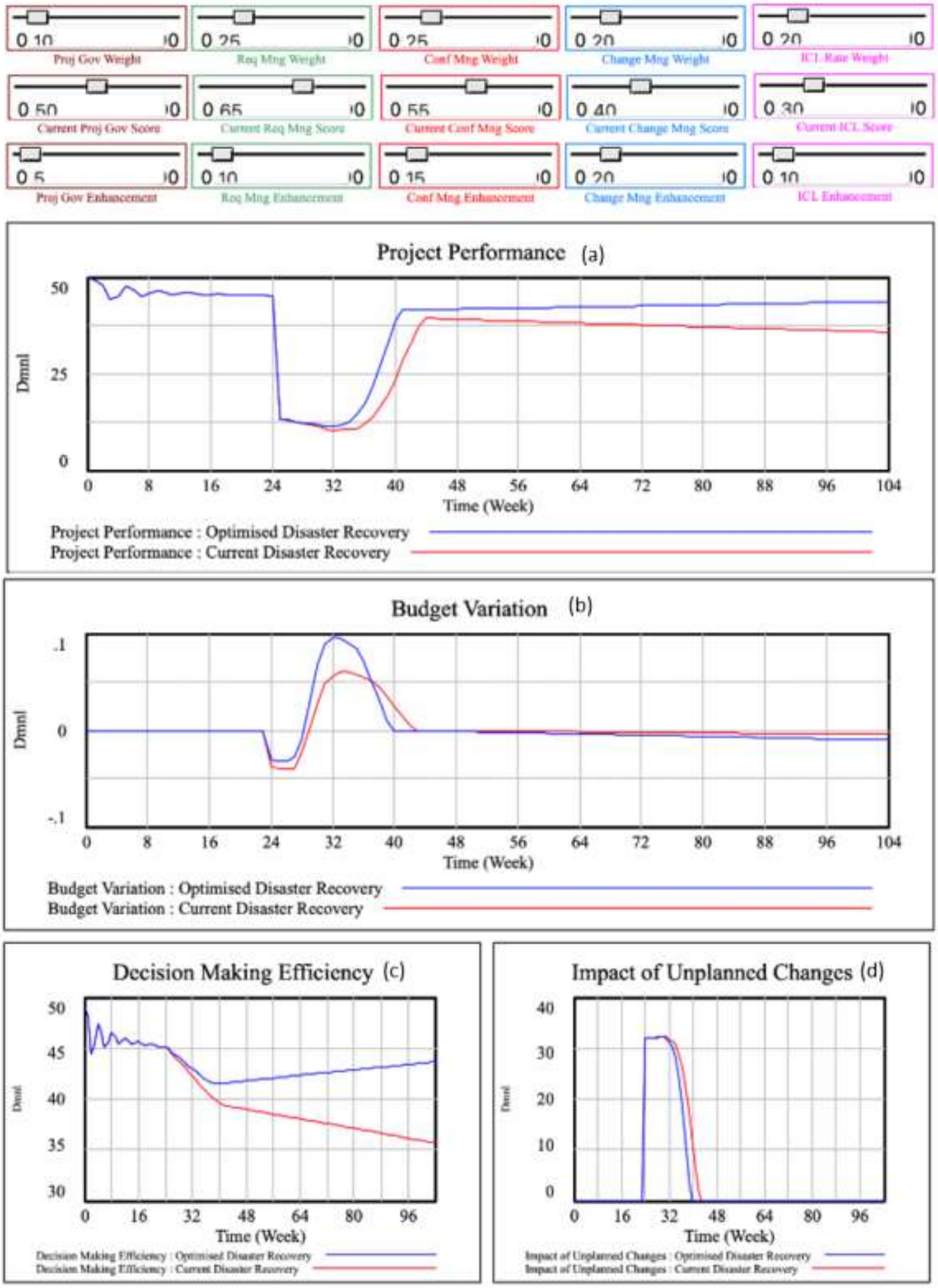


Figure 7-2 Formulated SFD designed to analyse project management resilience against disruption (author)

7.3.2 Results Analysis and Stock and Flow Diagram Applicability – Quantitative Analysis

As mentioned in the problem statement, one of the studied tramway construction projects faced an unexpected change (disruption) which negatively affected its performance, causing delays, cost overruns and led to stakeholder dissatisfaction. The disruption occurred six months (24 weeks) after the commencement of the whole project. The SFD is designed to achieve quantitative causal feedback for the system, including complex interdependencies' impact when the project faces a disruption.

Referring to the SFD, the project performance is fed by the quality of decision-making, and the impact of unexpected changes will reduce its value. The impact of each subsystem on the decision-making process, their causal interactions and consequently, the impact of the whole project management (as a system) on the project performance were extracted as a set of graphs. Graphs can be generated for each variable in the SFD structure. The SFD system behaviour against the exemplar disruption highlights the project performance affected by the disruption, which can be translated as the resilience of the project management to respond to unexpected disruption.

7.3.2.1 Project Performance Diagram

The resulting graph (Figure 7-2 a) illustrates and compares the project performance profiles for the states of disruption (in Red) and optimisation (in Blue). Studying the Blue diagram delivers important conclusions. The performance of the project for this specific case is captured as oscillating between 44% and 50%. This originated from the initial rating of the system (subsystem scores and weights) according to qualitative analysis of CLDs and observed facts. Nevertheless, initial scores and weights might be underrated, and the spotted fluctuation is still considerable, considering the size and complexity of the project.

This confirms the findings from the literature review that conventional project management approaches are based on linear tools and are not compatible with understanding the complex behaviour of projects due to interdependencies, unknowns, and causal effects. The oversimplification of the project complexity in the design and management of such complex projects usually considers project performance as linear and at its desired level under normal circumstances. The graph contradicts the conventional viewpoint and highlights the importance of applying tools like SFDs to assist in better understanding project behaviour in a complex environment.

Disruption appeared in week 24 of the project, and a significant drop in project performance was recorded as expected. As mentioned earlier, when a project faces a change or disruption, the time required to detect the disruption, decide how to mitigate its impact, and implement the solutions will shape the change latency, and a long time means more unexpected delays, cost overruns and benefit shortfalls (snowball impact).

For this exemplar disruption, it took 1.5 months for the project team to digest the causes and effects of the disruption, a month to decide, trade-off between options and choose the best option, and around a month to implement the alternative solution. Hence the project experienced more than 3 months of change latency. Referring to the red diagram, the project performance suddenly dropped, with a steep slope in week 24, and dropped from 45% to 14% in week 25. That shows the impact of change detection latency on project performance.

The slope of change reduced but constantly went down from 14% to 10% in week 32. This is where the decision-making was taking place (negotiating with the utility company and studying the options for redirecting the track alignment). The performance kept going down between weeks 32 and 36. This shows the impact of the implementation period on project performance.

The final choice was to redirect the gas pipe and continue the planned route for the track, but due to the level of complexity and poor project management resilience, it was a time-consuming process, causing a profound drop in project performance, from 45% to around 8%. From week 36, the performance began to show a rise with a moderate slope (compared to the performance drop rate), improving from 8% to 40% in week 44.

The graph highlights some interesting facts. Before the disruption, project performance fluctuated from 50% towards 45% at the point of disruption. This explains the situation and reveals that the natural tendency of the system had been moving towards a reduction in performance. This is rooted in the low resilience of the project management and the causal effects of the gaps and underestimated complexity in subsystems of the project management, as already identified via qualitative analysis of CLDs.

Analysing the system behaviour shows that gaps within the project management subsystems have had a knock-on effect on the emerged disruption, detection latency, decision latency and implementation latency. After passing the change latency period and implementing the contingency plans, despite the positive impact, the previous level of project performance (45%) could not be achieved, with only 40% (its highest level) being achieved in week 44.

This issue is due to the causal interactions between project management subsystems and the role of unknowns on project performance. It is an obvious message that when complex projects face a change or disruption, poor project management (low resilience) and the lack of a holistic overview of the project's whole lifecycle led to a dramatic loss in project performance, which is too much to recover. the

The Blue graph was generated after modifying the SFD characteristics by changing scores and adding the rate of enhancement for each subsystem. The weight of the subsystems (the proportion of impact) was assumed to be the same. Hence, the modeller could decide that each subsystem had higher performance (resilience), leading to a higher score, and determine the impact on project performance if a decision was made to invest in each system, for example, requirements management (by the enhancement rate).

Comparison of the Blue and Red graphs show a significant improvement in the project performance and change latency. In a nutshell, the blue graph is squeezed and lifted compared to the Red one. This represents the positive causal response of the system to the proposed improvements. The initial performance (before disruption) would be the same as the score for the system staying intact. Analysing the improvements of changes in the system's ability to manage disruption shows that the performance has dropped with a reasonable smoother slope (minimum performance of 14% compared to 8% before PM improvement).

Additionally, the recovery process happens more quickly, i.e., with a steeper slope, returning to almost the same point (before disruption) of about 43%. The increase in project performance after disruption shows an incremental trend. For instance, before improving project management, in week 104, which is almost at the end of the project, the performance was recorded as 37%, with a decremental slope. On the other hand, the impact of improvements depicted in the blue graph shows that, after disruption, project performance increased by an incremental slope, reaching about 55% approaching the end of the project.

This shows that the process of improving the project management subsystems (to increase the resilience of the whole project management) not only increases the project's ability to deal with disruption and reduce the impact of changes but also reduces the snowball impact of an unexpected change throughout the rest of the project's lifecycle. The graphs show that the time required for change detection, decision and implementation latency will be less once project management resilience improves. This can be interpreted as the enhancement of project management resilience using the SFD model and increasing the speed of response to disruption and mitigating unexpected changes.

The trade-off between different scores, weights and enhancement rates for each subsystem will provide a reliable systematic impact analysis tool and would help to make responsive decisions about how to improve project management resilience and achieve the desired project performance.

7.3.2.2 Decision-Making Efficiency

Comparative analysis of the decision-making and project performance graphs (Figure 7-2 c) shows that the efficiency of decision-making directly affects project performance. Similar waves of oscillation are observed from the beginning of the project, which shows the weak ability of the subsystems to keep the quality of the decisions at their desired level.

In week 24 and slightly before the disruption, the decision-making quality, according to the nature of the system and its interactions, is shown as 45%. From week 24 onwards until week 36 (the change detection, decision, and implementation latency), the efficiency dropped with a steep slope and reaches35% in week 36. The decremental trend continues, with a slightly smoother slope after week 36, where implementation of solutions was taking place.

Unfortunately, the efficiency of decisions affected by the impacts of the disruption continued and existed until the end of the project, due to the cumulative cause-effect impacts, affecting the whole project lifecycle. The final rate, based on the graph and quantitative analysis of the SFD, was about 28%. The low decision-making efficiency and poor project performance extracted from the quantitative analysis match the delay and cost overrun of the project.

The whole project for this specific phase experienced a cost overrun of £33m. The Blue graph, produced by analysis after the application of the project management alteration factors, shows a significant improvement in decision-making efficiency. At the point of disruption in week 24, the efficiency dropped with a smoother slope. Then it considerably reduced the change latency and facilitated the implementation of solutions in a shorter period, which meant a quicker recovery.

The simulation shows promising results, meaning that improving the project management subsystems not only improves the process of managing disruption but also positively affects decision-making efficiency, with an increasing slope, for the rest of the project lifecycle. In contrast, in the red graph, the analysis shows that decision-making efficiency would keep dropping with a steep slope for the rest of the project. This shows the domino impact of unexpected changes on decision-making efficiency and suggests that systematic enhancement of project management subsystems and ignoring the snowball impact of disruptions would profoundly affect the whole project lifecycle.

The difference between the area covered underneath the two graphs shows the potential improvement in decision-making efficiency through the systematic and responsive improvement of project management components that affect decision-making efficiency and project management resilience.

7.3.2.3 Unexpected Impact of Change Diagram

This diagram (Figure 7-2 d) is extracted from the SFD simulation and represents the rate of unexpected changes imposed by the disruption. As mentioned earlier, the unexpected impact of change is an output flow in the SFD model and, from an SD point of view, all the project management subsystems interact and perform to respond to other disruptions which emerged, through their impact on decision-making, reducing the time required and finally by reducing the unexpected impact of change on the project lifecycle. Analysis of the project performance and decision-making efficiency diagrams explains that the disruption has a negative impact not only on the change latency period but also on the whole lifecycle.

The diagram extracted for the unexpected impact of change confirms those findings. It rises sharply in the red diagram. After modifying the project management subsystems, the slope of impact reduces. Additionally, the blue diagram is squeezed, which means a reduction in the time for which the project suffers from unexpected changes. Reducing this period will lead to less budget variation and will affect project management resilience.

7.3.2.4 Budget Variation Diagram

The budget variation diagram (Figure 7-2 b) illustrates the analysis of the impact of disruption on the rate of budget variation. The SFD is designed to be capable of considering positive and negative budget variations. A small proportion of the budget was reduced when the project was paused, mostly those costs depending on project progress and accordingly not spent when there was no progress going on. However, most of the budget variation is the budget imposed by unexpected changes and increased change latency.

A comparison of the blue graph (simulation after improving subsystems) and the Red one (analysis of the budget variation for the initial state) shows that for the initial state of the project, the budget variation was smaller but happened over a longer period, compared with the blue graph extracted from analysing the budget after project management modification.

The analysis shows that modification of the project management subsystems would reduce the impact time of disruption (change latency), but then a greater variation in the budget would be inevitable. It means that, for this exemplar disruption, to reduce the change latency and save the whole lifecycle performance, a more considerable larger amount of budget needs to be spent in a short time, which is equal to a greater budget variation.

The previous graphs and analysis identified that investment in improving project management through improving its subsystems would positively affect project performance and the efficiency of decision-making. Hence, the reduced response time and shorter change latency could be interpreted as project management resilience. Analysing the graphs for budget variation shows that reducing change latency will improve the whole lifecycle budget variation; meaning a bigger portion of budget will be spent in a shorter period than was initially planned.

In the case of this example, accepting the more significant budget variation and achieving the minimum change latency was undoubtedly preferred. Because the project was time-critical and it was clashing with a safety-critical utility, any hour of delay could profoundly affect the welfare and safety of the society and lifecycle of the project. But in general, and in other projects, this would be an option to trade off. The provided SFD-based tool can be used by modellers to analyse the impact of changing different factors and decide which subsystem of the project management is worth more investment, to achieve the organisational and project targets.

Hence, the project team can decide on the optimal solution for spending its budget to manage disruptions. As an example, for this specific example, the project management team decided to allocate a lump sum to recruiting a change manager based on a fixed contract and similarly invest in its systems engineering team to increase the efficiency of documentation and requirements management resilience.

Summarising the findings and analysis, the author came up with an idea to define a novel two-dimensional model for project management resilience. The graph mentioned earlier as ‘project performance’ can now be labelled as ‘project progress performance’. Accordingly, project management resilience can be defined as a function of two main variables:

- Project progress performance, and

- Budget variations.

The concept of change latency and the impact of time and decision-making are balanced in these two concepts; hence the two-dimensional model delivers a holistic understanding of project management resilience. This model provides a benchmark for modellers and lets them trade-off between the different choices to achieve the optimal project management resilience aligned with the project's organisational priorities and policies.

7.3.3 Proposed Multi-Dimensional Model and Conceptual Formulas to Achieve Optimum Project Management Resilience

As mentioned earlier, analysing the dynamic behaviour of project management affected by disruption and linking this to resilience, it was identified that project management resilience could not be solely linked to the time taken to respond to disruption and the project performance. The reason was the findings from the budget variation diagram, which showed a different pattern. It means that achieving better project management resilience and reducing change latency usually imposes a higher rate of budget variation, as the project management team needs to perform a new set of tasks (contingency plans) in a short period, and this will increase the rate of budget expenditure.

Thus, to deliver a holistic picture of project management resilience and apply the lessons learned from SFD analysis, the author came up with a two-dimensional model to describe project management performance. Project performance would be a vector sum of two main variables, a) project progress performance, which is labelled as project performance in the graphs, and b) cost resilience. The conceptual process, associated graphs and proposed formulas are presented below.

The proposed two-dimensional resilience model for project management is a novel achievement, constructed from systematic analysis (qualitative and quantitative) of CLD and SFD models, which expands innovative research avenues for future researchers and additionally provides a comprehensive framework to assist railway project managers and decision-makers in identifying the right benchmarks for their decisions. This means that, when a project is facing disruption, managers have to trade-off between reducing the change latency and the impact of unexpected changes, by enhancing project progress resilience and allowing the maximum budget variation (cost resilience). This would profoundly affect the efficiency of the whole lifecycle of a project, considering the snowball and causal effects.

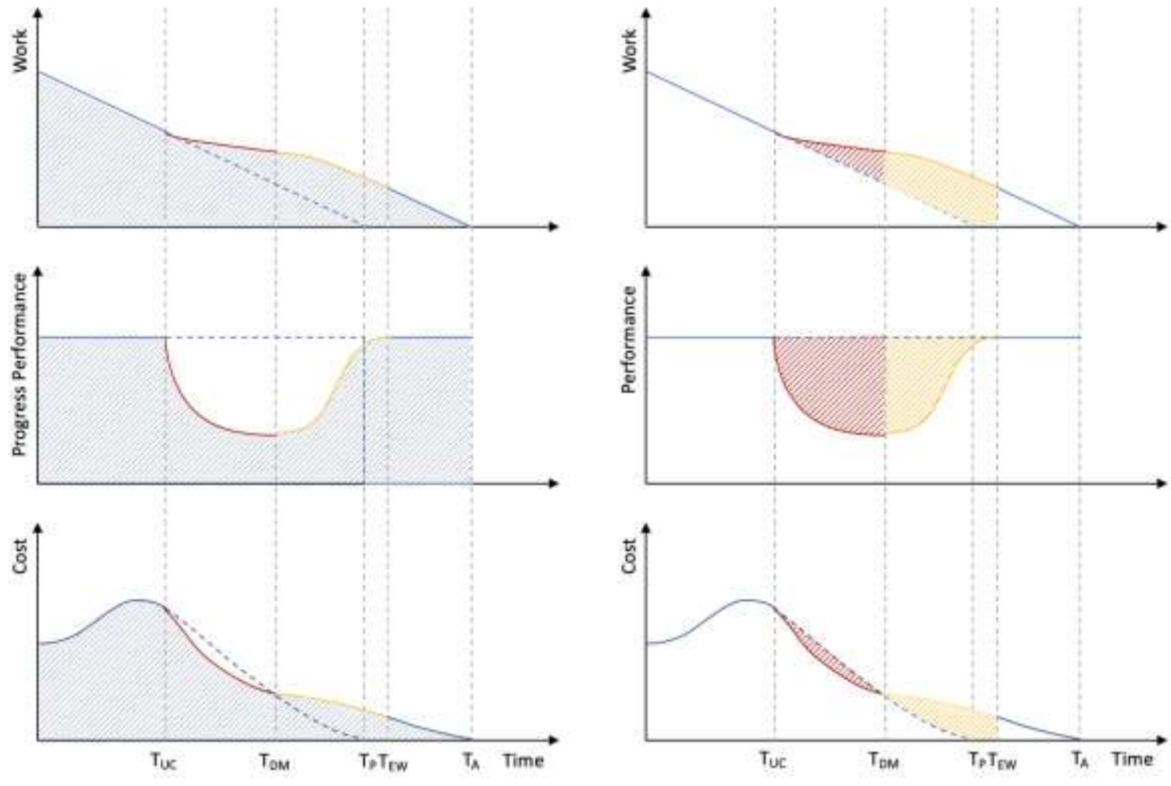


Figure 7-3 Schematic illustration of the impact of disruption on project work, progress performance and cost (author)

Where:

T_{UC}: time at which the unplanned change (UC) happens

T_{DM}: decision-making (DM) time

T_P: project's planned finish time

T_{EW}: time at which the extra work (EW) is done

T_A: project's actual finish time

And the disaster recovery phases are:

1. Determination phase
2. Decision phase
   2.1. Problem-solving phase
   2.2. Impact analysis
      - rework prevention
3. Deployment phase

(Eq. 1)

$$\Delta T\text{: Delay}_{\text{Total}} = \text{Delay}_{\text{Determination}} + \text{Delay}_{\text{Decision}} + \text{Delay}_{\text{Deployment}}$$

and

$$\text{Delay}_{\text{Decision}} = \sqrt{\alpha \times \text{Delay}_{\text{Problem Solving}}{}^2 + \beta \times \text{Delay}_{\text{Impact Analysis}}{}^2}$$

Where:

α & β: delay coefficients

(Eq. 2)

$$R \nearrow \propto \begin{cases} Minimise(Extra\ Delay) \\ Minimise(Extra\ Cost) \end{cases}$$

(Eq. 3)

$$W = \int_t P_P(t) \times dt$$

Where:

W: work done

P_P: progress performance

and:

(Eq. 4)

$$\Delta W = \int_{t=0}^{T_A} [P'_P(t) - P_P(t)] \times dt$$
$$= \int_{t=0}^{T_A} P'_P(t) \times dt - \int_{t=0}^{T_P} P_P(t) \times dt$$

Where:

ΔW: extra work

P'_P: progress performance in the presence of the unplanned change

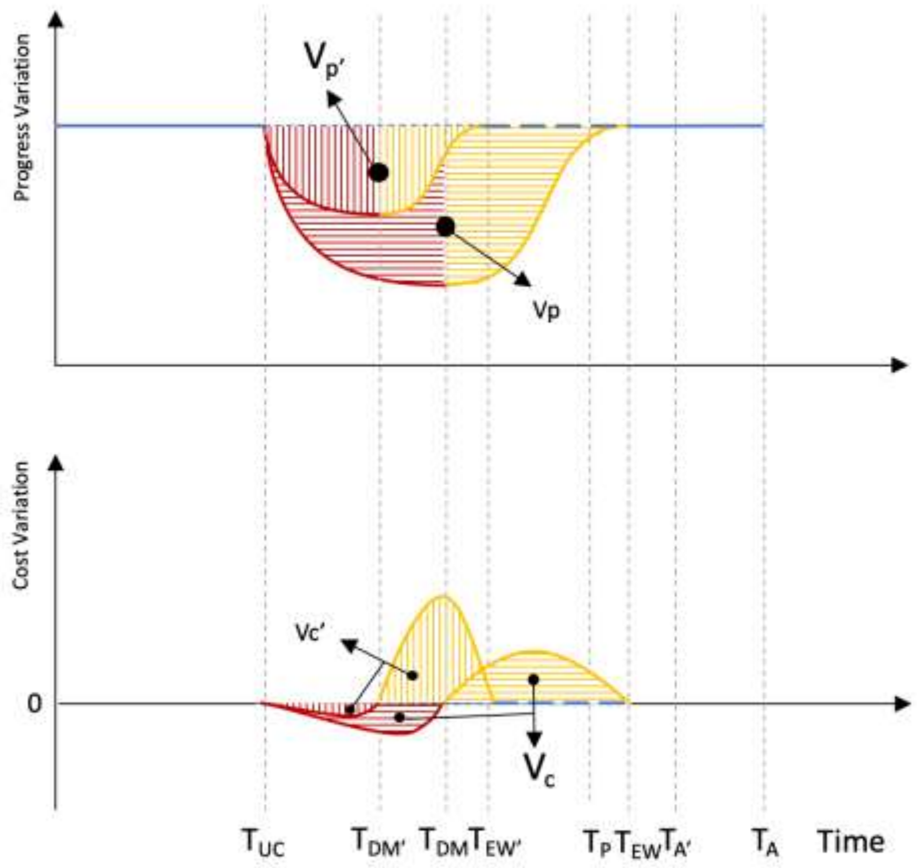


Figure 7-4 Conceptual view of progress performance and cost variations, affected by disruption (author)

$T_{DM'}$: optimised decision-making (DM) time

$T_{EW'}$: optimised time at which the extra work (EW) is done

(Eq. 5)

$$R_P = \frac{W}{\Delta W}$$

$\mathrm{R_P}$: progress resilience

(Eq. 6)

$$\mathrm{R}_{\mathrm{P}_{Optimised}} = \mathrm{R}_{PO} = \lim_{\Delta W \to \Delta W_{min}} \left(\frac{W}{\Delta W} \right)$$

$$\mathrm{R}_{PO} = \lim_{T_A \to T_P} \left(\frac{\int_{t=0}^{T_P} P_P(t) \times dt}{\int_{t=0}^{T_A} [P_P'(t) - P_P(t)] \times dt} \right)$$

$$\mathrm{R}_{PO} = \lim_{T_{EW} \to T_{UC}} \left(\frac{\int_{t=T_{UC}}^{T_P} P_P(t) \times dt}{\int_{t=T_{UC}}^{T_A} [P_P'(t) - P_P(t)] \times dt} \right)$$

Similarly, for the project cost:

(Eq. 7)

$$C = \int_t P_C(t) \times dt$$

Where:

C: total project cost

P_C: cost performance

And:

(Eq. 8)

$$\Delta C = \int_{t=0}^{T_A} [P_C'(t) - P_C(t)] \times dt$$

Where:

ΔC: extra cost or cost overrun

P_C': cost performance in the presence of the unplanned change

(Eq. 9)

$$\mathrm{R_C} = \frac{C}{\Delta C}$$

$\mathrm{R_C}$: cost resilience

(Eq. 10)

$$\mathrm{R}_{\mathrm{C}_{Optimised}} = \mathrm{R}_{CO} = \lim_{T_{EW} \to T_{UC}} \left(\frac{\int_{t=T_{UC}}^{T_P} P_C(t) \times dt}{\int_{t=T_{UC}}^{T_A} [P_C'(t) - P_C(t)] \times dt} \right)$$

(Eq. 11)

$$\mathrm{R_{PM}} = \sqrt{\mathrm{R_P}^2 + \mathrm{R_C}^2}$$

$\mathrm{R_{PM}}$: Project management resilience

(Eq. 12)

$$\mathrm{R_P}_{min} \leq \mathrm{R_P} \leq \mathrm{R_P}_{max}$$

$$\mathrm{R_P}_{max} = \lim_{t \to T_{EW_{min}}} (\mathrm{R_P}(t)) \quad \& \quad \mathrm{R_P}_{min} = \lim_{t \to T_{EW_{max}}} (\mathrm{R_P}(t))$$

$T_{EW_{min}}$ = minimum required time for disaster recovery

= time at which minimum work is required for disaster recovery

$T_{EW_{max}}$ = maximum acceptable time for disaster recovery

= time at which maximum work is doable for disaster recovery

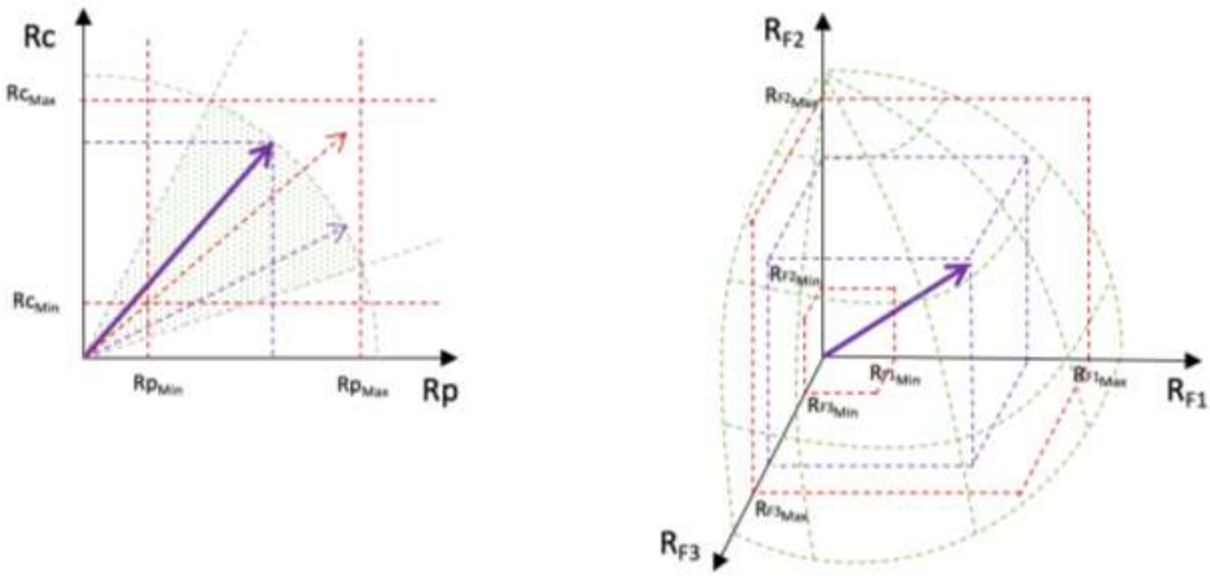


Figure 7-5 multi-dimensional project management resilience (author)

(Eq. 13)

$$\mathrm{R_{PM}} = \sqrt[N]{\sum_{i=1}^{N} (\propto_i . R_{F_i})^2}$$

Where:

$\mathrm{R_{PM}}$: project management resilience

N: number of resilience factors

F_i: factor i

R_{F_i}: resilience of factor i

$\propto_i$: factor i's coefficient

The proposed model and formula suggest that resilience in project management could yet be a function of other factors, which can be investigated in future research and increase the accuracy of the project management resilience.

Most of the graphs and formulas are self-explanatory, but the next few paragraphs explain the logic and details of some of the above-mentioned formulas. The diagrams on the left side of Figure 7-3 are a schematic view of the work supposed to be performed at a specific time. In the case of disruption or change, as analysed in the SFD model, there would be an unexpected delay (change latency).

Referring to Eq. 1, the author has proposed a modified definition of change latency and has defined decision latency as a function of problem-solving and impact analysis. The reason is that ; decision-making should be followed by impact analysis to systematically manage disruption. Hence the delay caused by decision latency can be calculated via the vector sum presented in Eq. 1. As concluded from the SFD graphs, project management resilience will be a function of project progress variation and cost variation, as schematically illustrated in Figure

7-3. Referring to the diagrams and annotations in Figure 7-3, mathematically, the extra work imposed by disruption can be determined through Eq. 4.

The diagrams in Figure 7-4 are the conceptual depiction of project performance and cost variations. The resilience of project progress is defined as the ratio of the actual work to the extra work imposed by change, as shown in Eq. 5. Eq. 6 explains the proposed formula to calculate optimised progress resilience. Optimised progress resilience is achievable by moving from extra work to the minimum extra work dictated by disruption. That explains the mathematical logic of Eq. 6.

Similarly, the project cost variation forced by disruption can be derived from Eqs. 7 and 8. Cost resilience can be defined as the ratio of the actual cost to the cost variation. Optimised cost resilience requires applying a ‘left-shift to the diagram in Figure 7-4 and reducing the time required to undertake extra work (inspired by Elliott 2014). Therefore Eq. 10 defines optimised cost resilience with a limit of a function, as it tends to push back the timing diagram to the left. Based on the vector sum, project management resilience can be calculated from Eq. 11.

It was also concluded from analysing the graphs from the SFD analysis that, mathematically and practically, the project management resilience value can never approach zero or infinity. Each project management model must respond to a disruption, which might not be fully efficient, but still gives resilience a value of greater than zero. Infinite resilience means that, in the case of disruption, the project management response will minimise the change latency and time variation imposed by change and make it zero. This would not be achievable in an actual project.

As shown in Eq. 12 and as it is, the project management resilience value will be limited between a minimum and a maximum value. These values would be determined by various factors such as project priorities in the case of disruption, organisational values, political restrictions, available contingency findings, type of governance (alliance governance will share benefit and loss) etc. Apart from organisational factors, the complex nature of projects, technical capabilities, official bureaucracies (like the exemplar disruption and negotiating with utility company) and many other factors dictate a minimum time ($T_{EW_{min}}$) required to rectify the affected progress and apply remedial solutions.

On the other hand, based on the scope and defined deadlines and agreements with project owners, each project has a defined maximum timeline, which would affect the maximum acceptable time for disaster recovery ($T_{EW_{max}}$). These concepts are utilised to formulise the maximum and minimum values for project management resilience, as shown in Eq. 12 using a limit of a function.

Figure 7-5 presents the author's proposed multi-dimensional model to capture the optimum project management resilience, utilising the developed SFD and associated analysis tool. The diagram on the left illustrates the two dimensions of project management resilience as mentioned earlier, project progress resilience and project cost resilience. The vertical axis shows the minimum and maximum achievable cost resilience, and the horizontal axis shows the minimum and maximum project progress resilience.

As described in the previous paragraph and concluded from analysis of the stock and flow model, the dynamic nature of the system, capabilities and organisational objectives of a project will allow minimum and maximum barriers for progress and cost resilience. The user panel designed and proposed by the author allows modellers and managers to choose different scores, weights and rates and run quantitative analysis to observe their impact on the cost and progress variations. Referring to the left-hand diagram in Figure 7-5 and Eq. 11, project management resilience would be a vector sum of the cost and progress resilience.

Connecting the minimum and maximum values on the X and Y axes creates a square-shaped area, which shows the realm of acceptable values for project management resilience. Any vector fitting in this area will deliver good resilience. The author's proposed approach, which provides an innovative combination of CLDs and SFDs presented as an interchangeable user interface, offers the opportunity to trade-off between different choices of decisions, improve different subsystems of the project management model and decide on the best option to mitigate the impacts of the unplanned change or disruption.

This would be achievable by a comparative analysis of graphs resulting from a quantitative analysis of the designed SFD. The right-hand diagram in Figure 7-5 demonstrates an extended version of the author's proposed multi-dimensional model to study project management resilience for future research. It describes that to achieve optimum resilience for the project management approach adopted in each project, there could be multiple variables affecting its value. Hence, the author has proposed a novel formula that delivers the optimum value for project management resilience Eq. 13 in which N is the number of effective factors and $\propto_i$ is the impact coefficient for each factor, which can be defined by the project team, based on the project's policies, priorities, and objectives.

Analysing project management behaviour as a complex system and improving its associated decision-making processes to achieve the optimum level of resilience will assist the project to reduce the time and budget required to manage the impacts of disruptions and accordingly mitigate their impacts on the project's whole lifecycle and lifecycle cost.

7.4 Application of the Proposed Approach and Innovative Model

The author's proposed SFD model and, accordingly, the novel control panel deliver a modifiable analysis tool for researchers, managers, and system analysts. The proposed SFD is designed for an exemplary disruption and formulated based on a combination of facts and assumptions from a specific project. The modular design and the systematic structure of the SFD make it flexible, so it can be easily modified based on an individual project and its characteristics.

Figure 7-6 explains the generic process proposed by the author for future researchers, managers, or system analysts. The generated CLDs are founded on real data and reflect the entity of the subsystems for most railway projects. Hence, they can be adopted by future modellers as reference models and then be modified according to the characteristics of each project.

Specific disruptions or changes can then be modelled using the reference SFD model, which can be generalised and modified for any disruption. The control panel allows simple and less sophisticated system modification and analysis by managers or planners. For deep analysis by researchers or system analysts, the formulas, and interactions of the SFD can be easily changed to make it bespoke. Modifying scores, weights and enhancement rates would be achievable using CLD analysis and cross-validating them by experts' opinions.

SFD quantitative analysis acts as an impact analysis and decision-making tool. It lets the managers or modellers decide the optimum solution to enhance the resilience of the adopted project management approach. For instance, if the SFD analysis concludes that the project management team needs to improve change management by 50% and requirements management by 45% to achieve the highest level of project management resilience, the modeller can go back to the CLDs and find out the key variables affecting the change or requirements management resilience.

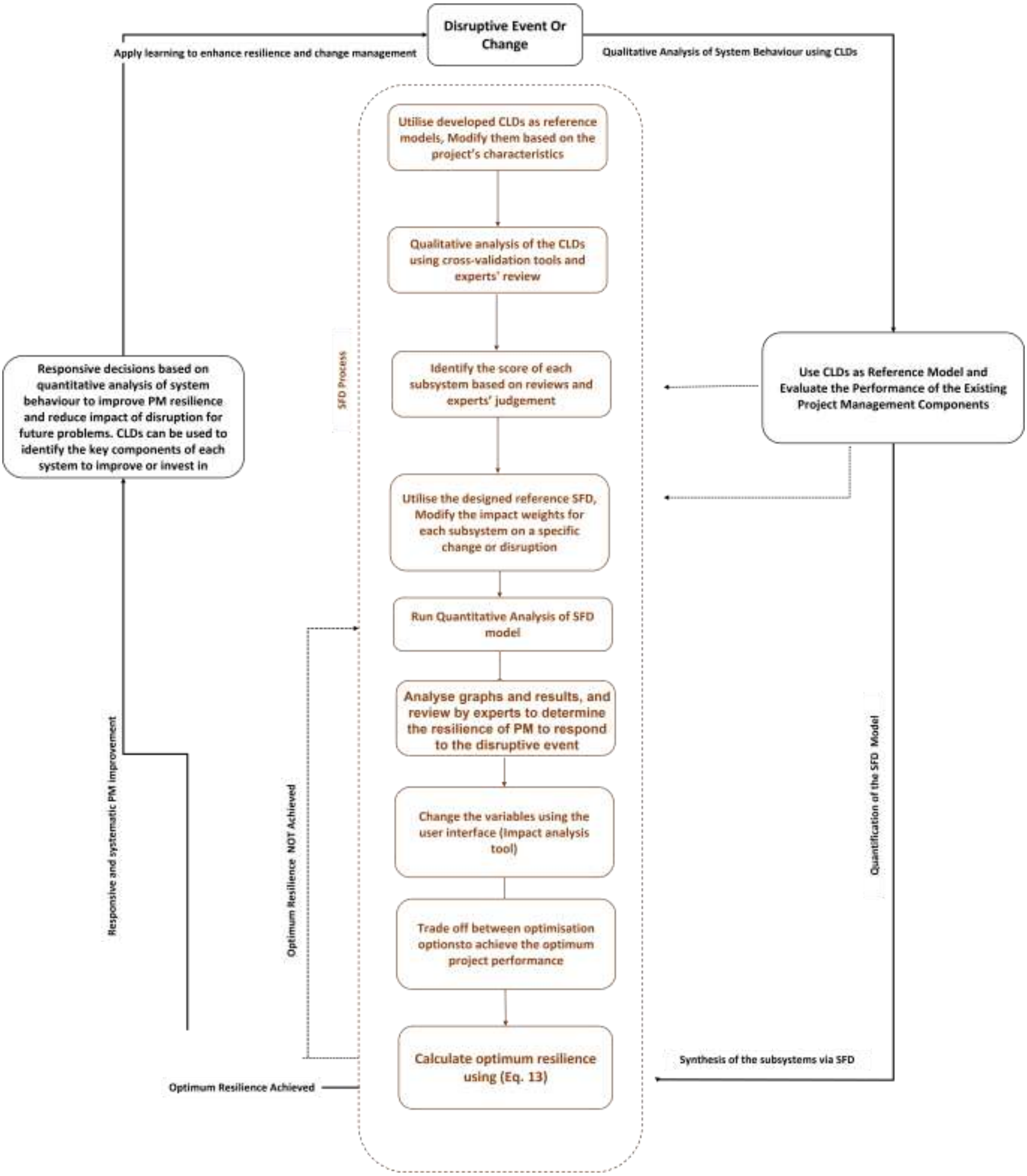


Figure 7-6 Application of the proposed innovative model for future researchers and managers to analyse project management resilience (author)

The findings can be used to modify the lifecycle of a current project already affected by the change and poorly managed due to a weakly resilient PM strategy. Additionally, combining CLDs and SFD analysis provides a learning legacy system. It provides a systematic traceable learning system, which helps to record the learnings from previous mistakes and avoid repeating them in future projects or even to optimise the subsequent phases of the current project.

7.5 Conclusion and Future Work

Literature review analysis and project documents state that large infrastructure projects, including railway projects, still face repetitive delays, cost overruns and benefit shortfalls.

Researchers have recommended moving from traditional risk management approaches towards more holistic risk management focused on project resilience. Resilience means the speed of a project's response to an unexpected change or disruption. Hence, resilience is linked to the vulnerability of a project when facing disruption and the time required for a project to return to its regular operation. The application of system thinking tools to project risk management can be categorised into two classes, qualitative and quantitative approaches.

Research shows that relying on purely qualitative tools does not deliver a clear understanding of complexity. Moreover, most current qualitative approaches are not used by practitioners and are mostly limited to academia. Hence, it is recommended that future research should focus on developing more reliable qualitative tools based on real projects and applicable to real projects by management practitioners.

On the other hand, reviewing the state-of-the-art quantitative system thinking tools for project management shows that most of the numerical approaches utilised to analyse the risk or resilience of projects (in general and in railway) are focused on thematic and case-specific components of the projects. Using fuzzy logic to assess the risk of metro operations, applying SD tools to assess urban development resilience, utilising BIM to identify risks of tunnel construction, utilising SD tools to analyse the risk of bridge construction, and optimising the location of relief trains are a few examples. Quantitative approaches are also identified as being sophisticated, which creates reluctance among practitioners to use them in real-life projects. Hence it is recommended to develop advanced quantitative tools which can be integrated with qualitative approaches and facilitate their application in real projects.

The author came up with a novel idea to bridge the identified gaps. Instead of focusing on a specific component of railway projects, the author came up with a hypothesis to apply system thinking tools to evaluate and enhance the whole project management of railway projects. The methodology and objectives are already mentioned in Chapter 1, but as a summary, the following section summarises the author's approach.

The author's research bridges some of the main gaps identified in the literature review and could offer a novel platform to apply SD tools to railway project management. The platform includes an innovative methodology, a set of reference CLDs and two innovative formulated SFDs, which provide a reliable scientific analysis tool, applicable to both research and management practice areas. The author has identified the following research avenues for future research and development:

- The author's research identified five key subsystems for project management (as a system). These subsystems were identified based on the problems common to the studied cases. For future research, it is essential to expand the author's proposed model and add more subsystems affecting project management resilience. The proposed model expanded an avenue and facilitated the application of SD tools to railway project management. Complexity is an endemic factor in project management, and, to achieve a more accurate understanding of how to mitigate its impacts, future research must investigate other subsystems and their impact on project management resilience.

- The proposed CLDs are generated based on the findings from multiple case study analysis and have been systematically simplified to make them understandable, convertible to SFDs and generalised. Future researchers can use these CLDs as reference models and expand their structure. Developing bespoke CLDs would be necessary to enhance the accuracy of understanding system behaviour.

- The proposed SFDs are novel and can be used as reference tools for SD analysis. It is recommended that future researchers add additional variables to the models, considering their interdependencies. This will add value to the field of project resilience.

- The unique two-dimensional model offered by the author creates a platform to move from a conventional simplified overview of project resilience towards a modern approach, which is more compatible with modern project complexity. Following the above-mentioned three recommendations, researchers are recommended to identify more resilience indicators through SD analysis and use the author's suggested formulas to calculate the resilience of the project management strategies adopted for specific projects.

- It is highly recommended to create a society of researchers active in the field of systematic project management, coordinate the research approaches and promote the culture of system thinking in project management society. This would be the first step to generating a learning legacy that allows managers and planners to learn from previous mistakes and avoid repeating the same systematic problems affecting project management resilience.

The proposed approach (CLDs and SFDs) can be a practical and intuitive tool to establish the desired learning legacy system within railway projects.

Chapter 7 provided a summary of the approach to generating stock and flow diagrams from CLDs, as a process of system dynamics tools (Quantitative Simulation). Qualitative data derived from CLDs in Chapter 6 were utilised to identify the critical stock and flows (using an example from one of the case studies). Five CLDs were integrated (systems integration) utilising an innovative SFD. This provided a platform to integrate and assess the system's full functionality and resilience (proposed project management structure in Figure 1-4) against an unplanned disruption. Simulating the SFD and extracted graphs provided some novel findings and recommendations for optimising railway project management strategies and decision-making processes using SFDs.

Chapter 7 presents quantitative aspect of the author's research, where an innovative approach was utilised to integrate the five key subsystems to assess the functionality and resilience of the project management structure and provide a systematic tool for system optimisation. The author developed his hypothesis from real-life projects and applied that to a real-life example (project disruption) to analyse the applicability of the proposed approach in the field of railway project management.

The author intended to assess the applicability of his hypothesis to improve the resilience of metro systems operation management (as a complex system) when facing disruption or a management-derived change (such as conversion to 24-hour operation). The approach and findings of this research (which is partially published as a conference paper (https://ieeexplore.ieee.org/document/7588736) are presented in Chapter 8).

Hence, in parallel research, the author conducted another multiple case study analysis for metro systems operation management. Therefore, Chapter 8 provides proof of concept from the author's proposed approach to assessing its functionality for the metro operation environment. This chapter is independent of the other main chapters (6 and 7).

This parallel research assisted the author to expand the horizon of the applicability of his proposed approach from railway construction project management to metro operation management. The nature of the context of Chapter 8 is not fully connected to the context of this thesis. However, the logic, methodology and field of investigation (railway) are the same. Hence, this provides a logical link between Chapter 8 and the rest of the thesis and, most importantly, introduces new reassert research avenues for researchers interested in applying system dynamics tools to metro operation management.

Chapter 8

APPLICATION OF PROPOSED APPROACH TO ANALYSE THE RESILIENCE OF METRO SYSTEMS OPERATION MANAGEMENT

8.1 Introduction

As described earlier, the author conducted parallel research to assess the applicability of his hypothesis and approach to another field in the railway context, called metro systems operation management. This research is independent of the content and findings from Chapter 6 and 7 but follows the same approach and methodology. In previous chapters, the author applied his proposed method to utilise system thinking to improve the railway project management structure's resilience to manage growing complexity. To examine the effectiveness of the approach in other fields of the railway industry, metro operation management was chosen as a case study. The aim of this chapter is to assess how the proposed methodology will be able to improve metro operation management resilience. To quantify the models, it was assumed that one the studied lines will be converted from normal to 24-hour operation. Then system dynamics tools were utilised to study the behaviour of metro system when faces this change and any associated disruptions. Results and findings are presented, and a series of recommendations are proposed on hoe to utilise this approach to improve the resilience of future metro systems and enhance decision-making efficiency.

Metros are complex large-scale, geographically distributed, interconnected, and interdependent socio-technical systems characterised by interactive complexity and tight coupling among system components (Wang *et al.* 2012; Li et al. 2017). Their complexities originate from a variety of complex functions and exogenous and endogenous functional dependencies and interdependencies (Deng et al. 2015). "It is obvious that increasing the size and complexities are making metro systems more dependent on systematic vulnerability analysis and formulation of corresponding coping strategies to increase the robustness of metro networks" (Xing et al. 2017).

Metro systems are multifunctional systems and any changes or disruption commonly adds more complexity to the system (Ziv et al. 2019). After failures of metro system components, there might be a recursive process that potentially increases the risks and damage to the system (Buldyrev et al. 2010). This occurs because of high and complex interconnections between crucial infrastructure systems, which makes them more vulnerable (Pederson et al. 2006; Wang et al. 2012).

8.2 Resilience and Vulnerability in Metro Systems

Resilience is a comprehensive system measure covering the following building characteristics representing distinct system states: vulnerability, survivability, response and recovery" (Bešinović 2020).

Referring to Figure 2-9, vulnerability is considered to be the ability of a system to provide the required level of performance within a disrupted circumstance (Khaled et al. 2014); survivability is the capability of a system to transfer from regular operation to a disrupted mode in a reasonable manner (Bešinović 2020); response is the set of decisions and actions required to bring the system back to a pre-disrupted steady-state operational level (Zhu et al. 2020); while recovery reflects the time taken for the system to be restored from disrupted to the normal operating state (Saadat et al. 2018). Complex Network Theories are a standard tool adopted within infrastructure megaprojects to identify their vulnerable components (Taylor and D'Este 2007; Ouyang et al. 2014). Studies in this area consider vulnerabilities as inherent flaws in the system and which should be addressed by specifically designed mitigations (Laporte et al. 2010; Zhang et al. 2011; Han and Cheng 2012).

The existing methodologies to assess resilience can be categorised into two groups: qualitative and quantitative. Doherty et al. (2012) investigated the requirements to improve the resilience of Britain's railway infrastructure. They concluded that "effective infrastructure management demands knowledge and understanding of asset behaviours and interactions across the integrated system and the consequences of decisions being quantified across all affected areas" (Doherty *et al.* 2012). In the design and management of transportation systems, it is vital to identify the key components and subsystems that contribute to the whole system's functionality and performance and, accordingly, to its vulnerability (Armstrong et al. 2017). Despite developing different approaches to analyse the resilience of metro systems, the absence of a comprehensive framework is tangible (Grabowski et al. 2019). The main reasons are "the complexity of the metro systems with interconnected subsystems, lack of historical data and performance indicators, and lack of a unified framework to integrate predicting future demand and decision-making systems" (Mohammadi et al. 2019). Resilience in complex systems has become an essential concern for managers dealing with risks (Fraccascia et al. 2018). Resilience is a complex entity and cannot be measured based on a single indicator, it is recommended that resilience should be measured about a certain level of system performance (McDaniels et al. 2008).

The work considered the two main components of resilience as robustness (the ability of the system to sustain its function after a disruption) and rapidity (the required time for the system to return to its full functionality). This work inspired (Bababeik *et al.* 2018) to study increasing the resilience level of a vulnerable railway network for the specific case of optimising the location of relief trains.

(Bešinović 2020) focused on transport systems and categorised the existing approaches to analyse resilience into three groups, namely, topological, simulation and optimisation.

(Bešinović 2020) concluded that to deal with combinatorial complexity emerging from multiple simultaneous disruptions within railway systems, optimisation tools would be more effective. Optimisation models can cope with the challenging task of capturing system dynamics, such as multiple disruptions (Babick 2009).

8.3 Objectives & Contributions of This Chapter

The focus of this chapter is to utilise system dynamics tools to visually model the complex environment of metro systems, as well as the key components and interactions, to identify the main vulnerabilities.

From the analysis of the causal loop diagram stock and flow, diagrams were produced for specific vulnerabilities to assess the resilience of increasing the operating hours for a metro system. The elements of the stock and flow diagram were arrived at through an analysis of the London Underground's Piccadilly Line.

- **Qualitative analysis of metro resilience against additional operation hours;** via generating a generalised CLD as a qualitative reference model based on real-life data derived from a multiple case study analysis. The reference model can be used as the backbone for all similar metro systems and be modified based on the individual properties of any specific system. The model can be used as visual system architecture and visualise the complex interactions between the most effective components affecting the defined deliverables of metro systems.

- **Quantitative analysis of metro resilience;** via design and development of a reference stock and flow model, which showcases the effectiveness of system dynamics tool to analyse the impact of changes and decisions on the resilience of complex metro systems when we aim to convert them to 24-hour operation. Again, the stock and flow diagram are not the final answer for all metro lines, but it provides an interchangeable platform, which allows modellers and managers to change the variables and quantitatively analyse the impact of the applied changes.

- **Innovative systematic operation optimisation tool via resilience analysis**; The combination of qualitative CLD and quantitative stock-flow diagrams provides a reliable impact analysis tool, which can improve the decision-making process within metro systems. These packages provide modellers and managers with a quantitative analysis toolset, which acts as a supplementary change management tool. This can be used to reinforce the conventional methods of metro operation management by focusing on resilience management. This will help systematically evaluate metro systems' resilience when facing disruption or changes and against different decisions.

8.4 Methodology

When undertaking this study, five international metro systems were considered to identify the range of different complex factors affecting metro system performance. Table 8-1 presents details of the studied systems and data gathering approaches. For London Underground and Tehran Metro, data collection was conducted via interviews and visits, whilst for New York City Subway, Beijing Subway and Guangzhou Metro data were collected through literature review only. System dynamics tools (causal loop diagrams and stock and flow diagrams) were utilised to model the complex environment and identify the key interfaces impacting the resilience in the presence of failure or change. The models were created in the context of the metro system is a complex system with inputs and outputs as defined by Figure 8-1**.** NVivo software was used to capture the qualitative output of interviews and reviewed documents, while Vensim software was used to create CLDs and Stock and Flow diagrams.

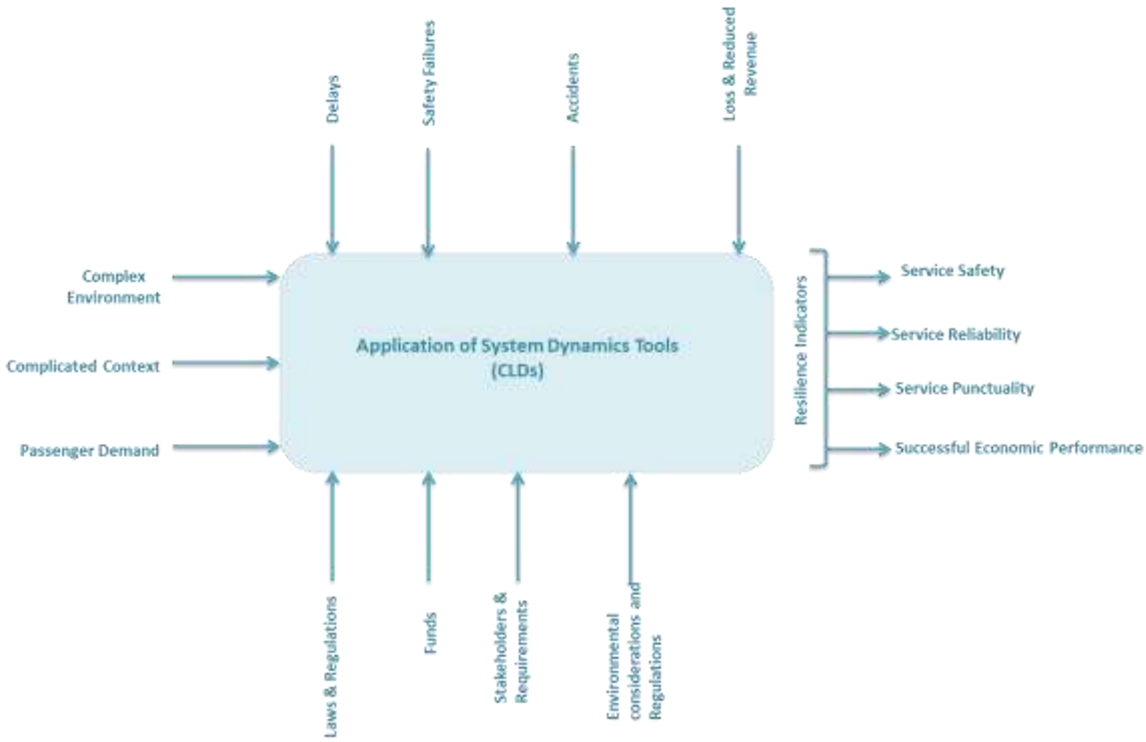


Figure 8-1 Functional view of a metro system

TABLE 8-1 CASE STUDIES

Case Study	Approach	Role of Interviewees
London Underground	Interviews, Visits & Literature Review	• 2 Project Managers • 2 System Engineers • 1 Operation Planner • 2 Signalling Designers
Tehran Metro		• 3 Project Managers • 1 Infrastructure Manager

	Interviews, Visits & Literature Review	• 2 Maintenance Engineers • 2 Track Engineers • 1 Operation Manager
New York City Subway	Interview	• 1 Systems Engineering Consultant
Beijing Subway	Literature review	N/A
Guangzhou Metro	Literature review	N/A

The London Underground, Piccadilly, Northern, Victoria and Waterloo lines were investigated. Converting the most demanding lines of the London Underground was a challenging problem for London Underground, based on a report published in 2014. Rolling contact fatigue, forecasting passengers demand, resilient operation management and the economic viability of the 24-hour metro systems were at the centre of interest for researchers. Tehran Metro was operating with 6 lines and the 7th line started operation in June 2017. The level of complexity involved in developing the 7th line was at the centre of attention for many researchers. Input from Tehran Metro and the level of complexity they experienced in the design, construction, and operation phases, added a remarkable value to this research.

The New York City subway with 36 lines, runs 24 hours and is one of the best examples to be studied for metro operation management. Unfortunately, due to the excessive restrictions, the author could only conduct a comprehensive interview with one of the systems engineers involved in the planning and operations phases of the metro system. Beijing subway, with 25 lines and 459 stations, was a very suitable case study to assess the impact of complexity on its operation. Because of the limitations, the author could only gather information through a literature review.

8.5 Developing CLDs and Stock-Flow Diagrams

8.5.1 Causal Loop Diagrams

An initial CLD (Figure 8.2) was generated in collaboration with practising railway engineers using Vensim. The resilience measures for focus within the study are shown on the right-hand side of the diagram safety, punctuality, reliability, and economic performance.

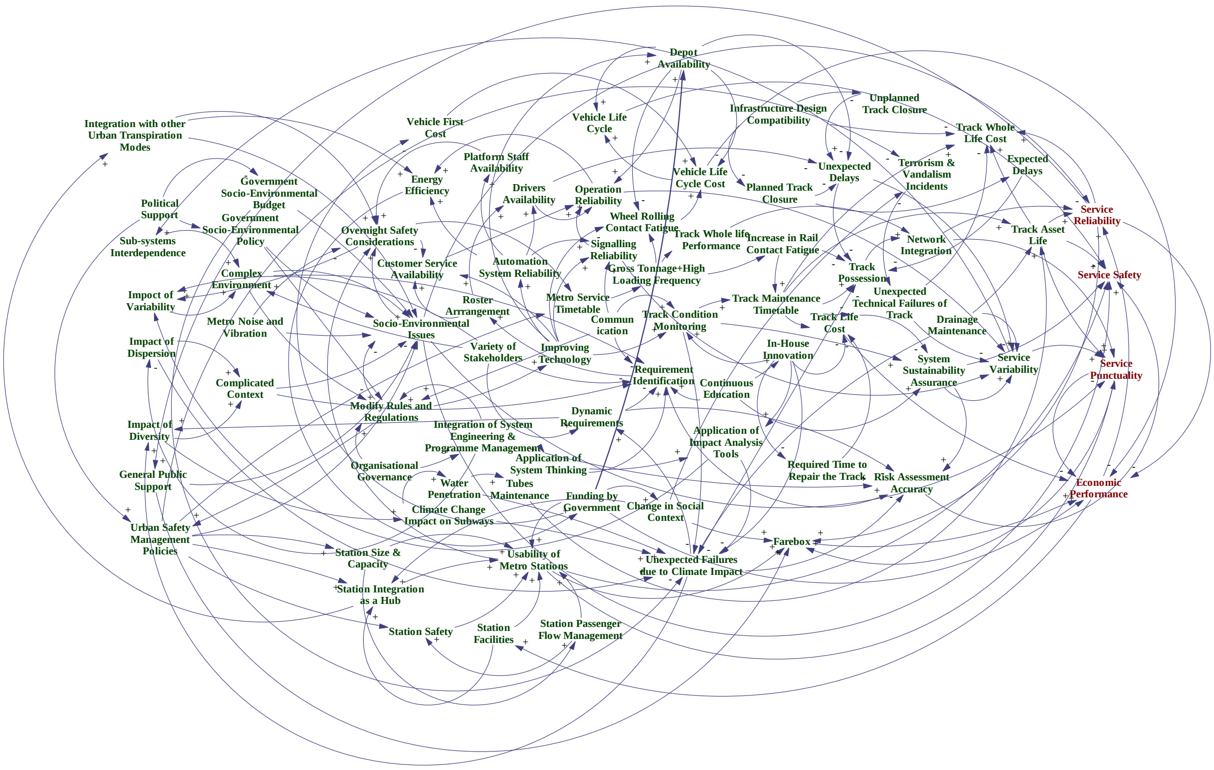


Figure 8-2 Initial generated CLD to model a generic operation environment of metro systems, derived from case studies (Author)

The initial CLD was taken as a reference model and experts were asked to explain what happens if a metro's service hours are extended. The experts were asked to adapt the CLDs and add additional variables they believed would emerge. The results from expert interactions in London and Tehran were cross-validated with literature reporting the impact of increasing operating hours in Beijing, Guangzhou, and New York. This allowed the model to be adapted to include new variables, thus creating an augmented CLD, as shown in Figure 8-3.

As expected, all interviewees agreed that when extending the operational hours of the metro, the key variables do not change, however, the vulnerability of some parts of the system is increased; these are shown by the changes in the two diagrams. Causes trees and uses trees can be used to cross-validate findings and better understand CLDs. Causes trees show the variables that affect a specifically selected component. On the other hand, using trees can assist in identifying the main variables, which the selected component will impact. A Uses tree derived from the second CLD is shown in Figure 8-4. The impacted variables are identified, along with the reason for the change. Together, the CLDs and causes and uses trees can be used to understand the causal feedback from a qualitative point of view.

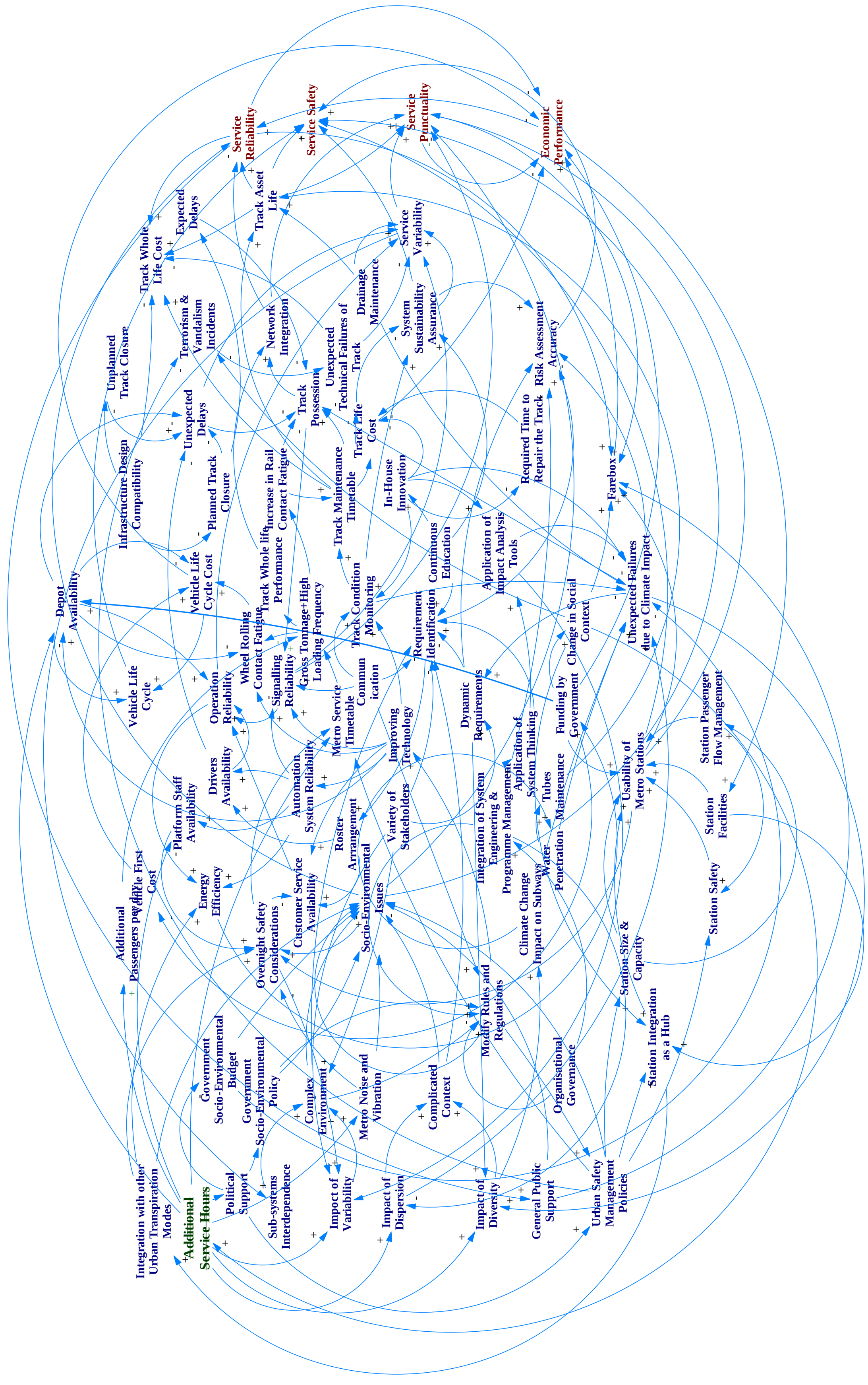


Figure 8-3 Updated CLD model to reflect the impact of adding additional service hours (Author)

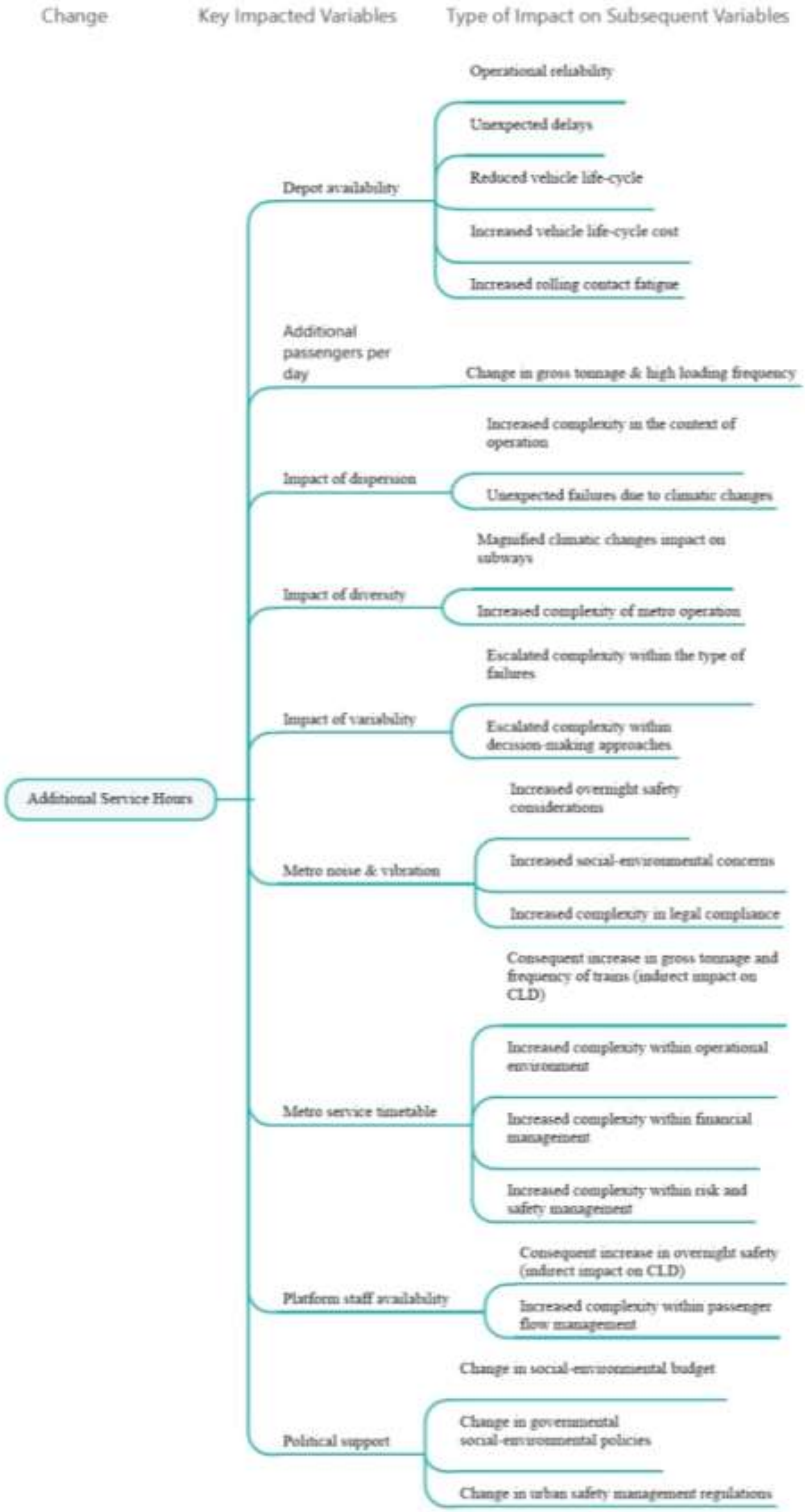


Figure 8-4 Uses Tree to show how adding service hours will affect the system (Author)

8.5.2 Stock and Flow Diagrams

Stock and flow diagrams provide a richer visual notation compared to causal loop diagrams. To generate stock and flow diagrams, the focus must be narrowed compared with the CLD so that only specific variables and interactions are considered. In this research, the generated CLD was reviewed by experts from the case study projects to identify the critical variables affecting the metro resilience indicator when operational hours are increased. Additional operational hours will result in additional trains that add load to the tracks. The experts' feedback and analysis suggested that in many metro systems, additional service hours would have the most significant impact on track loading. Additional track loading will, in turn, increase the likelihood of rolling contact fatigue, increase the maintenance cost, and would causally affect the safety, punctuality, reliability, and economic performance of the system. It was decided to focus on analysing the impact of additional operation hours on track loading and analyse its impact on metro resilience using stock and flow diagrams. Figure 8-5 represents the schematic link between the generated CLD and the designed stock and flow diagrams based on the analysis of the causal feedback of the CLD and experts' feedback. The model focuses on the impact of additional loading on track (due to additional service hours) for four resilience indicators of the metro system. To showcase the usability of the model in studying metro resilience, specific facts and figures were required; these were taken from London Underground's Piccadilly Line.

When constructing the diagrams, the formulations used were generated using qualitative information provided by experts and through literature review. This allows the benefits of the approach to be identified, but if the diagrams were to be used for real-world projects further work would be required to develop more accurate formulas.

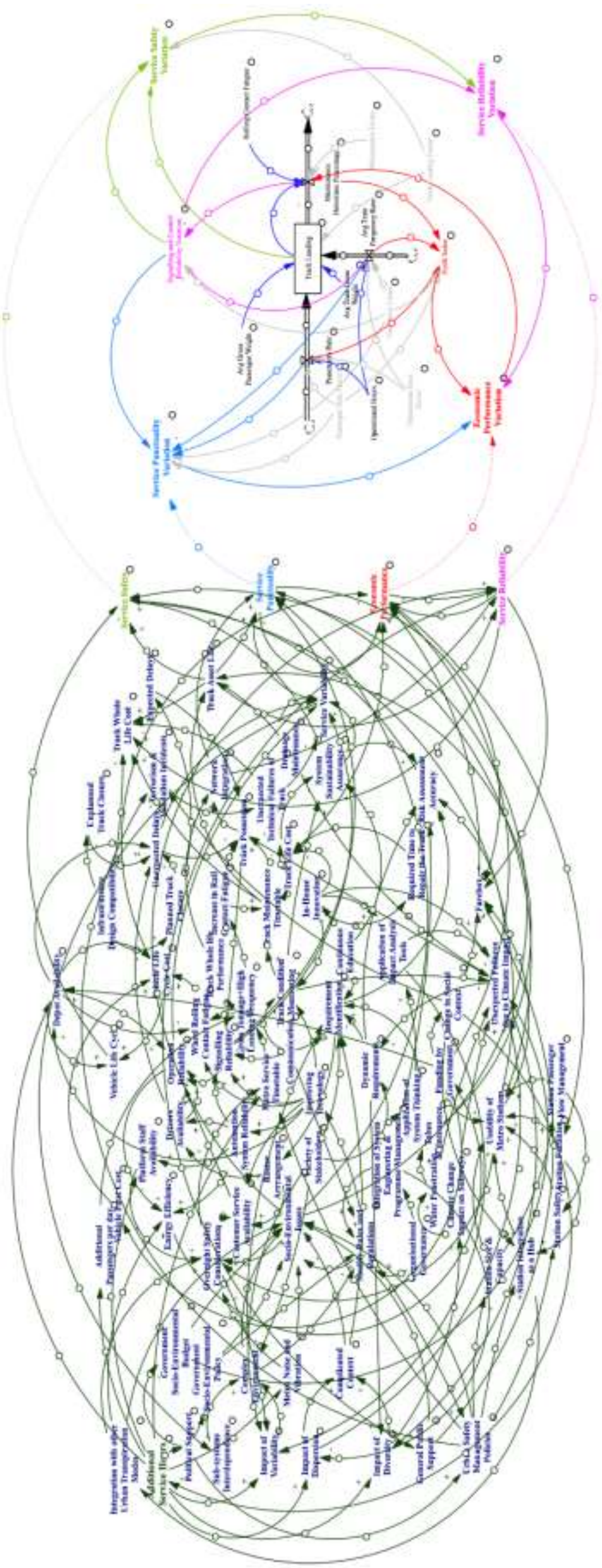


Figure 8-5 Stock & Flow diagrams to study the impact of additional service hours on metro resilience indicators (Author)

To convert CLDs into SFD, the following steps were followed:

1. Through analysis of the CLD and consideration of experts' views, the key variables that are impacted when the operational hours are extended are identified.
2. Using Vensim, a structured and simplified SFD is generated.
3. The inputs and outputs of the model are identified and formulated.
4. The syntaxes and units of the formulas are checked and verified.
5. Using a control panel to support the problem at hand, analyse the graphs to understand the impact of different levels of extended hours.
6. An appropriate solution is found.

Figure 8-6 presents the formulated stock and flow diagram and its associated control panel, which has been created by running a series of analysis for different operating hours. The control panel is a dynamic user interface that allows managers, modellers, and system analysts to assess trade-offs between operation hours by analysing the impact on different resilience factors of metro systems. The designed stock and flow diagram reflect the interactions between the critical resilience indicators and the interdependencies between additional service hours. track loading is impacted by additional trains and passenger numbers, which are inputs. Increased track loading will affect maintenance downtime, which is the critical factor affecting the metro system resilience. The slider bar at the top of the control panel allows analysts to add increased hours of operation to the metro system from 0 to 8 hours per day. In the model settings, a period of 60 months is considered. The illustrated graphs show the trade-offs between 16, 21 and 24 hours of operation. The change in the resilience factors over time can be seen. The graphs were reviewed by experts from London Underground to verify the findings with real-world experience.

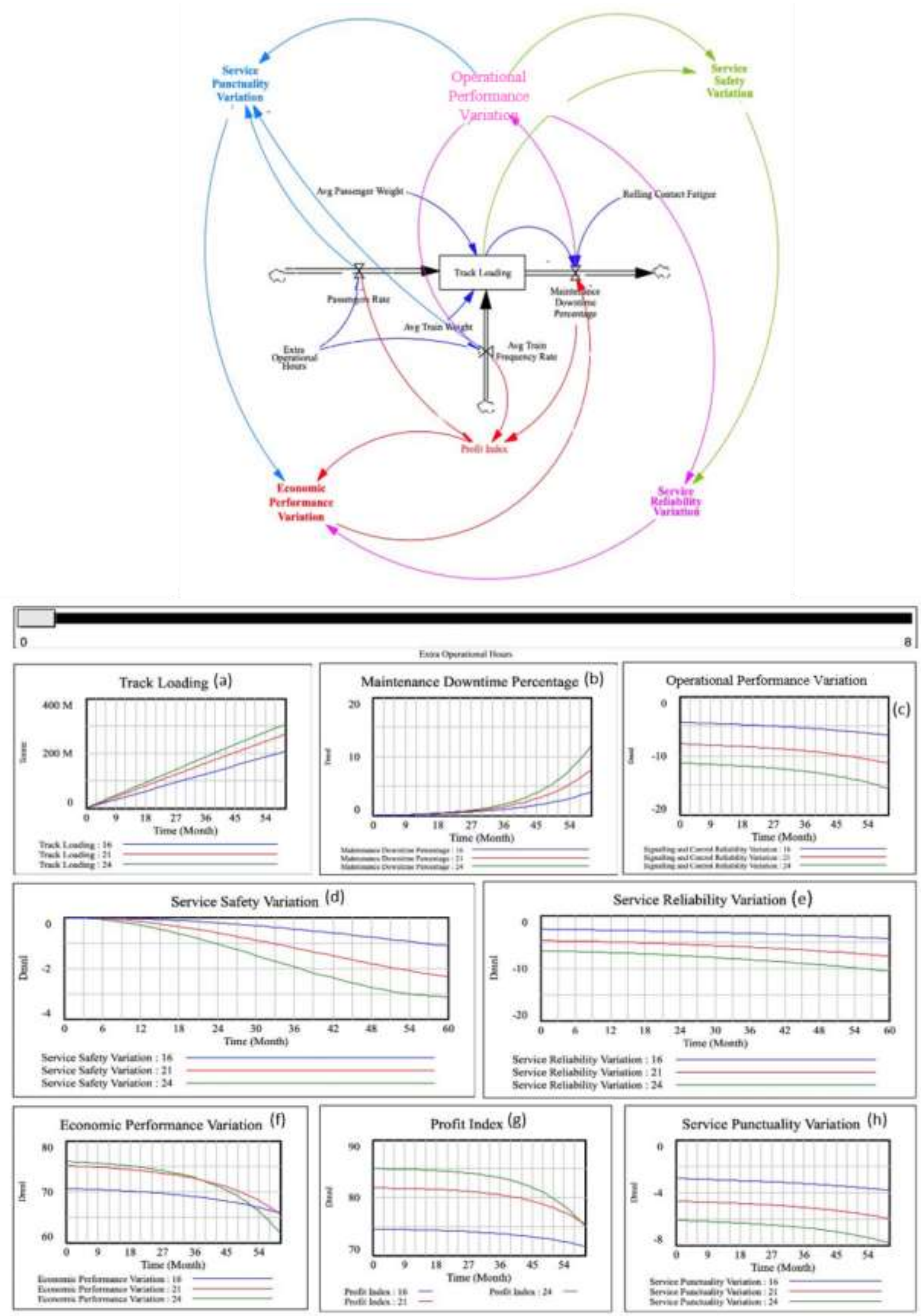


Figure 8-6 Stock-Flow model analysis, graphs, and innovative control panel (Author)

8.5.3 Interpretation of Graphs

This section provides a review of the results. The graphs in Figure 8-6 allow a comparison of the impact of additional service hours on different resilience indicators for the metro system. The normal operating hours are considered 16 hours per day, and the toolset allows modellers to add additional service hours to the metro for up to 24 hours and analyse and compare the associated impacts. This provides modellers, planners, and managers with an intuitive visual analytic tool, which can improve the impact analysis of additional service hours on metro resilience. The developed stock and flow diagram has considered the relationships and recursive interactions between four resilience indicators. Purely numerical analysis tools, such as finite element analysis, cannot represent the inherent feedback loops between indicators, which are key to understanding the impact of change in a timely, accurate and dependable manner.

The Track Loading results, Figure 8-6a, show the variation of the track loading for different operational hours. It can be seen from the graph that the studied line would exceed 40 million Gross Tonnes (MGT) slightly before the 5th year of operation in the case of 24-hour operation. This result confirms the findings from (PWI 2018) which states that "London Underground faces an enormous challenge to run a modern metro service over 40 MGT on Victorian infrastructure". that its additional service hours, the lifecycle of tracks becomes shorter; experts identified this as one of the main challenges in converting metros to 24-hour operations. The graph highlights that the causal tendency of the system is to achieve its highest wear and tear after five years.

Additionally, extra service hours affect the required type of interventions and time required for track maintenance. To address these issues, it is proposed that a reliability-centred maintenance regime must be adopted that utilises an appropriate blend of condition monitoring and maintenance interventions to optimise costs, safety, and performance of the network. A recent study by Vickerstaff et al. (2019) highlighted that London Underground is likely to experience serious challenges with the effectiveness of existing maintenance regimes as the number of services is increased, with particular problems occurring at the wheel-rail interface. Anticipated problems on London Underground's Victoria and Piccadilly lines are an increase in the occurrence of rolling contact fatigue and a reduced track lifecycle. The developed tool assists managers and analysts assessing the impact of additional service hours on track loading.

The Maintenance Downtime Percentage graph, Figure 8-6b, shows that the expected performance of the system, without any change to the maintenance regime, would result in a reduction in track availability by ~15% if the line were to be increased to 24-hour operation. Referring to the stock and flow diagram, increased maintenance downtime will have a significant impact on the economic performance of a railway. Good economic performance increases the available budget for track maintenance, innovation and adopting new technologies while adding further value to the economic performance over the longer term. A senior track engineer analysed the graph and agreed with its results that show that when operating hours are increased, there will also be an increase in the number of unexpected track failures. The increased number of failures results from: (i) an absence of a consistently applied, systematic and reliability focussed maintenance regime; (ii) a significant decrease in the available maintenance time; and (iii) an increase in the required time for each maintenance window due to the additional maintenance requirements.

The Operational Performance Variation, Figure 8-6c, represents the variation in line capacity (trains per hour) from a baseline rate, under different additional operational hours. The green line in the graphs shows that track failure or other issues that result in track unavailability reduce the line capacity. A 15% drop in operational performance is expected after five years when the line is changed to 24-hour operation.

The analysis shows the natural behaviour of the system over time if there are no contingency plans to compensate for the impacts of additional service hours. Comparing the graphs generated for 16, 21 and 24 operational hours shows that any increase in services will increase the risk of failure in operational performance, justifying the need to improve maintenance regimes. Understanding the cause and effect of the maintenance regime is necessary to mitigate the inherent decrease in performance that will otherwise occur. The developed tool can be expanded with higher accuracy models for specific lines to fully understand the expected impact on operational performance.

Service Safety (Figure 8-6d) shows the variation in service safety due to increased operational hours. Safety is not a straightforward concept to study and is dependent on numerous factors. The stock and flow diagram and causal feedback of the generated CLD for the studied projects help reduce the complexity of the modelling by aligning service safety to the causal impact of extra track loading. Undoubtedly, the simplified model does not cover all aspects of system safety, but the model can be further developed for specific case studies and areas of focus.

Referring to Figure 8-7d, for 24-hour operation, the causal interactions will result in the system experiencing around a 3% drop in safety five years after applying additional service hours (cumulative impact). The developed tool will assist modellers in evaluating the level of the safety performance of a system by understanding the link between operational hours and safety performance. The tool can be used to augment existing risk analysis approaches and to capture the dynamic, non-linear, and complex cause and effect, which can be considered one of the key resilience indicators.

Service Punctuality (Figure 8-6h) is simplified based on the causal response of the system and is a function of, operational performance variation, the number of passengers and service frequency. Experts from London Underground confirmed the tangible impact of passenger numbers, specifically in peak hours, on the punctuality of trains. Station and platform passenger flow management strategies are recommended to mitigate the negative impacts. Platform screen doors are one of the solutions adopted in a few London Underground stations to manage the platform-train interface (PTI).

The key impact of extra passengers on the London Underground network is increased dwell times due to congestion or passengers' interruption of train door operation. Dwell time plays a significant role in train punctuality and service frequency and regulation. Thoreau et al. (2016) recommend "multiple doors, dual-flow passenger exchange and dual corridors for consistently shorter dwell times for the same number of patrons".

In a recent study, the impact of passenger density within a train carriage on the boarding rate was studied (Luangboriboon et al. 2020). It was concluded that for high-frequency lines, such as metro systems, where the passenger density inside the carriage is already greater than 5 passengers/m2, any delay would progressively increase. Hence, passenger loading, and flow must be considered when considering timetable recovery strategies. 2016, London Underground assigned University College London to conduct research to deal with the impact of passengers on dwell time. The results recommended some physical measurements for the width of train doors and platforms, but the most important findings were that "There is a distinct dynamic which surrounds the boarding/alighting process which indicates that there should be a point during the door-open time after which the board/alighting flow rate is characteristically much slower. This means that an additional passenger joining the passenger movement process after this point will take longer than a passenger who completed their manoeuvre earlier. Thus, the passenger service time is not directly proportional to the number of passengers but depends on when during the door open time. It is thus nonlinear over time " (Thoreau et al., 2016).

Simulating the stock and flow diagrams shows that, in the case of 24-hour operation, in the middle of the fifth year of operation, the punctuality will fall by around (8%), which is significant and shows the importance of adopting compatible mitigation methods to enhance passenger flow, operational performance reliability and optimised train frequency. The developed tool lets the modeller consider different solutions and analyse each option's impact on system's punctuality. Future researchers should use the prospered system dynamics-based model to analyse the impact of dynamic passenger flow on punctuality over time. The dynamic impact of passenger flow on punctuality can be modelled separately for future research.

Service Reliability (Figure 8-6e) encompasses many aspects of railway functionality. “Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period” (Kiran 2017, p.391). The reliability of the railway system is complex and a function of many factors and hence not straightforward to define. It is, therefore, difficult to provide a definitive value for railway reliability (Vromans et al. 2006). Based on the causal interactions of the CLD and feedback from experts, the proposed model provides a simplified stock and flow diagram and enables modellers to quantify the reliability of the metro systems based on a consistent, systematic, and traceable approach. In the proposed model, the reliability is a function of operational performance reliability (which embeds the cause-effect impact of punctuality, whilst considering the impact of operational performance variation) and safety of the system (which embraces the effect of additional service hours on track maintenance and availability).

It is recognised that there are parameters not considered, such as environmental issues, due to model simplification and the specific scope of the research, which can be added to the model by future researchers. According to the graph and stock-flow analysis, the natural tendency of the system in the fifth year of 24-hour operation would be to drop reliability by 12%, which is a cumulative impact of numerous factors, as mentioned earlier. The tool provides the modeller with a systematic tool to assess the trade-off between different service hours and quantifies its impact on reliability variation. This will be essential and useful in the planning phase to adopt a change (additional service hours) or in the case of significant incidents, as planners can select the systems’ priorities and find a quantitative balance between different resilience factors.

Economic Performance Variation (Figure 8-6f) plays a significant role in the viability of metro systems. London Underground experiences 2.8 million daily trips with an estimated mean journey duration of 47 min (Smith et al. 2020). “The economic efficiency of railways is believed to be influenced heavily by the degree of government intervention and the institutional and regulatory setting within which the railways operate. The efficiency measured from observable data is heavily influenced by the market and operating environments to which the railways are subjected. Productive efficiency of railway systems may be significantly enhanced by an institutional and regulatory framework which provides greater freedom for managerial decision-making” (Oum and Yu 1994, pp.121-136).

In the proposed stock-flow diagram, economic performance is defined as a function of different factors. The first is service reliability. Service reliability can be defined as a factor, which affects the government subsidy and support, and hence can add value to the modelling process, however, the governmental support can be assessed in detail for future research. The second factor is service punctuality, which considers the potential revenue loss resulting from delays or cancellations. To make the modelling more realistic and accurate whilst keeping it simple, an auxiliary variable is defined as the so-called ‘profit index’, presented in Figure 8-6g.

Service punctuality is comprised of passenger rate (to cover income from tickets and onboard advertisement), average trains per hour (to cover the generic costs of operation), and maintenance downtime ratio (to cover the costs of the track maintenance, wear & tear, and generic loss of benefit due to unexpected track failures). The model includes some coefficients that were provided by experts from London Underground, literature, and mathematical calculations. Undoubtedly, future researchers can more robustly determine coefficients to accurately reflect the real nature of systems. Linking the profit index as an input to the economic performance would apply the generic costs to the stock and flow diagram analysis.

The comparative analysis of the provided graphs on the benefit index and economic performance variation shows that the estimated economic performance for 24 -hour operation would be higher than for normal operating hours. However, considering the cumulative costs of maintenance, operation, and poor reliability in the fifth year of 24-hour operation, the economic performance will fall under 80%. This would be the natural behaviour of the system to additional service hours, which can be mitigated by informed decisions made by managers and planners (such as reliability-centred maintenance, efficient passenger flow, investing in reliable technologies etc.).

8.5.4 Proposed Multi-Dimensional Resilience Model for Metro System Operation

The approach and models proposed in this paper have informed the development of an innovative tool based on system dynamics concepts that provide a reliable system analysis toolset to analyse the performance and resilience of metro systems operation when faced with disruption or change. The use of system dynamics tools to analyse the impact of changes in metro operation (additional service hours in this case) on the resilience indicators of metro systems allows both qualitative and quantitative analysis to be undertaken. Modellers and managers can change the operating hours and analyse the impact on resilience indicators. Results show that in a complex metro operating environment, change in operation hours creates recursive, dynamic, and non-linear interactions and drives the natural behaviour of the system towards disruptive events and unknown risks.

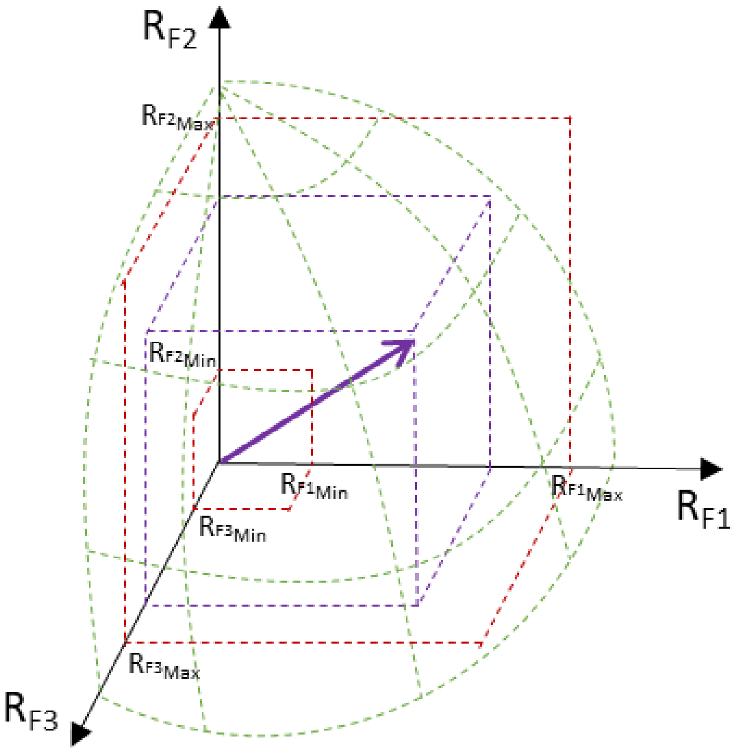


Figure 8-7 multi-dimensional model for metro resilience (Author)

The proposed approach delivers an innovative platform, which allows analysing the impact of changes (operation hours) on the indicator of metro resilience. The stock and flow diagram simulation captures the causal behaviour of the system and assists modellers understanding the risks and disruptions. Analysis of results suggests that to achieve good resilience in a metro system, this is necessary to make a balance between four resilience indicators.

Metro system resilience needs to be defined as a function of different indicators and more importantly, the importance of resilience indicators must be defined by managers, planners, and decision-makers, before converting metros to the 24-hour operation or adding any extra service hours. Optimum decision-making is achievable by finding a balance between resilience indicators and defining an optimum holistic resilience before the application of the change. Figure 8-7 illustrates the multi-dimensional model for metro resilience. In this paper, dimensions are considered, but future research could consider the use of more resilience factors that would increase accuracy. Each metro system-depends on its managerial policies- has a set of priorities and key performance indicators (KPIs), which identify the priorities for resilience indicators. In the case of the London Underground, safety is the top priority, while reliability is second on the list. Economic performance is the next priority. The proposed tool enables modellers to decide on the optimum resilience by trading off between different resilience factors and analysing their impacts through generated graphs.

So far, the resilience of systems, such as metros, has been mostly a qualitative concept. Application of system dynamics tools and utilising the proposed formulated stock and flow diagram proposes a platform to quantify the resilience of metro systems. Eq.1 presents the authors' proposed formula (based on the vector sum derived from Figure 8.7 to calculate resilience. $\propto_i$s are coefficient factors, which can be defined by future researchers and metro system decision-makers based on each metro system defined KPIs and priorities. Hence, for the model developed in this paper, the formula can be expanded in Eq.2.

(Eq. 1)

$$\mathrm{R_M} = \sqrt{\sum_{i=1}^{N} (\propto_i . R_{F_i})^2}$$

Where:

$\mathrm{R_M}$: Metro System Resilience

N: $Number\ of\ Resiliencefactors$

F_i: $Factor\ i$

R_{F_i}: $Resilience\ of\ Factor\ i$

$$\propto_i : Factor\ i's\ Coefficient$$

(Eq. 2)

$$R_M = \sqrt{\left(\propto_S . R_{safety}\right)^2 + \left(\propto_R . R_{Reliability}\right)^2 + \left(\propto_P . R_{Punctulity}\right)^2 + \left(\propto_{EP} . R_{Economic\ Perfromance}\right)^2}$$

Where:

$\propto_S$: *Safety Coefficient* $\propto_P$: *Punctuality Coefficient*

$\propto_R$: *Reliability Coefficient* $\propto_{EP}$: *Economic Performance Coefficient*

8.5.5 Conclusion, Contribution of Research, and recommendations

Metro systems are safety-critical and complex systems. In this chapter, the authors developed and proposed an innovative approach to systematically visualise the environment of metro systems and analyse their resilience against additional service hours (24-hour operation) through system dynamics tools. The essential purpose of this research is to evaluate the applicability of the proposed approach to analyse metro system resilience.

Four main indicators were defined for metro system resilience. Metro system was considered as a system, which its outputs were defined as resilience indicators, namely, punctuality, reliability, safety, and economic performance. To identify the main variables affecting the resilience indicators, a multiple case study analysis approach was adopted to derive findings from a set of case studies. System dynamics tools were then utilised to visually model the environment of metro systems through causal loop diagrams. Qualitative analysis of the CLDs provided the bedrock to design stock and flow diagrams as the quantitative analysis tool.

Accordingly, a set of innovative causal loop and stock-flow diagrams was developed and analysed for an exemplary disruption. The proposed models and generated graphs are limited and simplified based on the facts and findings derived from the studied projects. Nevertheless, the models and approach proposed in this paper can be used as a reference and a platform of thinking and facilitate the application of system dynamics tools to analyse the resilience of metro operations and improve it through systematic decision-making and impact analysis. Developed CLDs can be utilised as the skeleton to model any metro environment and the model can be modified based on any specific system characteristics. Stock and flow diagrams, designed and proposed in this paper, can be modified with more compatible formulas and more detailed interactions to enhance eth accuracy of analysis for any metro system.

To evaluate the vulnerability and resilience of the metro systems, in response to a disruption or change, the most important components of metro systems, which are prone to vulnerability by adding extra service hours were identified by studying the causal feedback of the generated CLDs and experts' feedback. tock and flow diagrams were designed to systematically quantify the impact of additional service hours (which means more track loading) on the defined resilience indicator, including, safety, punctuality, reliability, and economic performance. The provided stock and flow diagram were formulated based on some facts from the London Underground to provide a case-specific numerical analysis. The outcome was a set of comprehensive graphs, which deliver a quantitative analysis of the system behaviour under change.

In addition to the quantitative analysis of the model, the author designed a novel user interface based on the formulated stock and flow diagram. This tool is a reference tool which provides a systematic platform for quantitative analysis of metro systems. Each modeller can modify the model with a set of formulations according to the attributes of individual metro systems and analyse the resilience of the studied system. Since the proposed toolset offers the option to switch between different operational hours, it will enable modellers or planners to trade-off between various options and accordingly increase the operational resilience of the metro system through systematic impact analysis and reliable decision-making.

Future researchers are recommended to use the proposed approach to collect data from real projects and generate CLDs based on a systematic analysis and modify the proposed CLDs and SFDs. Future research can be more focused on adding extra layers of complexity to the stock-flow diagrams and considering the impact of factors such as climate change and the COVID-19 pandemic on metro systems' resilience in more depth. Chapter 8, as mentioned earlier, provides the author's findings from a parallel research study (independent from the actual topic of the thesis). The importance of this chapter is to prove how the proposed methodology would be beneficial for different ranges of project management, from construction management to operation management. Resilience thinking in metro operation management will define more research avenues for future researchers who are keen to optimise metro operation systems and reduce the risks and cost of operation or convert metro to 24-hour operation. The next chapter summarises the key findings and conclusions of the thesis.

Chapter 9

CONCLUSION

9.1 CONCLUSION and CONTRIBUTIONS

Chapter 9 summarises the thesis's most important findings are by a set of recommendations for project management practitioners and future researchers. The chapter has been divided into sections to reflect the findings according to the structure of the thesis and to provide reasonable coherence.

This thesis presented an innovative combination of qualitative and quantitative analysis approaches founded on system dynamics tools to evaluate the resilience of the railway project management model. The project management model was considered a complex system, formed of five main subsystems affecting its resilience, namely, project governance, requirements management, configuration management, change management and in-house engineering (responsive education, research, and innovation). The main idea was to propose an innovative and practical approach to applying system thinking to conventional project management strategies to reinforce it and bridge the existing gaps to manage the growing complexity of modern projects., as highly recommended by previous researchers.

The literature review identified substantial gaps within the existing project management models. Conventional project management approaches are diagnosed as linear tools, which makes them incompetent to manage the growing complexity of modern railway projects. The impact of complexity and associated uncertainty and unknowns on projects' cost, time and scope have been covered by different groups of researchers during the last decades, resulting in an emerging new school of thought.

Chapter 9 summarises the key findings from this research, followed by a series of recommendations and proposing future research avenues. The findings are presented in order of the thesis structure to facilitate traceability between the findings and the associated chapters.

Projects suffer from delays, cost overruns and benefit shortfalls. Changes and disruptions generate additional risks to the projects. Research confirms that conventional project management methods rely on hierarchical and control-focused planning. Accordingly, most of the existing research studies have underestimated the role of unknown risks. Most of the researchers applied system thinking to reinforce project management and have focused on specific risks, such as physical components. There are a group of researchers who have covered the performance of projects, but less attention has been given to the optimisation of the whole project management approach, utilising system thinking tools. This is necessary to adopt a more resilient method based on self-organising. The literature recommends moving from conventional project risk management toward resilience thinking and out resilience at the centre of attention.

Project resilience is influenced by the level of vulnerability, time taken to recover from disaster and the speed of project response to disruption. Because of the complex interdependencies between project components, the decisions have an impact on the project performance. SD tools, including CLDs and SFDs, are recommended as practical tools to analyse the dynamic and complex behaviour of complex projects.

Existing research projects have neglected or underestimated analysis of the resilience of the project management structure as an entity. Most of the projects have focused on evaluating the resilience of the actual projects. New research must, focus on finding systematic solutions to help practitioners analyse the impact of their decisions and enhance the resilience of the project management approaches when facing disruption or change.

This thesis represents the author's innovative research approach and findings to facilitate the application of system dynamics tools to assist managers, system analysts and researchers improving railway project management resilience. For the first time, this research defined the entity of project management as a complex system, formed of five critical subsystems, and was modelled employing system dynamics tools, then analysed both qualitatively and quantitatively.

Based on the literature review, most the existing research studies in the field of project resilience suffer from making a practical and applicable link between qualitative and quantitative analysis of project performance. This research bridges this gap and proposes a set of reference causal loop diagrams and stock-flow diagrams, which can assist managers and researchers optimising the decision-making process and evaluate the resilience project management approaches. This would improve project management performance to detect unknown risks and manage disruption with reduced change latency. This approach will help to optimise the whole project lifecycle and avoid repeating the same causes of failure for future railway projects.

9.2 Findings and Achievements from Generation and Analysis of Causal Loop Diagrams (Qualitative Analysis)

A set of modern UK tramway development schemes was selected as case studies to provide the author with real-life data and reflect the right level of complexity of the project environment. Data collected using multiple inputs, including Interviews, observations, documents, and literature reviews. Multiple case study analysis, with the aid of NVivo software, were utilised to analyse and filter data.

The proposed project management structure and its subsystems are modelled using the data derived from multiple case study analysis, causal loop diagrams (CLDs) and using Vensim software. Generated CLDs reviewed by a group of external experts and some from the studied projects to validate the realism of the CLDs. The CLDs have been simplified systematically to keep the reliability and at the same time applicability for analysis (Objectives 1 and 2).

CLDs provide a set of cross-validation tools such as the Uses Tree and Causes tree, which deliver traceability features of the generated CLDs. Uses trees can be used to trace the impact of any selected variable on the other components of the system. While a “Cause Tree” can be used to figure out the variables with an impact on any selected component. Employing these tools provided a reliable qualitative analysis tool and allowed the author to bring out the causal feedback of each CLD and identify the critical resilience indicators for each subsystem of the model (Qualitative analysis).

The qualitative analysis of CLDs highlighted the key resilience indicators affecting each subsystem and reflected the causal feedback of the loops. The traceability feature of the CLDs can be adopted as an applicable method to simulate the environment of complex projects and assist managers in visually tracing the impact of their decisions on the performance of the project. The key findings from the CLD analysis are listed below.

The complexity of urban environments was oversimplified in the design plan of the studied projects. This statement is supported by documented delays within the studied cases, especially the Birmingham Metro extension. The exemplar case utilised in developing the SFD can be referenced as one of the robust pieces of evidence. CLD analysis expressed that, the existing project management approaches mainly were founded on a set of known risks and accordingly, the risk mitigation strategies formed a set of hierarchical planning and decision tools. The knock-on effect of the identified problems emerged in the change management process of the projects when most project management approaches did not successfully manage unexpected changes. Unplanned delays and cost variations were observed as part of the poor change management consequences (Objectives 3 & 4).

The growing complexity and, application of systems engineering to project management and the move from conventional project governance to alliance governance, along with the culture of responsive continuous education and innovation, began to absorb the interests of the project management team in some of the studied projects. However, there is still a long way to go, as applying system thinking tools to conventional project management seems like a vague process which has remained in the theoretical realm. Hence the author's research emphasised the importance of developing innovative research projects in the field of project management to shed light on the process and details on how to apply system thinking tools to project management and make it compatible with the level of complexity and mitigate risks of unknowns.

9.3 Findings from the Development and Analysis of Stock and Flow Diagrams (Quantitative Analysis)

The next step of the research was to convert CLDs to SFDs as a platform for quantifying the qualitative CLDs. The resilience of project management is the capability and rapidness of its response to disruption or change. Qualitative CLDs identified the resilience indicators for project management subsystems (the breakdown of the system to study its components). Then the CLDs need to be integrated to form the whole system and enable analysing of the whole system's functionality and resilience (synthesis of components to evaluate whole system behaviour). Most preceding research studies had applied the quantitative analysis aspect of system dynamics tools to specific areas of projects, such as risk assessment or the resilience of the physical components such as tracks and stations. Project management is a conceptual, complex, and qualitative entity and is not straightforward to be quantified.

To enhance the accuracy of the model and its practicality for real projects, an innovative stock and flow diagram was designed with two innovative features. In this thesis, the SFD was shaped around a real unexpected disruption to the tramway construction process. There was a considerable delay and cost overrun, which led to a change in design in one of the studied projects due to an unforeseen clash with underground utilities. The model was designed and formulated to represent the interactions between project management subsystems and reflects the quantitative feedback of their impact on the unexpected disruption affecting the project performance. The designed SFD can be used to detect the origins of any specific change or disruption. The developed SFD offers an innovative and systematic toolbox, enabling researchers and managers to easily change the variations, the impact scores and coefficients of the formulas and run quantitative analysis to measure the resilience of the adopted project management model. Additionally, the tool lets managers trade-off between different choices and acts as an impact analysis tool for decision-making (Objectives 5 and 6).

Analysis of extracted graphs expanded the vision of resilience thinking in project management. Graphs extracted from analysing the developed SFD suggested that the resilience of project management is a multi-dimensional parameter. Studying the behaviour of the budget variation graph (affected by the disruption) over time the author concluded that reducing the time required to detect the change, make decisions, and implement solutions, would enhance the project performance, but not necessarily its resilience.

Since budget variation demonstrated a different behaviour than was expected, this recommends that to manage uncertainties and disruptions, managers should make a balance between project progress performance and budget variations. There is an inextricable bond between project performance end budget management in projects, including railways. Hence, the analysis shows that to achieve a more accurate understanding of project management resilience, it is inevitable to establish a systematic decision-making framework, like what the author developed and proposed in this thesis. Summarising these factors helped the author to come up with a new and innovative 2-dimensional model for project management resilience. The model suggests that using the proposed stock-flow diagram and developed analysis toolbox, managers and researchers could a trade-off between different options and achieve the optimum project management performance. The author's developed proposed formulas are presented in the main chapter **(Objective 7).**

9.4 Application of Proposed Approach to Analyse the Resilience of Metro Systems Operation Management

To evaluate the applicability of the proposed innovative approach to analyse and manage the resilience of metro systems operation management, parallel research was undertaken by the author to generate a causal loop diagram to represent the environment. The qualitative CLD is shaped based on ' key critical resilience indicators.

The CLD was then converted into an innovative formulated SFD, which provided a systematic tool to change the operation hours and measure its impact on the resilience of a metro system. The proposed model and approach delivered a unique and user-friendly system analysis tool, which can profoundly improve the decision-making process when metro systems face a change or disruption.

The combination of the qualitative and quantitative analysis highlighted some of the most vulnerable components of metro systems, which would be highly affected by changing the service hours and accordingly impact metro system resilience and performance. The proposed model considered multi-dimensional variables, including economic performance, to increase the systems' resilience study accuracy.

The proposed model and its formulation can be adopted as a reference model for all metro systems, and modellers can easily change its features to make it bespoke. Extract graphs can be used to optimise the metro operation environment by achieving a balance between safety, punctuality, reliability, and economic performance. This will keep a metro system at its optimum resilience level and reduces unexpected failures or changes due to the impact of unknown risks. The research contribution is briefly mentioned below:

- Developed and proposed an innovative methodology, combined with multiple case study analysis and system dynamics tools, which can be followed by future researchers to visualise the complex environment of the projects.

- Generated a set of reference CLDs to model the railway project management as a system. This model is developed for the first time and delivers a holistic overview of any similar railway project. Researchers can adapt these reference models and map their individual systems against the generated CLDs. Hence, CLDs can be modified to reflect the true nature of any specific system (Qualitative analysis tool for complex railway projects).

- Designed, formulated, and proposed a novel SFD to analyse the resilience of the railway project management model according to the resilience indicators identified via CLD analysis. Expanding the SFD, the author designed a unique user interface as a system analysis tool. This is the first-of-a-kind toolset, which allows managers and researchers to change the resilience indicators of the project management and analyse its impact on project performance and management resilience (A novel quantitative analysis tool applicable to all railway projects).

- Based on the findings from qualitative and quantitative analysis, the author developed a set of novel formulas and a conceptual two-dimensional model aiming at enhancing the understanding of project resilience. This creates a platform of thinking and proposes new research avenues for future researchers to focus on other dimensions with potential impact on resilience and achieve the optimum level of performance.

- Designed and proposed a formulated and structured system dynamic tool, to assist managers and planners to analyse the resilience of metro operation environments. The tools can be sued to manage disruption in the metro system or, in the case of converting metros to 24-hour metro operation and analyse its impact on the metro system resilience.

The combination of the above-mentioned contributions would be able to contribute to bridging some of the gaps identified in the literature review. Conventional project management approaches can be easily mapped against the proposed CLDs, and SFDs and modellers can modify the reference models to achieve an accurate version reflecting the studied project management approach. Models can then be quantitatively analysed to assist managers in analysing the efficiency and resilience of the adopted project-managed approach. This will reinforce the conventional project management tools with impact analysis features and will profoundly improve the decision-making quality when a project encounters disruption or change.

The proposed system analysis tools are user friendly, and the formulas, interactions and features can be easily modified based on the facts of each project. This will remove the sophistication of system analysis tools, which was identified as creating reluctance amongst practitioners leading to a gap between systems engineering and project management.

A combination of CLDs and SFD can establish a visual-numerical learning legacy, which helps projects to avoid making the same mistakes. The proposed approach can be used to modify the resilience of the existing brownfield projects, but most importantly, to ensure future railway projects will be managed by much more resilient project management approaches, capable of understanding the project complexity and eliminating risks in the planning phase of the project. Enhanced resilience of project management will ensure that responses to unexpected disruption will be systematic with a reduced chance latency mitigating the snowball impact. This will improve the project management methods to be able to manage the dynamic nature of the projects and optimise the whole lifecycle of project (Objective 8).

9.5 Limitations of the Overall Methodology

All research methodologies have inherent limitations. The overall methodology proposed and applied by the author to this thesis is no exception. Developing system dynamics models from multiple case study analysis might encounter researchers with some limitations as follows:

Biased Interpretations: Researcher's bias in interpreting data and concluding results might affect the reliability and accuracy of the research outcome. The bias would affect the interview process and its data analysis the most. On the other hand, the interviewees' bias might affect the validity and accuracy of the answers. That is why researchers must consider systematic methods to validate and cross-check the interview findings.

Accessibility: The overall approach is highly dependent on the arrangements of the selected case studies and the quality and accessibility of data. Hence, the progress speed of the projects, accessibility of experts and information and all associated restrictions would directly affect the research's speed, quality, and progression.

Conceptual Stretch: Conceptual validity refers to the identification of and measuring the indicators that best present the theoretical concepts. Many of the variables are soft data, which are not easily measurable. Hence, the researchers require to perform a "contextualised comparison". This will lead to search for analytically equivalent phenomena, even if they are expressed in different terms and contexts. This requires a detailed consideration of contextual factors, which is challenging to do in quantitative research, but is very common in case studies. Whereas quantitative research runs the risk of "conceptual stretching" by throwing together dissimilar cases to get a larger sample, case studies allow for conceptual refinements with a higher validity level over fewer cases (Starman 2013, p36).

Simplification: Generating causal loop diagrams should aim to reflect the true nature of the modelled system. This requires balancing the level of complexity and simplification of models, which is a function of the defined system boundary. Hence, the researchers must have proper knowledge about the subject of the study to enable them to define the right system boundary. Otherwise, the modelling process will not reflect the true nature of the problem.

Personal Perceptions: The approach relies on qualitative data analysis, also heavily dependents on individuals' perceptions. This applies to interviewees and researchers and might deliver distorted or inaccurate results. Hence, to mitigate the associated risks, researchers must combine manual and computer-aided qualitative data analysis and cross-check the findings from different sources. This must be acknowledged that mitigation methods cannot eliminate the associated risks completely. Hence for the research areas which are based on sensitive data, such as medical research, financial management studies and similar topics, focused group studies might be a safer choice with a fewer set of limitations. Extracting stock and flow diagrams (SFDs) from causal loop diagrams (CLDs) requires precise data analysis to identify the key variables, the leading stocks, and flows. Formulating the links (i.e., quantification) is not a straightforward process and is a time-taking and complex process. Defined formulas must reflect the variables' interactions, which can only be achieved by adequate iteration and improvement of formulas. This will create some limitations, which might affect the accuracy of the quantification process and results.

The above-mentioned limitations have been mitigated but could not be eliminated in this work. Therefore, researchers are recommended to (i) assess and analyse the potential impact of these limitations on the result and process, (ii) consider learning from the limitations imposed by circumstances to avoid them, and (iii) enhance the proposed mitigation techniques, for the future works on this research.

9.6 Future Work

It is important to note that, the scope and objectives do not include presenting accurate and definite formulations for the proposed SFDs. However, they are formulated accurately and based on a combination of some facts and assumptions for some exemplar changes or disruptions. Hence the formulated SFDs can be used and modified to analyse the resilience of any railway project management model. But in general, the key purpose of the thesis was to demonstrate the applicability of CLDs and SFDs.

To develop theories from real-life data, the author employed multiple case study analyses and individual cognitive interview techniques supported by applying a qualitative analysis tool (NVivo). Future researchers are recommended to adopt the author's methodology and develop CLD and SFD models to model the project management structure of a specific project (in-depth single case study). Shifting from multiple case study analysis toward the single case and from individual interviews to focus group interviews would provide researchers with an in-depth understanding of the project. This establishes the bedrock to write accurate numeric formulas for that specific project. This is inevitable, especially when projects tend to be investigated through the lifecycle operation and maintenance phases.

Future researchers must focus on developing more accurate formulas for each specific project. Developed formulas can be stored in a virtual library to be used by other modellers as reference formulas and be applied to future SFD models.

In this thesis, the author proposed a multi-dimensional model to measure the resilience of project management system. This model includes some impact factors, which need to be defined by future researchers and based on additional survey-based analysis of projects. To achieve this goal, researchers who are experts in their field need to adopt the proposed method presented in this thesis. But, to achieve detailed models capable of delivering accurate resilience factors and to design impact factors, the models need to be tailored to reflect the actual environment of that project.

It is recommended that the proposed methodology is adopted by future researchers who are interested in improving the configuration management of complex projects. The proposed approach is founded on system dynamics concepts; hence, it will inherently provide a systematic platform to document data and information. This approach can be considered a complementary tool to other existing configuration management tools (such as Jira). Further development of the approach, improving the accuracy of formulation and training people in project teams can offer an upgraded and reinforced layer of systematicity to the existing body of knowledge for project configuration management.

The following research avenues are recommended for future researchers, specifically in the railway industry field:

- How to provide railway systems with systematic change management tools providing impact analysis and informed decision-making features. This group of researchers can adopt the approach proposed in this thesis and try to design bespoke SFD interfaces for specific projects. The proposed approaches must apply to real-life rail projects to enhance their adaptive capacity and resilience.
- How to adopt the proposed approach and methodology to manage climate resilience and its impact on railway networks' performance, safety, and economic-environmental viability. This group of researchers will need to develop CLDs for climate changes and their impact on railway resilience factors. Identifying the key resilience factors will be the main challenge, as they will differ from one country to another.
- How to adopt the proposed approach to improve the resilience management of intermodal transportation systems. This group of researchers will need to focus on integrating railway networks with other modes of transportation. This will contribute to the quality of the decision-making and investment policies, and interoperability regulations.
- How to adopt the proposed approach to improve the functionality and resilience of the railway supply chain. Railway supply chain management requires modern approaches to be capable of managing emerging complexity and system dynamics can be adopted as a reliable tool to achieve this goal.
- Future researchers are recommended to adopt the author’s proposed approach presented in Chapter 5, to collect, analyse, verify, and validate data from multiple case studies, repeat the recommended steps and regenerate the existing CLDs and SFD. According to the process explained in Section 5.4.5, this will enhance the accuracy and quality of derived data, deliver a broader range of variables and interactions, and will capture a more in-depth

picture of the system. This will accordingly deliver CLDs and SFDs of a higher quality, which will provide modellers and system analysts with a more accurate analytic tool.

The concept of project management resilience is complex and less tangible to project management practitioners. The other potential research avenue would be to promote the application of the proposed modelling approach to real-life railway projects. Without establishing a link to establish the proposed technique for the railway projects, the industry will suffer from the same traditional linear project management approaches, and projects will not learn from each other's mistakes. Future academic researchers must keep the industrial partners involved in their research based on the methodology proposed and utilised in the author's research.

APPENDIX I - LIST OF PUBLICATIONS

Several publications have been developed during the research for this doctoral thesis. Some of the text in these publications has been included in the thesis, as indicated in the list below:

[1] Zolfaghari, M.R., and Schmid, F. 2015. 'Design Criteria for Tramway Systems'. In: Design and Management of Urban Railways (DMUR). Chapter 15. ISBN 13 9780952999751

[2] Zolfaghari, M.R. 2015. 'Aesthetic Design of Railway Infrastructures. In: Design and Management of Urban Railways (DMUR). Chapter 20. ISBN 13 9780952999751

[3] Zolfaghari, M.R., and Schmid, F. 2018. Explore the Fundamental of Change Strategy. Project Journal for APM. Pp:67-69. Issue 294, Spring 2018

[4] Zolfaghari, M.R., Roberts, C. and Schmid, F. (2016). Application of system dynamics tools to model 24-hour metro systems: Integration of system engineering and operation management. IEEE International Conference on Intelligent Rail Transportation (ICIRT). pp:224-230. DOI: 10.1109/ICIRT.2016.7588736

[5] Zolfaghari, M.R., Roberts, C., Jack, A. and Schmid, F. Application of System Dynamics Tools for Resilience Analysis of Metro Operations. Journal of Reliability Engineering & System Safety (Under Review).

APPENDIX II - AWARDS

[1] Overall Winner of ‘Image of Research Exhibition’, 2015, University of Birmingham

[2] The UK Finalist in Best Paper and Idea Competition, IET Railway Technical Professional Network, 2017

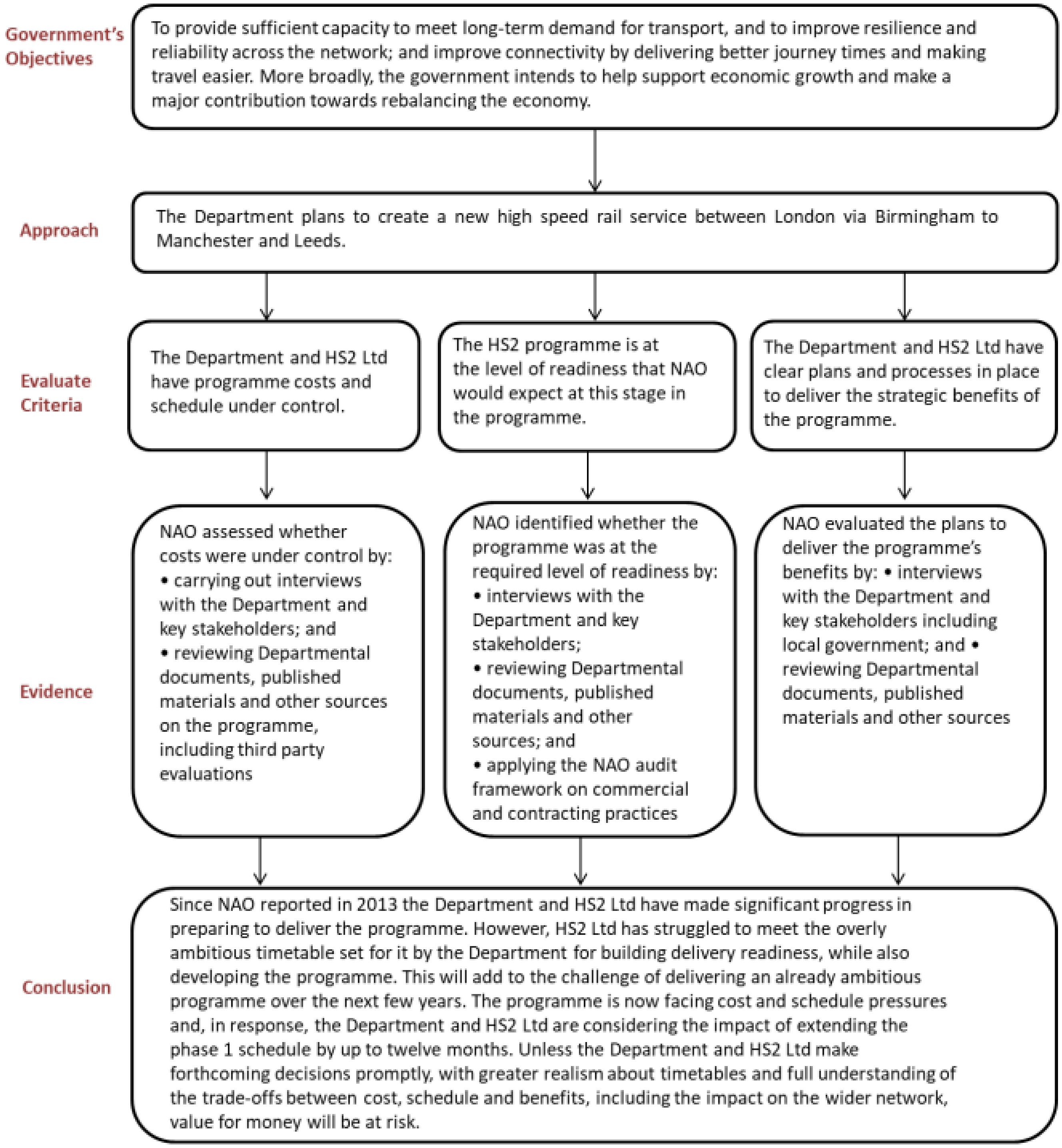
APPENDIX III - KEY REVIEWED PAPERS

Point of Departure	Highlighted Fact	Recommended Areas for Future Work
(Williams 2005)	"…for projects that are complex, uncertain, and time-limited, conventional methods might be inappropriate, and aspects of newer methodologies in which the project "emerges" rather than being fully preplanner might be more appropriate." (Page 497)	"Projects which exhibit specific characteristics, appear to lend themselves less to conventional methods (indeed, such methods can mislead) and newer methods might be more appropriate, such as opposing project-management methods often called agile or lean (Page 506)
Ackermann and Alexander (Ackermann and Alexander 2016), 2016	"To date, the application of causal mapping in projects has been researcher-led (for example Williams, 2004; Maytorena et al., 2004). There appear to be no examples of practitioner-led application. For the benefits of causal mapping to be extended to mainstream project management, rather than restricted to specialist use in complex projects, practitioner application will be necessary. Thus, another avenue for research concerns finding mechanisms to encourage the application of the approach by project management practitioners." (Page 899)	"There is a growing recognition within the project management community of the need for pluralism of approaches to create broader ranging perspectives on projects and thus improve our understandings of them. While the CLD technique is emerging within project management, the paper has suggested further avenues for research in which the technique could offer additional insights for both project theory and practice. These included the practitioner-led application of the technique, longitudinal analysis of projects and mixing the technique with more typical methods such as the survey design. Causal mapping is collaborative, engaged, draw on multiple perspectives and enables application." (Page 900).

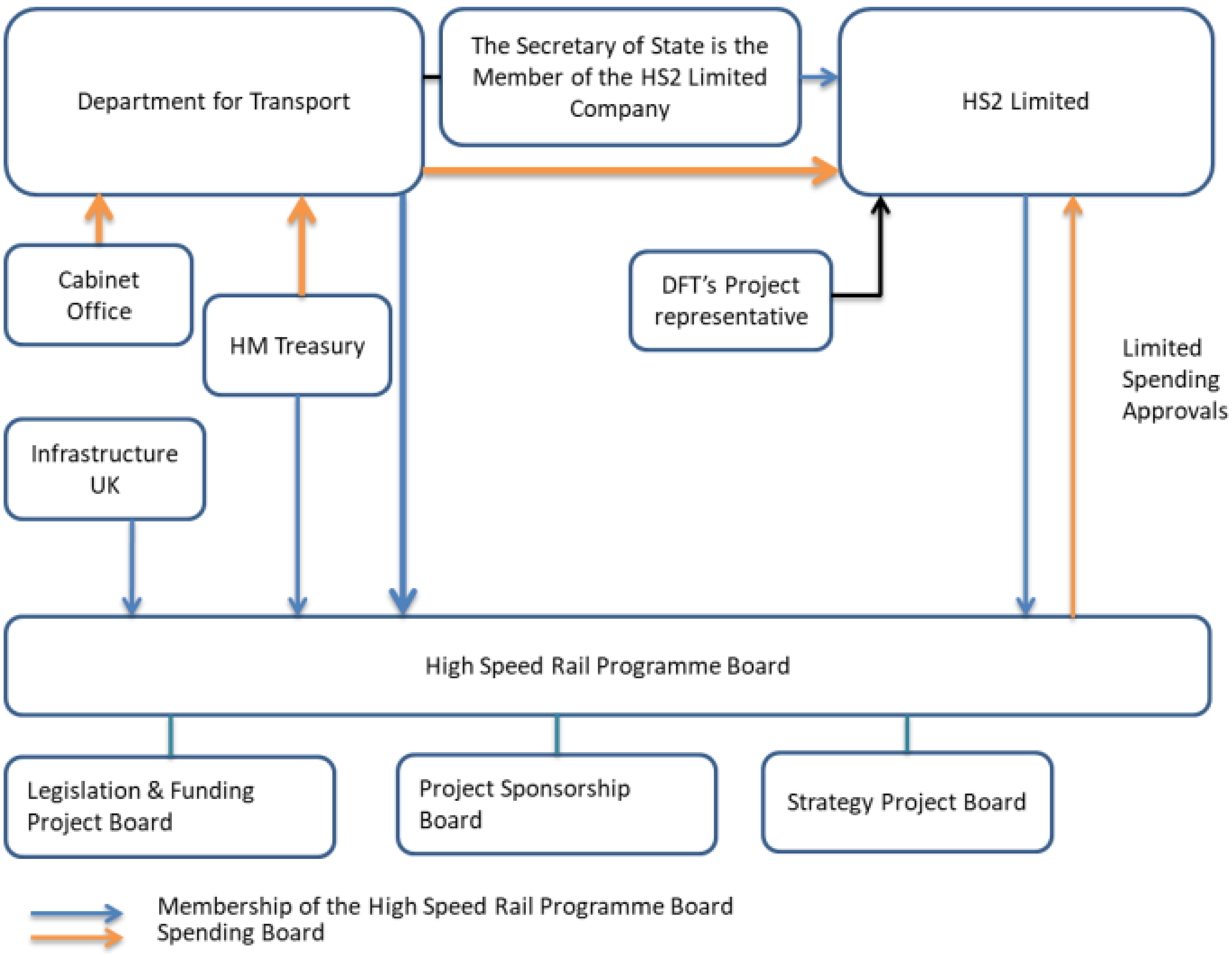
Point of Departure	Highlighted Fact	Recommended Areas for Future Work
(Maylor and Turner 2017)	"The relationship between complexity and response then is recursive and we propose conceptualising it as a duality, where the response is simultaneously enabled and constrained by the perceived complexity and vice versa." (Page 13) the development of the complexity "…Response framework allows researchers a theoretically and empirically grounded framework for analysing operation management practices in the context of projects. Secondly, the notion of complexity response as a linear system of cause and effect is an inadequate conceptualisation." (Page14)	"The understand – reduce – respond approach does not yet have comprehensive empirical data on whether it is effective (i.e., improves project performance) as part of regular project work. Many anecdotal accounts demonstrate this, but the collation of empirical data would be helpful in both building evidence for it as well as contributing to nuance the approach. Secondly, the responses to emergent complexities appear to be the biggest gap between the OM and PM literature and the practices are seen thus far. exploring the recursive nature of complexity and response appears to open many possibilities." (Page 15)
(San Cristóbal *et al.* 2018)	"When problems fundamentally dynamic are treated statically, delays and cost overruns are common. Traditional project management tools and techniques, based on the assumptions that a set of tasks can be discrete, with well-defined information about time, cost, and resources, and with extensive preplanning and control, are often found inadequate. These traditional approaches that utilise a static approach provide project managers with unrealistic estimations ignoring multiple feedback processes and nonlinear relationships of the project. The interrelationships between the components of a project are more complex that is suggested by traditional techniques, which makes them inadequate to the challenges of today's dynamic project environment." (Page 8)	"The new complex and dynamic environments require project managers to rethink the traditional definition of a project and the ways to manage it. Project managers must be able to make decisions in these dynamic yet unstable systems that are continuously changing and evolving randomly and are hard to predict, very different from the linear, predictable systems traditionally studied. To achieve this objective, more integrated approaches for managing projects in complex environments and new methods of planning, scheduling, executing, and controlling projects must be investigated. (Page 8)

APPENDIX IV- NAO AUDIT APPROACH

(NAO, 2014)



APPENDIX V - HS2 PROGRAMME GOVERNANCE STRUCTURE (NAO, 2014)



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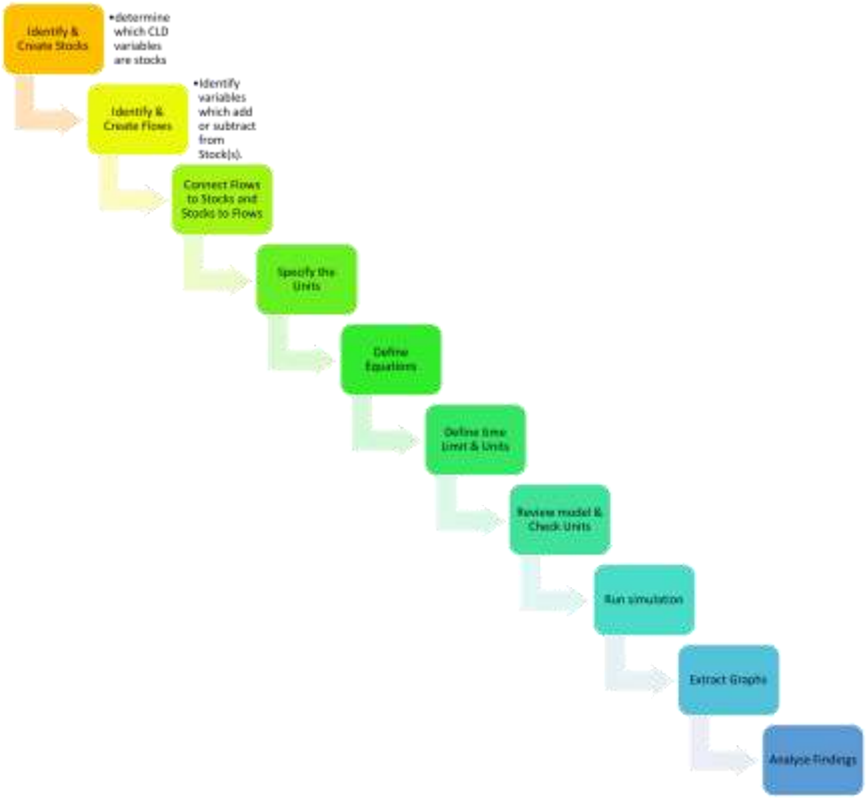
APPENDIX VI – VENSIM VARIABLES

- **Auxiliary**. Any dynamic variable that is computed from other variables at a given time. Auxiliaries are typically the most numerous variable type. An auxiliary variable has an expression involving other variables in its equation.
- **Constant**. A variable whose value does not change over time. Constants have numbers on the right side of their equations or can be defined using the GET XLS CONSTANTS function or the TABBED ARRAY function. A constant can be temporarily changed prior to simulating a model.
- **Data**. These have values that change over time, but do not depend on other model variables (except possibly other data). Data use an empty equation to denote raw data or a := equation to indicate the way in which they are derived. If a variable is used in a model, but not defined, it will be assumed exogenous and therefore treated as a Data variable. This makes it easy to run sections of a model without writing new equations.
- **Group**. Groups are not really variables, but a way to group different variables together. They have no values, but can be used to access collections of other variable types. Groups appear enclosed in special markers which consist of four (4) or more asterisks ****, or are defined by typing their name into the Group selector in the Equation Edit tool. Group names are shown preceded by a period . to prevent confusion with other variable names.
- **Initial**. Like a constant, except that it is the result of combining different variables at initialization time. Initials all have INITIAL or REINITIAL equations.
- **Level**. The dynamic variables in the model. Levels all have INTEG equations.
- **Lookup**. Nonlinear functions with numerical parameters (where the parameters are the x- and y-axis values). They are defined in equations beginning with a left parenthesis (and ending with a right parenthesis).
- **String Variable**. String Variables (also called String Constants take on a character string as a value. They are useful with the MESSAGE function and as labels in Venapps.
- **Subscript Element**. An element of a Subscript Range. These identify the meaning of specific values of a subscript. The Subscript Elements appear on the right hand side of a Subscript Range equation.
- **Subscript Range**. Rather than repeating the same equation with different names, you can write one equation using a subscript that takes on different values. We refer to variables in such an equation as subscripted, with one name representing more than one distinct concept. Subscript Ranges are defined using a special equation that begins with a colon :.
- **Time Base**. Like an Auxiliary, but with some special output and data interpretation features. These must use the TIME BASE equation as described in Chapter 4.
- **Units**. Units are defined as additional information about a model variable and can be used to check the model for dimensional consistency. Units are entered as an expression in the units field of an equation.
- **Unchangeable Constants:** These are Constants that can't be changed during simulation experiments. For example the number of days per year would sensibly be defined as an Unchangeable Constant. Equations for Unchangeable Constants are the same as those for Constants but use a double equal sign == for assignment.

APPENDIX VII – DEVELOPING STOCK & FLOW DIAGRAM



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