Integrating System Dynamics and Functional Resonance Analysis Method (FRAM) for Enhanced Complexity Management in Mega Construction Projects: A Case Study of the Channel Tunnel

by

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Intégration de la Dynamique des Systèmes et de la Méthode d'Analyse de Résonance Fonctionnelle (FRAM) pour une Meilleure Gestion de la Complexité dans les Mégaprojets de Construction: Une Étude de Cas du Tunnel sous la Manche

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RÉSUMÉ

Les mégaprojets de construction se caractérisent par leur vaste échelle et leur complexité, présentant des défis significatifs en matière de gestion de la complexité et de planification, souvent à l'origine de retards et de dépassements de budget. Cette recherche identifie la gestion de la complexité et de la planification comme des problèmes principaux dans les mégaprojets de construction. Les méthodologies traditionnelles de gestion de projet, comme celles du Project Management Body of Knowledge (PMBOK), échouent souvent à traiter les complexités non linéaires et les exigences de planification dynamique de ces projets de grande envergure. Cette étude explore des approches alternatives pour améliorer les pratiques de gestion de projet, en se concentrant sur l'intégration de la Méthode d'Analyse de Résonance Fonctionnelle (FRAM) et de la modélisation de la dynamique des systèmes.

La FRAM, développée par Hollnagel, propose une approche systémique pour gérer la complexité en analysant les variabilités dans les interactions de travail normales, ce qui la rend adaptée aux environnements complexes. La modélisation de la dynamique des systèmes offre un cadre robuste pour simuler les interactions complexes et les boucles de rétroaction au sein d'un projet, fournissant des informations précieuses sur les points de défaillance potentiels et les domaines nécessitant une intervention stratégique. En intégrant la dynamique des systèmes avec la FRAM, cette recherche développe une méthodologie de gestion de projet plus holistique et adaptative.

La méthodologie proposée est démontrée à travers une étude de cas du projet du tunnel sous la Manche, mettant en lumière l'application pratique et les avantages du modèle intégré. La validation qualitative du modèle a été réalisée par des entretiens avec des experts de l'industrie, confirmant sa pertinence et son applicabilité. Cependant, une validation quantitative est nécessaire pour confirmer davantage son exactitude et sa fiabilité. Les recherches futures devraient se concentrer sur l'extension du modèle de dynamique des systèmes pour inclure davantage de facteurs sous-jacents affectant le triangle de fer augmenté par le risque dans les projets de construction, ainsi que sur la modélisation, la performance et la validation quantitative du modèle.

Cette étude comble une lacune cruciale dans la littérature existante en proposant une intégration innovante de la FRAM avec la dynamique des systèmes, renforçant la résilience et la flexibilité des méthodologies de gestion de projet dans les mégaprojets de construction. Les résultats soulignent la nécessité de modèles plus adaptatifs et complets pour gérer efficacement les complexités et les risques associés aux projets d'infrastructure de grande envergure.

Mots-clés: Gestion de projet, compromis, FRAM, Dynamique des systèmes, PMBOK

Integrating System Dynamics and Functional Resonance Analysis Method (FRAM) for Enhanced Complexity Management in Mega Construction Projects: A Case Study of the Channel Tunnel

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ABSTRACT

Mega construction projects are characterized by their vast scales and complexities, presenting significant challenges in complexity management and scheduling, often leading to delays and budget overruns. This research identifies the management of complexity and scheduling as primary problems in mega construction projects. Traditional project management methodologies, like those in the Project Management Body of Knowledge (PMBOK), often fail to address the non-linear complexities and dynamic scheduling demands of such large-scale projects. This study explores alternative approaches to improve project management practices, focusing on the integration of the Functional Resonance Analysis Method (FRAM) and system dynamics modeling.

FRAM, developed by Hollnagel, offers a system thinking approach to manage complexity by analyzing variabilities within normal work interactions, making it suitable for complex environments. System dynamics modeling provides a robust framework for simulating complex interactions and feedback loops within a project, offering valuable insights into potential points of failure and areas requiring strategic intervention. By integrating system dynamics with FRAM, this research develops a more holistic and adaptive project management methodology.

The proposed methodology is demonstrated through a case study of the Channel Tunnel project, highlighting the practical application and benefits of the integrated model. The model's qualitative validation was achieved through interviews with industry experts, confirming its relevance and applicability. However, quantitative validation is necessary to further confirm its accuracy and reliability. Future research should focus on extending the system dynamics model to include more underlying factors affecting the risk-augmented iron triangle in construction projects, as well as performing and validating the model quantitatively.

This study bridges a crucial gap in existing literature by proposing an innovative integration of FRAM with system dynamics, enhancing the resilience and flexibility of project management methodologies in mega construction projects. The findings emphasize the need for more adaptive and comprehensive models to effectively manage the complexities and risks associated with large-scale infrastructure projects.

Keywords: Project management, FRAM, System Dynamics, PMBOK, Construction Project Management, Construction Project Complexity

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LIST OF ABBREVIATIONS

PMBOK	Project Management Body of Knowledge
CPM	Critical Path Method
PERT	Program Evaluation and Review Technique
FRAM	Functional Resonance Analysis Method
SD	System Dynamics
APM	Association of Project Management
MCA	Multiple Correspondence Analysis
AHP	Analytic Hierarchy Process
CEC	congress of evolutionary computation
ENAA	Engineering Advancement Association of Japan
FMV	FRAM Model Visualizer
FRAM	Functional Resonance Analysis Method
CPM	Construction Project Management
LC	Lean Construction
PCFA	Principal Component and Factor Analysis
PM	Project Management
PMI	Project Management Institute
WMM	Weighted Mean Method
TCQTP	Time Cost Quality Trade-off Problems
TCTP	Time Cost Trade-off Problems
BCWS	Budgeted Cost of Work Scheduled
ICT	Information and Communications Technology
SLR	Systematic Literature Review
AHP	Analytic Hierarchy Process
CLD	Causal Loop Diagram

GDP	Gross Domestic Product
KPI	Key Performance Indicators

INTRODUCTION

0.1 Research background

Mega construction projects are characterized by their vast scales and complexities, posing significant challenges in terms of complexity management and scheduling, often leading to delays and budget overruns. This research specifically identifies the management of complexity and scheduling in mega construction projects as the primary problem. Studies by Flyvbjerg (2014) highlight the trends and implications of mismanagement in large-scale infrastructure projects, including historical cases like the Channel Tunnel project. Traditional project management methodologies, such as those encapsulated in the Project Management Body of Knowledge (PMBOK), provide a structured approach to project management. However, their efficacy in dealing with the non-linear complexities and dynamic scheduling demands of mega projects is often limited, as discussed by Kerzner (2017), who critiques the rigidity of such frameworks in adapting to the dynamic needs of large-scale projects.

One method to cope with the challenges and complexities in mega construction projects is the Work Breakdown Structure (WBS), an essential tool. It effectively breaks down large-scale projects into manageable units, facilitating detailed task organization, resource allocation, and scheduling. The WBS allows project managers to decompose project deliverables into smaller, more manageable components, making it easier to oversee large and complex tasks. This hierarchical approach not only simplifies project management but also enhances clarity and improves communication among stakeholders, which is crucial in large-scale projects (Norman et al., 2008).

The Functional Resonance Analysis Method (FRAM), developed by Hollnagel (2014a), introduces a system thinking approach to manage complexity more effectively. FRAM illustrates how focusing on variabilities within normal work interactions can offer insights into potential non-linearities in project outcomes, making it suitable for complex environments like those seen in mega construction projects (Hollnagel, 2017a). This study addresses the research gap highlighted by the limited application of FRAM in the comprehensive management of mega projects. The integration of FRAM with PMBOK is suggested as a novel approach by recent studies, such as those by Woods (2017), which call for more adaptive project management models that combine systems thinking with traditional methodologies to enhance resilience and flexibility.

In addition to FRAM, system dynamics modeling presents a robust framework for understanding and managing the complexities inherent in mega construction projects. System dynamics enables the simulation of complex interactions and feedback loops within a project, offering valuable insights into potential points of failure and areas requiring strategic intervention. By integrating system dynamics with FRAM, this research aims to develop a more holistic and adaptive project management methodology. This combined approach leverages the strengths of both methods: FRAM's focus on variability and non-linearities, and system dynamics' capability to model and simulate complex systems over time.

The synthesis of system dynamics with FRAM enhances the ability to anticipate and mitigate emergent issues in mega projects, providing a dynamic model that adapts to changing project conditions. This integration is particularly beneficial in identifying and managing the ripple effects of project changes, ensuring that project managers can make informed decisions that consider both immediate and long-term impacts. The methodology section of this paper will outline the synthesis of system dynamics with FRAM, supported by a comprehensive literature review. The application will be demonstrated through a case study on the Channel Tunnel project, providing a practical example of the theoretical model's application and showcasing its utility in enhancing project management practices.

The construction industry, driven by the imperatives of cost, time, and quality—collectively known as the iron triangle—faces constant challenges in maintaining the delicate balance among these factors. System dynamics, a methodology grounded in the analysis of complex systems and their behaviors over time, provides a promising approach to enhance the predictive capabilities for these critical project parameters. This thesis aims to investigate the role of system dynamics in forecasting and managing the augmented risks associated with the iron triangle in construction project management.

The theoretical foundation of system dynamics, with its emphasis on feedback loops and stock-and-flow diagrams, allows for the creation of comprehensive models that simulate the interactions and dependencies among underlying factors affecting the risk augmented iron triangle elements. These models can illustrate how modifications in project scope, resource allocation, or schedule adjustments impact overall project performance in terms of quality, cost, and delivery time.

Recent academic efforts have applied system dynamics to various aspects of construction project management, showing its effectiveness in scenario planning and risk management. For example, research by Zou et al. (2007) demonstrated how system dynamics modeling could identify potential cost overruns and schedule delays before they become critical. Similarly, Xi and Poh, (2013) utilized system dynamics to optimize resource allocation and improve quality control processes, significantly enhancing project outcomes.

In the realm of construction and project planning, achieving optimal resource utilization presents a significant challenge for planners. They must navigate the delicate balance among various conflicting project aspects. An essential part of project management is understanding how to achieve an optimal balance between the project's objectives (Afshar et al., 2007).

The three criteria of time, cost, and quality collectively define project success, encapsulated in the concept known as the Iron Triangle. This framework, also referred to as the Triple Constraint or the Project Management Triangle, is fundamental to our comprehension of project success. The Iron Triangle represents the baseline criteria for measuring project performance – timely delivery, adherence to budget, and meeting predefined quality, performance, or scope levels. It has become the standard metric for assessing project performance routinely (Pollack et al., 2018).

Construction projects face inherent risks from their inception, necessitating a thoughtful assessment of risks and associated costs to mitigate them effectively. Identifying potential risks, estimating their impact, implementing preventative measures, and managing related expenses are crucial steps in minimizing errors. Real estate developers typically bear the cost of these risks, which can adversely affect profit margins not anticipated in advance. A proactive approach to risk management is crucial for cost reduction and error prevention. Despite the unique nature of construction projects, identifying recurring processes across phases can aid in scrutinizing project-specific risks, particularly during the implementation and realization phases (Schieg, 2006).

In contemporary times, construction projects are pivotal to the economic foundation of countries worldwide, leading governments to emphasize the expansion of this sector as a strategy for stimulating economic growth. According to the Project Management Institute (2021), project evaluation encompasses six fundamental pillars: Time, Cost, Quality—collectively known as the Iron Triangle—along with Risk, Requirements, and Scope. This thesis narrows its focus to four of these dimensions, introducing the concept of the Risk-augmented Iron Triangle, which includes time, cost, quality, and risk. Projects frequently grapple with challenges such as cost overruns, time delays, variations in quality, and unforeseen risks. Identifying and understanding the potential factors that affect project performance is crucial. In our study, these are referred to as underlying factors, which play a significant role in the overall success or failure of construction projects.

0.2 Problem Statement

Historically, projects have played a pivotal role in human endeavors, intertwining with the essentials of survival such as securing food and shelter. With the advent of industrialism in the 19th century, the standardization of products facilitated mass production, making goods accessible to a wider audience and signifying the importance of project management in economic growth (Cicmil et al., 2009).

Systems theory offers a lens to examine how components within a system interact to achieve a shared goal. This theoretical framework is particularly applicable to the study of projects within organizations, viewing them as complex systems with defined tasks allocated by sponsors or owners (Morris & Morris, 1994). Clarke (1999) argues that conventional project management methods may not effectively facilitate change, potentially leading to issues like project overload, cultural conflicts, and resistance to standardized procedures.

The Critical Path Method (CPM) has been crucial for optimizing project completion times and managing time/cost trade-offs. Nonetheless, its effectiveness is questioned when it comes to enhancing project performance quality, suggesting a gap in supporting project managers with decision-making regarding project progress (Kelley Jr & Walker, 1959; Kerzner, 2017).

Addressing project delivery times has been a consistent challenge, paralleled by developments in methods like CPM and the Program Evaluation and Review Technique

(PERT). The dynamic nature of project priorities—driven by political, economic, and social changes—necessitates efficient resource utilization and maximization of project revenues (Haghighi & Mousavi, 2019).

In efforts to expedite project delivery, the acceleration of certain activities might lead to higher costs, positing a compromise between time, cost, and quality. This scenario, known as the Time Cost Quality Trade-off Problem (TCQTP), highlights the complexity of project scheduling and resource allocation (Orm & Jeunet, 2018).

Conducting a cost sensitivity analysis allows for an examination of the impacts of activity duration changes, aiming to identify an optimal mix that minimizes project costs while balancing direct and indirect expenses. This approach supports project managers in making strategic resource allocation decisions within the constraints of time and budget (H. Li et al., 1999).

Traditional project management tools contrast with the system dynamics approach, which emphasizes the interconnections within a project. System dynamics provide strategic insights, while traditional methods offer operational support (Rodrigues & Bowers, 1996). Viewing project management within the framework of systems theory highlights the interrelatedness of subsystems and their collective pursuit of project goals (Love et al., 1999, 2002; Miller & Rice, 2013).

The concept of "dynamic engagement" introduced by Stoner et al. (1995) advocates for adaptable project management strategies in the face of external changes. This approach is essential for managing unforeseen project alterations and maintaining project planning and control amidst challenges.

This research endeavors to identify and understand the underlying factors affecting the risk-augmented Iron Triangle in construction projects through a systematic literature review. It aims to explore the impact of these factors on project success and investigate tools for visualizing and managing their effects. Furthermore, the study will consider the application of system dynamics to gauge the influence of these factors on the risk-augmented Iron Triangle, offering insights into strategic project management adaptations.

0.3 Motivation

Project management is an intricate blend of art, knowledge, and effort, aiming to optimally utilize available resources within the constraints of time and cost. Given the unique nature and specific conditions of each project, creating universal, comprehensive standards for project management is challenging. The core of project management standards lies in maintaining a delicate balance between time and cost, a feat often difficult to achieve in practice.

A direct correlation exists between reducing time and cost and the resultant quality of a project, necessitating a judicious balance among these elements. Despite clear goals set regarding time, cost, and quality at the outset of a project, numerous projects fail to meet these objectives, often exceeding budget and timeline constraints and falling short in quality. The complexity of project risk is a significant factor that has been underexplored in research due to its intricate implications on scheduling. It is important to distinguish between risks and uncertainties in project management. Risks are potential events with known probabilities that can impact the project's objectives, whereas uncertainties refer to unknown or unpredictable elements that may affect the project (Pmi, 2016).

Given these challenges, there is a pressing need to devise and recommend a methodology that aids project managers in achieving optimal scheduling, selecting suitable execution modes, and determining appropriate levels of activity compression. Such an approach aims to complete projects within the shortest possible time, at minimal cost, with desired quality, and with minimal risk exposure. Furthermore, a deep understanding of activity sequencing, schedule decomposition, and viewing a project as a dynamic system is essential for superior project management. Identifying the factors that influence the risk-augmented Iron Triangle and understanding their impacts are critical for effective project management.

This motivation underscores the significance of developing a comprehensive framework that not only addresses the conventional constraints of project management but also incorporates risk management as a central component of project planning and execution. By doing so, it endeavors to provide project managers with the tools and insights necessary for navigating the complexities of modern project environments, thereby enhancing the likelihood of project success.

0.4 Research Question

Can system dynamics be applied in project management to predict the behavior of the risk-augmented Iron Triangle in construction projects?

0.5 Research Objectives

1. **Identify Underlying Factors:** To identify the underlying factors that influence the Risk-augmented Iron Triangle in construction projects, providing a comprehensive understanding of the variables impacting time, cost, and quality.
2. **Tool Identification and Implementation:** To identify an appropriate tool for integrating system dynamics within project activities, considering the underlying factors and stages, and to implement this tool following the Project Management Body of Knowledge (PMBOK) guidelines.
3. **Utilization of System Dynamics:** To Utilize System Dynamics modeling to illustrate the impact of underlying factors on the Risk-augmented Iron Triangle, thereby offering insights into how changes in one dimension affect the others.
4. **Assessment of Applicability and Expert Interest:** To assess the applicability of System Dynamics in project management and gauge the interest among experts in employing such a methodology for improving project outcomes.

0.6 Research Plan

In order to address the research questions and attain the research objectives, the following research methodology, derived from Dresch (2015), was designed and adopted:

1. Awareness of the problem,
2. Decision on the problem to be solved,
3. Suggestion,
4. Development of models,
5. Evaluation to confirm the solution,
6. Decision on the solution to be adopted.

0.7 Thesis Structure

Introduction

- Background: Overview of challenges in managing complexity and scheduling in mega construction projects.
- Problem Statement: Identifying primary problems and limitations of traditional methodologies.
- Motivation: Importance of improving project management practices.
- Research Questions: Key questions addressed by the research.
- Objectives: Goals of the study.
- Thesis Structure: Outline of the chapters.

Literature Review

- Project Management Fundamentals: Definitions and PMBOK framework.
- The Iron Triangle: Challenges in balancing time, cost, quality, and risk.
- FRAM: Principles and applications in complexity management.
- System Dynamics: Concepts and benefits in project management.
- Integration: Combining FRAM and system dynamics, relevant studies.

Methodology

- Research Design: Approach and Justification.
- Data Collection: Sources and methods, surveys, and interviews.
- Model Development: Steps and tools for developing the integrated model.
- Validation: Qualitative and empirical validation.

Case Study: The Channel Tunnel Project

- Overview: Background and challenges of the project.
- Model Application: Implementation and analysis.
- Findings: Results and insights from the case study.

Results

- Model Validation: Summary of validation.
- Impact: Practical implications for managing complexity and scheduling.
- Discussion
- Comparison: Evaluation against traditional methodologies.
- Theoretical Contributions: New insights into complexity and risk management.

Conclusion

- Summary of Findings: Recap of key results.
- Future Work: Suggestions for extending the research.
- Final Remarks: Concluding thoughts on the research impact.

CHAPTER 1

METHODOLOGY

In the pursuit of robust and insightful research outcomes, the methodology employed holds paramount importance. A well-structured methodology not only facilitates the attainment of research objectives but also significantly influences the dependability of the findings. This chapter presents the research methodology adopted to answer the study's question. The research design is visualized in Figure 1.1, illustrating the comprehensive research map.

This design is adopted from Design Science Research by Takeda et al. (1990), encompassing a systematic approach to problem-solving in scientific research. The steps outlined by Takeda et al. (1990) are meticulously integrated into the structure of this study to ensure a rigorous and effective exploration of system dynamics within project management. The steps are as follows:

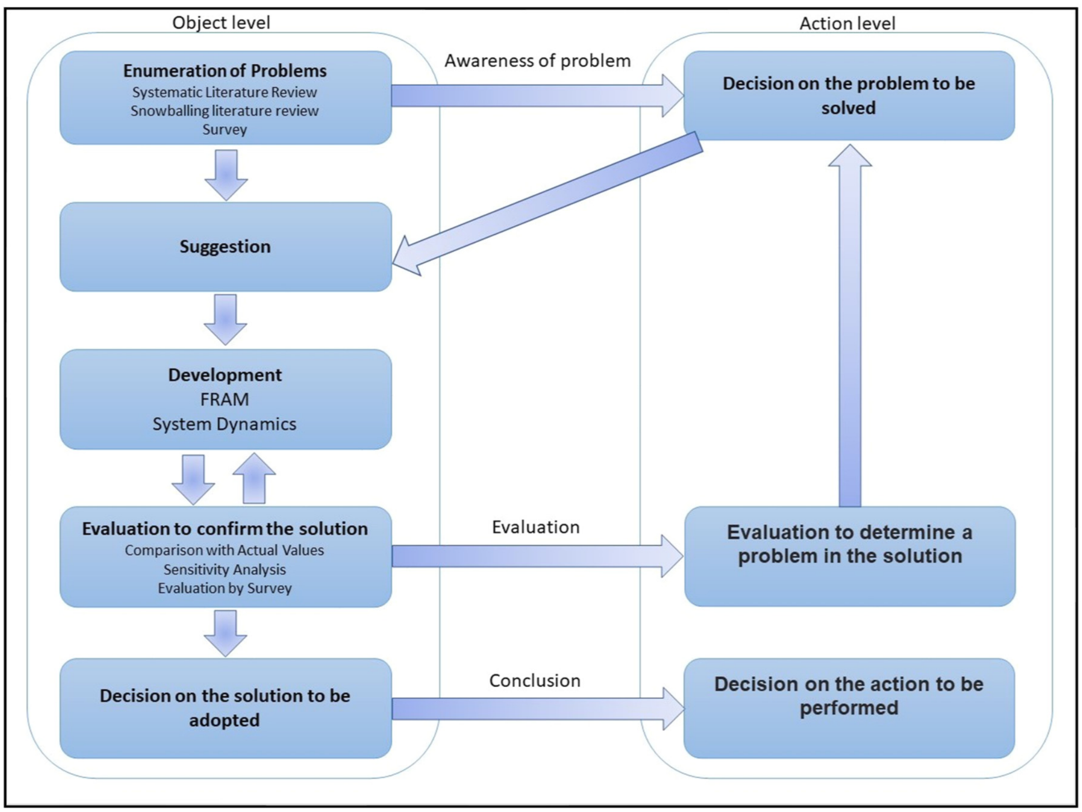


Figure 1.1 Design cycle
Taken from Takeda et al. (1990)

1. Awareness of the problem
    - Systematic literature review
    - Snowballing literature review
    - Survey
2. Decision on the problem to be solved
3. Suggestion
4. Development of models
    - FRAM
    - System Dynamics
5. Evaluation to confirm the solution
    - Comparison with actual values in case study
    - Sensitivity analysis
    - Survey
6. Decision on the solution to be adopted

1.1 Awareness of the problem

To identify and comprehend the problem, the following actions are undertaken:

1.1.1 Systematic literature review

A systematic literature review is employed as a rigorous method to identify, evaluate, and synthesize all relevant studies related to a specific research question or phenomenon. The motivations behind conducting such reviews vary, including the desire to summarize existing evidence on a topic, identify research gaps to suggest future study directions, and provide a comprehensive background for new research initiatives. Systematic reviews are instrumental in assessing the alignment of empirical evidence with theoretical hypotheses and can even facilitate the generation of new hypotheses (Kitchenham, 2004).

In conducting a systematic literature review, researchers define related keywords to perform exhaustive searches across multiple databases. These keywords encapsulate the core concepts of the research topic, enabling the retrieval of pertinent studies. Through the strategic selection and use of these keywords, the review aims to achieve an exhaustive examination of the literature, thus enriching the understanding of the subject matter.

1.1.2 Snowball literature review

Within the framework of systematic literature reviews, snowballing techniques—both backward and forward—are employed as supplementary methods to extend the literature corpus beyond initial database searches. Backward snowballing entails reviewing the references of initially retrieved articles to discover foundational, yet potentially overlooked, literature. Conversely, forward snowballing involves identifying subsequent articles that have cited the initial set of studies (Jalali & Wohlin, 2012). This technique is beneficial for uncovering more recent research that builds upon the initially identified works. By integrating both backward and forward snowballing with systematic database searches, the study aims to capture a comprehensive range of relevant literature, ensuring a deep and broad understanding of the field related to the research topic.

1.1.3 Finding keywords

In the process of conducting a systematic literature review, identifying relevant keywords associated with the study's topic and the problem was a critical step. This involved a detailed examination of scholarly articles, journals, and other academic publications to identify recurring themes and central concepts related to the research question. The search spanned an extensive range of literature available on databases such as Web of Science, Scopus, and Google Scholar, covering studies from 1970 to 2023.

The initial phase of the keyword search focused on articles containing terms directly related to the core methodologies and theoretical foundations of the study, such as 'system dynamics,' 'project management,' and 'system theory.' To refine the search and ensure a focused review relevant to the specific aspects of the research inquiry, additional keywords were subsequently included. These included 'iron triangle,' 'risk management,' and the combination 'iron triangle AND PMBOK.' The inclusion of these keywords aimed to narrow down the literature to those works most pertinent to understanding the application of system dynamics in project management, particularly within the framework of the Iron Triangle and PMBOK guidelines.

By systematically identifying and employing these keywords, the literature review aimed to capture a comprehensive body of knowledge, ensuring a robust foundation for exploring the intersection of system dynamics, project management, and risk within the context of construction projects.

1.1.4 Survey

Following a thorough literature review and the identification of specific issues related to the research topic, a survey was deployed to confirm these findings. The survey was designed to capture participants' perceptions regarding the existence and significance of the identified problems, aiming to validate the preliminary insights gained from the systematic literature review. Participants were invited to share their opinions on the challenges identified, contributing to a more nuanced understanding of the issues at hand.

This approach was intended to not only validate the existence of these problems but also to gauge their perceived impact within the field. By engaging directly with individuals knowledgeable about or affected by these issues, the survey provided a means to collect empirical evidence supporting the initial literature-based findings. The insights gained from participants' responses were instrumental in reinforcing the study's foundational premises and informed the subsequent stages of research, including the development of potential solutions to the addressed challenges.

By employing a straightforward, yet effective, survey methodology, the study aimed to bridge the gap between theoretical literature findings and practical, experiential knowledge from the field, laying a solid foundation for further investigation.

1.1.4.1 Determining sample size

1.1.4.1.1 Empirical Saturation Method

In qualitative research, determining the appropriate sample size is crucial for ensuring the depth and relevance of data collected. The empirical saturation method is a strategic approach employed to ascertain the adequacy of sample size for comprehensive data collection. This method hinges on the principle of continuing data collection until new information ceases to emerge, indicating that the data has reached a point of saturation. This point is characterized by the recurrence or redundancy of insights and information provided by participants, signaling that additional data is unlikely to yield new, substantial findings.

The empirical saturation approach is particularly valuable in exploratory research aimed at thoroughly understanding a phenomenon, discovering underlying insights, or validating theoretical propositions. It aligns with the goals of this study, which seeks to explore and confirm identified issues within the field. By adopting this approach, the research ensures that the sample size is sufficient to achieve a deep and comprehensive understanding of the subject matter. It avoids the pitfalls of excessive data collection, focusing instead on gathering meaningful, impactful data until the saturation point is reached.

Through the application of the empirical saturation method, this study secures a sample size that is both effective and efficient, enabling a thorough exploration of the research topic while ensuring the quality and relevance of the data collected.

1.1.4.1.2 The rationale for choosing the empirical saturation approach

The empirical saturation method was chosen to deeply investigate the impacts on cost, time, risk, and quality in construction projects, aiming to validate known underlying factors and uncover new insights. This method, ideal for our exploratory goals, allows for flexible sample size adjustments based on participant feedback, ensuring comprehensive coverage of the topic without collecting redundant data.

By adopting this approach, we ensure our data collection is both thorough and efficient, ceasing once a 95% threshold of critical information has been reached. This threshold reflects our commitment to resource efficiency and the avoidance of unnecessary data gathering, striking a balance between depth of understanding and research practicality.

1.1.4.2 Respondent's characteristic

The survey targets respondents with specific traits to validate a system dynamic model examining project management's cost, time, risk, and quality dynamics. These characteristics are essential for ensuring the survey's findings are credible and relevant:

1. Expertise in Project Management: Selected for their deep understanding of project complexities.
2. Diverse Professional Backgrounds: To capture a wide range of industry perspectives.
3. Relevant Academic and Professional Credentials: Indicating formal training and competence in project management.
4. Practical Experience: Including practitioners actively engaged in project management to draw on real-world insights.
5. Decision-making Roles: Chosen for their ability to effectively evaluate the model's applicability and implications.
6. Familiarity with System Dynamics Modeling: Ensuring they can assess the model's practical value accurately.

By carefully selecting respondents with these qualifications, the survey aims to gather informed feedback on the system dynamics model from a representative expert panel. Their collective expertise and diverse views are crucial for evaluating the model's accuracy and potential to improve project management practices across various contexts.

1.1.4.3 Survey Design

An online survey was developed using Google Forms to explore the identified issues within project management. This platform was chosen for its broad accessibility, facilitating participation from respondents both within Canada and internationally. The survey aimed to validate the findings from the literature review regarding the challenges in managing the cost, time, risk, and quality dimensions of projects.

To invite participants, emails and LinkedIn messages were sent, briefly explaining the study's objectives and the importance of their contributions. To accommodate respondents in Quebec Province, the survey was available in both English and French.

The survey was structured into three main sections:

1. Introduction: Outlined the study's purpose, participation benefits, and authorization by the university research ethics committee.
2. Demographics: Gathered respondent information to match the survey with the target expert profile.
3. Underlying Factors: Presented factors from the literature review and solicited suggestions for any additional factors influencing the project management dimensions. A short answer option allowed for detailed responses, supported by a reference table of key factors.

The survey comprised four questions, designed to efficiently capture the prevalence and perception of the identified project management challenges among professionals in the field.

1.1.4.4 Searching for potential respondents

The initial step involved compiling a list of companies engaged in mega construction projects globally. This task utilized Google Search, Wikipedia, LinkedIn, and additional platforms to identify companies and potential respondent profiles within them. Subsequently, the search expanded to acquiring contact information, focusing on obtaining company email addresses.

Communications were directed to the human resources departments of these companies, providing them with the survey link and requesting dissemination among employees suited for the survey, such as engineers and project managers. In parallel, targeted outreach was conducted through LinkedIn, where email addresses of specific engineers, project managers, and industry experts were collected. These professionals received direct invitations to participate in the survey, along with the survey link, via email.

This approach aimed to engage a diverse and informed group of respondents from across the construction industry, enhancing the relevance and depth of the survey data collected.

1.1.4.5 Sending process

The survey, hosted on Google Forms, included a concise introduction outlining its objectives and ethical considerations. For accessibility, both English and French versions of the survey were prepared (see appendix II for additional survey details). These were shared through invitation emails, which contained links to the respective survey versions.

The distribution phase spanned from May 5th to June 22, 2023, focusing on reaching professionals at prominent companies in Canada, North America, and multinational enterprises. Additionally, targeted invitations were sent via LinkedIn to engineers and project managers, emphasizing the research nature of the survey and assuring the confidentiality of participants' responses. This method aimed to ensure a wide-reaching and ethically responsible approach to gathering valuable insights from across the construction industry.

1.2 Decision on the problem to be solved

At this stage, a specific issue identified within the domain undergoes a thorough examination for potential investigation and resolution. Utilizing insights from systematic literature reviews and surveys, a critical analysis will be performed to assess the problem's significance and the practicality of addressing it. Considerations will include the problem's urgency, its relevance to the field, and the availability of necessary resources. This decision-making process aims to pinpoint the primary issue for focus. It sets a targeted course for the research, guaranteeing that efforts to concentrate on a significant, well-defined challenge relevant to the selected domain.

1.3 Suggestion

This stage of the research methodology concentrates on formulating potential solutions or interventions for the pinpointed problem, drawing upon insights from earlier phases of research. It encompasses a detailed synthesis of findings from systematic and snowballing literature reviews, alongside surveys from the problem awareness phase, to evaluate applicable suggestions from existing studies. This step entails a thorough investigation of established methodologies and strategies that have been applied in similar contexts. Should existing literature not offer direct solutions or if the problem has not been precisely defined previously, the research will shift focus to developing innovative approaches tailored to address the specific challenge at hand. Characterized by both creative and critical engagement with existing knowledge, this stage aims to generate actionable recommendations for the identified issue or to introduce new solutions to bridge gaps found within the current body of research.

1.4 Development

1.4.1 Identifying a tool to understand and visualize problem

During the development phase, the focus is on selecting an appropriate tool that aligns with the specific needs of our project-based case study, especially regarding the Risk Augmented Iron Triangle framework. The goal is to find a tool that allows for the effective visualization and analysis of the interactions between key factors influencing the Risk Augmented Iron Triangle. This process involves a thorough review of various analytical and visualization tools to evaluate their compatibility with the project's requirements. The ideal tool should possess strong capabilities for depicting the relationships and dependencies among the underlying factors that impact risk within the project, facilitating a deeper understanding of the complex dynamics at play.

1.4.1.1 FRAM

For our study, the Functional Resonance Analysis Method (FRAM) was operationalized using the FRAM Model Visualizer (FMV) software 0.4.0, sourced from its official platform at functionalresonance.com.

FMV is designed specifically to support the visualization, development, and management of FRAM models. It enables the depiction of relationships, dependencies, and interactions among system functions in line with FRAM principles. The software allows for the creation of graphical representations of FRAM models, enhancing the understanding of how functions interrelate and the pathways through which errors might propagate within a system. FMV is equipped with visual diagraming tools, features for modeling and simulating various scenarios, and capabilities for analyzing or assessing system behaviors using the FRAM approach.

1.4.1.2 Case Study

This study delves into a case study for three primary reasons:

1. Understanding Project Management: To gain a deeper comprehension of project management process groups and the knowledge areas as per PMBOK.

2. Implementing FRAM Model: Identifying activity sequences and correlations in a real project and applying the FRAM model.

3. System Dynamics Implementation: Utilizing the System Dynamics model to establish connections between activities derived from FRAM, and determining root causes related to cost, time, quality, and risk found in literature reviews.

The chosen case study is the Channel Tunnel project, the study carried out by Anbari et al. (2005), a monumental endeavor aimed at connecting England and France via a tunnel. Notably, it stands as one of the largest privately funded construction projects ever attempted. The project involved collaboration between two national governments, funding from banking institutions, multiple contractors, and several regulatory bodies. Moreover, due to unforeseen conditions and the demands of various stakeholders, significant technological adaptations were necessary during the construction and engineering phases.

Managing a project of this magnitude posed considerable challenges, even assuming seamless operations. As revealed in this case study, numerous factors influenced the project's trajectory significantly. Despite its eventual completion, the Channel project suffered delays and exceeded its budget. The case study thoroughly discusses and analyzes the reasons behind missing critical cost and schedule deadlines, addressing various factors related to Project Management Knowledge Areas and processes.

This case study encompasses diverse Project Management Knowledge Areas (Guide, 2008) across four project phases: inception, development, implementation, and closeout. It delves into the activities, achievements, and deficiencies in performance within the initiating, planning, executing, monitoring and controlling, and closing processes within each project phase.

1.4.2 Designing System Dynamics

This phase is dedicated to constructing a system dynamic model to meticulously analyze the behavior of each component within the system and their interrelations. Utilizing system dynamics methodology, the goal is to develop a holistic framework that encapsulates the intricacies of the Risk Augmented Iron Triangle along with its foundational factors. Through this approach, the study seeks to illustrate the complex dynamics governing the interactions among risk augmented iron triangle in project management, providing insights into how these elements collectively influence project outcomes.

1.4.2.1 System Dynamics modeling software

For this study, the System Dynamics model was developed using VENSIM PLE version 7.3.5. VENSIM is a software tool designed specifically for system dynamics modeling and simulation, facilitating the understanding of complex systems, their behavior over time, and the exploration of various scenarios through simulations.

System dynamics modeling represents real-world systems via feedback loops and stocks to depict their behavior dynamically. VENSIM's visual interface allows users to build models by outlining the relationships between system components. This capability enables simulations to demonstrate the impact of changes within one part of the system on the overall system dynamics, making it an invaluable tool for analyzing the intricate interactions within the Risk Augmented Iron Triangle.

1.5 Evaluation to confirm the solution

1.5.1 Comparison to actual values

During this phase, the study involves a detailed comparison between data generated by the model and actual data from the case study project. The purpose of this comparison is to evaluate the model's accuracy and reliability in mirroring real-world scenarios and outcomes, providing insights into the model's effectiveness in predicting project dynamics within the framework of the Risk Augmented Iron Triangle.

1.5.2 Sensitivity Analysis

In this stage, the research undertakes a sensitivity analysis by executing various scenarios to understand the model's responsiveness. This involves altering input parameters and underlying assumptions to observe how such changes impact the model's outputs. The goal is to evaluate the model's reliability and robustness, ensuring it delivers consistent and credible outcomes under a range of conditions. Sensitivity analysis is crucial for confirming that the model can accurately reflect the dynamics of project management, even when subjected to fluctuating variables and assumptions.

1.5.3 Evaluation of model reliability by survey

This phase focuses on assessing the model's overall reliability and its practical applicability through a survey targeting experts and stakeholders in the field. The survey will measure their interest in utilizing the model for real-world projects, aiming to validate the model's usefulness and effectiveness in addressing the complexities of project management. This evaluation seeks to understand the model's relevance and potential impact on enhancing project outcomes by incorporating the perspectives of those with direct experience in the domain.

1.5.3.1 Evaluation survey design

The evaluation survey, devised for model validation, was structured into three main sections (see appendix II for more details):

1. Introduction: This section introduced the study's objectives, highlighted the benefits of participation, and mentioned the oversight by the university committee, setting a clear context for the respondents.
2. Model Explanation: Detailed the system dynamics model showcased within the survey, including the specific scenarios it was applied to. This aimed to familiarize respondents with the model's functionality and its potential applications.
3. Demographic Information: Gathered information about the respondents to verify that their profiles aligned with the desired characteristics for the study, ensuring the relevance and accuracy of feedback.

The survey culminated with a series of questions designed to evaluate the model:

- Likert Scale Questions: Five questions measured the applicability of and interest in using the System Dynamics method for project management, allowing for quantifiable feedback.
- Open-Ended Question: Invited participants to offer suggestions for the model's improvement and practical application in projects, seeking qualitative insights into enhancing its utility and effectiveness.
- This survey design aimed to systematically gather expert opinions on the model's reliability, applicability, and potential areas for refinement.

1.5.3.2 Sending process

The evaluation survey was created using Google Forms, with a clear description of its purpose and its compliance with university research ethics guidelines. To accommodate respondents, the survey was made available in both French and English, with links included in an invitation email designed for this purpose.

The outreach effort spanned from September 8th to November 13, 2023, focusing on large corporations within Canada and North America, as well as multinational companies. The criteria for selecting these corporations included their involvement in mega construction projects, their size in terms of revenue and number of employees, and their influence in the industry. Additionally, targeted invitations were sent through LinkedIn to engineers and project managers, highlighting the survey's aim for academic research purposes and ensuring the confidentiality of the data provided by the respondents.

This targeted distribution strategy was intended to gather insights from a broad and knowledgeable respondent base, thereby enhancing the survey's contribution to understanding the system dynamics model's effectiveness in practical project management environments.

1.5.3.3 Survey Data Analysis Software

For the analysis of survey data, we utilized the Multiple Correspondence Analysis (MCA) method, facilitated by XLSTAT software, version 5.2.1413.0. XLSTAT is a versatile statistical analysis tool that integrates seamlessly with Microsoft Excel, thereby augmenting Excel's native functionalities with an extensive suite of advanced statistical and data analysis features. As an add-on for Excel, XLSTAT broadens the scope of data manipulation and analysis possibilities available to researchers, offering tools for descriptive statistics, regression analysis, multivariate analysis, time series analysis, among others. This software choice enabled us to perform in-depth analysis of the survey responses, leveraging its capabilities to extract meaningful insights from the collected data.

CHAPTER 2

LITERATURE AND REVIEW

2.1 Definitions

2.1.1 Project

PMI PMBOK (2021) “A project is a short-term effort to develop something unique, like a product, service, or outcome. Its temporary nature means there's a clear start and finish to the work involved or a stage within the work. Projects can be independent or part of a larger program or group of projects. “

APM BOK (2012) “A project is a specific task aimed at reaching planned goals, which could involve producing certain results. It's considered successful if it meets its objectives within an agreed-upon timeframe and budget.”

2.1.2 Project Management

Project management is the application of knowledge, skills, tools, and techniques to project activities with the aim of meeting project requirements. It involves guiding the project work to deliver the intended outcomes. Project teams can achieve these outcomes through a broad range of approaches, including predictive, hybrid, and adaptive methodologies (Project Management Institute, 2021)

2.1.3 Project management process groups

Project management processes are structured into logical groupings of inputs, tools, techniques, and outputs tailored to meet the specific needs of the organization, stakeholders, and the project. It's important to note that these groups of processes do not constitute project phases; instead, they interact within each phase of a project life cycle. It's entirely feasible for all processes to occur within a single phase, and they may be iterated throughout the phase or life cycle. The frequency of iterations and interactions varies depending on the project's requirements.

Projects that adhere to a process-based approach often adopt the following five process groupings as an organizational framework:

- **Initiating:** These processes define a new project or a new phase of an existing project by obtaining authorization to commence the project or phase.

- **Planning:** Processes within this grouping establish the project's scope, refine objectives, and define the necessary course of action to achieve the project's goals.
- **Executing:** Processes in this group carry out the work defined in the project management plan to fulfill project requirements.
- **Monitoring and controlling**: Processes in this group track, review, and regulate project progress and performance, identifying areas where plan adjustments are necessary and initiating corresponding changes.
- **Closing:** Processes within this group formally complete or close a project, phase, or contract.

These process groups operate independently of delivery approaches, application areas (e.g., marketing, information services, accounting), or industries (e.g., construction, aerospace, telecommunications). In a process-based approach, the output of one process typically serves as an input to another process or becomes a deliverable of the project or project phase. For instance, outputs such as a project management plan and project documents produced in the planning process grouping serve as inputs to the executing process grouping, where updates are made to associated artifacts (Guide, 2008).

2.1.4 Project success

Project success criteria have been measured in various ways. While conventional measurement methods have focused on tangible, current thinking suggests that project success is best assessed by stakeholders, particularly the primary sponsor (R. Turner & Zolin, 2012). According to Shenhar et al. (1997), assessing success is time-dependent: "As time progresses, it becomes less significant whether the project has adhered to its resource constraints; typically, after approximately one year, this becomes entirely irrelevant." After the project is completed, the significance of the second dimension, which pertains to the impact on the customer and customer satisfaction, becomes more pronounced. Turner & Serrador (2015) imply that project success extends beyond the traditional 'iron triangle' concept of project efficiency. It encompasses a broader spectrum of factors. While project efficiency correlates with project success, analysis reveals that efficiency alone does not encapsulate all aspects of project success, nor can it be disregarded.

2.1.5 Iron Triangle

In numerous instances, three questions have been employed to assess whether a project succeeded or failed shortly after its completion. Did it adhere to the schedule, stay within budget, and meet the specified requirements for the delivered product? Conventionally, if any of these criteria are not met, the entire project may be deemed a failure (even if it fulfills the other two). These three elements (see Figure 2.1) are often referred to as "the Iron Triangle of project management" due to their tight integration (Barnes, 1988; Olsen, 1971).

While the three constraints are pertinent to various aspects of project management success, the intricacies of how the triangle of factors interacts are not immediately obvious (Weaver, 2012).

For instance, there's an inverse connection between output and the other two dimensions: reduced output may be unfavorable, yet less time or cost could be advantageous. While expanding the scope usually results in increased time and cost, rises in cost or timeframe might not directly correspond to scope. Efforts to shorten a project's duration might elevate its cost and diminish its scope. Even a slight budget reduction can significantly impact a project's scope and timeframe (Bronte-Stewart, 2015).

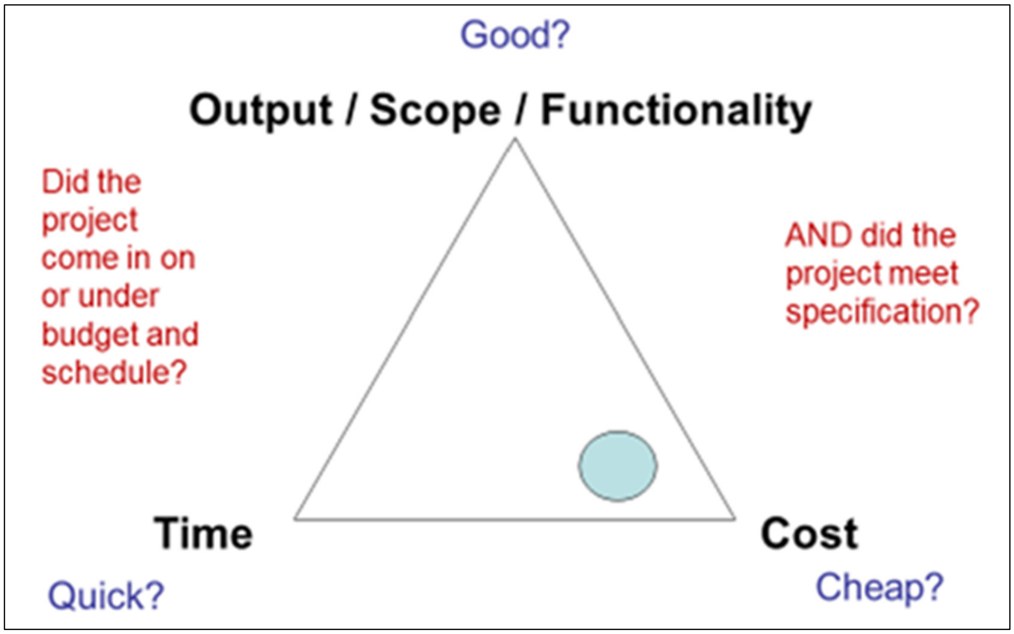


Figure 2.1 Iron Triangle
Taken from Bronte-Stewart, M. (2015)

According to Bronte (2015), the iron triangle falls short in showing the overall project status. Changing the triangle's shape might give a basic view of actual progress versus planned estimates, but it wouldn't capture the full complexity of success and failure. While tools like Gantt charts, financial status graphs, and product status matrices help to illustrate different parts of a project's life, it would be better if these aspects could be shown side by side for easier comparison. This could be especially helpful if included in a broader project status model that covers other important information like benefits, risks, stakeholder acceptance, and the project quality plan.

According to PMBOK, projects are evaluated based on six criteria: Time, Budget, Scope, Requirements, Quality, and Risk. In this study, our focus is on visualizing four of these aspects. It would be beneficial to clarify these four aspects:

Time: The time needed to complete the project and deliver the product(s) is typically calculated and transformed into a schedule, which may incorporate milestones and other developmental details. This information is commonly presented through schedules and plans on Gantt charts, which can be linked to Work or Product Breakdown structures.

Cost/Budget: The allocated project budget encompasses all cost estimates, which may be further itemized into detailed expenditure predictions, potentially forming a BCWS (Budgeted Cost of Work Scheduled). It also involves a projection of spending over time.

Quality: Quality outlines and describes the characteristics and attributes of a product. It offers a clear definition of the standards against which the project's products are evaluated. Typically, various parties, including those reliant on, dependent upon, or possibly opposed to, the implications and results of any ICT project (Information and Communications Technology), are involved. Such projects often entail organizational changes and may disturb the existing situation. Different stakeholders may have varying perspectives on their expectations and concerns regarding the project. Each stakeholder group may assess the project's success based on different sentiments, beliefs, and metrics.

Risk: Risk identification, assessment, prioritization, and management involve evaluating the likelihood of perceived threats occurring and the extent of their impact. This analysis also considers the project's methodology and team. It occurs before and during the project, with the maintenance of a risk register, and may also be conducted after the project concludes. This retrospective analysis reflects on the entire project experience and seeks to extract lessons learned. It actively engages with the opinions and experiences of the project team. Area of review might include the effectiveness and efficiency of techniques and tools, team performance (such as governance, leadership, group size and composition, skills, technical strengths and weaknesses, training, collaboration, teamwork), project management processes and methods, project administration (involving the collection, recording, monitoring, and control of project aspects), risk anticipation and mitigation strategies, the effort required to rectify errors, and the suitability of the methodology used.

Scope: The delineation of the project's deliverables and the scope of the tasks to be completed. Clarifying what is to be encompassed and what is to be excluded.

2.1.6 Project management knowledge areas, process groups and processes

The application of project management methods and processes in the construction industry is predominantly based on widely accepted best practices that are generally applicable to most projects in most instances. However, what sets this industry apart is the unique manner in which these practices are implemented.

Although the Knowledge Areas outlined in the PMBOK Guide are relevant to construction projects, certain modifications need to be made to accommodate the distinctive attributes, practices, and applications across both the Process Groups and Knowledge Areas. The actions derived from these Knowledge Areas are subsequently implemented in each distinct phase of the construction project.

It is crucial to emphasize that the project manager in the construction field carries the responsibility of not only understanding the needs of the project owner but also comprehending how common practices and specific construction applications should be appropriately employed.

To aid practitioners in fulfilling this responsibility, Table 2.1 has been devised, which aligns the process groups with the corresponding Knowledge Areas.

Table 2.1 Process Groups and Knowledge Areas Mapping
Taken from PMBOK, construction management extension (2016)

Knowledge Areas		Project Management Process Groups				
		Initiating Process Group	**Planning Process Group**	**Executing Process Group**	**Monitoring and Controlling Process Group**	**Closing Process Group**
1	**Project Integration Management**	■	■	■	■	■
2	**Project Scope Management**	■	■		■	
3	**Project Schedule Management**		■		■	
4	**Project Cost Management**		■		■	
5	**Project Quality Management**		■	■	■	
6	**Project Resource Management**		■	■		•
7	**Project Communications Management**		■	■	■	
8	**Project Risk Management**		■	■	■	
9	**Project Procurement Management**		■	■	■	■
10	**Project Stakeholder Management**	■	■	■	■	
11	**Project Health, Safety, Security and Environmental Management**		■	•	•	
12	**Project Financial Management**		■		•	
■ PMBOK Guide Knowledge Areas and Process Groups Included in Construction Extension • Construction Specific Knowledge Areas and Process Groups Unique to Construction Extension						

2.1.7 The concept of Trade-off

In project management, a trade-off refers to the decision-making process that involves balancing between competing objectives, constraints, or requirements in a project. Trade-offs often require compromising on one aspect to achieve gains in another, recognizing that resources like time, cost, scope, and quality are limited and can conflict with one another.

The most common trade-off in project management is between time, cost, and scope/quality, known as the project management triangle or iron triangle (Bragadin et al., 2022). Trade-offs represent a fundamental aspect of decision-making across various fields, including economics, project management, and engineering. A trade-off occurs when choosing one option results in the compromise of another, essentially requiring a balance between two or more competing factors or objectives. This balancing act is critical for achieving the most effective and efficient outcomes in projects and organizational strategies (Kerzner, 2017).

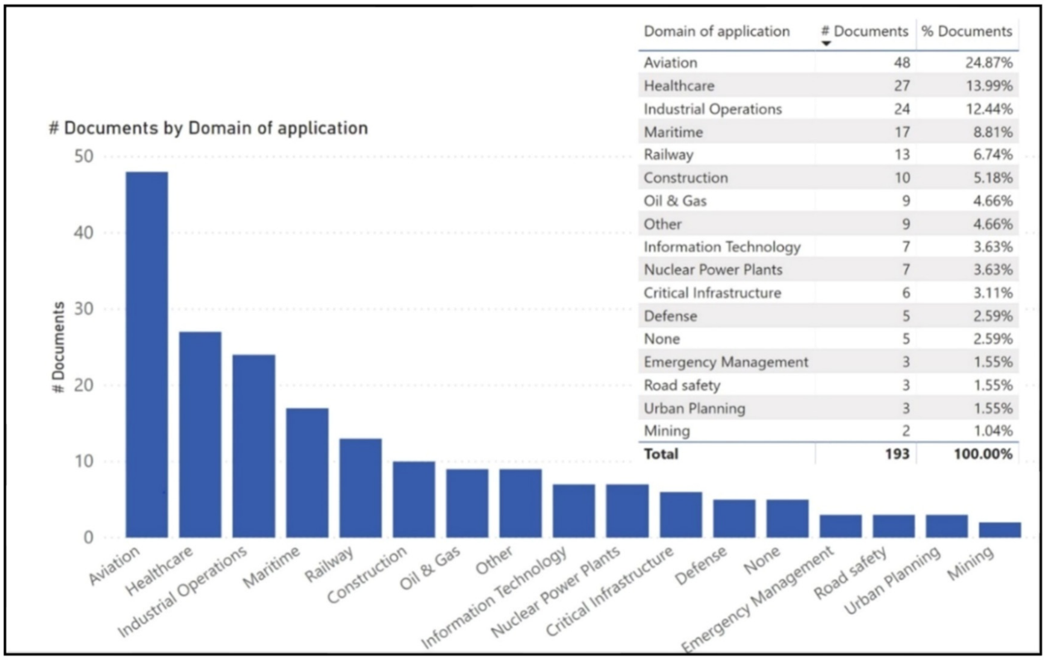
Addressing trade-off problems in project management requires a methodical decision-making strategy that harmonizes competing project goals like time, cost, quality, and scope. Effective resolution begins with the clear delineation of project objectives, constraints, and stakeholder priorities to guide informed decisions. Utilizing project management tools and techniques, including the Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), and Gantt charts, is essential for meticulous project planning and understanding trade-off implications on timelines and resources. Additionally, the application of optimization models—ranging from linear and dynamic programming to heuristic and metaheuristic algorithms—enables the identification of optimal compromises among conflicting project objectives, facilitating strategic project execution amidst complexities (Nowakowski et al., 2014). Various tools and methodologies have been developed to address and solve trade-off problems by facilitating decision-making processes that consider multiple objectives simultaneously. One widely recognized approach is the Analytic Hierarchy Process (AHP), which helps decision-makers prioritize various criteria by breaking down complex decisions into a hierarchy of simpler problems, thus making the trade-offs more manageable (Saaty, 1980).

Recent advancements in decision-making software and project management tools have incorporated these methodologies to assist in solving trade-off problems. Software such as Microsoft Project and Primavera P6 offer sophisticated resource allocation, scheduling, and optimization features that enable project managers to make informed decisions by visualizing the trade-offs between different project variables (Shtub et al., 2005).

2.2 Functional Resonance Analysis Method (FRAM)

2.2.1 Domain of application FRAM

The Functional Resonance Analysis Method (FRAM) can be applied to a wide range of domains, including aviation, healthcare, construction, nuclear power, transportation, manufacturing, and other complex socio-technical systems. As depicted in the accompanying Figure 2.2, the popularity of the FRAM in these domains is notable. Specifically, the chart demonstrates that the aviation and healthcare industries have been among the most prominent users of the FRAM methodology, while the construction sector has also shown a notable level of interest in the approach. Early proponents of the FRAM methodology had a pronounced emphasis on aviation safety, which remains a primary area of focus, as indicated in Figure2.3.



Domain of application	# Documents	% Documents
Aviation	48	24.87%
Healthcare	27	13.99%
Industrial Operations	24	12.44%
Maritime	17	8.81%
Railway	13	6.74%
Construction	10	5.18%
Oil & Gas	9	4.66%
Other	9	4.66%
Information Technology	7	3.63%
Nuclear Power Plants	7	3.63%
Critical Infrastructure	6	3.11%
Defense	5	2.59%
None	5	2.59%
Emergency Management	3	1.55%
Road safety	3	1.55%
Urban Planning	3	1.55%
Mining	2	1.04%
Total	**193**	**100.00%**

Figure 2.2 Domain of FRAM application
Taken from Patriarca (2020)

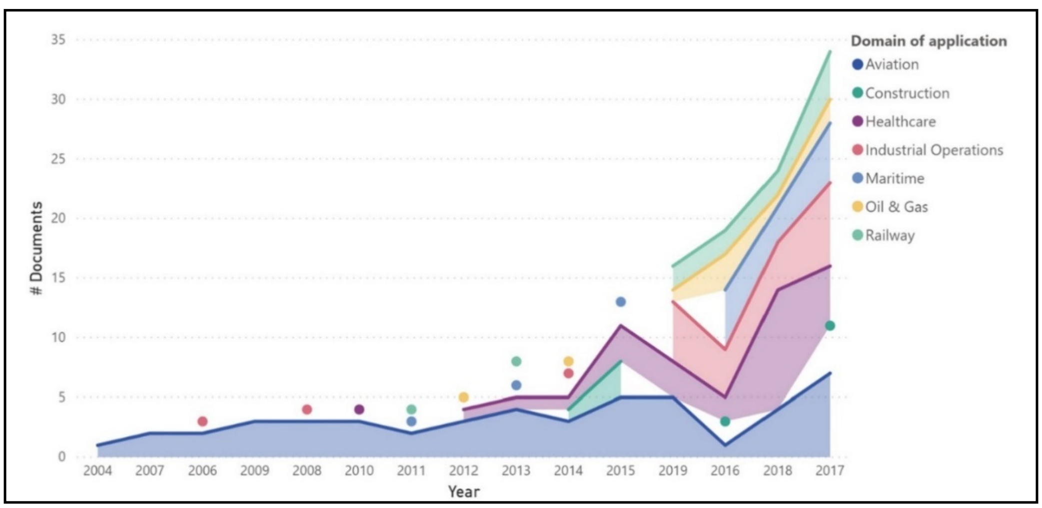


Figure 2.3 Evolution of the top domain of application
Taken from Patriarca (2020)

2.2.2 The basic principles of the FRAM

Hollnagel et al. (2014a) described the Functional Resonance Analysis Method (FRAM) is based on four principles or assumptions about the nature of events, which are illustrated in Figure 2.4. The four principles are as follows:

1. The principle of equivalence highlights that both good and bad outcomes occur in similar ways. It suggests that the ability of individuals, groups, and organizations to adapt to new situations and unexpected events is crucial for achieving positive outcomes and avoiding negative ones.
2. The principle of approximate adjustments suggests that for work to be successful, it needs to be constantly adapted to the current conditions such as available resources, time, tools, requirements, and interruptions. The adjustments made will not be exact because resources are always limited and not completely specified.
3. The principle of emergence, which states that both good and bad outcomes can occur due to small adjustments made in everyday situations, rather than being caused by the failure of specific parts in a system.
4. The principle of resonance, which states that a single task or function usually doesn't cause a system failure due to its limited variability. However, when multiple tasks or functions with weak variability interact, they can intensify and amplify each other, leading to increased variability and potentially causing failure of the entire system (Hollnagel et al., 2014a).

2.2.3 FRAM implementation in practice

To use FRAM for analyzing complex socio-technical systems, there are four main steps (Hollnagel et al., 2014a).

Firstly, identify and describe the required tasks/activities/functions of the system.

Secondly, determine the variability of each task/activity/function.

Thirdly, search for functional resonance by examining how the variability interrelates.

Finally, identify potential solutions to maintain work operations at an acceptable level.

The first step of FRAM involves identifying and describing the essential functions of a system, including technological, human, and organizational activities of everyday work.

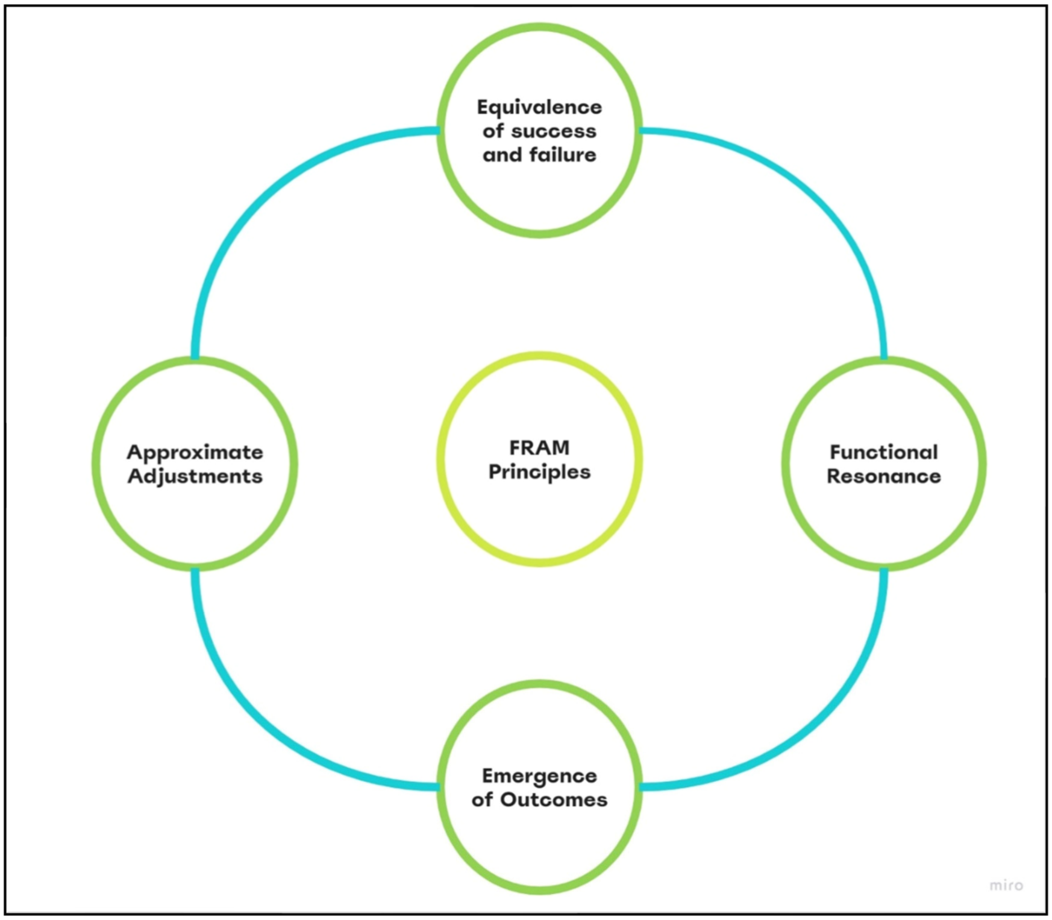


Figure 2.4 The FRAM principles

2.2.4 FRAM aspects

The Functional Resonance Analysis Method (FRAM) characterizes functions using six aspects:

Input: Input in a function is typically defined as matter, energy, or information that is transformed to create the Output. However, it can also refer to the activation or starting of a function, such as a clearance or instruction. Input is viewed as a form of data or information, or as a state change that signals the function to begin. Inputs result from a change in the condition of something and are described as a noun or noun phrase. In FRAM, foreground functions require defined inputs, while background functions do not.

Output: The Output of a function refers to the result of the function's actions, such as the outcome of processing the Input. This result can be represented by matter, energy, or information, including permissions or decisions. The Output signifies a change in the system's state or output parameters, and it can be the signal to begin another function. It is important to describe the Output using a noun or a noun phrase (Hollnagel, 2017a).

Precondition: Functions often require one or more Preconditions to be fulfilled before they can start. Preconditions can be viewed as a system state that must be True, or as conditions that should be verified before a function can proceed. However, a Precondition alone cannot trigger a function. In contrast, an Input can activate a function. It is not crucial for a FRAM analysis to differentiate between Inputs and Preconditions, if they are included in the model. A Precondition must always originate from another function's Output and should be described as a noun or a noun phrase.

Resources (execution function): A Resource is something necessary or used up during a function, such as matter, energy, information, software, tools, and manpower. Time can also be seen as a Resource but is considered separately. Proper Resources are consumed during a function, while Execution Conditions only need to be available while a function is active. It is useful to distinguish between the two. The difference between a Precondition and an Execution Condition is that the former is only necessary before the function starts, not during the function. Resources and Execution Conditions should be described as a noun or a noun phrase.

Control: Control, or control input, refers to the means of overseeing or regulating a function to achieve the desired output. This can take the form of a plan, a schedule, a procedure, guidelines, instructions, an algorithm, or a "measure and correct" function. Social control, which can be external or internal, is another form of control that is less formal and based on expectations of how work should be done. The description of Controls should be a noun or a noun phrase

Time: This aspect focuses on how Time affects the execution of a function. Time can act as a form of control when it determines the sequence of events. For example, one function may need to be completed before or after another function, or simultaneously with it. Time can also be considered a resource, as tasks may need to be completed within a specific time frame. Time can also be a precondition, where a task cannot begin until a specific time or after another task is complete. However, Time is given its own aspect because of its unique role in function execution. The description of Time should be a noun or noun phrase (Hollnagel et al., 2014).

The guiding principle of FRAM is that an aspect should only be described by the analysis team if it is deemed necessary or appropriate, and if there is enough information or experience available to do so. It is not obligatory to describe all six aspects of every function, and it may not always be feasible or logical to do so (Hollnagel & Goteman, 2004). Figure 2.5 shows the six aspects of FRAM.

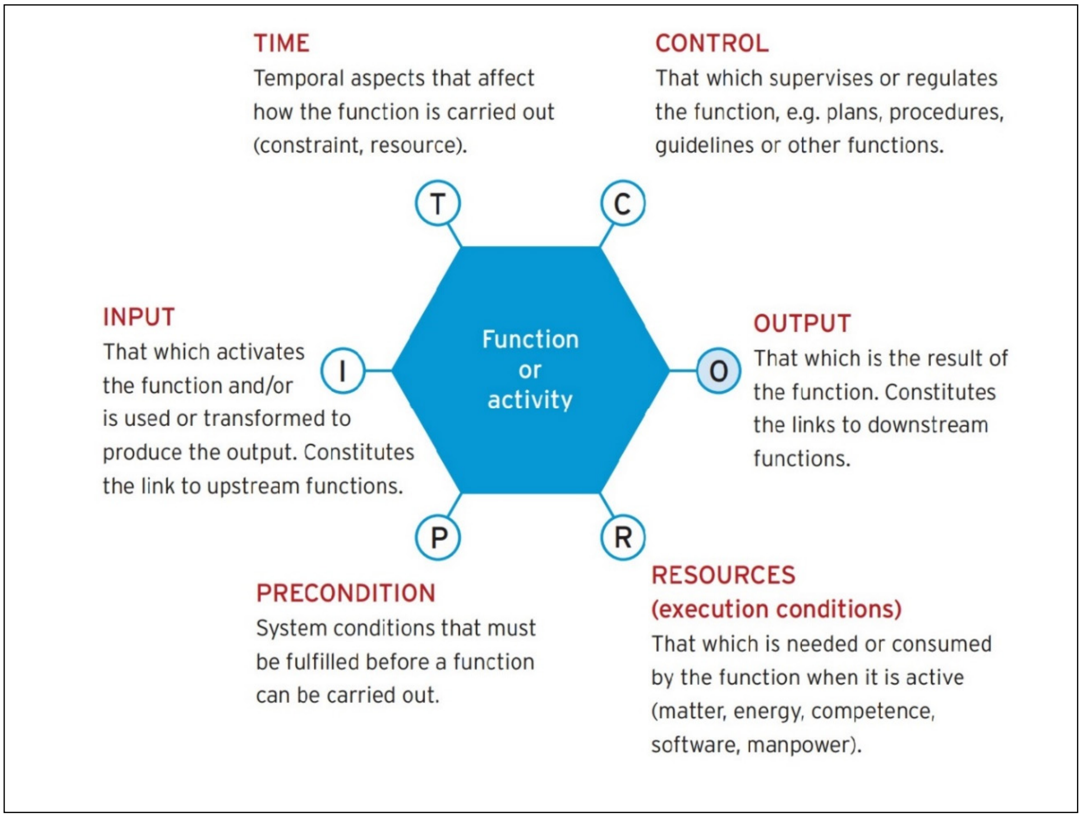


Figure 2.5 The FRAM aspects
Taken from Hollnagel et al. (2014a)

The second phase involves describing both the expected and observed levels of variability related to the functions identified in the first step. Once possible sources of variability are identified, it's important to describe it. One way to do so is by looking at the time and precision of the function's output. Variability can be categorized into three types: internal (coming from within the system), external (coming from outside the system), and couplings between upstream and downstream functions (Hollnagel et al., 2014a).

Step three of the FRAM process involves examining functional resonance, which refers to how the variability of one function can affect other functions it is linked to. This step considers the potential and actual variability of multiple functions and how they may interact and amplify each other to create unexpected outcomes. Couplings refer to the links between functions and their dependencies, and by examining these couplings, researchers can gain insights into the potential risks and instabilities within a system (Alvarenga et al,. 2014)

The fourth stage of FRAM provides suggestions on how to find solutions to maintain work operations in standard conditions (Hollnagel, 2017b).

The performance of a function can varies due to factors related to the function itself, environmental conditions, or upstream functions. FRAM distinguishes between three types of functions: human, organizational, and technological. Additionally, the variability in function output can be categorized according to time (on time, too late, or omitted) or precision (precise, acceptable, or imprecise). Omission refers to situations where the function result will not occur or is too delayed to be useful (Hollnagel et al., 2014a).

2.2.5 Techniques for gathering data and validating in the application of FRAM

It is necessary to use a combination of data collection methods to create and authenticate FRAM models. Multiple sources and diverse techniques should be utilized to obtain the necessary data for developing a FRAM model. Interviews are a commonly used method to gather the required data for building a FRAM model. One of the reasons for the prevalence of interviews is that it is a direct communication method that could provide a deeper understanding of the functions, their attributes, and descriptions required for identifying them, according to (Settanni et al., 2017).

2.2.6 Implementation of FRAM

In this study, the Functional Resonance Analysis Method (FRAM) was used by following the guidelines established by (Hollnagel et al., 2014b). The first step was to define the process and functions in project management regarding the risk augmented iron triangle that was discussed in this paper. The six aspects of each function were identified including input, output, precondition, resource, control, and time. The FRAM model was then created using FRAM Model Visualizer (FMV) version 0.4.1. Before moving on to the next step, the draft model was reviewed and revised with experts.

Step 1: Identifying functions and aspects related to the goal of the system

The initial phase of the FRAM method involves establishing the objective of project management, which encompasses the tasks of project design, planning, execution, control, and closure.

The primary function of the system is determined by considering the goal and understanding of its operation. Functions are categorized into three types: human, organizational, and technical activities. When identifying functions, no distinction is made based on the type of entity performing the task. The description of each function should contain the essential information needed to achieve the specified goal. Functions that are directly linked to the system goals are referred to as "main functions."

Next, various aspects are defined in relation to each identified function. These aspects are conceptualized similarly to the typical FRAM approach. The first aspect is the output (O), which represents the result of the function, either in terms of achieving a goal or progressing towards the next task. For instance, the output function could involve obtaining the desired product or successfully delivering the project. The second aspect is the input (I), which initiates the function and encompasses the preliminary factors that influence the function in relation to our dimensions. An example of input for achieving the desired quality could be effective supervision in projects. The third aspect is the pre-condition (P), which refers to the conditions that need to be fulfilled before executing the function. For example, to treat a risk, it must first be identified, making risk identification a pre-condition for treatment. The fourth aspect is resources (R), which are necessary for carrying out the function. This includes equipment, instruments, utilities, human resources, and labor. The final aspect is control (C), which signifies the ability to manage and control all functions, typically done by supervisors or project managers.

Step 2: Determining interaction between functions

The interconnection among functions, along with their respective aspects, can be identified to illustrate the linkages between preceding and succeeding functions (França et al., 2020). Each aspect of a function's description refers to one or more additional functions, as those related functions need to fulfill the requirements of that aspect.

Step 3: Identify variability in functions and aspects

This step involves assessing the potential variability that can occur in each function and its aspects. Variability is determined by considering the possibility of abnormal performance. One way to evaluate this is by examining the time and precise of the function's output. The potential performance of a function can be classified into four categories: Precise, Omitted, Imprecise, and Too late/stopped in the middle. These categories are described as follows:

1. Precise: The function is executed as required, within the specified time frame, and with the expected level of precision.
2. Omitted: The function is not performed at all, despite being required.
3. Imprecise: The function is performed inadequately, with unacceptable precision or accuracy.
4. Too late/stopped in the middle: The function is either performed late or is interrupted before completion (Hollnagel et al., 2014b).

The variability of a function is closely interconnected with its other aspects, such as input, pre-condition, resources, and control. Any deviation or change in the performance of these aspects will impact the output function and its alignment with the intended goal. The performance of these aspects is reflected in the performance of the preceding function. When multiple functions exhibit variability that aligns or resonates, it can lead to unexpected variations in the outcomes of upstream functions. It is important to note that the variability of a single function alone is typically insufficient to cause an incident. However, when the variability of multiple functions resonates or amplifies, it can surpass the standard limits and potentially result in an incident (Hollnagel & Goteman, 2004). Table 2.2 outlines the descriptions of the variability observed in the aspects and the potential consequences it may have on the output.

Table 2.2 Variability of aspects and possible output variability
Adapted from Sultana & Haugen, (2023)

Variability of aspects and possible output variability.

Aspect	Variability of the aspect	Description	Possible output variability
Input	Omitted	Not executed at all	Not executed
	Imprecise	Executed with deficiency	Imprecise/Not executed
Pre-condition	Omitted	Pre-condition could not be met	Imprecise/not executed
	Imprecise	Pre-condition met with deficiency	Imprecise/not executed
	Late/stopped in the middle	Pre-condition met later	Later/not executed
Resource	Omitted	Resource is absent	Imprecise/not executed
	Imprecise	The resource is present with a deficiency	Later/imprecise/not executed
	Late/stopped in the middle	The resource is present later	Later/imprecise/not executed
Control	Omitted	Control is absent	Imprecise/not executed
	Imprecise	Control is present with deficiency	Imprecise/not executed
	Late/stopped in the middle	Control is present later	Later/imprecise/not executed
Time	Too short	Function execution took a longer time	imprecise
	Too late	Function execution took a longer time	Later
	Stopped in middle	Function interrupted in the middle	Later/imprecise/not executed

2.3 System dynamics

2.3.1 Concept of system dynamics

System dynamics is a modeling and simulation approach used to analyze complex systems and understand their behavior over time. We live in a constantly changing and complex world, where we encounter various intricate challenges in fields such as agriculture, biology, environment, technology, and socioeconomics. These issues require comprehensive understanding and effective management for sustainable development. At a global level, there is a significant debate surrounding global warming and its implications for agriculture, energy, and the environment. Furthermore, we often come across reports on economic cycles that lead to financial panics. At regional and local levels, we face numerous problems inherent to complex and dynamic systems.

The system dynamics methodology, which incorporates feedback concepts, is employed to manage the non-linearity, multi-loop, and time-lag characteristics found in complex dynamic systems. By utilizing this methodology, it becomes possible to model and simulate these intricate systems, enabling a deeper understanding of their dynamics. Furthermore, it allows for the development of management policies aimed at promoting sustainable development.

System dynamics is a methodology that utilizes feedback systems from control theory to effectively address the complexities of dynamic systems, including non-linearity, time delays, and multi-loop structures. System dynamics methodology serves as a basis for constructing computer models that enable rational analysis of complex social systems, including their structure, interactions, and behavioral patterns. This approach provides a framework for testing strategies and exploring options while maintaining flexibility. The availability of software tools such as STELLA, VENSIM, and POWERSIM has revolutionized system dynamics modeling, offering intuitive interfaces and the ability to model virtually any process or system. These advancements have greatly enhanced the field of system dynamics and its applications (Bala et al., 2017).

A system refers to a collection of interconnected components working together towards a common purpose. It can encompass both physical and human elements. For instance, a tractor is a system consisting of various parts functioning together for cultivation. Similarly, a family serves as a system for living and raising children. Systems can involve biological and economic aspects, known as bioeconomic systems. Examples include agricultural and aquacultural systems, such as crop irrigation and prawn production systems. Economic systems, like price forecasting, also exist. Complex systems incorporate physical, economic, social, biological, technological, and political components. Agricultural production systems impacted by climate change exemplify this complexity, involving interactions among various elements.

Systems can be classified as open or feedback systems. Open systems respond to input but lack of influence over it, and past actions do not affect future actions.

Feedback systems, on the other hand, incorporate a closed-loop structure where the output affects the input. Feedback can be positive, leading to growth, or negative, leading to goal-seeking behavior (Bala et al., 2017).

2.3.2 System Dynamics complexity

Dynamic complexity arises in systems due to the following characteristics:

Constantly Changing: Systems undergo continuous change, even if they may appear stable in the short term. Change occurs at various time scales, and different scales of change can interact with each other. For example, stars evolve over billions of years before a sudden supernova explosion, and bull markets can last for years before crashing in a matter of hours.

Tightly Coupled: Actors within a system have strong interactions with each other and the natural world. Everything is interconnected, and actions in one part of the system can have repercussions throughout the entire system.

Governed by Feedback: The interconnectedness of actors in the system leads to feedback loops. Our actions have consequences that feed back into the system, causing changes in the environment and influencing the behavior of others. This dynamic interplay of feedback loops gives rise to system behavior.

Nonlinear: Cause and effect relationships in systems are rarely proportional. Local changes in a system may not apply universally, and nonlinear effects can emerge from the fundamental physics of systems.

Multiple factors interacting in decision-making can lead to nonlinear outcomes. For instance, pressure from a boss to achieve greater results may initially increase motivation, but beyond a certain point, it can result in frustration and decreased motivation.

History-Dependent: Choices made in the past can constrain future options and determine the system's trajectory (path dependence). Many actions have irreversible consequences, and stocks, flows, and long-time delays can create different time constants for actions and their undoing. For example, the accumulation of weapons-grade plutonium during the Cold War cannot be easily reversed due to its long half-life.

Self-Organizing: System dynamics emerge spontaneously from the internal structure of the system. Small perturbations can be amplified and shaped by the feedback structure, leading to patterns in space and time. Self-organization is observed in various phenomena, such as the pattern of stripes on a zebra, the rhythmic contraction of the heart, and cycles in the real estate market.

Adaptive: Agents in complex systems adapt and change over time. Evolutionary processes result in the selection and proliferation of certain agents while others become extinct. People also adapt through learning, finding new ways to achieve their goals in the face of obstacles. However, not all adaptations are beneficial.

Characterized by Trade-Offs: Time delays in feedback channels can cause long-term responses to interventions to differ from short-term responses. High-leverage policies may initially worsen the situation before leading to improvement, while low-leverage policies may offer temporary improvement before the problem worsens again.

Counterintuitive: In complex systems cause and effect relationships can be distant in time and space. Our tendency is to seek causes near the events we aim to explain, while the true causes may operate in different parts of the system. High-leverage policies and effective solutions are often not immediately apparent.

Policy Resistant: The complexity of systems often surpasses our ability to fully understand them. Consequently, many seemingly straightforward solutions to problems fail or even exacerbate the situation (Sterman, 2001).

2.3.3 Justification for employing System Dynamics

Construction project management (CPM) constitutes a distinct discipline with its own set of tools and techniques. Traditional control mechanisms like Work Breakdown Structure, Gantt Charts, PERT/CPM networks, Project Crashing Analysis, and Trade-off Analysis, while valuable, may not fully suffice for managing complex projects. Researchers have proposed the utilization of a system dynamics (SD) methodology for planning project activities (Love et al., 2000) and identifying the causes of rework in construction projects (Love et al., 1999). Furthermore, a system dynamics methodology can enhance strategic-level decision-making (Love et al., 2002).

Rodrigues and Bowers (1996) proposed a categorization for project management as follows:

Level 1: Involves considering the interactions of a specific project with the overall contractor company. The primary focus is on assessing whether the project objectives align with the company's overarching goals.

Level 2: Management at this level is primarily concerned with the strategic alternatives of an individual project. This includes determining major targets (milestones) and the preferred organizational structure.

Level 3: Involves delving into specific details of a project, such as targets, activity schedules, manpower allocation, etc.

Traditional CPM tools and techniques excel in handling specifics at Level 3 but fall short in addressing issues at Levels 1 and 2. This is where System Dynamics (SD) proves valuable, providing a holistic perspective on the project management process. SD emphasizes information feedback and offers a method for modeling and analyzing complex project systems (Stoner, 1995).

2.3.4 Modes of Behavior of Dynamic Systems

The feedback loop structure is a closed path that involves a decision based on the current state and desired goal of the system, leading to action and resulting in a flow or level within the system. Information about the system's stock or level is fed back to the decision-making point, influencing further action. The available information and the system's goal serve as the basis for the decision that controls action. Through this process, the system's condition is changed. The single feedback loop structure represents the simplest form of a feedback system.

The dynamic behavior within a system is simulated through the feedback loop structure, where all dynamics emerge from the interactions between two types of feedback loops: positive and negative feedback loops. Positive feedback loops are self-reinforcing and lead to growth. An illustration of a positive feedback loop is the causal loop involving population, birth, and population in sequence (depicted in Figure2.7), which reinforces the population level. On the other hand, negative feedback loops, such as the one depicted in Figure 2.7, death and population, work to balance the system.

The dynamic behavior of positive and negative feedback systems is illustrated in Figure 2.8. Positive feedback systems exhibit exponential growth, as shown in Figure 2.8 a, while negative feedback systems aim to reach a specific goal, as depicted in Figure 2.8 b.

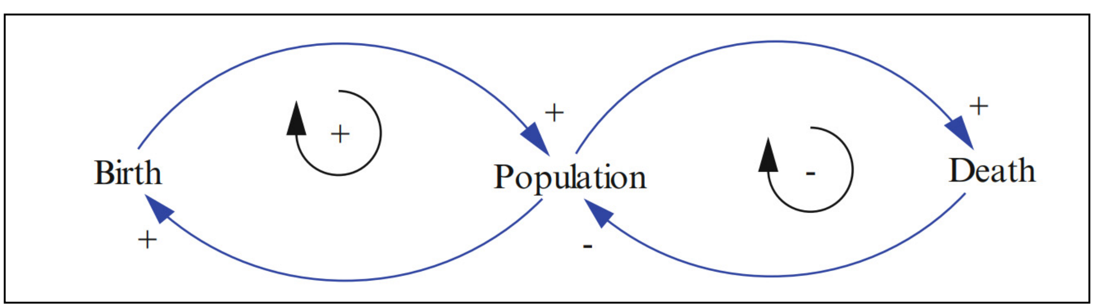
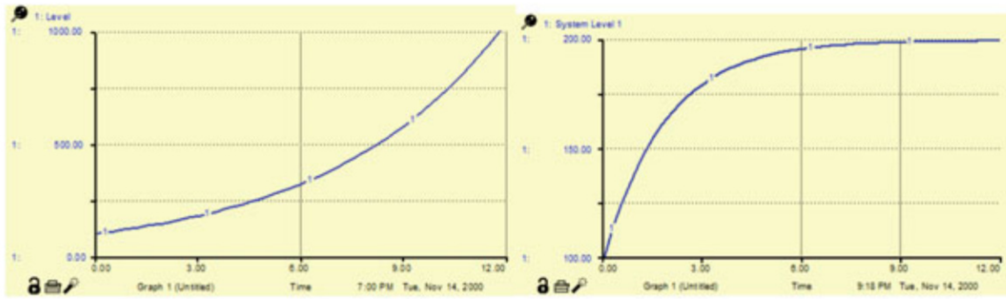


Figure 2.7 Casual loop
Taken from Bala et al., (2017)



(a) (b)

Figure 2.8 Dynamic behavior of positive feedback and negative feedback systems
Taken from Bala et al., (2017)

2.3.5 Systems Thinking and Modeling

To effectively model and simulate complex dynamic systems, we require guiding principles and structures. The systems approach involves considering the entire system rather than isolated components, and it involves a collection of conceptual and analytical techniques used for the purpose of systems thinking and modeling (Cavana & Maani, 2000).

The systems thinking and modeling includes problem statement, causal loop diagram, stock-flow diagram, scenario planning, modeling, implementation, and organizational learning. These elements collectively contribute to understanding and addressing complex issues and problems. Below is a summary of the steps involved in simulating a system dynamics model:

1. Identify the problem and develop a mental model by describing the issue verbally. This encompasses the process of identifying and conceptualizing problems, as well as formulating a dynamic hypothesis that elucidates the problematic behavior using causal loop diagrams and the stock and flow structure of the system.
2. Develop a foundational causal diagram utilizing the verbal model as a basis.
3. Improve the causal loop diagrams by converting them into system dynamics flow diagrams.
4. Convert the system dynamics flow diagrams into a suitable software platform such as STELLA, VENSIM, or a set of simultaneous difference equations.
5. Estimate the model parameters, which involves assigning values to the variables and relationships within the system.
6. Validate the model by testing its accuracy and reliability. Analyze its sensitivity to different inputs and evaluate the policy implications derived from the model.

7. Apply the model to gain insights and make informed decisions based on the simulated behavior of the system (Bala et al., 2017).

2.3.6 Validity of models

The assessment and validity of dynamic models should not be based on an idealized notion of perfection, but rather on their relative value compared to other existing mental and descriptive models. When evaluating a mathematical simulation model, its usefulness should be measured against the mental image or alternative models that would be employed in its absence (Forrester, 1968). In both the realms of physical and social science, there is no aspect for which we possess complete and comprehensive knowledge. It is impossible to claim that a model perfectly mirrors reality. However, it is also true that there is nothing of which we are entirely ignorant. Therefore, models should not be evaluated based on an absolute standard, but rather on a comparable scale. If models enhance our understanding and offer valuable insights into systems, they should be considered valuable (Bala et al., 2017).

CHAPTER 3

REPORT OF RESULTS

In this chapter, the results of the study are presented. Two types of studies, namely, the quantitative and qualitative approaches for system dynamics modeling, were employed, along with the collection of qualitative data from two surveys. In this chapter, both approaches and the results obtained from different approaches will be shown and discussed.

3.1 Identifying and awareness of the problem

3.1.1 Systematic Literature Review result

In this study, a systematic literature review guided by Kitchenham's (2004) methodology was performed. The review process involved planning, conducting, and documenting the review. We commenced with a search across databases including Web of Science, Scopus, and Google Scholar, covering literature from 1977 to 2023. This research encompassed four distinct phases to construct the systematic review. The initial phase aimed to perform a descriptive analysis, focusing on the annual distribution of publications, domains most frequently associated with project management (PM) simulations in system dynamics (SD), journals that predominantly feature articles on PM simulations using SD, and authors who have been significant contributors to the field. The culmination of this descriptive analysis was the compilation of an academic publications database consisting of 153 articles.

The second phase of the research centered on simulating project management (PM) through system dynamics (SD). This phase aimed to discern the variables frequently employed in SD models by various authors, specifically those stemming from the iron triangle—cost, time, and quality—as well as the extended groups of PMI processes, including initiating, planning, executing, monitoring and controlling, and closing. Additionally, there was a significant focus on the utilization of SD models for risk assessment in projects within this stage.

In the third phase, we investigate the root causes of risk and the iron triangle in mega construction projects. The focus includes keywords such as 'root causes of cost overrun,' 'root causes of time delay,' 'root causes of risk,' 'root causes of quality,' and 'construction project.'

The fourth phase delves deeper into each stage using the backward and forward snowballing method to discover articles related to system dynamics (SD), underlying factors influencing the risk-augmented iron triangle, and the Functional Resonance Analysis Method (FRAM).

This review examines scholarly works and authoritative texts on project management methodologies, focusing on large construction projects. It explores traditional methods like PMBOK and systems thinking approaches like FRAM, aiming to integrate these to manage the complexities of large-scale projects effectively. The PMBOK framework, developed by the PMI is noted for its structured approach but criticized for its lack of flexibility and adaptability in dynamic environments. Figure 3.1 shows the process of systematic literature review.

1	Search keywords queries: "System Dynamics" AND "Project Management", Time Span: 1977 - 2022	272	Web of Science
		510	Scopus
		17000	Google Scholar
2	Refine by categories: management (162), business (59), Construction (18)	239	Web of Science
	Filter by subject area: Engineering (266), Business and Management (203)	469	Scopus
	Search keyword queries: "sytem dynamics and project management" ; "Project management and system dynamics"	134	Google Scholar
3	Merging Articles and Removing Duplicates from Web of science, Scopus and Google Scholar	232	
4	Articles that provide SD model	153	
5	Articles that criticize SD modelling	11	

Phase 1

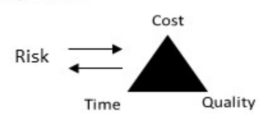
Descriptive Analysis

Articles obtained from Scopus, Web of Science and Google Scholar
Publications per year
Most publish journals
Most related SD to PM

Phase 2

Project management using System Dynamics

Identifying Risk augmented Iron Triangle



Identify PMI process groups

Initiating	Planning	Executing	Monitoring & Controlling	Closing

Identify SD models by authors

Phase 3

Risk augmented Iron Triangle underlying factors

To search articles related to root causes of Risk augmented Iron Triangle. Keywords: "Root causes of Cost and Construction Project", "Root causes of time and Construction Project", "Root causes of quality and Construction Project" and "Root causes of Risk and Construction project"
To search for appropriate tool to ascertain underlying factors to risk augmented iron triangle with keywords: "FRAM and project management" "FRAM and Construction project"

Phase 4

Snowballing Method

Identify proposed SD models
Identify underlying factors affecting risk augmented Iron triangle
Identify FRAM using in construction

Figure 3.1 Systematic literature review process

According to Kerzner (2017), while PMBOK provides a robust set of processes and guidelines, it is inherently prescriptive and tends to enforce a one-size-fits-all approach. This can be problematic in projects where changing conditions and unforeseen Secondly, PMBOK's focus on process over people can sometimes overlook the human elements crucial to project success. As discussed by Too and Weaver (2014), PMBOK's methodology is heavily skewed towards technical aspects of project management, such as scope, time, and cost, with less emphasis on leadership, team dynamics, and stakeholder engagement. This oversight can result in the underutilization of human resources and a lack of emphasis on building effective team collaborations, which are essential for navigating the complexities and challenges of large projects. The framework often assumes that project success is primarily the result of well-followed processes and overlooks the nuanced human factors that can significantly influence outcomes. Lastly, the PMBOK framework sometimes fails to effectively manage project risks and uncertainties, particularly in complex projects. While PMBOK includes risk management as one of its core knowledge areas, the traditional risk management approaches it advocates often fall short in predicting and mitigating the kinds of emergent risks that characterize mega projects. Williams (2016) criticizes PMBOK's conventional risk management tools as being too static, as they frequently rely on historical data and fail to account for the unique and evolving risks in large-scale projects. This can lead to a lack of preparedness and agility in dealing with issues that have not been previously encountered, further exacerbating project vulnerabilities.

Recent studies continue to highlight these challenges. For instance, Mir and Pinnington (2014) argue that while PMBOK's structured approach provides a solid foundation, it requires adaptation to fit the dynamic nature of mega projects. Similarly, Biesenthal and Wilden (2014) emphasize the need for a more flexible and adaptive project management methodology to handle the inherent uncertainties and complexities of large-scale projects.

On the other hand, the Functional Resonance Analysis Method (FRAM), developed by Hollnagel (2014b), introduces a system thinking approach to manage complexity more effectively. FRAM illustrates how focusing on variabilities within normal work interactions can offer insights into potential non-linearities in project outcomes, making it suitable for complex environments like those seen in mega construction projects (Hollnagel, 2017a). However, some researchers argue that FRAM alone may not provide sufficient structure and discipline needed for managing large projects comprehensively. The integration of FRAM with PMBOK is suggested as a novel approach by recent studies. For example, Woods (2017) calls for more adaptive project management models that combine systems thinking with traditional methodologies to enhance resilience and flexibility. This integration aims to harness the strengths of both FRAM's dynamic variability analysis and PMBOK's structured project management approach to create a more robust framework for managing mega projects.

However, there are debates within the literature regarding the practical implementation of such integrated approaches. Some scholars argue that the integration of FRAM and PMBOK could lead to increased complexity in project management practices, potentially making them less accessible to project managers who are not familiar with systems thinking methodologies. This viewpoint is countered by studies like França et al. (2020), which demonstrate the practical benefits of integrating FRAM with PMBOK in offshore oil well drilling projects, suggesting that such integration can enhance project outcomes by addressing both human and technical factors. This study aims to contribute to this ongoing debate by developing a FRAM-PMBOK integrated framework and testing its practical applicability through a case study of the Channel Tunnel project. By doing so, it seeks to provide empirical evidence to support the theoretical advantages of such integration and address concerns about its complexity and practicality.

The Project Management Body of Knowledge (PMBOK) guide, developed by the Project Management Institute (PMI), organizes project management into five distinct process groups. Each group represents a phase in the project management cycle: Initiating, Planning, Executing, Monitoring and Controlling, Closing.

The construction extension of the PMBOK guide (2016) expands the standard project management framework to specifically cater to the construction industry, incorporating twelve Knowledge Areas. These include Project Integration Management, Project Scope Management, Project Schedule Management, Project Cost Management, Project Quality Management, Project Resource Management, Project Communications Management, Project Risk Management, Project Procurement Management, and Project Stakeholder Management. Additionally, it introduces Project Health, Safety, Security, and Environmental Management, and Project Financial Management to address specific needs in managing construction projects, ensuring comprehensive oversight from safety standards to financial operations.

Integrating the Work Breakdown Structure (WBS) with the Functional Resonance Analysis Method (FRAM) offers a powerful approach to managing mega construction projects. WBS structures these complex projects into manageable units, simplifying resource allocation and scheduling. Concurrently, FRAM assesses the variabilities within these units, identifying potential resonances that might impact project outcomes. This integration enhances project management by combining WBS's organizational clarity with FRAM's insights into system behaviors, ensuring a more adaptive and resilient approach to managing large-scale projects (Hollnagel, 2017b).

Liu et al. (2019) conduct a systematic review on the application of system dynamics modeling (SDM) in construction management research, revealing its crucial role in addressing the complexities of the industry. The study identifies eight significant research topics where SDM is instrumental: sustainability, project planning and control, performance and effectiveness, strategic management, site and resource management, risk analysis and management, knowledge management, and organization and stakeholder management. These topics demonstrate the diverse applications of SDM in exploring intricate causal relationships and improving management practices at various levels within the construction sector.

The definition of a system varies based on users, environment, and objectives. In business, a system is seen as a group of elements, human or nonhuman, organized to work together toward a common goal. Systems comprise interacting subsystems that, when organized effectively, produce synergistic outcomes and are delineated by boundaries. Systems can be closed, under complete management control, or open, interacting with the environment; social systems are examples of open systems with permeable boundaries. Extended systems, dependent on other systems for survival, are subject to constant change and may challenge those seeking structured environments. Programs serve as fundamental elements or subsystems of a system, with a defined time-phased effort, while systems operate continuously. Projects, shorter than programs, represent the primary breakdown of a program, and both project and program managers are commonly employed in today's industrial sector (Kerzner, 2017).

Understanding project complexity and its management is crucial for project managers. Differences in decision-making and goal achievement are often linked to project complexity (Baccarini, D. 1996). With projects growing increasingly complex, there's a rising concern regarding project complexity. Traditional tools and techniques designed for simple projects are often deemed inadequate for handling complex projects (Morris & Morris, 1994).

The importance of complexity in the project management process is widely acknowledged for several reasons. Firstly, it helps determine planning, coordination, and control requirements.

Secondly, it hinders the clear identification of goals of major projects. Thirdly, it can affect the selection of an appropriate project organization form and experience requirements of management personnel. Fourthly, it can be used as a criterion in the selection of a suitable project management arrangement. Lastly, it can affect different project outcomes such as time, cost, quality, safety and so forth (Rowlinson, 1988).

In their research, Turner and Cochrane (1993) propose a classification system for projects based on the clarity of their goals and methods. They classify projects into four distinct types using their Goals and Methods Matrix. Type 1 projects are characterized by well-defined and understood goals, where the project manager assumes the role of a conductor. Type 2 projects feature clear goals but poorly defined activities, necessitating the project manager to act as a coach and employ a rolling wave technique for planning. Type 3 projects have poorly defined goals but well-defined methods, requiring planning in life-cycle stages, and the project manager adopts the role of a craftsman. Lastly, Type 4 projects lack both defined goals and methods. This classification system provides valuable insights into the varying degrees of project clarity and underscores the importance of tailored approaches to project planning and management based on the level of clarity regarding project goals and methods.

Stacey, (1996) examines complexity along two dimensions: the degree of certainty and the level of agreement. He constructs a matrix with distinct zones to categorize organizational situations. The first zone, close to agreement and certainty, is conducive to simple projects where traditional project management techniques excel, aiming for maximum efficiency and effectiveness. In contrast, the second zone, far from agreement but close to certainty, requires coalitions, compromise, and negotiation to address complexities. Techniques like Game Theory or Hypergames prove valuable in such scenarios. Moving to the third zone, close to agreement but far from certainty, traditional project management techniques may falter, prompting the use of leadership approaches to navigate uncertainty effectively. Finally, the fourth zone represents a realm of anarchy, characterized by high uncertainty and minimal agreement, where traditional management techniques are ineffective. Here, leadership approaches become indispensable for managing complexity and fostering innovation. Stacey's research underscores the importance of understanding and navigating complexity in organizations to promote creativity and adaptability.

The paper authored by San Cristóbal. (2017) delves into the intricate realm of project complexity and its management within contemporary project environments. With projects increasingly becoming more complex, there arises a pressing concern regarding the adequacy of traditional tools and techniques in addressing the nuanced dynamics inherent in complex projects. Through a systematic literature review, the paper identifies a lack of consensus in defining project complexity and critiques existing complexity models for their limited scope. The methodology entails an in-depth analysis of project complexity concepts and the presentation of various complexity models. The results underscore the necessity of embracing systems thinking in project management, emphasizing a holistic approach that considers interrelationships, patterns of change, and emergent properties within complex systems. The conclusion emphasizes the imperative for project complexity models to incorporate critical aspects such as the social and political context, as well as project managers' skills and attributes. Future work entails refining project complexity models to encompass these essential elements and developing project management processes capable of navigating the complexities of dynamic and uncertain project environments effectively.

Rodrigues and Bowers (1996) study explores system dynamics as a holistic approach to project management, emphasizing its focus on interrelationships and its contrast with traditional methods. It discusses system dynamics' applications across industries and proposes a quality and rework model for project execution and control. The study highlights system dynamics' strategic value alongside traditional techniques in project management. The author investigates project management dynamics, emphasizing risk and quality control. Lyneis and Ford (2007) proposed model enhances risk and quality management during the project's control phase. It integrates system dynamics and project management principles, offering valuable insights for practitioners. Madachy (1996) proposed a dynamic simulation model for inspection-based software lifecycle processes, integrating the Constructive Cost Model for calibration. The model demonstrates the cost-effectiveness of inspections, highlighting their impact on development effort, testing, and schedule. It offers insights into error generation, detection, and management, providing a scalable framework for process evaluation and project planning. Nasirzadeh et al. (2008) developed a system dynamics (SD) model for infrastructure construction projects, integrating risk analysis and response processes. They employed fuzzy logic to address the uncertain nature of risks, particularly focusing on machinery breakdown risks and alternative response scenarios.

Akkermans and Van (2018) explored Balanced Scorecard development using system dynamics, emphasizing the need to question assumed relevance and leverage SD for deeper insights. Their process involved qualitative causal diagraming and quantitative simulation, revealing insights into causal relationships and time delays. The study by Ding et al. (2018) introduces a system dynamics-based model for evaluating environmental benefits in construction waste management. Applied system dynamics methodology is employed to simulate reductions in waste generation and significant environmental gains, including lowered greenhouse gas emissions and saved landfill volume. The study by Guo et al. (2018) proposes an SD model integrating evolutionary game theory for construction quality supervision, addressing stakeholder interactions. It examines penalty-reward dynamics' impact on stakeholder behavior, highlighting organizational challenges. The model provides insights into quality supervision dynamics, emphasizing the role of penalty-reward scenarios in enhancing stakeholder interactions.

The paper by Abotaleb and El-adaway (2018) offers a comprehensive review of dynamic modeling applications in construction project management. It proposes a System Dynamics (SD) model to capture complex project dynamics, addressing parameters like rework and schedule pressure. The model aims to enhance decision-making processes and minimize redundancies in construction project management. The dynamic model by Alasad and Motawa (2015) evaluates demand risk in toll road projects, addressing uncertainties in traffic projections. Sustainable development models societal, economic, and environmental subsystems through the population, employment, and GDP variables.

Table 3.1 Summary of the identified System Dynamics models

	PM performance elements (Risk augmented Iron Triangle)				PMI project management process groups					
Author	Time	Cost	Quality	Risk	Initiating	Planning	Executing	Monitoring and controlling	Closing	Domain
Rodrigues et al. 1996		×	×				×	×		Industry
Lyneis et al. 2007			×	×				×		Project Management
Madachy 1996		×	×			×	×	×		Software Engineering
Nasirzadeh et al. 2008	×	×		×			×	×	×	Construction
Akkermans et al. 2018	×		×			×	×			Insurance Industry
Ding et al. 2018	×			×	×	×	×	×		Construction waste management
Guo et al. 2018			×	×		×	×	×		Construction
Abotaleb et al. 2018	×					×		×		Construction
Alasad et al. 2015	×			×			×			Traffic Management

Table 3.1 presents a summary of the system dynamics models discovered within the dataset. The models are arranged by authors and categorized based on project management performance, known as the Iron Triangle, and risk, as well as the extended PMI process group.

In the literature review, numerous studies have addressed project management issues using system dynamics. An effort has been made to examine these studies and the utilization of system dynamics across various domains of project management. Previous studies are categorized into two main groups: project management performance elements, including cost, time, quality, and augmented risk, and project management process groups according to PMBOK, which encompass initiating, planning, executing, monitoring and controlling, and closing phases.

Project performance measurement and predictability are hotly debated in project management, focusing on accurately predicting outcomes amidst project complexities. Lauras et al. (2010) and Shen et al. (2005) advocate for a comprehensive approach that includes various performance dimensions and calls for advanced methodologies beyond traditional metrics. Similarly, Choi and Bae (2009) highlight the importance of adapting to project changes using system dynamics alongside static models, pointing to a shift towards more dynamic evaluation methods that better reflect the reality of projects.

System dynamics (SD) is highlighted as a powerful tool for measuring and predicting project performance, offering insights into project evolution and the impact of various factors through simulations. Cited works by Shen et al. (2005) and Choi and Bae (2009) demonstrate SD's use in analyzing sustainability and enhancing prediction accuracy in dynamic project settings. While SD allows for detailed, forward-looking project management, its effectiveness depends on the precision of input data and model complexity, emphasizing the importance of careful model construction and validation. Nasirzadeh et al. (2008) apply System Dynamics and fuzzy logic in construction risk management to improve PMBOK's Risk Management processes, focusing on the elements of risk, time, and cost. This method addresses the complex and dynamic nature of risks in construction projects. Alasad and Motawa (2015) apply System Dynamics (SD) to toll road projects for demand risk assessment, focusing on the project risk management in the execution process. Their methodology integrates SD modeling and Monte Carlo simulation to predict and manage demand risks. Their objective was to formulate a cross-disciplinary research plan designed to enhance and extend Project Management beyond its usual theoretical roots (Strand 1). Traditional Project Management was found to be lacking in effectively addressing the initial phases of projects. Furthermore, there was a recognized need to 'enhance the quality of research in the field of Management of Projects' (Cooke-Davies, 2004). The network provided a framework encompassing five pathways. The initial pathway connected theories related to the practice, drawing from the project life cycle model and Project Management, to theories addressing project and Project Management complexity (Winter & Szczepanek, 2008).

An intriguing insight has emerged from this review, shedding light on the use of system dynamics (SD) in forecasting project performance and risk assessment within the construction sector across all PMBOK process groups. This paper endeavors to demonstrate the application of SD models in simulating project management, identifying variables that influence risk and project performance, and proposing a model to predict the dynamics of the risk-augmented iron triangle. Our literature review unveiled a notable gap in employing SD within construction project management to evaluate the risk-augmented iron triangle. Hence, the core discussion of this paper centers on the necessity of simulating projects throughout all PMBOK project process groups and pinpointing variables that affect project performance. The findings highlight the integration of SD modeling across various levels of project management, impacting different facets of project performance.

3.1.2 Gap of study

Traditional project management methodologies, such as those encapsulated in the Project Management Body of Knowledge (PMBOK), provide a structured approach to project management. However, their efficacy in dealing with the non-linear complexities and dynamic scheduling demands of mega projects is often limited, as discussed by Kerzner (2017), who critiques the rigidity of such frameworks in adapting to the dynamic needs of large-scale projects.

Other traditional methodologies like the Waterfall model and the Critical Path Method (CPM) also have their limitations. The Waterfall model, which follows a linear and sequential approach, often fails to accommodate changes once the project is in the testing phase, making it inflexible for dynamic project environments (Royce, 1970). The CPM, while useful for optimizing project schedules, does not effectively address quality improvements and often overlooks the complexities of resource allocation and risk management in large-scale projects (Kelley Jr & Walker, 1959; Kerzner, 2017).

One method to cope with the challenges and complexities in mega construction projects is the Work Breakdown Structure (WBS). It is an essential tool that effectively breaks down large-scale projects into manageable units, facilitating detailed task organization, resource allocation, and scheduling. The WBS allows project managers to decompose project deliverables into smaller, more manageable components, making it easier to oversee large and complex tasks. This hierarchical approach not only simplifies project management but also enhances clarity and improves communication among stakeholders, which is crucial in large-scale projects (Norman et al., 2008).

Despite the usefulness of these traditional methods, there is a clear need for an alternative approach that can address the complexities inherent in mega construction projects more effectively. This new approach should integrate the benefits of traditional methodologies while overcoming their limitations, particularly in managing non-linear complexities and dynamic scheduling demands. By developing and validating such an approach, future research can bridge the gaps identified in the existing literature and provide project managers with more adaptive and comprehensive tools for managing mega construction projects. This new approach should be able to identify the functions and causes of the risk-augmented iron triangle, integrate them effectively, and couple these causes in a causal loop using system dynamics.

In summary, the gaps in the study highlight the need for:

Implementation of Advanced Methods: Empirical validation of advanced methods across construction projects with varying complexities and stakeholder dynamics.

Quantitative Analysis: Incorporation of statistical evidence to measure the benefits and impacts of these methods.

Comparative Analysis: A framework to benchmark the new approach against traditional methodologies.

Expert Feedback: Comprehensive validation through broad-spectrum expert feedback.

Lessons Learned: Documentation of specific lessons from real-world applications to refine the new approach.

3.1.3 Root causes of Cost, Time, Quality and Risk

In this research, we have identified four key dimensions of project management that we named risk augmented iron triangle that requires exploration. It is crucial to identify the factors that influence costs and can potentially result in cost overruns. Similarly, there are factors that impact project scheduling, causing delays beyond the initially projected timeframe during the design and planning stages. Additionally, it is important to identify the underlying factors that affect quality and risk. By uncovering these factors, we gain a better understanding of their interdependencies and the magnitude of their impact.

In relation to the underlying factors that influence Risk augmented Iron Triangle examined in this research, Doloi (2013) conducted a study on Australian construction projects to identify the key factors that influence cost overruns. Through a literature review, a total of 73 attributes associated with cost performance were identified. By utilizing the relative importance weighing technique on 48 attributes, the study revealed the main five factors that significantly impact cost overruns: accurate project planning and monitoring, effective site management, contractors' efficiency, design efficiency, and communication. Asiedu and Ameyaw (2021) conducted a study with the aim of developing and empirically testing a system dynamics causal loop model to explore factors contributing to the risk of cost overruns in construction projects within developing countries. The study utilized data from the construction industry in Ghana and proposed a conceptual system dynamics model, which was then tested through empirical analysis.

The findings of the study, supported by empirical evidence, revealed that the inadequate technical capacity of consultants serves as the fundamental cause of cost overruns in government projects. The results of the system dynamics causal loop model demonstrated a significant relationship between poor contract planning and supervision, change orders, project team competence, and the lack of effective coordination among the contractual parties.

These findings contribute to the understanding of the factors influencing cost overruns in construction projects within developing countries. Subramani et al. (2014) Conducted Study on causes of cost overrun in construction projects, this research employed a desk study and questionnaire survey. A total of 30 questionnaires were collected from clients, consultants, and contractors. Participants rated causes based on occurrence probability and impact severity. The importance of each cause was determined by considering cumulative occurrence and impact. Spearman rank order correlation analysis assessed consensus between respondent groups (client versus consultants, clients versus contractors, and consultants versus contractors). Findings revealed major causes of cost overrun, including slow decision-making, poor schedule management, increased material/machine prices, inadequate contract management, design-related issues and delays, rework due to errors, land acquisition problems, inaccurate estimation methods, and lengthy design-to-bidding/tendering periods.

Adam et al. (2017) conducted a study to clarify the factors causing cost overruns and time delays in large public construction projects. Through an analysis of 40 journal articles, they examined the impact of cost overruns and time delays on these projects. The study utilized a Kiviat diagram/radar chart to visually rank the occurrence of factors contributing to cost overruns and time delays. The findings highlighted eight root causes are communication issues (insufficient and lack of communication between contractor and client), financial challenges (delayed payments, poor financial planning, price increases), management issues (poor site management, inadequate managerial skills, poor monitoring and control, poor labor planning), material related problems (poor material planning, equipment shortages), organizational issues (poor organizational structures, poor process procedures), project factors (project complexity, project duration), psychological factors (optimism bias, deception), and weather-related challenges (harsh weather conditions, unforeseen ground conditions). These identified causes emphasize the significance of addressing these factors to mitigate cost overruns and time delays in large public construction projects. Doloi et al. (2012) conducted a comprehensive analysis to understand the reasons for delays in construction projects and establish their impact. This research focused on the Indian construction industry and utilized a set of 45 selected attributes. Through questionnaire surveys and personal interviews, the study identified key factors affecting delays. Factor analysis and regression modeling were employed to assess the significance of these delay factors. The findings revealed seven critical factors: lack of contractor commitment, inefficient site management, poor site coordination, improper planning, lack of clarity in project scope, lack of communication, and substandard contracts. The regression model indicated that slow decision-making by the owner, poor labor productivity, architects' reluctance to embrace change, and rework resulting from construction mistakes significantly contribute to project delays.

Sweis (2013) conducted a study in Jordan to identify the major factors contributing to project time overruns. A descriptive study approach was employed, and data were collected through two sources. Overrun variables were extracted from the literature and gathered from the perception of 30 engineers, who ranked them based on their Severity Index (a combination of Importance Index and Frequency Index). Using Principal Component and Factor Analysis (PCFA) on both secondary and primary data, the study identified the top ten factors causing time overruns in construction projects. Among these factors, four were found to be the most significant: poor qualification of consultants, engineers, and project staff; inadequate planning and scheduling by the contractor; adverse weather conditions at the job site and design changes.

The study conducted by Wang et al. (2011) examines the factors influencing the risk attitudes of decision makers in construction projects. The research specifically focuses on improving risk-based decision-making by investigating the critical factors that impact contractors' risk attitudes in Chinese construction projects. The identification of these factors is based on literature reviews, interviews, and questionnaires. Statistical methods such as ranking analysis and factor analysis are employed for verification and analysis. The findings indicate that three factors hold the highest importance: "consequences of decision-making," "engineering experience," and "completeness of project information." Mohammadi et al. (2018) conducted a comprehensive study that reviewed 90 papers to identify the factors influencing safety performance in construction projects. Through qualitative content analysis, they extracted key factors such as motivation, rules and regulation, HSE (health, safety, environment) competency, safety investment and cost, financial and productivity, resources and equipment, work pressure, work conditions, culture, safety programs. A hierarchical framework was developed to illustrate the relationship between these factors and safety. The framework was validated through expert interviews, providing valuable insights for enhancing safety practices in construction projects. In their study, Siraj et al. (2019) investigated various risk identification tools, risk classification methods, and common risks in construction projects. They conducted a systematic review and thorough content analysis of 130 articles from reputable academic journals published in the past three decades. The selected articles primarily utilized a combination of information-gathering techniques for risk identification, while diagramming and analysis-based techniques were less commonly employed. The most frequently identified risks included unexpected changes in the inflation rate, design errors and inadequate engineering, and alterations in government laws, regulations, and policies impacting the project, weather conditions (continuous rainfall, snow, temperature, wind); and unpredicted adverse subsurface conditions. Abas et al. (2015) conducted a study to examine the factors influencing the quality of construction projects, both positively and negatively. They developed a questionnaire based on these factors and sought the opinions of construction experts. The feedback received was then analyzed using statistical tools such as Chi-square and weighted mean method (WMM) to determine the significance of each factor. The critical factors identified include continuous improvement, collaborative working, effective communication, availability of technical personnel, ISO certification, and the procurement unit of the contractor. Contractors should prioritize these factors when undertaking construction projects and focus on implementing new technologies, effective risk management, quality management, and daily supervision. Ye et al. (2015) conducted a study to investigate the causes of quality issues and rework in construction projects. Through a literature review and interviews with experienced construction professionals in China, a total of 39 causes were identified. A questionnaire survey was then conducted to prioritize these causes, and the top-ranked causes were found to be unclear project process management, poor quality of construction technology, and the use of substandard construction materials. Factor analysis revealed 11 major underlying dimensions of these causes, including design management, communication management, field management, project scope management, project process management, active rework, project plan changes, subcontractor management, contract management, owner capability, and the external environment.

Table 3.2 presents a comprehensive overview of the underlying factors that impact Risk augmented Iron Triangle in construction projects.

Table 3.2 Root causes for the time, cost, quality and risk

	Scope change
Root causes of cost overrun	Project planning and monitoring
	Site management
	Design efficiency
	Communication
	Technical capacity of consultants
	Change orders
	Competence of the project team
	Inadequacy of staff, labor, plant, materials, time or finance
	Defective materials or workmanship
	late supply of information
	uninsurable matters
	gaps and time limits in insurance cover
	funding constraints
	Delayed material delivery (supply chain issues)
	Optimism bias among local officials
	Deliberate cost underestimation
	Slow decision making
Root causes of cost overrun	Schedule management
	Increased material/machine prices
	Poor contract management
	Poor design
	Design delay
	Wrong estimation method
	Rework due to poor quality
	Delayed payments
	Financial planning
	Labor planning
	Poor material planning
	Equipment shortages
	Project complexity
	Optimism bias
	Harsh weather conditions
	Unforeseen ground conditions
	Communication
	Delayed payments
	Financial planning
	Price increases
	Site management
	Delayed material delivery (supply chain issues)
	Managerial skills
	Monitoring and control
Root causes of Time	Labor planning
	Material planning
	Equipment shortages
	Organizational structures
	Process procedures
	Project complexity
	Project duration
	Optimism bias, deception
	Weather-related challenges

	Contractor commitment Poor site management Poor site coordination Project scope change Qualification of consultants, engineers, and project staff Planning and scheduling by the contractor Design changes
Root causes of Risk Root causes of Risk	Consequences of decision making Engineering experience Completeness of project information Motivation Rules and regulations HSE (Health, Safety, Environment) competency Safety investment and cost Financial and productivity Resource and equipment Work pressure Work conditions Culture Safety program Unexpected changes in inflation rate Design errors Alterations in government laws, regulations, and policies impacting the project Weather conditions (continuous rainfall, snow, temperature, wind) Unpredicted adverse subsurface condition
Root causes of Quality	Continuous improvement Collaborative working Effective communication Availability of technical personnel ISO certification Procurement unit of the contractor Design management Communication management Field management Project scope management (defining requirements, preventing scope creep, optimizing resource allocation, quality assurance/control processes) Project process management Active rework Project plan changes (Change in scope, resource allocation) Subcontractor management Contract management Owner capability External environment

Effective project scope management is crucial for maintaining high project quality, as it ensures a clear definition of objectives and deliverables, controls scope creep, and facilitates efficient resource allocation. By providing a framework for understanding what is included in the project and managing changes carefully, it helps in mitigating risks and aligning the project with stakeholder expectations. Furthermore, it underpins quality control and assurance processes by establishing agreed-upon quality standards and requirements. Thus, robust scope management is instrumental in achieving satisfactory outcomes that meet or exceed quality benchmarks, directly influencing the success and quality of the project. Changes to the project plan can impact project quality in notable ways. Introducing new risks and uncertainties can challenge the project's stability, potentially compromising quality if the team is unprepared for these shifts. Misalignments with stakeholder expectations may arise, affecting satisfaction and perceived quality if stakeholders are not fully informed or disagree with the changes. Additionally, these modifications can strain quality control processes, as changes made without full consideration of quality standards or without allowing time for thorough testing and revisions may result in deliverables that do not meet the desired quality benchmarks (Ye et al., 2015).

3.1.3.1 Cost and schedule overrun

Cost is a crucial factor in every stage of project management and holds significant importance as a key determinant of project success. It is widely recognized that the cost aspect plays a vital role in ensuring project objectives are met. However, it is not uncommon to witness construction projects that fail to achieve their goals within the planned budget. Flyvbjerg and Budzier (2019) represent cost overruns are a prevalent occurrence and are often observed in the construction industry, where the actual project costs can surpass the initially estimated expenses by more than 100%. Cost overrun pertains to the circumstance wherein the actual cost of a project surpasses the originally budgeted or estimated cost. The calculation of cost overrun entails a comparison between the initial budget or estimated cost and the tangible expenses incurred throughout the project's duration. It is determined by dividing the actual cost by the estimated cost, with the costs being measured in real terms, devoid of the influence of inflation. Conversely, the actual cost comprises solely the costs incurred during the construction phase, excluding any operating costs, and is assessed at the initiation of revenue-generating operations related to the project. Additionally, schedule overrun is determined by dividing the actual duration of the project, measured from the date of the decision to commence construction until the initiation of revenue operations, by the estimated duration of the project.

Cost overruns have detrimental effects on investments, diminishing their effectiveness and necessitating the procurement of additional funds. In the context of public works contracts, cost overruns have the adverse consequence of redirecting funds from other projects, thereby generating negative ripple effects on the broader economy. In the private sector, the supplementary costs must be sourced from reserves or obtained through borrowing. Within contracting organizations, inadequate cost performance serves to diminish or eradicate profit margins. In severe cases, this unfavorable outcome may even culminate in the failure of a project or the entire company (Hongtao, 2014).

According to Hughes et al. (2015), risks are inherent and cannot be entirely eliminated in projects. Regardless of the thoroughness of project planning, events will inevitably arise that complicate or alter the original basis and pricing of the project. Many of these events will lead to additional costs in completing the project, and someone ultimately bears the responsibility for these costs. Typically, employers are responsible for covering the additional expenses resulting from specific instructions given by architects or employers' representatives. Employers can also be held liable for their own or their consultants' actions that cause delays or disruptions to the contractor's progress. Additional costs arising from uncontrollable events, such as extreme weather, are typically allocated based on the circumstances, often resulting in losses for both parties involved. Contractors are required to absorb additional costs in cases where they are at fault or when they have agreed to undertake a specific risk. It is highly likely that cost overruns and delays occur when risks and uncertain events materialize.

However, Flyvbjerg et al. (2019) contend that while all the factors mentioned in the previous table can contribute to cost overruns and schedule delays, they may not be the actual underlying cause. The primary cause of overruns lies in the tendency to overlook risks associated with complexity, changes in scope, and other factors. It is important to note that the root cause of cost overruns and schedule delays is not solely the occurrence of unforeseen conditions and adverse events during a project. Rather, the root cause can be traced back to the project's level of preparedness in anticipating and managing these unforeseen conditions and adverse events.

During the progression of projects from concept to reality, it is common for the scope to undergo changes. These changes can arise from uncertainties related to factors such as project ambition, specific requirements, technical standards, safety, environmental concerns, project interfaces, and geotechnical conditions. Additionally, uncertainties regarding the prices and quantities of project components further contribute to the risk. To effectively address the issue of underestimating cost and schedule risks, it is crucial to identify the root causes. These causes can be categorized into three main groups: (1) occurrences of bad luck or errors; (2) optimism bias, where overly positive assumptions are made; and (3) strategic misrepresentation, which involves intentional misrepresentation of project expectations.

As a result, there will always be a certain level of risk associated with cost and schedule. However, this risk is not unknown and should be adequately assessed and documented at each stage of the project. Therefore, instances of cost overruns and schedule delays should be viewed as an underestimation of the associated risks.

3.1.4 Survey validation of identified problem

After a thorough literature review, specific issues pertaining to the topic were identified. To validate these problems, a survey was conducted to gather opinions from participants.

The aim of the survey was to confirm the existence and significance of these issues, ensuring a comprehensive understanding.

To utilize system dynamics effectively, it is imperative to identify the underlying factors influencing risk augmentation within the project management process groups. Additionally, focusing our study within the construction domain of project management is necessary. Numerous factors were identified through a systematic literature review and snowballing, as outlined in Table . While these studies pertain to construction projects in other countries from previous years, the decision was made to validate these underlying factors in Canada, update them, and identify any new underlying factors.

3.1.5 Survey result

To collect participant opinions, emails were sent to potential respondents' email addresses. Several companies engaged in large-scale projects, such as those collaborating with Hydro Quebec, Montreal municipalities, and LinkedIn profiles of managers, were identified. The email campaign ran from May 5th to June 22, 2023, during which 49 emails were dispatched to targeted recipients, yielding 6 responses. Figure 3.2 displays the educational backgrounds of the respondents: 50% hold master's degrees, 33.3% possess bachelor's degrees, and 16.7% have obtained PhDs.

Figure 3.3 presents the years of experience of respondents: 66.7% have over 10 years of experience, 16.7% have between 5 to 10 years, and 16.7% have less than 5 years of experience.

Figure 3.4 illustrates the job positions of respondents: 75% are project managers, while 25% are engineers. It is noteworthy that only four respondents disclosed their job positions within the project in their answers.

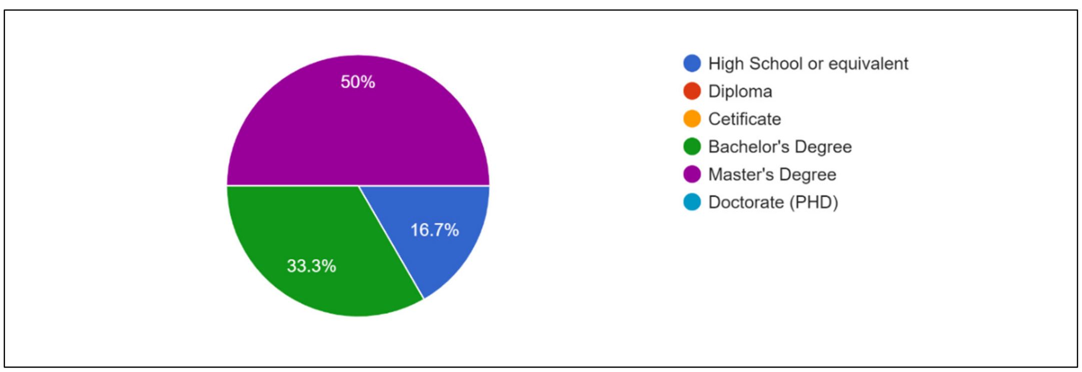


Figure 3.2 Education background

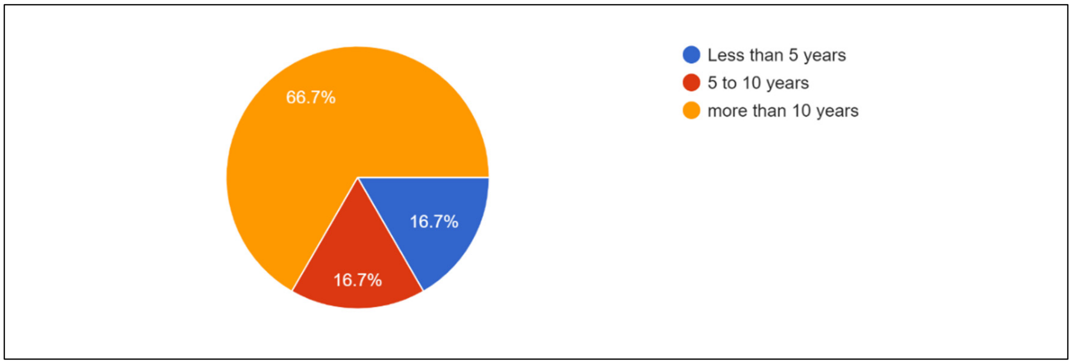


Figure 3.3 Years of experience

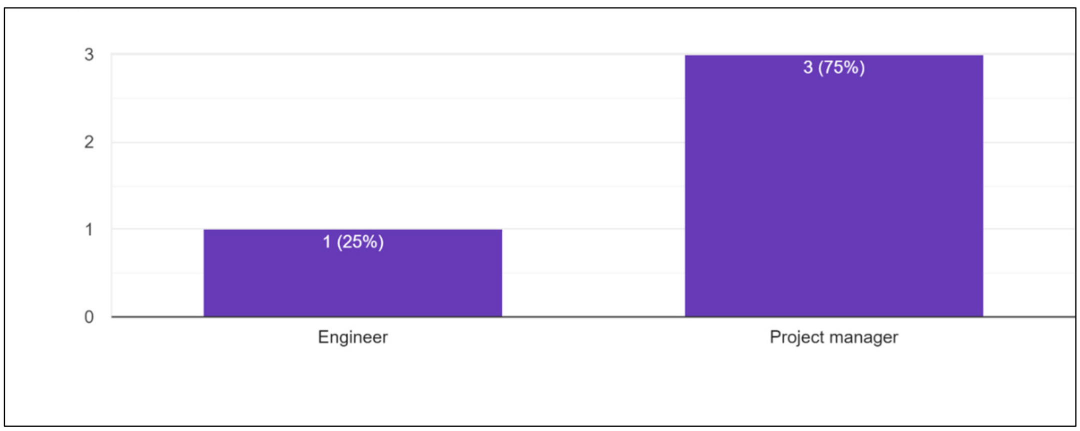


Figure 3.4 Position of participants

Figure 3.5 indicates the type of projects they are involved in, with 60% of respondents working on private projects and 40% on public projects.

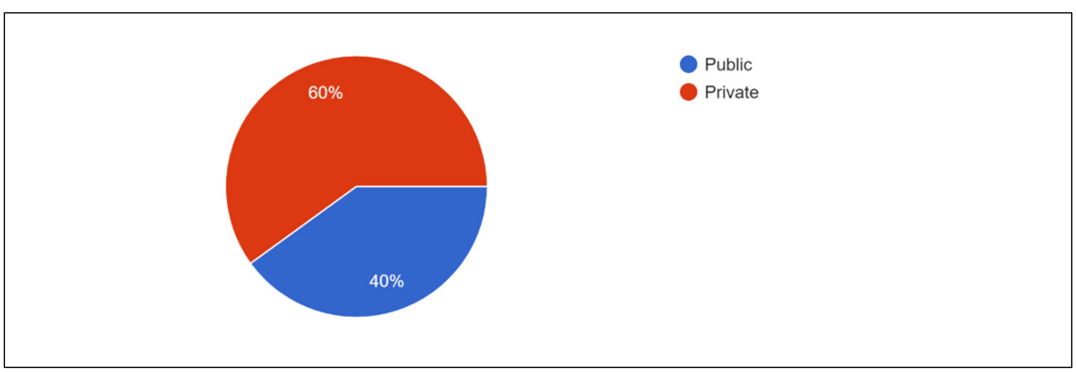


Figure 3.5 Type of projects

Additionally, the types of organizations represented are shown in Figure 3.6: 60% of respondents are contractors, 20% are consultants, and the remaining 20% are clients.

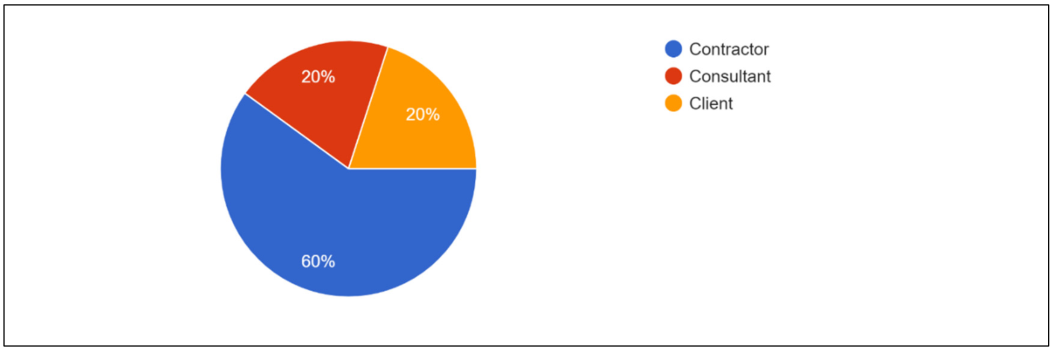


Figure 3.6 Type of organization of participants

3.1.6 Identification of new underlying factors:

In our pursuit to identify new root causes of cost in construction projects, our survey yielded 4 additional underlying factors. Among these, 'Labor strike and disputes' and 'Inadequacy of staff and labor' were identified, with the former being repetitive. 'Stakeholder conflict' identified as a new underlying factor not previously recognized. 'Project complexity,' while initially identified, was reaffirmed. Lastly, 'Unforeseen natural disaster' was found, already acknowledged as "harsh weather conditions" or "unforeseen ground conditions". The literature review had initially identified 34 underlying factors for cost.

For time underlying factors in construction project, we initially identified 24 through systematic literature review within phase 3 and 4.

Regarding risk underlying factors, 18 were already identified through the literature review, with an additional factor, 'Bidding wars put risk on project profitability,' being identified. Quality factors were the focus next, with 18 initially identified through literature review.

3.1.7 Survey sample size:

The saturation method in determining survey sample size is grounded in the principle of collecting data until no new information emerges, a concept integral to qualitative research. According to Fusch and Ness (2015), data saturation is reached when additional data collection no longer provides new insights, themes, or patterns, thereby signaling a comprehensive understanding of the research subject. This iterative process involves conducting interviews, focus groups, or surveys until the responses become redundant, indicating that the sample has sufficiently captured the variability and complexity of the topic under investigation.

The approach is adaptive, ensuring efficient and thorough data collection without the excesses of oversampling or the risks of under sampling. Guest, Bunce, and Johnson (2006) emphasize that saturation is achieved when additional data collection yields diminishing returns, meaning further sampling does not significantly enhance understanding or add meaningful detail. While the saturation method does not specify a fixed number of participants, it underscores the importance of iterative data collection and continuous analysis.

A total of 94 underlying factors affecting the risk-augmented iron triangle were identified through a systematic literature review. These factors have been previously documented in academic and industry publications. Subsequently, a survey conducted with six respondents revealed three new underlying factors. The Table 3.3 shows the result of identifying new underlying factors affecting risk augmented iron triangle by surveys. The calculation for the saturation threshold is as follows:

Table 3.3 Result of identifying new underlying factors affecting risk augmented iron triangle by survey

Survey	Number of obtained new underlying factors
1	1
2	1
3	1
4	0
5	0
6	0
Total	3

Figure 3.7 demonstrates the graph representing the cumulative new factors identified over the surveys.

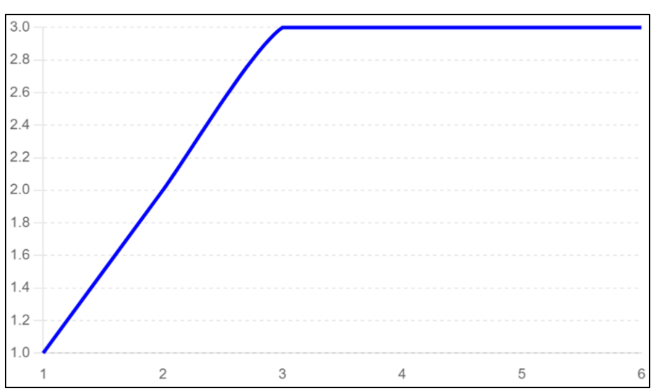


Figure 3.7 Saturation Curve of
Cumulative New Factors Found Over Surveys

As observed in the provided table and graph, we have reached a saturation point where no new underlying factors are collected from surveys 4, 5, and 6. Therefore, it is unnecessary to continue collecting data. These new underlying factors are as follows:

Cost-Related Underlying Factor:

- Stakeholder conflict as a root cause for cost overruns.

Time-Related Underlying Factors:

- Software issues causing delays in project timelines.

Risk-Related Underlying Factor:

- Bidding wars posing a risk to project profitability.

3.2 Decision on the problem to be solved

This review has unveiled a fascinating observation regarding the utilization of system dynamics (SD) for the prediction of project performance and risk assessment across all PMBOK process groups within the construction industry. The objective of this paper is to illustrate how SD models can be utilized in project management simulation, identifying variables that impact risk and project performance, and to introduce a model for predicting the behavior of the risk-augmented iron triangle. A significant gap was identified in the existing literature concerning the application of SD in construction project management for assessing the risk-augmented iron triangle. Therefore, this paper focuses on the imperative of simulating projects across all PMBOK project process groups and identifying the variables that influence project performance. The findings underscore the role of SD modeling in integrating various project management levels, thereby affecting different aspects of project performance.

Bronte-S (2015) critiques the traditional iron triangle model for its lack of comprehensive insight into the overall project status, noting that mere adjustments to the triangle's structure provide only a superficial gauge of progress relative to plans, omitting the intricate details of success and failure. The literature review and survey revealed multiple underlying factors influencing the risk-augmented iron triangle across all project process groups, pointing to a research void in examining their behaviors and interrelations to forecast project performance. While the literature review acknowledges some attempts to apply SD to projects in diverse domains, these efforts have not thoroughly addressed all underlying factors and project process groups. Table 3.1 underscores the research gap regarding the risk-augmented iron triangle across all project management process groups, leading to a systematic approach to tackle this issue in our study.

3.3 Suggestion

Leon et al. (2018) highlights the potential of investigating data from project performance over a longer period to enhance understanding of correlations and dependencies among the underlying factors. They also suggest that integrating the System Dynamics model with case-based reasoning or expert systems could provide comprehensive support to project managers, effectively addressing the identified research gap of comprehensively modeling the interdependencies among project performance indices in construction project management.

3.4 Development

During Step 4, Development, the study aims to find an appropriate tool that aligns with the intricacies of the project-based case study, specifically regarding the Risk Augmented Iron Triangle framework. The main goal is to identify a tool that can accurately depict and sequence the interaction among crucial factors influencing the Risk Augmented Iron Triangle. This involves a thorough investigation of analytical and visualization tools to determine their suitability for the project's context. The chosen tool should provide strong capabilities for illustrating the relationships and interdependencies among the underlying factors impacting risk within the project.

3.4.1 Tools for ascertain underlying factors on Risk augmented Iron Triangle

Through our research, we've discovered that project management constitutes a complex system. Therefore, to effectively visualize and sequence the underlying factors influencing the risk augmented iron triangle, we must explore potential tools and carefully choose the most suitable one.

3.4.1.1 Ishikawa Diagram

The Ishikawa Diagram, also known as the Fishbone Diagram due to its skeletal fish-like structure, was introduced by Professor Kaoru Ishikawa, a pioneer in quality management processes at Kawasaki Shipyards in the 1960s. This diagram, commonly referred to as a cause-and-effect diagram, visually represents the relationships between an effect and its numerous potential causes. It aids in identifying the possible causes of a specific event or problem by organizing and correlating each cause using a classification system. Essentially, it offers an analysis of the factors contributing to observed phenomena. The Fishbone Diagram finds widespread applications across various functions of a company's quality assurance processes. Its structured format encourages team members to think systematically, facilitating the identification of root causes using a methodical approach. Constructing a Fishbone Diagram offers several benefits, including simplifying the study by highlighting areas where data collection is necessary. Moreover, it serves multiple functions applicable to manufacturing, sales processes, and marketing strategies, each with its distinct characteristics (Septiawan & Bekti, 2016).

To categorize the elements, the problem (referred to as the fish head) is positioned on the right side of the diagram. The essential factors are then segmented into various categories, further subdivided into smaller categories by the primary divisions on the left side of the diagram. To enhance clarity in illustrating the hierarchical branches, the current situations typically entail the major issues placed at the fish-head position, intermediate issues at the fish-body position, and minor issues at the fishbone position (Abdel Aziz Allam et al., 2022).

3.4.1.2 Bayesian Networks

Bayesian Networks represent a specific type of graphical model used in various fields. A graphical model, as defined by Goodall (1990), serves as a tool to visually illustrate and manage conditional independencies among variables within a given problem domain. Two variables are considered conditionally independent if they have no direct impact on each other's value, exemplified by the condition $P(A|B,C)=P(A|B)$ (Cowell et al., 1999). The graphical model elucidates intermediary variables that separate two conditionally independent variables, enabling them to indirectly influence each other. Comprising nodes to represent variables and edges to connect them, a graph can depict causal relationships or correlations between variables. Directed edges denote causal relationships, while undirected edges indicate correlations between variables (Cowell et al., 1999). For instance, if variables A and C are conditionally independent but both directly relate to variable B, edges would connect A-B and B-C nodes. These edges would be undirected if the relationships between A-B and B-C operate bidirectional. Although A and C depend on variable B, the absence of an edge between nodes A and C signifies their conditional independence given variable B, indicating that B encapsulates information influencing both A and C reciprocally. Bayesian networks constitute a specialized category within graphical models. A Bayesian network is characterized by its directed acyclic graph structure, where all edges in the graph have a defined directionality, and the graph lacks cycles, meaning there is no path that allows one to navigate from any node and return to the starting node by following directed edges in the correct direction (Stephenson, 2000).

3.4.1.3 Functional Resonance Analysis Method

The Functional Resonance Analysis Method (FRAM) is a method used for analyzing complex socio-technical systems to understand how work is done and to identify potential sources of variability and emergence that can impact performance. The FRAM was first developed around the year 2000 and the first description of the method was published in 2004. Initially, the acronym "FRAM" stood for "Functional Resonance Accident Model" because it was developed in the context of safety research, which was closely related to accidents. However, it became clear during discussions in the first FRAMily meetings that the FRAM was a method rather than a model, and that it could be used to analyze complex socio-technical systems in general, not just for accident analysis. Therefore, the acronym was changed to "Functional Resonance Analysis Method". The FRAM identifies the functions required to complete a task or achieve a goal and then analyzes the interactions between these functions to produce a representation or model of how work is done.

The FRAM is based on the idea that performance variability and emergence can be beneficial for understanding successful action and performance. However, methods that facilitate analysis and understanding of everyday performance variability according to this perspective have lagged. The FRAM helps to fill this gap by providing a framework for analyzing complex socio-technical systems and identifying potential sources of variability and emergence that can impact performance (Patriarca et al., 2020).

3.4.1.4 FRAM background studies

Regarding the FRAM, a particular area of research has connected a lean approach with the utilization of the FRAM as a means of comprehending issues associated with complexity (Saurin, 2016).

Saurin and Sanches, (2014) have formulated a resilience engineering framework that is specifically tailored to address a particular issue. Despite the increased interest and research funding that has been directed towards improving the resilience of critical infrastructures in recent times, it has had minimal influence on the primary directions of FRAM applications.

Anvarifar et al. (2017) have examined the applications of FRAM in the management of risk and resilience, with a focus on the challenges posed by complexity and interdependence. Specifically, they have outlined the utilization of FRAM to analyze the integration of flood protection structures with urban infrastructure. In a study conducted by (Saurin, 2016), the FRAM was explored as a tool for modeling variability propagation in Lean Construction (LC). The FRAM was found to be compatible with the principles of LC and was shown to encourage managers to appreciate the variability of functions and agents unrelated to the function in which the detrimental effects of variability are visible. By focusing on emergence instead of cause-effect relationships, the FRAM can help LC practices manage interactions rather than fixing individual parts of the system, resulting in more realistic explanations of project outcomes. The study also suggests that the FRAM can be useful for anticipating the impact of small intentional and non-intentional changes on the functions involved in a construction project. Combining FRAM and Analytic Hierarchy Process (AHP) methods enables the evaluation of sustainability and the impact of performance variability. This approach enables the investigation of criteria and alternatives, identification of safety behavior variability, and establishment of likely scenarios. It provides a new way to evaluate construction sustainability, emphasizing safety as a key component of sustainability (Haddad & Rosa, 2015). (Scheepbouwer & van der Walt, n.d.) (2017) developed FRAM to Construction Safety that called FRAM-CS method for assessing safety in the construction industry. This approach involves five steps: identifying functions, determining interactions, assessing performance variability, simulating performance propagation, and designing adaptive strategies. By using this approach, they can analyze the evolution of safety risk over time by modeling performance variability and simulating its aggregation.

Huang et al. (2022) presented an original formulation of the formation mechanism behind the variability of the Functional Resonance Analysis Method (FRAM). This marked the first time such an approach was undertaken. The authors examined the impact of human factors, mechanical failures, adverse environmental conditions, and organizational factors on the variability observed during the operational process of the system. They collected historical data on the occurrence frequency of each risk factor and identified the interconnections and interactions among these factors. To assess the intensity of coupling risks, they employed the N-K model, which allowed for a quantitative evaluation of the variability of the functional module. Furthermore, the researchers conducted a case study on a railway dangerous goods transportation accident, demonstrating the effective use of the N-K model in calculating the variability of the functional module. The N-K model, drawing inspiration from fitness landscape theory, offers organizations a structured framework to align performance measures with strategic objectives, optimizing overall performance across diverse systems.

In their research, Del Carmen Pardo-Ferreira et al. (2020) implemented the FRAM to gain insights into construction activities associated with the development of concrete structures. The objective was to enhance the management of resilient safety by examining available documentation, conducting on-site interviews, and making observations. Through the FRAM analysis, the researchers discovered several important findings. Firstly, they observed that the construction phase health and safety plan was seldom utilized. Additionally, they identified that safety was influenced by organizational pressures, and that leading indicators for monitoring routine work were not being utilized effectively. Furthermore, the researchers highlighted the significance of two key factors: the delivery of concrete on-site and crane operations, as these factors exerted a notable influence on variability. The study emphasized the potential of the FRAM model as a foundation for conducting comprehensive and systematic analyses of daily performance, shedding light on previously underestimated issues.

Kim et al. (2021) used FRAM to analyze system behavior, focusing on variability and relative risk levels. They proposed a quantitative scheme for risk assessment, considering variability propagation and aggregation. Testing their method on an emergency response system for infectious diseases, they demonstrated its usefulness in assessing risks and critical conditions. The proposed method can support strategic decision-making in large-scale crisis responses. Haddad et al. (2015) employed FRAM to illustrate how the combination of function coupling can lead to variations in performance, which in turn poses an occupational risk. Their primary focus was on evaluating risk in conventional tools and comparing it to the FRAM approach. Additionally, they made advancements in the field of FRAM by suggesting the utilization of the analytic hierarchy process. This process helps examine the relative significance of criteria and alternatives for identifying performance variability patterns, as well as aggregating the variability.

3.4.1.5 Rationale of implementing FRAM

In selecting the appropriate tool for visualizing and understanding the intricate relationships within our project management framework, we carefully considered various factors to ensure an optimal choice. Among the available options, the Functional Resonance Analysis Method (FRAM) emerged as the most suitable tool for several reasons. First, FRAM offers the capability to sequentialize project activities, providing a clear depiction of the task progression over time. Its inherent flexibility allows for seamless adaptation to diverse project structures and requirements. Moreover, FRAM's unique feature of six aspects labeling enables precise categorization of underlying factors or activities within complex interactions. Additionally, FRAM excels in modeling complex socio-technical systems, capturing dynamic relationships and emergent behaviors that influence project outcomes. Furthermore, previous research and case studies have highlighted the effectiveness of FRAM in similar contexts, providing empirical evidence of its utility and relevance. It focuses on the dynamic interactions between functions and how variability in these interactions can lead to different outcomes. Moreover, given the functional nature of the project and the FRAM method's alignment with functional activities, it corresponds more effectively with the case study presented in this thesis. Given these compelling attributes, FRAM stands out as a powerful tool for illuminating the complexities inherent in our study.

3.4.1.6 Implementing FRAM for the Case Study

In this study, the Functional Resonance Analysis Method (FRAM) is used by following the guidelines established by Hollnagel (2014b). The first step was to define the process and functions in project management regarding the risk augmented iron triangle that was discussed in this paper. The six aspects of each function were identified including input, output, precondition, resource, control, and time. The FRAM model was then created using FRAM Model Visualizer (FMV) version 0.4.1. Before moving on to the next step, the draft model was reviewed and revised with experts.

Step 1: Identifying functions and aspects related to the goal of the system

The initial phase of the FRAM method involves establishing the objective of project management, which encompasses the tasks of project design, planning, execution, control, and closure.

The primary function of the system is determined by considering the goal and understanding of its operation. Functions are categorized into three types: human, organizational, and technical activities. When identifying functions, no distinction is made based on the type of entity performing the task. The description of each function should contain the essential information needed to achieve the specified goal. Functions that are directly linked to the system goals are referred to as "main functions."

Next, various aspects are defined in relation to each identified function. These aspects are conceptualized similarly to the typical FRAM approach. The first aspect is the output (O), which represents the result of the function, either in terms of achieving a goal or progressing towards the next task. For instance, the output function could involve obtaining the desired product or successfully delivering the project. The second aspect is the input (I), which initiates the function and encompasses the preliminary factors that influence the function in relation to our dimensions. An example of input for achieving the desired quality could be effective supervision in projects. The third aspect is the pre-condition (P), which refers to the conditions that need to be fulfilled before executing the function. For example, to treat a risk, it must first be identified, making risk identification a pre-condition for treatment. The fourth aspect is resources (R), which are necessary for carrying out the function. This includes equipment, instruments, utilities, human resources, and labor. The final aspect is control (C), which signifies the ability to manage and control all functions, typically done by supervisors or project managers.

Step 2: Determining interaction between functions

The interconnection among functions, along with their respective aspects, can be identified to illustrate the linkages between preceding and succeeding functions. Each aspect of a function's description refers to one or more additional functions, as those related functions need to fulfill the requirements of that aspect.

Step 3: Identify variability in functions and aspects

This step involves assessing the potential variability that can occur in each function and its aspects. Variability is determined by considering the possibility of abnormal performance. One way to evaluate this is by examining the time of the function's output. The potential performance of a function can be classified into four categories: Precise, Omitted, Imprecise, and Too late/stopped in the middle.

To apply FRAM to our case study, we integrated all activities and underlying factors in the case study within the areas of knowledge and project management process groups, as detailed in Table 3.4, within the case study scenario. This integration resulted in the breakdown of all activities and project procedures, subsequently organized into the six aspects outlined in the FRAM table. This (Table 3.4) explicitly represents these procedures based on the FRAM framework.

Table 3.4 Project functions integrated in FRAM Table

Project process	**Function**	**Input**	**Output**	**Precondition**	**Resource**	**Control**	**Time**
Integration management in the Initiating process	Ask for proposal	Task	Proposal document Stakeholder engagement plan Bid price Identify contractors Planning for one contract in one language	Bid feasibility of project Adequate resources and expertise	Expertise Data and information Technological tool	Document control	
Stakeholder management in the initiating process	Identify stakeholders	Task	Identify stakeholders				

Project process	**Function**	**Input**	**Output**	**Precondition**	**Resource**	**Control**	**Time**
Integration management in the planning process	project office tasks		Planning Designing Detailing phases				
Scope management in the planning process	Define scope	Task	Work breakdown structure Define activities Planning technical equipment	Stakeholder identification	Project manager Project team		
Schedule management in the planning process	Planning all activities	Define activities Project scope Work breakdown structure WBS	Sequence activities Project schedule Resource allocation Activity duration estimate Making reports for investors	Detail design Contractor hiring Safety requirement understanding IGC standard approval	Expertise and contractors Construction Equipment	Schedule adjustment Communication and coordination	Delayed due to safety requirement changes by ICG
Cost management in the planning process	Cost estimation	Construction contract with TML Target cost for tunneling Lump sum for terminals Procurement contract for rolling stock	Cost estimate Cost plan Cost documents Cost forecast Renegotiating with banks(financial) Issuing fixed-price contract	Define project scope Stakeholder engagement Clear understanding and agreement on cost-sharing mechanisms	Cost estimator Cost manager software Project team	Cost control measures Earned value Identification and management of cost overrun Mitigation of risk	Early deadline
Quality management in the planning process	Quality planning	Quality standards and requirement	Quality management plan	Clear understanding of project requirements	Quality management team and experts	Monitoring and control of quality	Delayed

Project process	Function	Input	Output	Precondition	Resource	Control	Time
		Stakeholder inputs and feedback Safety standards by IGC Little margin for error Advance technological equipment		and quality expectations.	Quality control documentation Testing and inspection equipment		
Resource management in the planning process		Project scope and deliverables Project schedule and timeline Budget and financial resources identifying	Resource management plan Establish project team Estimate resources Communication technologies Resource allocation plan Financial Managers and Experts Budget allocation for HSSE activities Procurement technical team Risk assessment and analysis tools Testing and inspection equipment		Human resources Financial resources Physical resources (equipment, facilities, tools)	Control resources Manage project team	

Project process	**Function**	**Input**	**Output**	**Precondition**	**Resource**	**Control**	**Time**
Communication management in the planning process	Project communication planning	Project information, plans, and documentation Communication requirements and objectives Stakeholder communication and engagement plans Information distribution, issue tracking and performance report	Communication management plan	Stakeholder communication platforms	communication requirements and objectives Communication tools and technology	Monitoring and control of project communication Ensuring timely and accurate communication	
Risk management in the planning process	Identifying risk and making a strategic plan	Project scope and deliverables	Identifying engineering risks Identifying Material risk Establishing risk strategy Risk assesses Risk of safety IGC Prepared for financial risk sharing risk information with stakeholders Managing technical risks	Understanding of project scope	Risk management team and experts Risk assessment and analysis tools	Monitoring and control of identified risks	On time

Project process	Function	Input	Output	Precondition	Resource	Control	Time
Procurement management in the planning process	Procurement strategies and policies and contract	cost estimates	Contracts with selected vendors and suppliers Procurement plan	Clearly defined project requirements and scope	Vendor and supplier databases Procurement Planning technical team	Risk management	
Stakeholder management in the planning process		Stakeholder requirements Identify stakeholders	Stakeholder management plan Stakeholder communication plans Vendor and supplier databases Stakeholder inputs and feedback	Stakeholder identification and analysis	Communication tools and technology	Addressing stakeholder conflicts and issues	
HSSE management in the planning process		Regulatory and safety standards Risk assessments and identification of potential hazards Safety standards by IGC Environmental impact assessments	Health and safety and environment management plan	Commitment from stakeholders to prioritize HSSE communication channels for sharing HSSE information	Budget allocation for HSSE activities		
Financial management in the planning process	Financing the project	Regulatory framework Managing technical risks Prepared for financial risks	Budget and financial resources identifying Financing Plan Cash Flow Projections identifying financial institutions	Market Analysis	Financial Managers and Experts Project manager and team Financial Software and Tools	Financial Monitoring and Reporting Compliance with Regulatory Framework Cost control	

Project process	Function	Input	Output	Precondition	Resource	Control	Time
Integration management in the executing process	Concession contract build own transfer	Contractor identification	Contract with Channel tunnel group CTG and France manche FM Creating client-contractor relationship				
Quality management in the executing process		Quality management plan	Rework Quality report			Monitoring and control of quality	
Resource management in the executing process		Resource allocation plan	Resources supply			Monitoring and control of resources	
Communication management in executing process	Creating client-contractor relationship	Communication management plan	Creating client-contractor relationship		Communication tools and technology	Ensuring timely and accurate communication	
Procurement in executing process		Contracts with selected vendors and suppliers		Procurement plan			
Stakeholder in executing process		Stakeholder inputs and feedback	Stakeholder engagement				
HSSE management in executing process		Health and safety and environmental management plan				Controlling Health and environment	
Integration management in controlling and monitoring process		Task	Control changes Monitoring integration				
Scope management in controlling and monitoring process			Warning sign and scope definition Check the scope modification	Regulatory framework			

Project process	Function	Input	Output	Precondition	Resource	Control	Time
			Control scope				
Schedule management in controlling and monitoring process	Government consultation		Controlling of time delays Government consultation Implementation of fast-tracking Implementing of overlapping Managing rolling stock correspondent Managing unknown unknowns	Sequence activities Activity duration estimate			delayed
Cost management in controlling and monitoring process		The well-defined scope of the project Cost plan Cost documents Issuing fixed-price contract	Controlling the interest of the contractors Government consultation Monitoring fixed-price contract Managing rolling stock correspondent	Target cost for tunneling		Monitoring cost overrun prevention	
Quality management in controlling and monitoring process		Quality management plan	Obtaining approvals from governments Government consultation Controlling based on issued quality framework				
Resource management in controlling and monitoring process		Project team	Control resources Manage project team				
Communication managements in controlling and		Communication management plan	Controlling contracts and perusing connections between contractors	Ensuring timely and accurate communication			

Project process	Function	Input	Output	Precondition	Resource	Control	Time
monitoring process		Communication plans for sharing risk information					
Risk management in controlling and monitoring process		Communication plans for sharing risk information	Controlling the risk of contractor cost Controlling risk of subcontractor cost Controlling the risk of vendor cost plus extended overhead Controlling the risk of overlapping method Controlling risk of fast-tracking method		Risk management team and experts		
Procurement management in controlling and monitoring process		Procurement plan	Administer procurement Controlling sufficient procurement resources				
Stakeholder management in controlling and monitoring process		Stakeholders' engagement plan	Monitoring stakeholder engagement Addressing stakeholder issues				
HSSE management in controlling and monitoring process		Safety standards by IGC	Obtaining approvals of standards from governments Controlling based on issued safety framework				
Financial management in controlling and		Cash Flow Projections	Obtaining approvals from				

Project process	**Function**	**Input**	**Output**	**Precondition**	**Resource**	**Control**	**Time**
monitoring process		Financial Management Plan	governments for financing Controlling and stick to financial model issued by governments				
Integration management in closing process		Addressing stakeholder issues Project scope and deliverables	minimize the number of claims awarded Total Cost Impact Analysis Handing Over the Fully Operational Project Managing the claims Collect lessons learned				
Resource management in closing process		Resource allocation plan	Cost overrun analysis Resource Performance Reports Lessons Learned Documentation Final Resource Inventory				
Procurement management in closing process		Financial Closure Information Contract Documentation	Closing out the project and prepare total reports Closed Procurement Contracts Lessons Learned				

3.1.1.7 FRAM model Overview

The diagram in Figure 3.8 illustrates the visual representation generated by the FRAM Model Visualizer (FMV) software, showcasing the various functions involved in the Channel tunnel project management process. The diagram uses different colors to denote different aspects of the project.

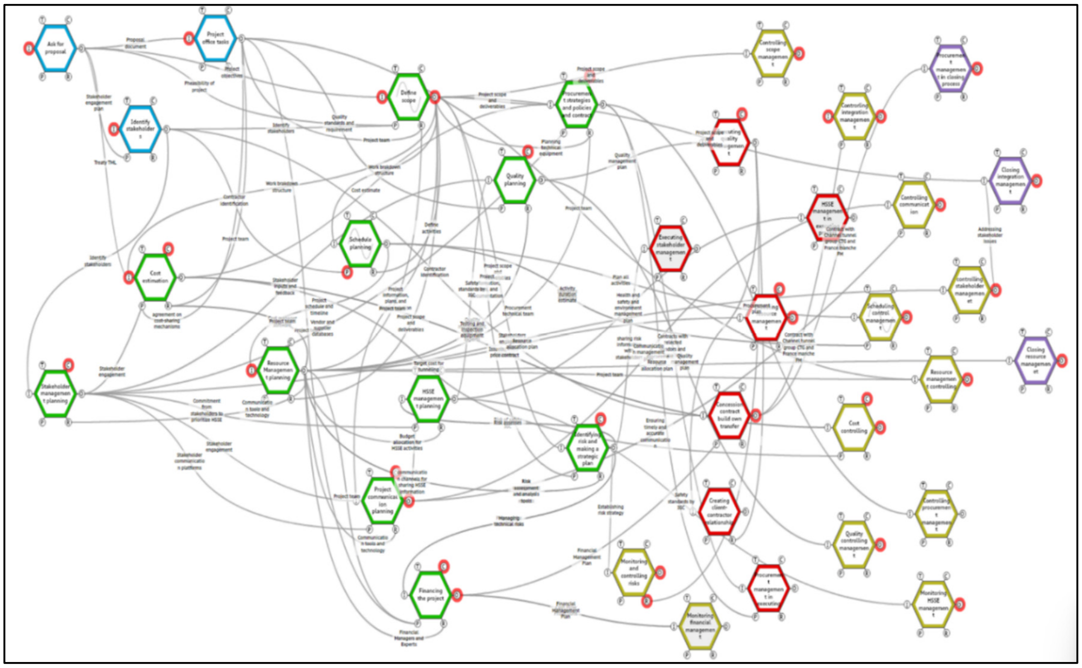


Figure 3.8 Project functions' FRAM diagram

The initial construction management processes are represented by the blue color, while the green color represents functions related to project planning. Functions associated with project execution are depicted in red, and the yellow hexagons represent the controlling processes of management. Finally, the purple functions represent the project closure activities. These processes and their respective areas of knowledge are derived from the construction guidance version of the Project Management Body of Knowledge (PMBOK).

Within the FRAM model, all project activities and stages are meticulously broken down and interconnected. For instance, in Figure 3.9, displays a reduced section of the designed FRAM diagram of the initial task in the project—requesting proposals—yielding four outputs.

1. Proposal Document: This serves as input for project office tasks.

2. Project Objectives: Acts as input for defining the project scope.

3. Stakeholder Engagement Plan: A precondition for identifying stakeholders.

4. Treaty TML: Functions as input for cost estimation.

The Treaty TML (Transmanche Link) synthesizes information from the proposal documents, stakeholder engagement plan, bid prices, project objectives, and feasibility study. It formalizes the agreements on how the project will be managed and executed. The Transmanche Link agreement ensures that all aspects of the project, including scope, cost estimation, and scheduling, are thoroughly planned and agreed upon. This treaty is essential for coordinating the multinational efforts involved in the Channel Tunnel project and ensuring its successful completion.

Moreover, the comprehensive details within the FRAM table are visually represented in the FRAM diagram.

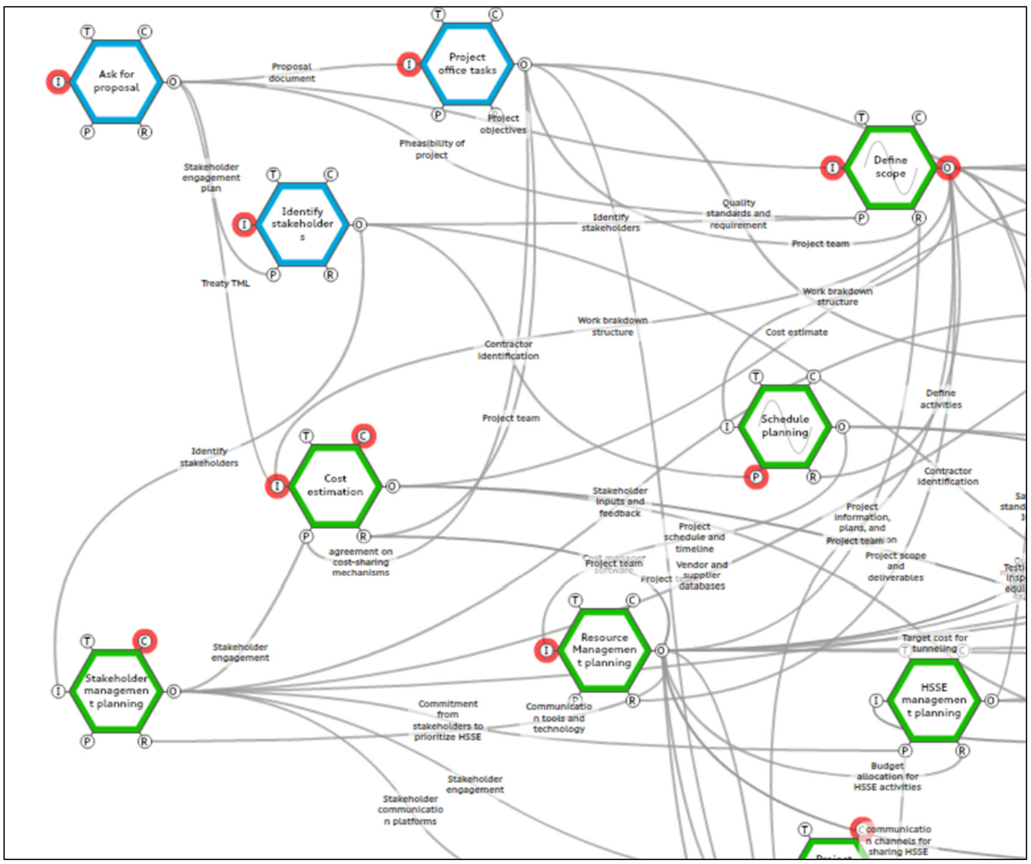


Figure 3.9 Reduced section of FRAM model

The FRAM diagram depicted in Figure 3.8 provides a visual representation of the main functions and their interconnectedness. The diagram shows how upstream functions are connected to downstream aspects such as input, pre-condition, time, control, or resource. For instance, the functions of estimating activity duration and sequencing activities are preconditions for the development of the schedule. Another example is the identification of risk, which precedes the assessment and treatment of that risk. Identifying risk serves as a resource for assessing risk and is also a pre-condition for the subsequent treatment of the identified risk.

3.4.2 Implementing System Dynamics in case study

System Dynamics (SD) aims to understand real-world systems by examining their structure and how they evolve over time, employing a network of cause-and-effect relationships and feedback loops. The Causal Loop Diagram (CLD) plays a crucial role in this process, facilitating the visualization of the interconnections between various system variables and illustrating the feedback mechanisms within the system. CLDs are composed of variables interlinked through arrows that represent causal effects among these variables. Each link is depicted as a line with an arrow at one end, connecting two variables, and is labeled with a polarity sign, either positive (+) or negative (–). These polarities reflect how one variable's change influences another. Specifically, a positive polarity suggests that both variables move in tandem (for instance, an increase in one lead to an increase in the other), while a negative polarity indicates that the variables move in contrary directions (for example, an increase in one result in a decrease in the other). Feedback loops form when these causal relationships create a circular chain, allowing the outcome of certain actions to inform and drive subsequent actions (Sterman, 2001).

A construction project represents a multifaceted system where various components interact and influence one another. For instance, the overall project cost is affected by overhead costs, which in turn are impacted by the project's time. The project time is also shaped by numerous factors, including active rework and communication, with active rework being affected by the project's quality. These complex interactions need to be evaluated and considered to accurately predict a construction project's performance. The causal loop diagram, depicted in Figure 3.10, aids in elucidating the factors driving the system's behavior. It visually delineates the interconnectedness among the underlying factors and risk-augmented iron triangle.

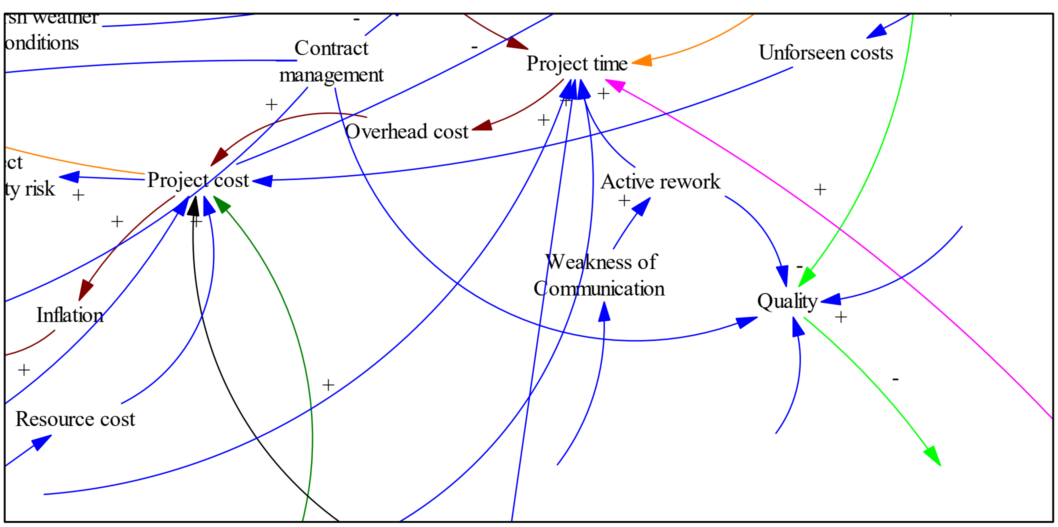


Figure 3.10 Causal loop diagram

To apply system dynamics within the Channel Tunnel case study, we connected essential elements that influence cost, duration, quality, and risk, as identified through literature review. This process entailed identifying and analyzing both reinforcing and balancing feedback loops, as well as scrutinizing how these elements interplay. A literature review facilitated the identification of each element's polarity, highlighting whether they have a positive or negative effect. An exemplar finding was the positive correlation between rework and project delay, indicating that increased rework leads to extended project timelines. Subsequently, the model was structured to simulate these dynamics, thereby quantifying their effects. Expert interviews, alongside literature reviews and prior studies, confirmed the relationships among the variables in our model.

The research introduced a model which was applied to a case study for evaluating its effectiveness and applicability. In the context of this project, the model facilitated an examination of the impacts resulting from behavioral changes and modifications in the risk-augmented iron triangle, recognizing their inherent interdependence. The focus of this case study is the Channel Tunnel project.

This study examines the Channel Tunnel, a landmark engineering project that established a direct railway link under the English Channel, connecting the United Kingdom and France. The project was initiated on December 1, 1987, and reached completion on May 6, 1994, lasting approximately six and a half years. Distinguished by its engineering achievements, it includes a 50.45-kilometer tunnel, the longest undersea section of any tunnel globally at 37.9 kilometers. Initially estimated at $7 billion, the project's costs escalated to around $15 billion due to unexpected challenges and complexities encountered during construction. The Channel Tunnel's successful realization marked a significant milestone in engineering and international collaboration, markedly enhancing connectivity and trade between the UK and mainland Europe (Flyvbjerg et al., 2002). The proposed model can simulate different scenarios for each performance index, enabling the exploration of the most effective management scenario to follow.

3.4.2.1 Anticipating cost over time dynamics in SD model

In construction, payments for the whole project are usually made as the work progresses. The client gives progress payments to the contractor, based on how much work was done the month before. Future payments are guessed using an estimated curve of progress, called an S-curve. But often, there's a big difference between these guesses and what really happens. How well the costs are predicted depends a lot on using a good model and the experience of the engineer.

Gates's and Scarpa (1979) study breaks down a project into three phases. In the initial third of the project's timeline, 25% of the tasks are completed. The subsequent third sees the completion of half of the project's work. Lastly, in the final third of the timeline, the remaining 25% of the work is finished. The S-curve is a common graphical representation in project management, depicting cumulative costs, work, and other metrics over time. Here’s why an S-curve is anticipated for time and cost in our model:

Early Phase (Slow Start): Construction projects usually start slowly as the project ramps up. This initial phase involves planning, obtaining permits, and mobilization. Expenses and progress are relatively low, resulting in the lower, flatter part of the S-curve.

Middle Phase (Rapid Growth): As the project enters its main execution phase, activities increase significantly. This period is characterized by rapid spending and progress as construction is in full swing, materials are being purchased, and labor is most intensive. This acceleration is represented by the steep middle portion of the S-curve.

Final Phase (Tapering Off): Towards the completion of the project, the pace of spending and progress slows down again. Most tasks have been completed, and the work focuses on finishing touches, inspections, and addressing any remaining issues. This slowdown results in the upper, flatter part of the S-curve, completing the characteristic S shape.

Cheng et al. (2011) utilized the concept of dividing a project into three phases, as shown in Figure 3.11 a, to illustrate that the project's cost follows an S-curve pattern over time. They further explore the discrepancy between estimated and actual project costs in Figure 3.11 b and propose a related equation.

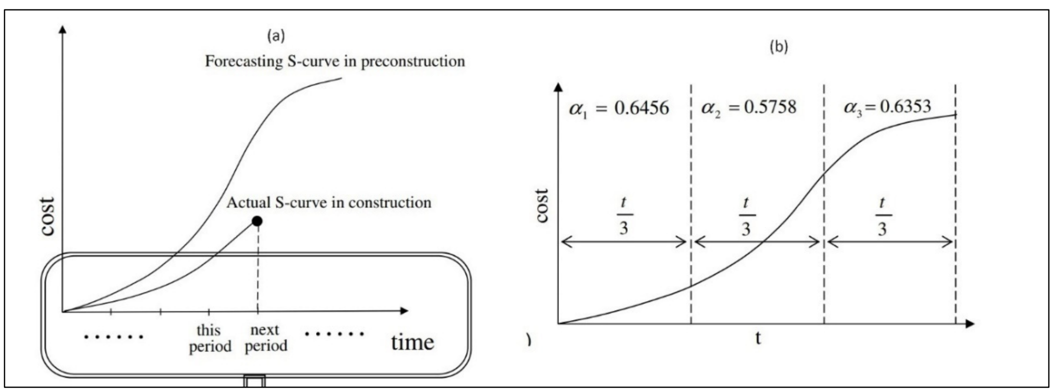


Figure 3.11 The cost over time curve (a) difference between estimated cost and actual cost (b) three project phase
Taken from Cheng et al. (2011)

Cristobal (2017) introduces an S-curve envelope concept, using a sigmoid function with specific coefficients to calculate project cost and time. This method's equation demonstrates that the cost vs timeline curve takes an S-curve shape, as shown in Figure 3.12.

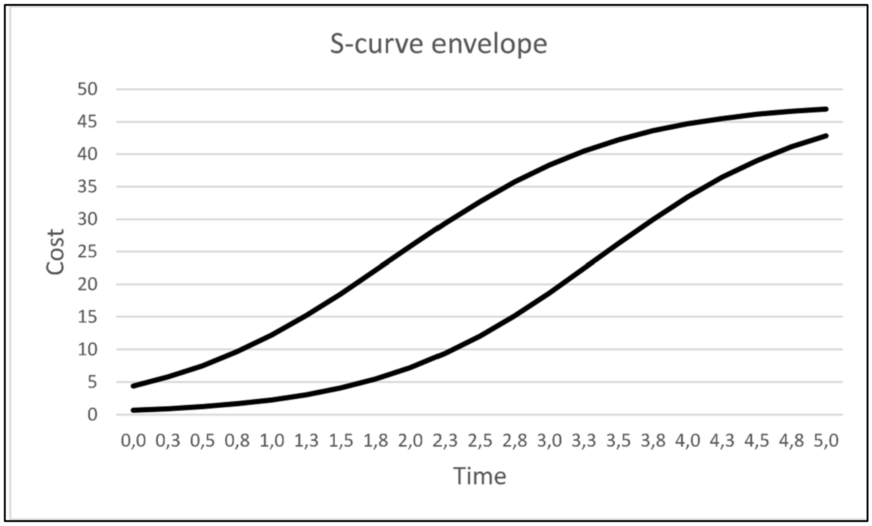


Figure 3.12 Cost over time S-curve envelope
Taken from Cristobal (2017)

Konior and Szostak (2020) introduce a novel methodology for planning the cumulative cost curve in construction projects, applying a technique to form the S-curve, a concept well recognized in academic and practical realms. Their research, conducted within a focused group of hotel facilities, identifies specific regions of the curve crucial for accurate cost planning in construction, setting the limits for anticipated cumulative costs. This methodology builds on the authors' extensive experience and professional practice, drawing on data from Bank Investment Supervision activities between 2006 and 2019, conducted for banks providing investment loans for private sector projects. Their findings confirm that the cost-time relationship in construction projects exhibits an S-curve pattern, with Figure 3.13 illustrating the S-curve of 9 construction projects.

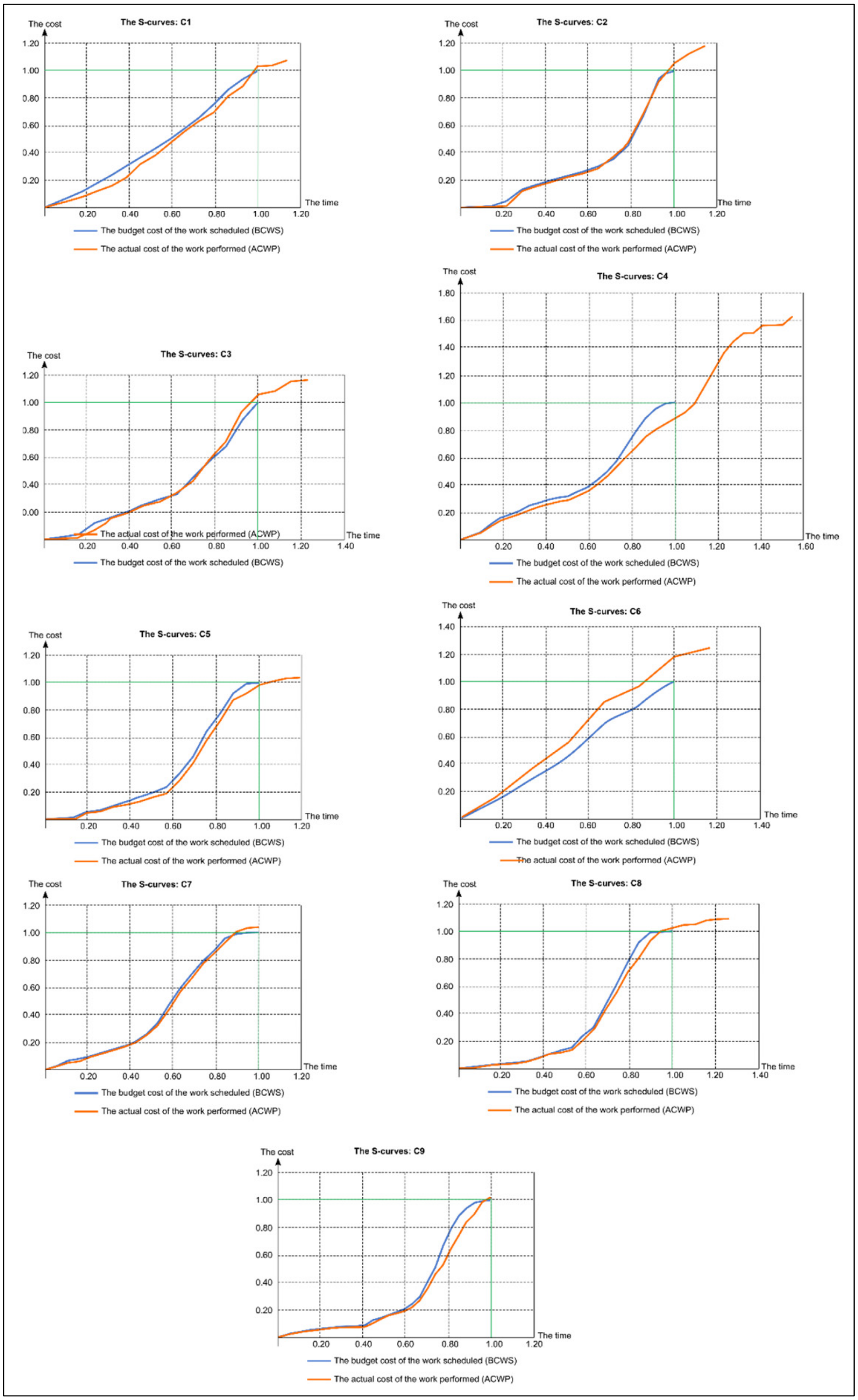


Figure 3.13 Cost over time S-curve in 9 construction projects
Taken from Konior and Szostak (2020)

Cioffi (2005) developed a mathematical model that cleverly applies a differential equation, often used in ecology, to project management. This approach creates a way to produce the S-curve, which shows how project costs, labor, or other measures accumulate over time, starting and ending with slow growth and peaking in the middle. What makes this model particularly useful is its flexibility, allowing for adjustments to how quickly costs rise and when they reach their halfway point. They introduced an equation to model the S-curve in project management, given by:

$$y(\beta) = y\frac{1-exp\,(-8r_{0.67}\beta)}{1+\gamma exp\,(-8r_{0.67}\beta)} \tag{3.1}$$

This formula calculates the progression of project metrics such as costs or labor over time, with β representing the normalized project timeline, y the final value of the measured project metric, $r_{0.67}$ a parameter influencing the curve's steepness, and γ a factor adjusting the curve's midpoint.

$r_{0.67}$ represents a factor that modifies the slope of the S-curve during its steepest part. When $r_{0.67}$ = 1, the middle third of the project timeline is characterized by a rapid rise, accounting for two-thirds of the total rise from start to finish. This setting reflects a typical project spending pattern where most expenses or efforts are concentrated in the middle phase of the project. If $r_{0.67}$ is set greater than 1, the rise in the middle phase of the project becomes steeper, indicating an even more concentrated burst of activity or spending. Conversely, a value less than 1 flattens the curve during this phase, suggesting a more evenly distributed activity or spending throughout the project.

β is a parameter used to describe the normalized time along the project's duration. It is expressed as a fraction of the total project time t_1, where β is calculated as β =t/ t_1. This parameter helps to scale the project timeline from 0 to 1, making the analysis and application of the S-curve model more universal and scalable across different projects regardless of their actual time spans.

γ is defined as the ratio Y/Y_0, where Y is the maximum cost of the project and Y_0 is a scaling factor related to the initial value of the project cost at the start. Essentially, γ represents the total range of the project cost from its start to its maximum, scaled by the initial metric value. A higher value of γ implies a greater total increase relative to the starting point.

In our SD modeling, we incorporate this differential equation along with specific variables to represent cumulative cost and time, aiming to align our model closely with real-world outcomes. Our method involves initially applying the equation to calculate the cost and duration of the Channel Tunnel project. We previously noted that the actual cost amounted to 15 billion dollars, with the project's completion stretching over a span of 6 and half years, equivalent to 72 months. For the initial month, we perform calculations as follows, and for subsequent periods, the results are detailed in Table 3.5.

y_∞= *15 billion dollars*

t_1= *72 month*

$r_{0.67} = 1$

$\gamma = 5.389$

For t=1

$$y(1) = 15 \times 10^9 \frac{1 - exp\,(-8 \times 1 \times \frac{1}{72})}{1 + 5.389 exp\,(-8 \times 1 \times \frac{1}{72})}$$

$$y(1) \approx 0.3405 \times 10^9 \;\; dollars$$

Table 3.5 Cost over time in Channel project

Time (Month)	Cost
1	0.3405
12	4.303
24	10.214
36	12.147
48	13.225
60	14.274
72	14.686

The resulting curve is depicted in Figure 3.14, illustrating the cost over time as an S-curve.

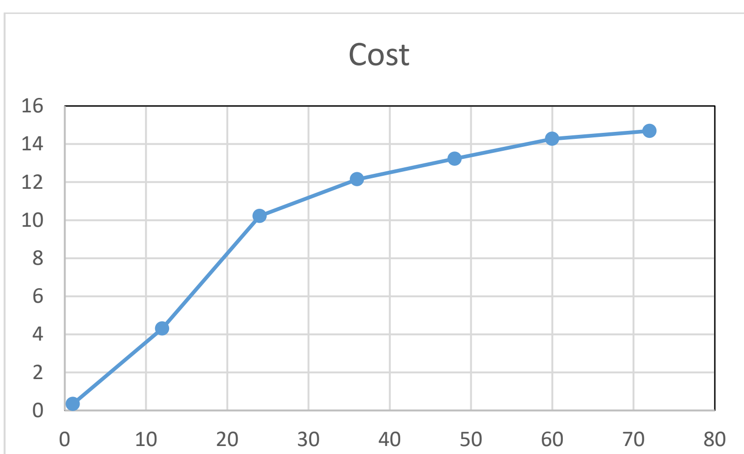


Figure 3.14 The modelled actual cost over time in Channel tunnel project

3.4.2.2 System Dynamic modeling

Initially, we endeavored to establish a model depicting the relationship between cost and time, utilizing an equation and key variables that influence this cost-time dynamic. Figure 3.15 illustrates the model: 'Curve's midpoint' represents γ, and 'Expected time' denotes β in this model. Maximum cost is indicated by y in the equation, and 'Mid-phase acceleration' stands for $r_{0.67}$.

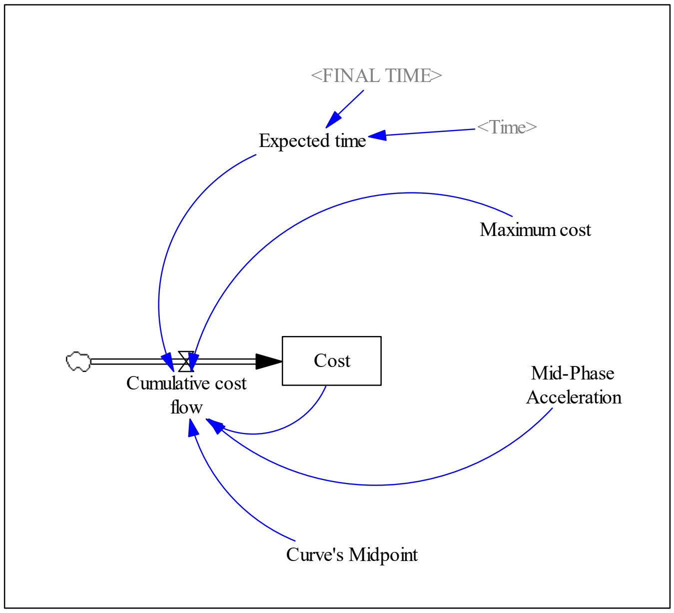


Figure 3.15 Cost and time causal loop

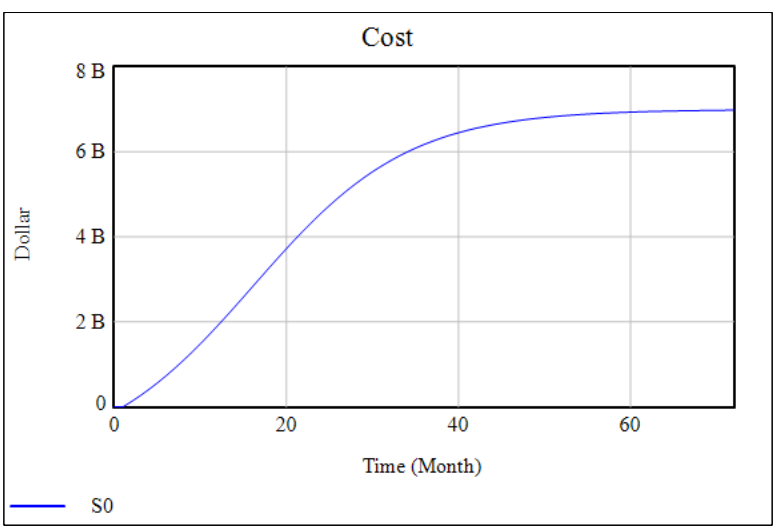


Figure 3.16 Cost over time of Channel tunnel project

As we can see from the presented model in Figure 3.16, the cost-to-time graph corresponds to the project values. It means the time of project is 6 and half years which is approximately 72 months, and the estimated project cost is about 7 billion dollars, and the curve shape is s-curve.

The expectation that quality over time in projects exhibits goal-seeking behavior is grounded in the fundamental objectives of project management, which include continuously striving to minimize deficiencies and errors. As projects progress, the management teams focus on reducing reports of poor quality by implementing systematic improvements and corrective actions. This iterative process of identifying quality gaps, applying solutions, and monitoring outcomes is encapsulated in a causal loop model (see Figure 3.17), illustrating the dynamic relationship between quality initiatives and their impact over time. Such a model underscores the goal-seeking nature of quality management, aiming to steadily enhance quality towards a defined standard or benchmark. The behavior of steering the project towards fewer defects and higher quality is inherently goal-seeking, as it involves deliberate efforts to move closer to desired quality levels with each iteration of the process. Figure 3.18, depicting the quality over time graph, visualizes this trajectory, showcasing how quality initiatives progressively align the project's outcomes with its quality objectives, thereby validating the goal-seeking paradigm of quality improvement in project environments.

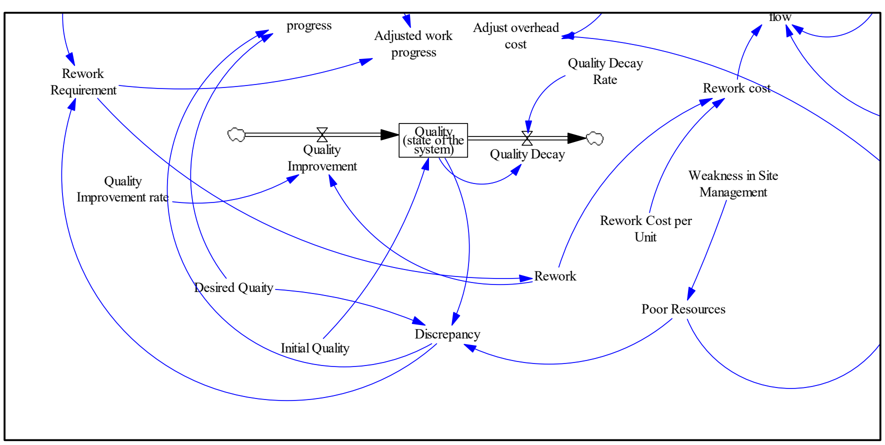


Figure 3.17 Causal loops of quality

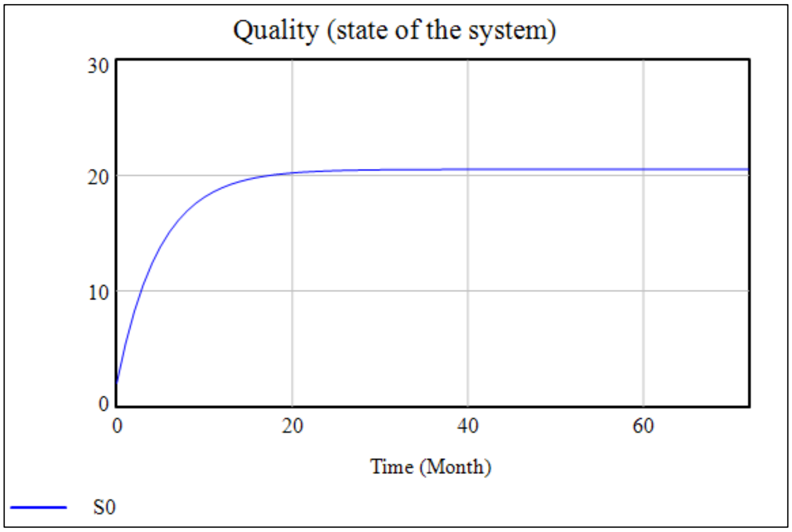


Figure 3.18 Quality behavior diagram

Figure 3.18 illustrates a trend towards the reduction of reports of poor quality, aiming ideally for zero, though such an outcome is not practically achievable.

Measuring Quality in Project Management Models

Quality in project management can be represented in several ways, each providing a different perspective on the performance and outcomes of the project. Common methods to measure quality include:

- Unitless Index: Quality can be expressed as a percentage or a value on a scale (e.g., 0 to 1, or 0 to 100). For example, a quality score of 0.8 on a scale of 0 to 1.
- Defects per Unit: Quality can be quantified by the number of defects per unit produced or processed, such as 5 defects per 1000 units.
- Customer Satisfaction: This is often measured by customer satisfaction scores, which are dimensionless. For instance, an average customer satisfaction rating of 4.5 out of 5.
- Compliance Rates: Quality can also be assessed by the rate of compliance with standards or specifications, such as 95% compliance with quality standards.

In our project management model, quality is represented through a causal loop diagram that focuses on the relationship between desired quality and actual quality. Here's how the model works:

Desired Quality: This is the target quality level that the project aims to achieve. It is represented as a unitless index or score, such as a value of 25 in our model. This desired quality could be derived from customer expectations, industry standards, or internal benchmarks.

Actual Quality: This represents the current state of quality in the project. It is measured through a quality index, score, or customer satisfaction rate that reflects the system's performance.

Discrepancy: The discrepancy is the difference between the desired quality and the actual quality. This variable is crucial as it drives the rework process. The formula for discrepancy is:

$$\text{Discrepancy} = \text{Desired Quality} - \text{Actual Quality}$$

Rework Requirements: If the discrepancy is greater than zero, it indicates that the actual quality is below the desired quality. The model then triggers the rework process to improve quality. The rework efforts aim to reduce defects, enhance customer satisfaction, or increase compliance rates, thereby closing the gap between actual and desired quality.

Goal-Seeking Behavior: As depicted in Figure , the model exhibits goal-seeking behavior, striving to minimize the discrepancy and achieve the desired quality. Despite the system's efforts, it might not completely reach the desired quality due to various constraints, but it aims to get as close as possible.

The model demonstrates how quality escalates in a project. Initially, the actual quality might be significantly lower than the desired quality. Through continuous rework and quality improvement processes, the actual quality increases, thereby reducing the discrepancy. This iterative process helps the project progressively enhance its quality, moving closer to the desired target.

In our model, quality is treated as a unitless measure, meaning it doesn’t have a specific unit of measurement. Instead, we use a random number to represent the scale of quality changes. This abstraction allows us to focus on the relative changes and improvements in quality without being constrained by specific units.

In modeling the dynamics of risk within our project, it is critical to acknowledge that risk levels are inherently high at the onset due to the myriad uncertainties, such as those related to project scope, requirements, and the forming stage of the team. As the project advances, a deeper understanding and refinement of processes contribute to a more streamlined operation, effectively reducing perceived risks. This reduction, as captured in our system dynamics model, follows an inverse logistic curve trajectory, reflecting an initial high risk that gradually mitigates over time. Interestingly, while our model aligns with the inverse logistic curve pattern, indicating a decrease in risk as the project moves towards completion, discussions in the field suggest that risk over time could also be modeled as a linear progression, depending on the nature and management of the project. The insights gained from expert opinions have been invaluable in shaping our understanding and modeling approach, allowing us to encapsulate the complex nature of project risk and its evolution over time accurately. Figure 3.19 presents the system dynamics model, incorporating risk among its variables. Additionally, Figure 3.20 illustrates the graph of risk over time.

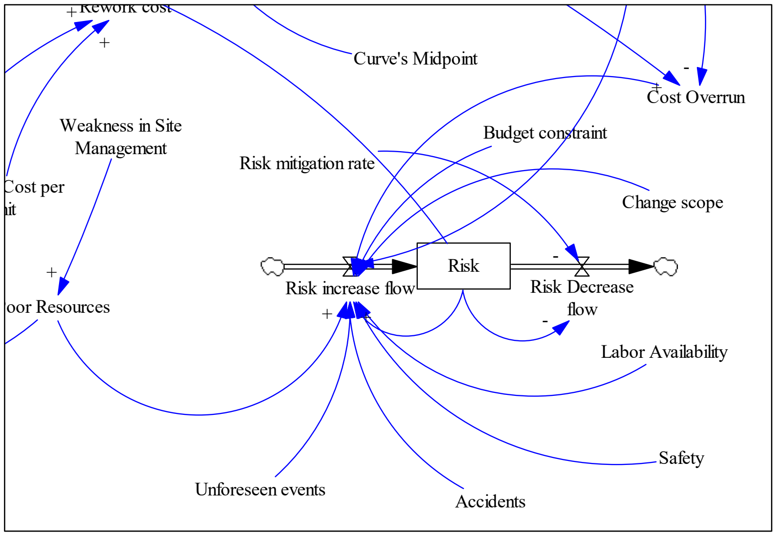


Figure 3.19 Basic presented model

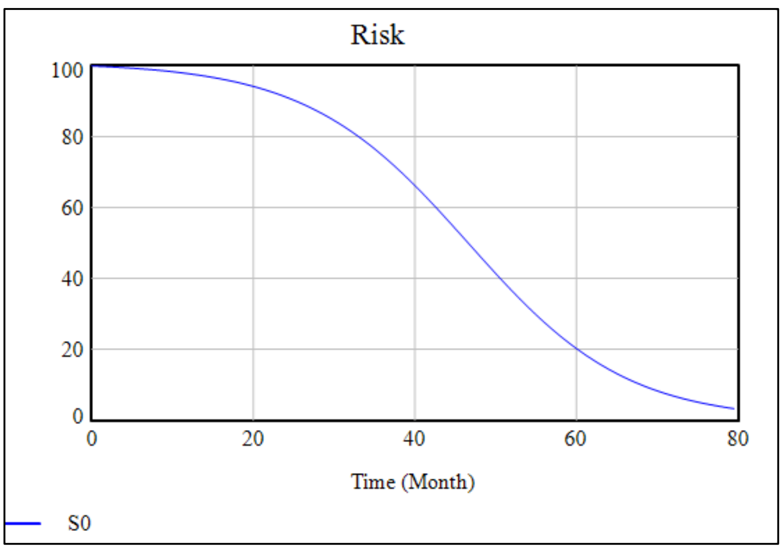


Figure 3.20 Risk behavior of Channel tunnel project

In our model, we present the project schedule, defined as the ratio of 'Expected Completion Time' to 'Actual Time.' The actual time is represented in the model with the built-in variable '<TIME>' in the VENSIM software. A project schedule value less than 1 indicates the project is ahead of schedule, a value of 1 indicates the project is exactly on schedule, and a value greater than 1 indicates the project is behind schedule. As illustrated in Figure 1, the project is on schedule at month 72 but subsequently falls behind. Since the real project was estimated to be completed in 72 months but was finished in 99 months, we can see the actual project schedule in Figure 3.21.

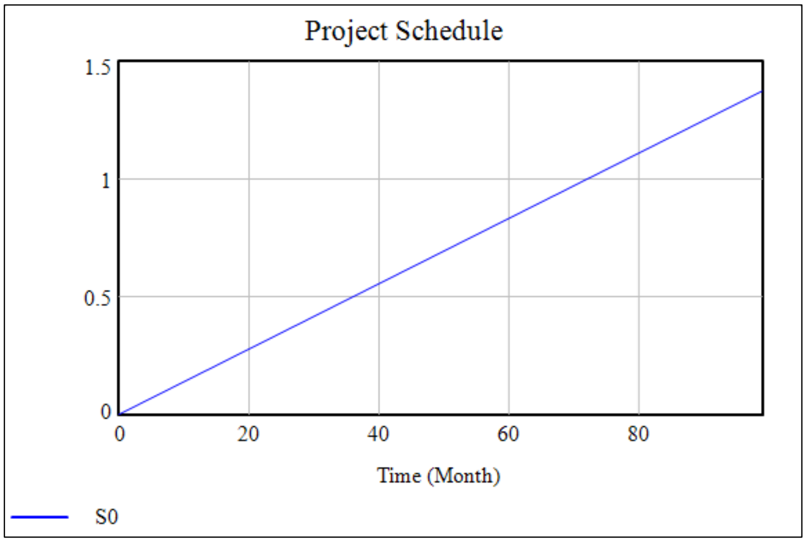


Figure 3.21 Project schedule behavior

3.5 Evaluation to confirm the solution

3.5.1 System dynamics analysis

Building confidence in system dynamics models involves conducting tests that primarily focus on validation, sensitivity analysis, and policy analysis. Testing and validation are essential aspects of establishing confidence in these models. Testing involves comparing the model with empirical reality to determine its acceptance or rejection, while validation is the process of establishing confidence in the reliability and utility of the model. During the testing phase, system dynamics models are compared to real system structures and behaviors based on available descriptive knowledge. Behavior testing is commonly employed in system dynamics models, especially when data for certain variables is lacking. In such cases, assumed relationships are derived from existing literature, and their suitability is justified within the overall context of the model's behavior. The model has been developed to incorporate the underlying factors of the augmented iron triangle of risk, as illustrated in Figure 3.22.

The main reason for the limited use of statistical testing in system dynamics is the inclusion of variables for which real-life data is unavailable. Since system dynamics models incorporate both statistically validated and assumed variables, the potential degradation of model behavior due to the inclusion of statistically non-tested variables cannot be asserted. In fact, the incorporation of assumed variables can enhance the model's capacity to generate behavior, indicating successful improvement. Model building and validation become relatively straightforward when the modeler possesses a clear understanding of the system's behavior and supporting data (Bala et al., 2017).

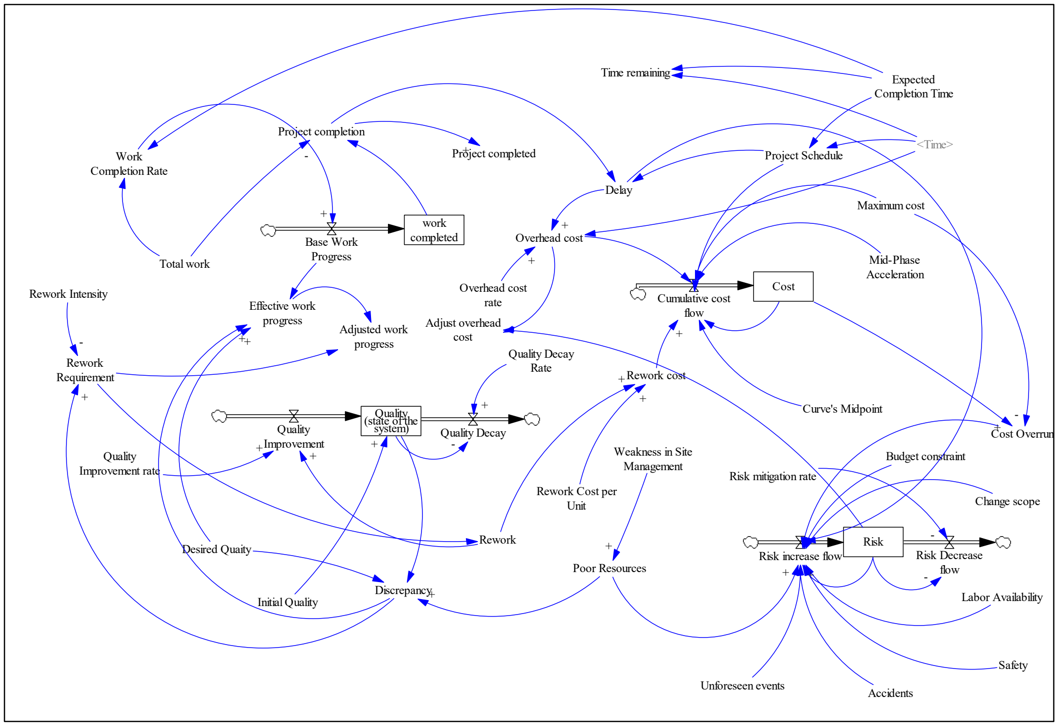


Figure 3.22 System dynamics model of Channel project

Behavior sensitivity testing examines the model's response to changes in parameter values, determining whether plausible shifts in parameters cause the model to fail previously passed behavior tests. This test involves experimenting with different parameter values and analyzing their impact on behavior. Generally, system dynamics models exhibit insensitivity to plausible changes in most parameters, suggesting that systems themselves are insensitive. However, both real systems and models can demonstrate sensitivity to a few specific parameters. Identifying a sensitive parameter does not necessarily invalidate the model; even though it significantly affects behavior, plausible variations may not result in the failure of other behavior tests.

3.5.2 Sensitivity analysis result

Scenario I

To assess the model's reliability, several scenarios were conducted to analyze its functionality and the interaction between different variables.

In the first scenario, we imposed a delay of 17 months to observe the effects on variables such as project schedule, cost, risk, and quality. Initially, in scenario 0, the project cost is approximately 7 billion dollars. When the expected completion time is extended in scenario 1, the cost remains lower initially, until month 35, compared to scenario 0. This is because the project falls behind schedule, delaying many tasks and thus incurring no expenditure for them. After month 35, the cost escalates sharply, reaching approximately 15 billion dollars by the end of the project. Figure 3.23 illustrates the change in cost.

The project schedule is also influenced by both the expected completion time and the actual time. This schedule impacts project delays, which in turn affect the overhead costs. Essentially, any delay results in an increase in project overhead costs.

Regarding risk, project delays and subsequent cost increases result in cost overruns, which elevate project risk. As depicted in Figure 3.23, the initial risk is 100 units. In Scenario 0 (S0), the risk gradually closes to zero, indicating improved project performance and better communication over time. However, in Scenario 1 (S1), the risk does not tend to zero, and the graph's slope is less steep than in S0, indicating a remaining total project risk. Additionally, as illustrated in Figure 3.23, the project quality does not experience fluctuations. This is because changes in time and cost do not have any effect or interrelation with the quality factors in the modelled project.

In Figure 3.22 of the model, it is evident that there are no variables directly affecting project quality from project schedule, cost, and risk. However, there are variables that extend from quality, such as 'rework time', 'rework cost', and others. This indicates that while changes in the project schedule do not directly alter the project's quality, they do affect elements that stem from quality. Consequently, the quality of the project remains unchanged when delays occur, as demonstrated by the overlapping S0 and S1 graphs in Figure 3.23. This overlap implies that the project's quality is unaffected by system-induced delays.

To elucidate further, the analysis of Figure 3.23 reveals a critical insight: project quality maintains its integrity irrespective of fluctuations in the project schedule. The factors of schedule, cost, and risk, which typically have a significant impact on various project dimensions, do not directly influence the quality in this model. Instead, the outflow variables from quality, such as 'rework time' and 'rework cost', suggest that quality has downstream effects on these factors.

The overlapping S0 and S1 graphs serve as a visual confirmation of this phenomenon. Both graphs, representing different states or scenarios of the project, indicate no deviation in quality despite changes in the schedule. This outcome could suggest a robust quality assurance framework within the project that ensures quality is maintained consistently, or it could indicate a model design where quality is insulated from scheduling impacts.

In practical terms, this could imply that the project has implemented effective quality control measures that are not easily disrupted by schedule variations. Alternatively, it might suggest that quality is more resilient or has been prioritized in a manner that isolates it from other project variables like cost and risk.

This observation underscores the importance of understanding how different project factors interact and affect each other. While delays and changes in the project schedule are often perceived to have broad implications, this model's outcome highlights that with the right measures in place, project quality can remain steadfast, ensuring that deliverables meet the required standards regardless of timeline fluctuations. This insight can be crucial for project managers aiming to maintain high-quality outputs even in the face of scheduling challenges.

In the realm of system dynamics, it is crucial to acknowledge that models do not always necessitate the output of exact quantitative values to be effective. As highlighted by Coyle (1999), the inherent complexity and uncertainty involved in modeling 'soft' variables—such as consumer satisfaction or organizational morale—often limit the precision of quantitative outputs. Instead, the value of system dynamics models may lie in their ability to elucidate patterns, explore systemic relationships, and offer strategic insights rather than in their capacity to deliver precise numerical data. This perspective shifts the emphasis from seeking absolute accuracy to understanding broader trends and dynamics, which can be particularly valuable in strategic decision-making and policy development. Therefore, embracing both qualitative and quantitative approaches can enhance the model's relevance and utility, accommodating the complexities inherent in real-world systems.

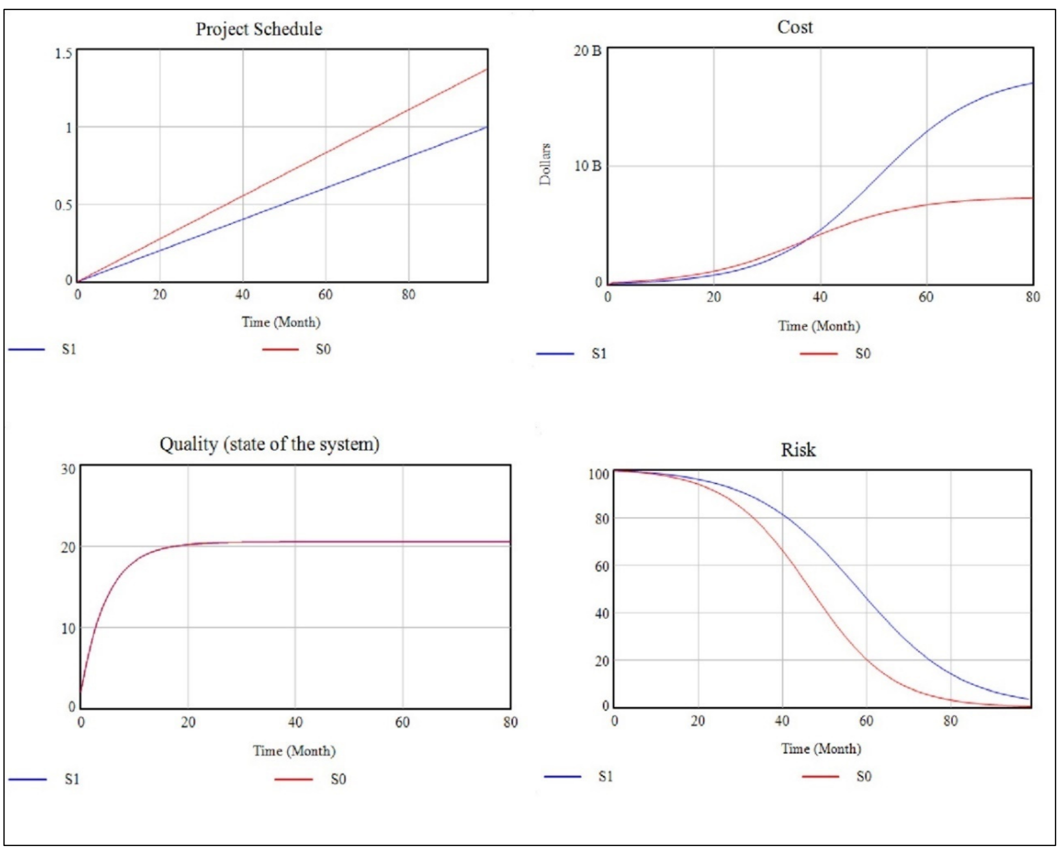


Figure 3.23 Changes of risk augmented iron triangle in scenario 1

Scenario II

In Scenario 2, labeled as such for clarity, we begin by manipulating the variable 'weakness in site management' by 30 percent. An increase in this variable directly correlates with an increase in 'using poor resources' due to their positive relationship. Consequently, the increased use of poor resources widens the discrepancy between the desired quality and the quality resulting from the system's current state. If this discrepancy is greater than zero, the system identifies a need for rework to achieve the desired quality.

This rework incurs additional costs, represented by the 'rework cost' variable in the model, which impacts the 'cumulative cost flow.' As a result, rework imposes additional costs on the project. If there is a cost overrun, defined as the difference between the actual cost and the estimated cost, the estimated cost is represented in the model by the 'maximum cost' variable. Additionally, rework can affect work progress, causing further delays and increasing the project's overall cost. The increased cost overrun, and project schedule delays can also elevate the project's risk. Figure 3.24 illustrates the changes in quality, cost, risk, project schedule, and project completion. In Scenario 0, the risk tends to zero over time. However, when risk arises from cost overruns and delays in the project schedule—stemming from poor quality and rework—the risk tends to increase to 10, with a delay. This indicates that weaknesses in site management can adversely affect quality, increase costs, extend project time, and elevate overall risk.

Project completion is calculated as the work completed divided by the total work, where total work equals the initial work plus rework. When project completion equals 1, it indicates that the project is completed at that time.

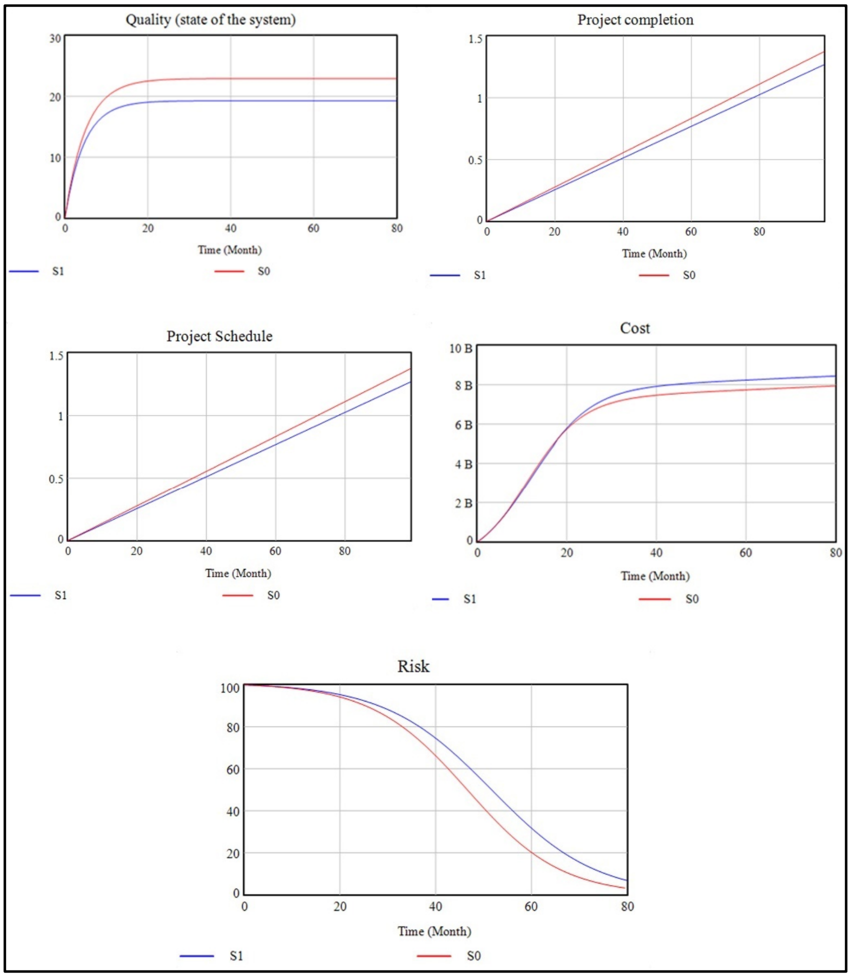


Figure 3.24 Variations in Risk augmented iron triangle in scenario II

In the causal loop diagram for quality, depicted in Figure 3.25, the quality illustrates the level of quality based on project standards. An improvement in quality reduces this discrepancy, indicated by a negative sign (-) on the arrow. Conversely, an increase in discrepancy necessitates more rework to diminish the gap and elevate the quality to the desired standard.

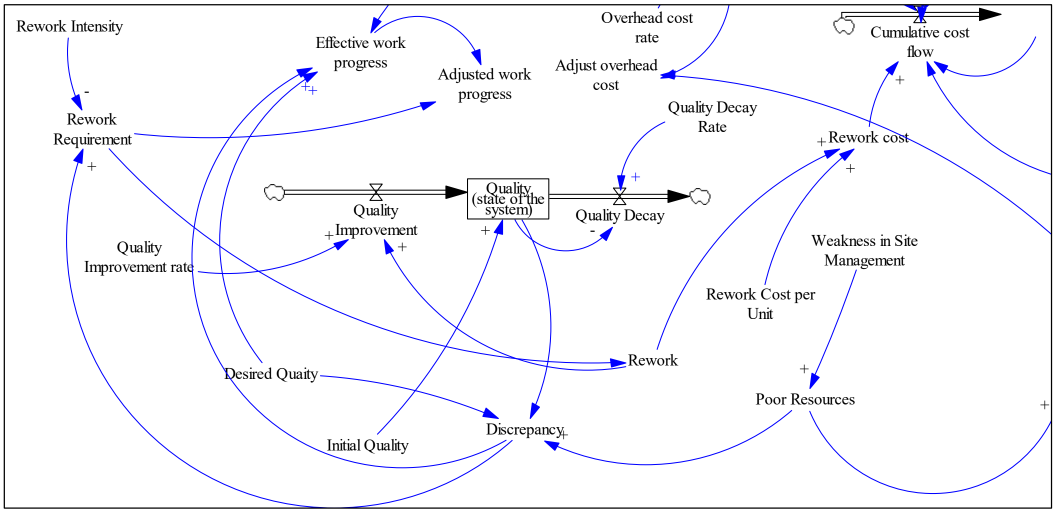


Figure 3.25 Causal loop diagram of quality and rework

3.5.3 Evaluation of model reliability by survey

To validate the model and ensure its applicability to real construction projects, a survey was conducted. The survey was sent via email to approximately 150 companies and individuals involved in the construction industry. Data collection spanned over a period of two months, with active participation from 16 individuals.

The survey primarily aimed to introduce the model and featured five questions that utilized a Likert scale for responses. Participants were asked to assess the extent to which the model is applicable to their real projects, using a scale of 1 (very low) to 5 (very high). Additionally, the last question inquired about participants' interest in using this method for project management, with response options ranging from 1 to 5, representing a scale from very low to very high.

In Figure 3.26, the education degrees of the participants are depicted. The largest portion holds a bachelor's degree at 62.5%, while the master's degrees and certificates each account for 18.8%.

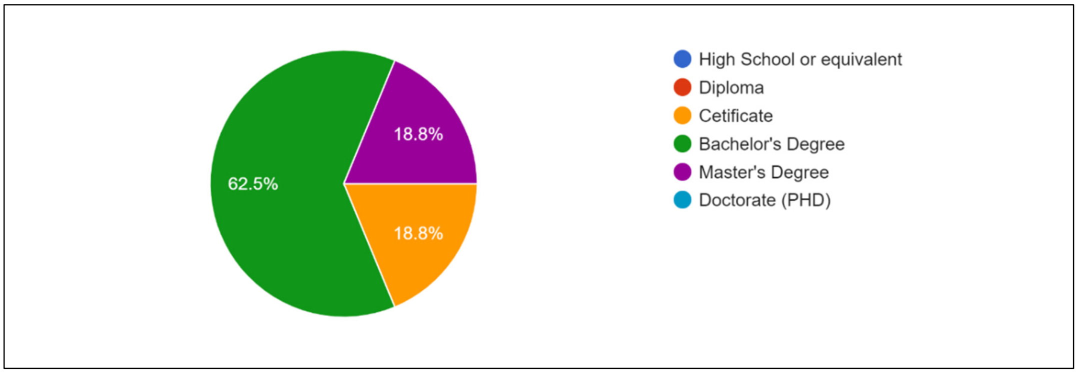


Figure 3.26 Participants' education degree

Figure 3.27 illustrates the experience levels of the participants. The majority, at 50%, has over a decade of experience, followed by 37.5% with 5 to 10 years of experience, and 12.5% with less than 5 years of experience.

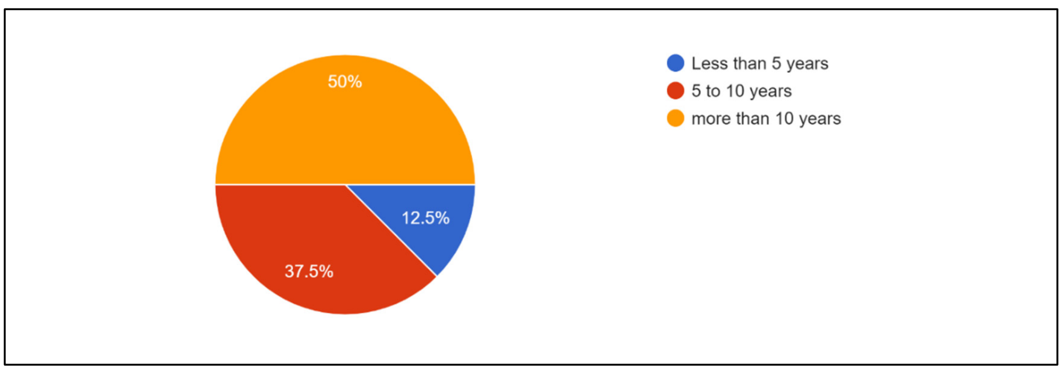


Figure 3.27 Participants' Experience

Figure 3.28 depicts the participants' familiarity with system dynamic modeling, with 62.5% indicating that they are not familiar with it, while the remaining 37.5% are familiar with the concept.

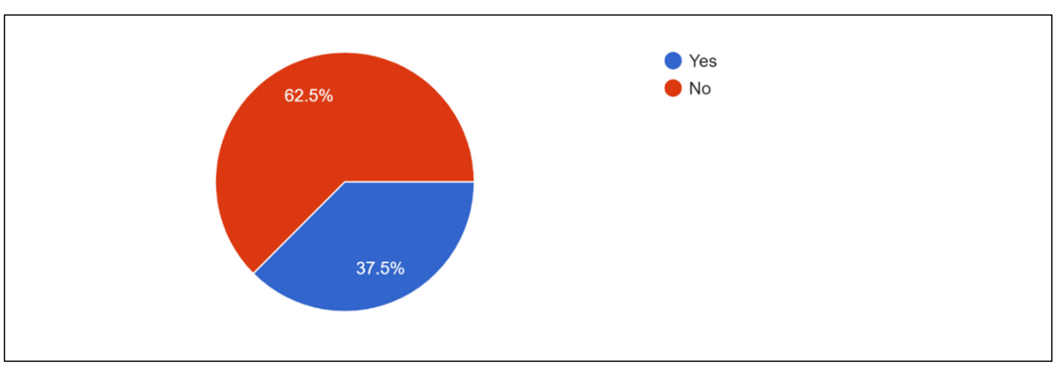


Figure 3.28 Participants' Familiarity with System Dynamic Modeling

The data gathered from the Likert scale presents a unique challenge due to its non-numerical nature. Traditional statistical methods like calculating the mean and standard deviation are ill suited for interpreting Likert scale data, as it is qualitative and categorical. Likert scale data captures respondents' subjective opinions and perceptions, making it inappropriate for numerical analysis.

To address this issue and gain a deeper understanding of the distributional properties and relationships within Likert scale data, we employ Multiple Correspondence Analysis. Correspondence Analysis is a robust statistical technique designed specifically for exploring relationships and patterns in categorical data. It allows researchers to identify associations and dependencies among various categories or responses within the Likert scale. This method is particularly well suited for uncovering the underlying structure of the data, making it a more suitable choice for our study's data analysis. Table 3.6 presents the participants' responses, constituting raw data.

The table is organized such that the rows represent the participants who took part in the survey, while the columns correspond to the questions posed. This survey comprised five questions focused on assessing the model's predictive capabilities in project management across various dimensions:

1. To what extent do you believe the proposed model can predict costs in projects?
2. To what extent do you believe the proposed model can predict time in projects?
3. To what extent do you believe the proposed model can predict risk in projects?
4. To what extent do you believe the proposed model can predict quality in projects?
5. To what extent are you interested in implementing SD model in the projects you are involved in?

The numerical values in each cell reflect the respondents' ratings for each question, using a scale ranging from very low (1), low (2), moderate (3), high (4), to very high (5).

Table 3.6 Survey responses

ID	Q1	Q2	Q3	Q4	Q5
P1	4	4	4	4	5
P2	3	3	3	3	2
P3	5	5	5	5	5
P4	4	4	4	4	3
P5	5	5	5	5	5
P6	4	5	4	4	5
P7	4	4	4	4	4
P8	4	4	4	4	3
P9	5	5	5	5	4
P10	5	5	4	5	5
P11	3	4	1	1	2
P12	4	2	1	2	2
P13	2	1	2	2	3
P14	4	3	1	3	3
P15	4	5	1	2	3
P16	3	4	2	3	4

Participants' Response Description

To fulfill this objective, a frequency table depicting the opinions of participants is provided, accompanied by a mosaic diagram. Table 3.7 illustrates the distribution of participants' opinions, presented as percentages.

Table 3.7 Frequency table of participants' responses

Response Dimension	Very Low	Low	Moderate	High	Very High	Mode
Cost	0 (0%)	1 (6.3%)	3 (18.8%)	8 (50%)	4 (25%)	High
Time	1 (6.3%)	1 (6.3%)	2 (12.5%)	6 (37.5%)	6 (37.5%)	High, Very High
Risk	4 (25%)	2 (12.5%)	1 (6.3%)	6 (37.5%)	3 (18.8%)	High
Quality	1 (6.3%)	3 (18.8%)	3 (18.8%)	5 (31.3%)	4 (25%)	High
Interest	1 (6.3%)	3 (18.8%)	5 (31.3%)	3 (18.8%)	5 (31.3%)	Moderate, Very High

To improve the visual depiction of the data, Figure 3.29 displays a mosaic plot. This figure indicates that responses from participants with 'high' and 'very high' opinions predominate over the other responses.

- In terms of interest in using this model, it is inferred that half of the participants are in favor or strongly in favor of using this model, while the other half are either opposed or somewhat in agreement.
- In the cost and time management section, it can be stated through system dynamics that three-fourths of the participants have expressed that this model can manage time and costs.
- Four participants, constituting one-fourth of the total, have declared that they strongly disagree that system dynamics can optimize risk management.

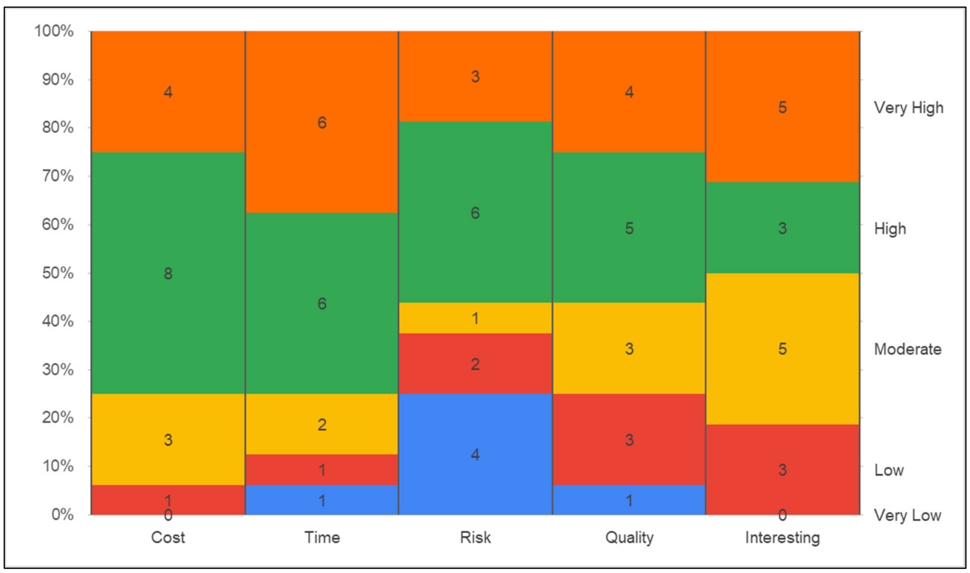


Figure 3.29 Mosaic plot of participants' opinions

Analysis of Dimensional Agreement Size

In this section, pairwise agreement of all dimensions is reported.

Table 3.8 Kappa table for pairwise agreement of the examined dimensions

	Cost	Time	Risk	Quality	Interesting
Cost	1	0.86	0.5	0.5	0.66
Time	0.86	1	0.5	0.55	0.73
Risk	0.5	0.5	1	0.64	0.47
Quality	0.5	0.55	0.64	1	0.53
Interesting	0.66	0.73	0.47	0.53	1

Table 3.8 reports the pairwise agreement of dimensions. Only the interest dimension shows moderate agreement with the time dimension compared with other dimensions. This implies that wherever participants have assessed the model's capability for time management positively, they also show interest in using this model. Table 3.8 is Cohen's kappa coefficients for inter-rater agreement between different dimensions (Cost, Time, Risk, Quality, and Interest). Each cell represents the kappa statistic for the agreement between the dimensions indicated by the row and column. The interpretation of kappa values comes as follows:

Cost and Time: Kappa = 0.86, which suggests substantial agreement.

Cost and Risk: Kappa = 0.5, indicating moderate agreement.

Cost and Quality: Kappa = 0.5, suggesting moderate agreement.

Time and Risk: Kappa = 0.5, which is moderate agreement.

Time and Quality: Kappa = 0.55, indicating moderate to substantial agreement.

Quality and Risk: kappa = 0.64, suggesting substantial agreement.

Interest and Cost: Kappa = 0.66, suggesting substantial agreement.

Interest and Time: Kappa = 0.73, suggesting substantial agreement.

Interest and Risk: Kappa = 0.47, which suggests moderate to fair agreement.

Interest and Quality: Kappa = 0.53, again moderate agreement.

A few points to note:

A value near 0, like for Interest and Cost (0.01), indicates that there is practically no agreement between the raters, or that any agreement is likely due to chance.

Values in the moderate range (0.41-0.60), like the kappa between Risk and Quality, suggest a reasonable level of agreement, but there may still be a significant amount of disagreement to consider.

The substantial agreement (values between 0.61 and 0.80), such as between Cost and Quality, indicates a high level of concordance between the raters on these dimensions.

The diagonal cells ("-") are blank because they would represent the agreement of dimensions with themselves, which would be perfect by definition and therefore not informative in this context.

In summary, this matrix suggests varying levels of agreement between different dimensions with generally fair to substantial agreement, except for the dimension of Interest, which seems to have a notably lower agreement with quality and risk.

CHAPTER 4
DISCUSSION

4.1 Introduction

This study embarked on an exploration of the complexities involved in managing the trade-offs within the Risk-augmented Iron Triangle of construction projects, with a particular focus on the Channel Tunnel case study. By employing System Dynamics (SD) modeling coupling with FRAM within the PMBOK guidelines, this research sheds light on the intricate interplay between time, cost, quality, and risk, presenting a nuanced critique of traditional models through a dynamic, integrative lens. Moreover, this section compares the behaviors and results of our System Dynamics (SD) model with those from recent studies in construction project management. This comparison validates our model by highlighting consistencies and exploring reasons behind any inconsistencies, providing a comprehensive understanding of the factors affecting the risk-augmented Iron Triangle—time, cost, quality, and risk—in construction projects.

4.2 Comprehensive Insights from System Dynamics Modeling and Sensitivity Analysis

SD modeling has illuminated the interconnectivity of project management variables, revealing the cascading effects of alterations within one dimension on others. The implementation of FRAM and SD modeling offered a comprehensive view of the project dynamics, enhancing our understanding of the significant factors influencing the dimensions of the Iron Triangle.

The sensitivity analysis, a pivotal part of our methodology, assessed the model's stability and functionality against real-case data. The analysis demonstrated the model's enhanced reliability in accurately predicting time and cost outcomes compared to risk and quality. This distinction is attributed to the numeric and quantifiable nature of time and cost, which renders them more predictable within project scenarios—a conclusion echoed by the survey results.

4.3 Survey Analysis and Participant Interest

The survey aimed to delve deeper into the practical applicability of the model. Findings indicate that participants who recognized the model's strength in time and cost prediction were keen on employing and implementing this model in their project management practices. This interest not only validates the model's practical utility but also marks a positive reception among project management professionals towards innovative methodologies for managing time.

4.4 Consistencies

Our findings align with several recent studies utilizing SD models to analyze the dynamics of construction project management. Love et al. (2021) examined the impact of rework on project performance, finding that effective quality control measures significantly reduce time and cost overruns, consistent with our findings on the Channel Tunnel project. Similarly, Liu et al. (2024) focused on tunnel security risk management, emphasizing the importance of real-time adaptation of risk control strategies and reducing management delays to enhance efficiency. This aligns with our results on proactive risk management and dynamic response strategies. A study by Chen and Tan (2020) highlighted the critical role of resource allocation and lean procurement strategies in managing construction project costs and schedules. Their SD model showed that optimizing inventory days and employing resources of high quality can improve cost performance and schedule adherence, resonating with our observations on the interplay between weaknesses in site management, using poor resources and project outcomes.

In addition, the study by Boateng et al. (2022) applied SD modeling to assess the impacts of construction delays and identified cost behaviors following an S-curve pattern. Their findings showed that the cumulative cost curve typically follows an S-shape, indicating initial slow cost accumulation, rapid growth during the main construction phase, and tapering off as the project nears completion. This aligns well with our observations in the Channel Tunnel project, further validating the use of S-curve modeling in SD analyses for construction costs.

4.5 Inconsistencies

Despite these alignments, some studies present findings that diverge from ours. Olafsdottir et al. (2016) explored the influence of stakeholder engagement on project success and found a more pronounced effect on project quality and satisfaction compared to our model's outcomes. This discrepancy might be due to the specific focus on stakeholder dynamics in their study, which was not as prominently featured in our analysis.

Ansari et al. (2022) investigated the impact of claims on construction project performance using an SD model. Their study found that claims significantly impact project Key Performance Indicators (KPIs) such as scheduling, sustainability, and customer satisfaction. However, their model emphasized the management of claims as a primary factor influencing performance, which was less prominent in our analysis focused more on proactive risk management and quality control strategies. This difference might be due to the specific context of claims in their study, which differed from the primary focus of our research.

4.6 Limitations of the Study

The research navigated through several challenges, with a primary limitation being the small sample size, a direct result of using an online survey method. Online surveys, while accessible and cost-effective, typically suffer from low response rates. This limitation restricted the breadth of data collected, potentially impacting the study's representativeness and generalizability. The student's limited capacity to incentivize participation further constrained the potential to gather a more diverse and comprehensive dataset. As the survey was disseminated via LinkedIn and direct emails, the resultant self-selection bias—where individuals with a pre-existing interest in the subject matter may be more inclined to participate—could skew the findings.

Another significant constraint was the time-bound nature of a master's thesis. The elaborate process of modeling and analyzing the interactions within the Risk-augmented Iron Triangle, alongside the implementation of System Dynamics modeling, necessitated a substantial investment of time for thorough development and insightful analysis. The academic timeframe within which this thesis was conducted placed inevitable restrictions on the extent of data collection, the scope of analysis, and the depth of model testing achievable.

The model, validated through sensitivity analysis, represents a component of the proposed framework. Given the time constraints associated with this master's thesis, it is not feasible to develop a comprehensive model that addresses all the underlying factors influencing the risk-augmented iron triangle. Although the model has been qualitatively validated via survey methods, empirical validation through sensitivity analysis remains incomplete.

These limitations warrant a cautious interpretation of the findings. While the outcomes offer valuable insights into the application of System Dynamics modeling in project management, the constraints encountered underline the necessity for further empirical research. Future studies could explore broader and more varied participant engagement and might consider employing alternative data collection methods to reinforce the robustness and applicability of the findings.

4.7 Future Work

For future research, this study proposes the development of an extended system dynamics model that incorporates a broader range of underlying factors affecting the risk-augmented iron triangle in construction projects. The risk-augmented iron triangle includes the dimensions of time, cost, quality, and risk, and this extended model aims to provide a more comprehensive understanding of the complex interactions and feedback loops that influence these critical project parameters. The model's enhanced capabilities will allow for more detailed simulations and scenario analyses, helping project managers to anticipate potential issues and devise more effective mitigation strategies.

Figure 4.1 illustrates the extended system dynamics model, highlighting the additional underlying factors and their interactions. This figure serves as a visual representation of the proposed model's structure and complexity, demonstrating how various elements within a construction project are interconnected and how changes in one area can ripple through the system, affecting overall project performance.

The qualitative validation of this model was achieved through interviews with industry experts, who provided valuable insights and feedback on the model's structure and assumptions. These experts confirmed the relevance and applicability of the additional factors included in the model, as well as the overall approach to managing the complexities of mega construction projects. However, the model requires quantitative validation to confirm its accuracy and reliability. This will involve detailed data collection and analysis to compare the model's predictions with actual project outcomes, ensuring that it can be reliably used for project planning and management.

Future research should focus on the quantitative modeling, performance, and validation of the extended system dynamics model. By conducting empirical studies and leveraging real-world project data, researchers can refine the model, validate its predictions, and further enhance its utility as a tool for managing the complexities and risks associated with large-scale construction projects.

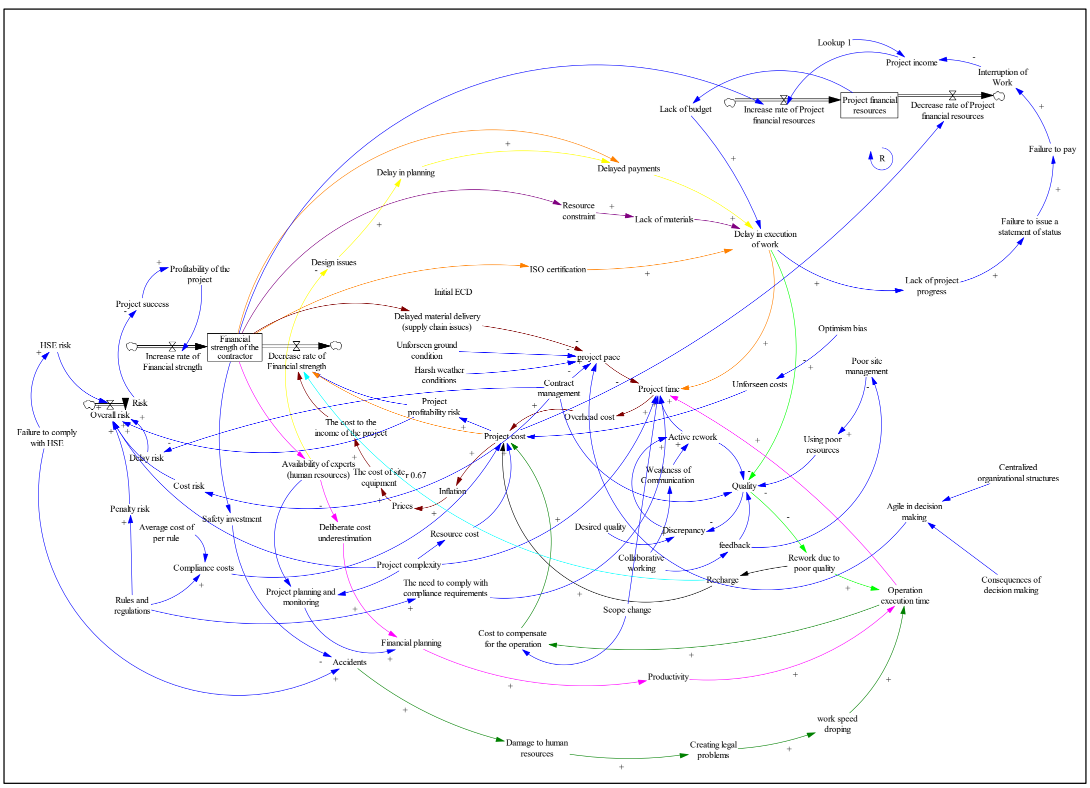


Figure 4.1 Proposed SD model for managing mega construction projects

CHAPTER 5

CONCLUSION

Acknowledging these limitations does not diminish the significance of the conducted research but rather sets the stage for future inquiry. This study lays a foundational step towards the integration of System Dynamics modeling with PMBOK guidelines, offering a fresh perspective on navigating the complexities of construction project management. It is anticipated that subsequent research will build upon these initial findings, addressing the limitations highlighted and further elucidating the dynamic relationships between time, cost, quality, and risk in effective project management.

This study aims to uncover the fundamental factors influencing risk augmented iron triangle within project activities. It explores how these factors interact as a system and to what extent. Using FRAM, it investigates the breakdown of activities within projects—an innovative approach in scientific inquiry. The innovative aspect of this study lies in its integration of the Functional Resonance Analysis Method (FRAM) with the Project Management Body of Knowledge (PMBOK) to navigate the complexities inherent in project management. This integration offers a novel approach by combining the systemic and adaptive strengths of FRAM with the structured and widely recognized processes of PMBOK. Additionally, the study employs System Dynamics tools to model and simulate the interactions between key project elements, such as the risk-augmented iron triangle encompassing time, cost, quality, and risk. Additionally, this study presents these underlying factors and risk augmented iron triangle not only as constituent elements but also examines their interactivity, revealing varying intensities and subsequent impacts on the entire system. These trade-offs are elucidated using System Dynamics tools. FRAM modeling offers a viable method for structuring and managing project activities and routines within project management. Additionally, system dynamics elucidate the interactions between underlying factors and key dimensions within projects. Survey outcomes reveal expert consensus, suggesting that this modeling approach in system dynamics yields more accurate results, particularly concerning time and cost. This alignment appears reasonable considering that sensitivity analysis is more accurate with these factors, and the nature of time and cost tends to be more quantifiable within projects.

APPENDIX I

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Navigating Complexity in Mega Construction Projects: Integrating FRAM with PMBOK for Enhanced Project Management — A Case Study of the Channel Tunnel Project

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Abstract

The management of complexity and scheduling in mega construction projects is a persistent challenge due to their vast scope and inherent intricacies. This study explores the application of the Functional Resonance Analysis Method (FRAM) in construction project management, focusing particularly on its utility for large-scale projects. Through an extensive literature review, a notable gap was identified in the application of FRAM throughout the entire lifecycle of mega projects. To address this, the study proposes an innovative model that integrates FRAM with the Project Management Body of Knowledge (PMBOK) process groups and enhances it using the Analytic Hierarchy Process (AHP) across all knowledge areas. This model is exemplified through a case study of the Channel Tunnel project, demonstrating FRAM's ability to dissect complexities, highlight critical factors, and sequence activities effectively. Our findings illuminate the nuanced interdependencies within the Channel Tunnel project and showcase the efficacy of the FRAM model in enhancing project visibility, decision-making, and overall management. By promoting the integration of FRAM, this study contributes a novel perspective to the field of project management, advocating for a more resilient and adaptive approach to managing the challenges of mega construction projects.

Keywords

FRAM, Project Management, Construction Project Management, Construction Project Complexity

1. Introduction

Mega construction projects are characterized by their vast scales and complexities which pose significant challenges, including delays and budget overruns. These issues are emphasized in studies by Flyvbjerg (2014), who specifically discusses the trends and implications of mismanagement in large-scale infrastructure projects, including historical cases like the Channel Tunnel project. The traditional project management methodologies, such as those encapsulated in the Project Management Body of Knowledge (PMBOK), provide a structured approach to project management. However, their efficacy in dealing with the non-linear complexities of mega projects is often limited, as discussed by Kerzner (2017), who critiques the rigidity of such frameworks in adapting to the dynamic needs of large-scale projects.

One method to cope with the challenges and complexities in mega construction projects is the Work Breakdown Structure (WBS), it is an essential tool. It effectively breaks down large-scale projects into manageable units, facilitating detailed task organization, resource allocation, and scheduling. The WBS allows project managers to decompose project deliverables into smaller, more manageable components, making it easier to oversee large and complex tasks. This hierarchical approach not only simplifies project management but also enhances clarity and improves communication among stakeholders, which is crucial in large-scale projects (Norman et al., 2008).

The Functional Resonance Analysis Method (FRAM), developed by Hollnagel (2004), introduces a system thinking approach to manage complexity more effectively. FRAM illustrates how FRAM's focus on variabilities within normal work interactions can offer insights into potential non-linearities in project outcomes, making it suitable for complex environments like those seen in mega construction projects (Hollnagel, 2017c). This study addresses the research gap highlighted by the limited application of FRAM in the comprehensive management of mega projects. The integration of FRAM with PMBOK is suggested as a novel approach by recent studies, such as those by Woods (2017), which call for more adaptive project management models that combine systems thinking with traditional methodologies to enhance resilience and flexibility. The methodology section of this paper will outline the synthesis of FRAM with PMBOK, supported by a literature review. The application will be demonstrated through a case study on the Channel Tunnel project, providing a practical example of the theoretical model's application, and showcasing its utility in enhancing project management practices.

1.1 Objectives

The primary objective of this study is to develop and evaluate an innovative project management framework that integrates the Functional Resonance Analysis Method (FRAM) with the Project Management Body of Knowledge (PMBOK) process groups. This integrated model is designed to enhance the management of mega construction projects by offering a more dynamic and adaptive approach to handle their inherent complexities. The study aims to analyze the limitations of traditional project management methods like PMBOK in dealing with the intricacies of mega projects, explore the potential of FRAM to address variabilities and interdependencies within project systems, develop a synergistic framework that combines the strengths of FRAM and PMBOK for holistic project management, and apply this model to a case study of the Channel Tunnel project to demonstrate its practical implications and effectiveness in a real-world scenario. Through this objective, the research seeks to contribute a significant advancement in project management strategies, specifically tailored to meet the challenges of large-scale construction endeavors.

2. Literature Review

This review examines scholarly works and authoritative texts on project management methodologies, focusing on large construction projects. It explores traditional methods like PMBOK and systems thinking approaches like FRAM, aiming to integrate these to manage the complexities of large-scale projects effectively. The PMBOK framework, developed by the PMI, is noted for its structured approach but criticized for its lack of flexibility and adaptability in dynamic environments. According to Kerzner (2017), while PMBOK provides a robust set of processes and guidelines, it is inherently prescriptive and tends to enforce a one-size-fits-all approach. This can be problematic in projects where changing conditions and unforeseen events demand quick decision-making and adaptation. PMBOK’s structured phases and rigorous documentation requirements can lead to rigidity, making it difficult for project managers to respond swiftly to changes without going through cumbersome procedural adjustments. This criticism is echoed by Turner (2009), who notes that the linear and often siloed approach of PMBOK does not effectively accommodate the fluid and interconnected nature of modern mega projects. Secondly, PMBOK’s focus on process over people can sometimes overlook the human elements crucial to project success. As discussed by Too and Weaver (2014), PMBOK's methodology is heavily skewed towards technical aspects of project management, such as scope, time, and cost, with less emphasis on leadership, team dynamics, and stakeholder engagement. This oversight can result in the underutilization of human resources and a lack of emphasis on building effective team collaborations, which are essential for navigating the complexities and challenges of large projects. The framework often assumes that project success is primarily the result of well-followed processes and overlooks the nuanced human factors that can significantly influence outcomes. Lastly, the PMBOK framework sometimes fails to effectively manage project risks and uncertainties, particularly in complex projects. While PMBOK includes risk management as one of its core knowledge areas, the traditional risk management approaches it advocates often fall short in predicting and mitigating the kinds of emergent risks that characterize mega projects. Williams (2016) criticizes PMBOK's conventional risk management tools as being too static, as they frequently rely on historical data and fail to account for the unique and evolving risks in large-scale projects. This can lead to a lack of preparedness and agility in dealing with issues that have not been previously encountered, further exacerbating project vulnerabilities.

The Project Management Body of Knowledge (PMBOK) guide, developed by the Project Management Institute (PMI), organizes project management into five distinct process groups. Each group represents a phase in the project management cycle: Initiating, Planning, Executing, Monitoring and Controlling, Closing

The construction extension of the PMBOK guide (2016) expands the standard project management framework to specifically cater to the construction industry, incorporating twelve Knowledge Areas. These include Project Integration Management, Project Scope Management, Project Schedule Management, Project Cost Management, Project Quality Management, Project Resource Management, Project Communications Management, Project Risk Management, Project Procurement Management, and Project Stakeholder Management. Additionally, it introduces Project Health, Safety, Security, and Environmental Management, and Project Financial Management to address specific needs in managing construction projects, ensuring comprehensive oversight from safety standards to financial operations.

Integrating the Work Breakdown Structure (WBS) with the Functional Resonance Analysis Method (FRAM) offers a powerful approach to managing mega construction projects. WBS structures these complex projects into manageable units, simplifying resource allocation and scheduling. Concurrently, FRAM assesses the variabilities within these units, identifying potential resonances that might impact project outcomes. This integration enhances project management by combining WBS's organizational clarity with FRAM's insights into system behaviors, ensuring a more adaptive and resilient approach to managing large-scale projects (Hollnagel, 2017a).

2.1 Functional Resonance Analysis Method

The Functional Resonance Analysis Method (FRAM) offers a nuanced approach to managing complexities in project environments, particularly focusing on human, time, and cost factors. Developed by Erik Hollnagel, FRAM is adept at identifying and understanding the variabilities that occur in human interactions and system functions, which traditional project management methods often overlook. Hollnagel (2017c) highlights how FRAM's ability to map complex processes and interactions helps in predicting how these variabilities can combine and affect overall project outcomes. This ability is crucial for managing projects efficiently, as it allows project managers to foresee potential problems in the domains of time and cost management, thereby reducing the likelihood of delays and budget overruns. Additionally, by focusing on human aspects, FRAM enhances the capacity to tailor management practices to better fit the dynamic needs of the project team, ultimately leading to improved project performance and worker satisfaction. This holistic view supports a more adaptive and resilient approach to project management, which is particularly valuable in complex, large-scale projects where traditional methods may fall short.

FRAM is grounded in four principles that revise traditional risk management:

Equivalence of Success and Failure: Success and failure arise from the same work variabilities, reframing failures as normal outcomes that could lead to success under different conditions.

Approximate Adjustments: In complex work environments, exact adjustments are unfeasible; workers instead make approximate adjustments to manage ongoing conditions, necessitating continual adaptation.

Emergence: Outcomes in complex systems are emergent, not direct results of plans, requiring a flexible and adaptive management approach.

Functional Resonance: Outcomes depend on how variabilities within normal performance resonate, either amplifying or dampening effects, crucial for managing system performance and preventing failures.

Building a Functional Resonance Analysis Method (FRAM) model involves a structured approach to understand and visualize the complexities of socio-technical systems. Here’s a detailed description of the process divided into coherent steps:

1. Defining the Purpose and Scope of the Model

The initial step in constructing a FRAM model requires defining the model’s purpose and its scope. This involves specifying the goals of the analysis and identifying the particular system or process to be analyzed. It's essential to establish clear boundaries for the model to keep it focused and manageable, concentrating on the aspects of the system that are most critical for the analysis. Whether the aim is to assess normal operations, potential risks, or opportunities for enhancing resilience, this stage sets the foundation for a targeted and effective study.

2. Identification and Description of Essential Functions

Following the scoping, the next step involves identifying the essential functions that comprise the system or process under scrutiny. In FRAM, functions are the fundamental units of analysis and are defined by variabilities in their input, output, preconditions, resources, time, and control mechanisms. Each function requires certain inputs to start, generates specific outputs, operates under preconditions, consumes resources, is constrained by time, and needs certain controls for monitoring and regulation. Accurately describing these functions in terms of these six aspects helps in understanding how changes in one function can influence others.

3. Mapping the Functional Interdependencies

Once the functions are identified and described, the third step is to map the interdependencies among them. This mapping involves linking the outputs from one function to the inputs of another and examining how variations in preconditions, resources, timing, and controls might influence these connections. The goal here is to create a visual representation of how variabilities in these aspects might resonate across the system, potentially leading to emergent behaviors not predictable from the individual functions alone.

4. Analyzing Possible Variabilities and Their Resonances

The final step in building a FRAM model is to analyze the potential variability in each function and explore how they might interact with variability in other functions. This analysis looks at scenarios where changes in one function could amplify or dampen effects in others, leading to outcomes that differ from expected. By identifying these potential points of resonance, the analysis seeks to pinpoint possible points of failure or highlight areas where improvements could be made, thus providing valuable insights into the system's dynamics (Hollnagel et al., 2014a).

In the study by França et al. (2020), the Functional Resonance Analysis Method (FRAM) combined with Analytic Hierarchy Process (AHP) is applied to offshore oil well drilling, focusing on human factors. This research, which spans the Planning and Monitoring and Controlling process groups of the PMBOK, analyzes significant operational variabilities and their impacts on safety.

The study by Rosa et al. (2015) addresses the limitations of traditional risk assessments in construction by integrating FRAM with the Analytic Hierarchy Process (AHP). This approach better captures the complexities of construction sites, focusing on how variability in worker performance can lead to safety risks. The research primarily engages with the Planning and Monitoring and Controlling process groups of PMBOK, promoting a more dynamic and inclusive risk management strategy that involves multiple experts and stakeholders in the construction industry. The study by Saurin (2016) explores the use of the FRAM in lean construction to understand and manage variability in project processes, particularly during safety inspections. It aligns with the Planning process groups. The study by Haddad and Rosa (2015) uses FRAM and AHP to advance risk assessments in construction, aligning with the Planning and Monitoring and Controlling PMBOK process groups. This approach enhances safety management by addressing gaps in traditional methods and effectively identifying critical risks. The study by Qiao et al. (2019) evaluates Systems-Theoretic Accident Model and Processes (STAMP), FRAM, and the "2–4" model for analyzing coal mine accidents, finding STAMP and FRAM ideal for complex cases due to their detailed analysis (Monitoring and Controlling), while the "2–4" model suits larger volumes with its simplicity (Planning).

The study by Guo et al. (2024) combines FRAM and Bayesian Networks (BN) to enhance resilience evaluation in construction emergencies, specifically analyzing a scaffold collapse case. This integration improves prediction and management of emergencies, leading to more effective construction safety strategies.

The study by Li and Wang (2023) investigates the impact of multiteam system (MTS) coordination on task safety within the construction industry by leveraging FRAM and a multiplex network. The methodology is validated through case studies in shield tunneling construction, highlighting its effectiveness in modeling and analyzing complex interdependencies and safety risks. This approach offers new perspectives for assessing and managing safety risks in socio-technical systems, emphasizing the need for further research to refine these models. The study by del Carmen et al. (2020) applies the Functional Resonance Analysis Method (FRAM) to improve safety management in concrete structure construction, identifying critical variabilities in activities like concrete delivery and crane operations. It highlights the underuse of safety plans and the potential for FRAM to advance a proactive, resilience-based safety approach (Safety-II). Fisher et al. (2015) evaluates handpump sustainability in the Greater Afram Plains region of Ghana, focusing on the determinants of rural water source functionality. Utilizing Bayesian Networks and logistic regression, the research identifies management practices, such as tariff collection and tool accessibility, as critical to improving handpump functionality. Table depicts the previous study and the framework integration with FRAM.

While previous studies have demonstrated the utility of FRAM for analyzing complex systems and enhancing understanding of operational and safety variabilities, there is a significant gap in applying FRAM systematically across all PMBOK process groups (Initiating, Planning, Executing, Monitoring and Controlling, and Closing). Furthermore, the integration of FRAM with AHP to quantitatively prioritize factors and decisions within these process groups remains underexplored. Most existing research tends to focus on either qualitative or semi-quantitative approaches to system safety and efficiency, without fully integrating these methods into a structured project management framework like PMBOK.

This study aims to fill this gap by developing a FRAM model that is explicitly integrated within the PMBOK framework, supported by the quantification capabilities of AHP. This approach could potentially offer a more robust and detailed analysis of project management complexities, particularly in construction. By aligning FRAM's analytical depth with PMBOK’s structured approach and AHP’s decision-making clarity, this study provides actionable insights into both project execution and safety management, enhancing the predictability and resilience of project outcomes.

Table 1 Previous study using FRAM

Research	Project Management Process Groups					
	Initiating Process Group	**Planning Process Group**	**Executing Process Group**	**Monitoring and Controlling Process Group**	**Closing Process Group**	**Framework Integration**
França et al. (2020)		■		■		AHP
Rosa et al. (2015)		■		■		AHP
Saurin (2016)		■				—
Haddad and Rosa (2015)		■		■		AHP
Qiao et al. (2019)				■		STAMP 2–4
Guo et al. (2024)		■				BN
del Carmen et al. (2020)		■		■		Safety-II
Fisher et al. (2015)		■				BN

3. Methodology

The methodology began with a detailed literature review using databases like ScienceDirect, Scopus, and Google Scholar, focusing on terms such as "Construction Projects," AND “Functional Resonance Analysis Method, " "Project Management," and "PMBOK". Publications from the last 10 years relevant to construction project management methodologies were selected based on their focus on methodological frameworks and case studies.

Framework Integration and Data Collection

This study introduces an integrated framework combining the Functional Resonance Analysis Method (FRAM) with PMBOK's process groups, enhanced by the Analytic Hierarchy Process (AHP). Data collection involved analyzing documentation, conducting stakeholder interviews, and observing management practices within the Channel Tunnel project. This approach allowed for practical application and evaluation of the integrated framework.

Analytical Approach and Case Study Application

Using AHP, the study prioritized variabilities identified by FRAM to map interactions within the project. The framework was applied to the Channel Tunnel project case study conducted by Anbari et al. (2005) to test its effectiveness in improving project management by enhancing decision-making and addressing project complexities. The outcomes were evaluated to determine the framework's impact on project performance, focusing on safety, efficiency, and compliance with timelines.

This methodology provides insights into the benefits of merging systems thinking with traditional project management approaches, proposing a new model for managing large-scale construction projects more effectively.

4. Results

The application of the Functional Resonance Analysis Method (FRAM) to the Channel Tunnel project has been visualized using the FRAM Model Visualizer (FMV) software, which facilitated a comprehensive mapping of the project management process. As illustrated in

Figure , the FRAM diagram employs a color-coded system to differentiate between the various PMBOK process groups and their associated functions:

Blue: Represents initiating construction management processes, laying the groundwork for the project's operational framework.

Green: Denotes functions related to project planning, highlighting the strategic activities essential for setting project objectives and timelines.

Red: Depicts functions associated with project execution, focusing on the active management of resources and task completion.

Yellow: Indicates the controlling processes, which are crucial for ongoing monitoring and adjustment of the project's progress against its planned benchmarks.

Purple: Represents the project closure activities, emphasizing the final steps required to conclude the project formally and evaluate its overall success.

This color-coded FRAM diagram not only provides a visual representation of the project management activities but also clearly delineates how these activities interconnect across different PMBOK knowledge areas and process groups. This visual mapping aids in identifying potential resonances and variabilities that could impact the project's outcome, offering a dynamic tool for enhancing understanding and management of complex project elements.

The FRAM diagram depicted in Figure 1 provides a visual representation of the main functions and their interconnectedness. The diagram shows how upstream functions are connected to downstream aspects such as input, pre-condition, time, control, or resource. For instance, the functions of estimating activity duration and sequencing activities are preconditions for the development of the schedule. Another example is the identification of risk, which precedes the assessment and treatment of that risk. Identifying risk serves as a resource for assessing risk and is also a pre-condition for the subsequent treatment of the identified risk.

The FRAM model effectively delineates the interconnections within the Channel Tunnel project's activities, as illustrated in Figure . This diagram focuses on the initial project task—requesting proposals—and its outputs, which are critical for subsequent project stages:

Proposal Document: Serves as input for subsequent project office tasks, organizing the administrative framework.

Project Objectives: Guides the development of the project scope, ensuring alignment with set goals.

Stakeholder Engagement Plan: Essential for identifying and engaging stakeholders, informing early project phases.

Treaty TML: Influences the cost estimation process, impacting financial planning and resource allocation.

This segment of the FRAM diagram exemplifies how early project activities, such as requesting proposals, provide foundational inputs that affect later project management processes, demonstrating the model's ability to map complex project interdependencies.

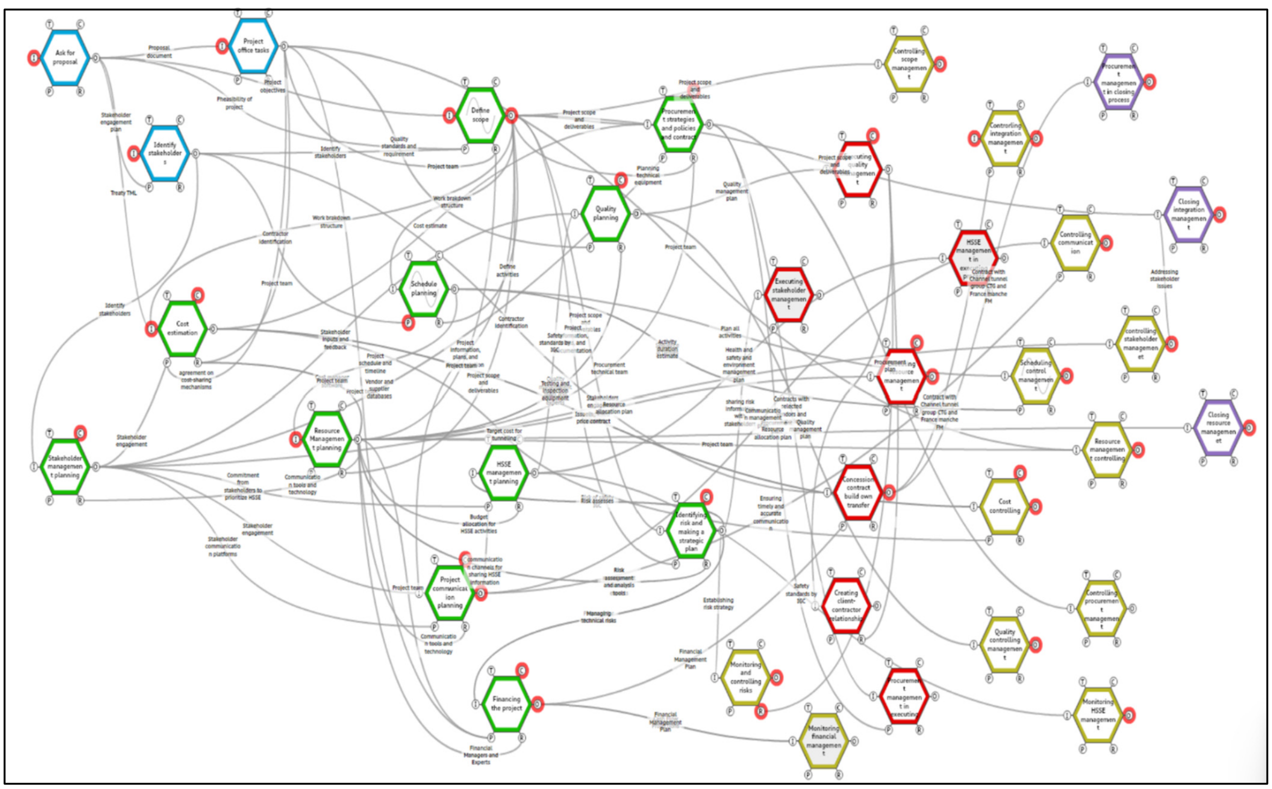

Figure 1 FRAM diagram in PMBOK process groups

Gap in the study

This research has made significant strides in integrating the Functional Resonance Analysis Method (FRAM) with the Project Management Body of Knowledge (PMBOK) process groups for managing mega construction projects. However, despite the theoretical and practical advancements it offers, there remain areas that have not been fully explored, constituting gaps that hold potential for further investigation.

Implementation of FRAM in PMBOK Process Groups

While this study has developed a conceptual framework for applying FRAM within the PMBOK process groups, the practical implementation across diverse construction projects remains underexplored. The intricacies of applying such an integrated approach in varying project environments, with different scales, complexities, and stakeholder dynamics, have not been sufficiently studied. This gap highlights the need for empirical validation and adaptation of the framework across a broader spectrum of construction projects.

Quantitative Analysis

The current study primarily focuses on qualitative assessments and theoretical integration of FRAM with PMBOK. There is a notable gap in quantitative analysis that would provide statistical evidence of the benefits, efficiencies, and impacts of this integration. Metrics such as project completion times, budget adherence, risk mitigation effectiveness, and overall project success rates need systematic collection and analysis to substantiate the advantages quantitatively.

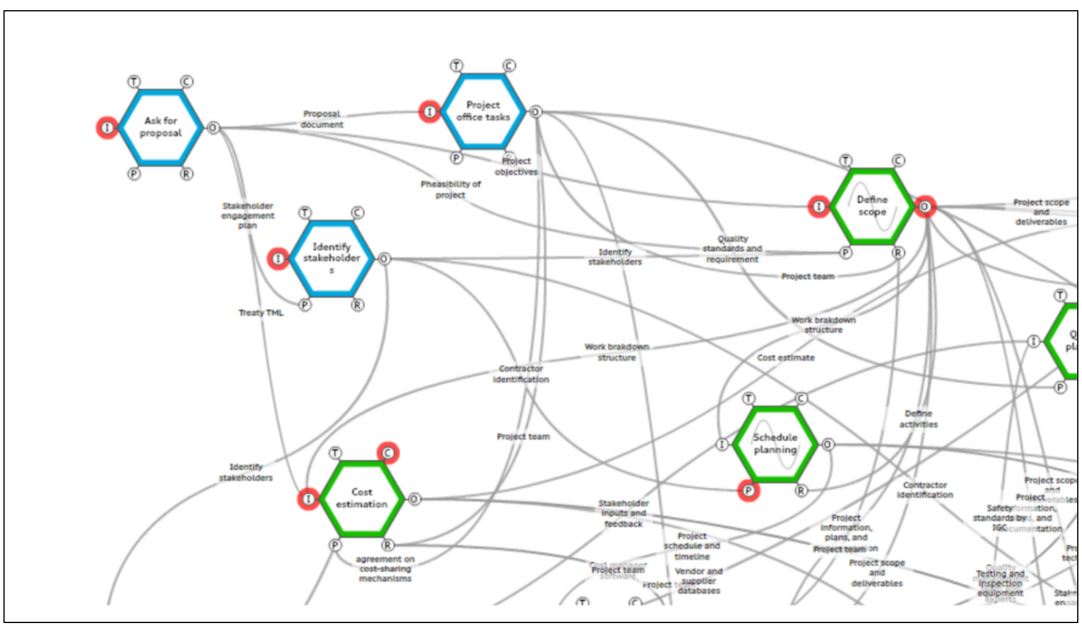

Figure 2 FRAM diagram in initiating process

Comparative Analysis

A comparative analysis with projects that do not use the integrated FRAM and PMBOK approach could significantly enhance understanding of its effectiveness. This study lacks a detailed comparative framework that would allow project managers and scholars to benchmark the outcomes against traditional project management approaches, providing a clearer picture of the improvements or setbacks introduced by the integration.

Expert Feedback

Gathering and analyzing feedback from experts and stakeholders involved in projects where FRAM and PMBOK are integrated is crucial. This study has not captured a broad spectrum of expert opinions and experiences, which are essential to validate the model's practicality, usability, and adaptability in real-world settings.

Risk Management Analysis

The study introduces theoretical enhancements to risk management through the FRAM model but does not delve into detailed, specific risk management case studies within the construction industry. Detailed analyses of how FRAM's application to PMBOK process groups can alter risk assessment and mitigation strategies are needed to provide a deeper understanding of its operational impacts.

Lessons Learned

While this research proposes a novel integration of methodologies, it stops short of providing a comprehensive analysis of lessons learned from its application. Future studies should focus on documenting specific lessons learned from the deployment of this integrated approach in various construction projects, helping refine the model based on practical experiences and challenges.

Conclusion

This study has embarked on an exploratory journey to integrate the Functional Resonance Analysis Method (FRAM) with the Project Management Body of Knowledge (PMBOK) process groups, specifically tailored for the complexities inherent in mega construction projects. The synthesis of these methodologies was demonstrated through a case study of the Channel Tunnel project, showcasing potential enhancements in project visibility, decision-making, and overall management effectiveness. The integration aimed to harness the strengths of both FRAM's dynamic variability analysis and PMBOK's structured project management approach to foster a more adaptive, resilient, and efficient project management framework.

Despite the theoretical advances and the practical insights gained from the initial application, several gaps remain that highlight the need for further research. First, the broad-scale implementation and empirical validation of the FRAM and PMBOK integrated approach across diverse construction environments are crucial. This includes quantitative analyses to substantiate the benefits claimed regarding project efficiency, risk mitigation, and budget adherence. Comparative analyses with projects not utilizing this integrated approach are also essential to objectively evaluate its efficacy and identify areas for improvement.

Furthermore, the study identified a significant need for comprehensive expert feedback to refine the integration framework. This feedback is vital to ensure that the framework's application is practical and beneficial across various project scenarios. Detailed risk management analysis using the integrated approach could provide deeper insights into its practical impacts on identifying, assessing, and mitigating project risks.

As we look to the future, several research directions are clear:

Empirical Validation: Conducting extensive empirical studies across different types of construction projects to validate and refine the integrated FRAM and PMBOK approach. Validating the FRAM is complex due to the dynamic nature of mega projects. Key challenges include simulating interactions and varying behaviors accurately. Future research should focus on developing rigorous empirical testing methods through controlled environments or retrospective analyses, ensuring FRAM's applicability and effectiveness in real-world scenarios.

Coupling FRAM with Systems Dynamics Approaches: Integrating FRAM with systems dynamics offers a promising advancement for project management frameworks. This approach can enhance predictive capabilities and management strategies for complex projects. Future work should focus on developing and testing integrated models in simulations to refine these methods before practical application, ensuring a comprehensive management strategy.

Quantitative Impact Studies: Developing quantitative metrics and conducting systematic analyses to assess the impact of the integration on project outcomes.

Comparative Effectiveness Research: Implementing comparative studies to provide a robust benchmark against traditional project management practices.

Expansion of Expert Feedback: Gathering a broader spectrum of feedback from project managers and stakeholders to enhance the understanding and usability of the integrated framework.

In-depth Risk Management Case Studies: Exploring detailed case studies on risk management within the integrated framework to illustrate specific risk mitigation strategies and their outcomes.

Documentation of Lessons Learned: Documenting and analyzing lessons learned from various implementations of the integrated approach to continuously improve its effectiveness.

By addressing these gaps and exploring these future research directions, the field of project management can significantly advance, particularly in the management of mega construction projects. This ongoing research will not only refine the theoretical framework presented but also enhance practical applications, leading to more successful project outcomes and greater satisfaction among stakeholders in the construction industry.

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Biography

Yvan Beauregard, Professor in the Department of Mechanical Engineering at École de Technologie Supérieure, holds degrees from Polytechnique Montréal (B.Eng.), McGill (MBA), and Concordia University (Ph.D.). His research interests cover aeronautics, aerospace, and health technologies, focusing on project and quality management, product development, and lean engineering. A skilled educator and innovator, he adeptly bridges theory with practical applications.

Amir Atariani, is a master's student in Mechanical Engineering at the École de Technologie Supérieure, supervised by Professor Yvan Beauregard. He holds a BSc from Azad University of Birjand and has extensive experience as a project manager in construction. His research interests include project management and applying system dynamics and system thinking to project execution.

APPENDIX II

Survey Questionnaires

Survey part I

Demographics

Dear [Company name] Team,

Or

Dear [the respondent's name],

I hope this message finds you well. My name is Amir Atariani, and I am conducting a research survey on critical factors affecting construction projects. The aim of this study is to gain insights from professionals like project managers and engineers who are actively involved in the industry.

I kindly request your assistance in distributing this survey to your Human Resources department. Once received, HR can then forward it to the relevant project managers and engineers within your organization. Their valuable input will significantly contribute to our research.

The survey is designed to be brief and will take only a few minutes to complete. It focuses on various aspects of construction projects, such as cost management, time schedules, quality, and risk assessment.

Confidentiality: Please assure your team members that their responses will remain strictly confidential, and the data collected will be used solely for research purposes.

Survey Link:

English version:

https://forms.gle/XmofC9mu9hf77BeL9

French version:

https://forms.gle/vPRA1j5p95xgGoRy7

Your cooperation in helping us reach the right professionals is greatly appreciated. If you have any questions or require further information, please do not hesitate to contact me at amir.atariani@gmail.com

Thank you for your support in advancing our understanding of the construction industry's challenges. We look forward to the valuable insights your team can provide.

Sincerely,

Amir Atariani
master's student
École de technologie supérieure ÉTS

Understanding the Factors Affecting Construction Project Costs, Timelines, Risks, and Quality

Welcome to the Construction Mega Projects Research Survey. Your insights are crucial for our study on factors impacting mega construction projects. We want to assure you that your responses will be kept strictly confidential. This survey aligns with the guidelines and approval of the ETS University Committee. Please take a few minutes to share your valuable expertise. Your input will help us better understand and improve the industry. Thank you for your participation.

Demographics	
Degree of education	High school☐ Diploma☐ Degree☐ Master☐
Year of experience	Less than 5 years ☐ 5 to 10 years ☐ more than 10 years ☐
Position	
Characteristic of project	Public☐ private☐
Type of organization	Client ☐ Contractor ☐ Consultant☐

Factors Validation and Identification:

We would like to gather your insights on the factors that contribute to cost overrun/underrun, time delay/on-time delivery, risk, and quality in projects. Please review the list of factors below and if you have encountered any other factors not mentioned here, please feel free to provide your input.

Root causes of cost overrun/underrun	Scope change Project planning and monitoring Site management Design efficiency Communication Technical capacity of consultants Change orders Competence of the project team Inadequacy of staff, labor, plant, materials, time or finance Defective materials or workmanship Late supply of information Uninsurable matters Gaps and time limits in insurance cover Funding constraints Delayed material delivery (supply chain issues) Optimism bias among local officials Deliberate cost underestimation Slow decision making Schedule management Increased material/machine prices Contract management Poor design Design delay Wrong estimation method Rework due to poor quality Delayed payments Financial planning Labor planning Poor material planning Equipment shortages Project complexity Optimism bias Harsh weather conditions Unforeseen ground conditions
Please specify any additional factors related cost overrun you have encountered:	
Root causes of time delay/on-time delivery	Communication Delayed payments Financial planning Price increases Site management Delayed material delivery (supply chain issues) Managerial skills Monitoring and control Labor planning Material planning Equipment shortages Organizational structures Process procedures Project complexity Project duration Optimism bias, deception Weather-related challenges Contractor commitment Site management

	Site coordination Project scope Qualification of consultants, engineers, and project staff Planning and scheduling by the contractor Design changes
Please specify any additional factors related time delay you have encountered:	
Root causes of risk	Consequences of decision making Engineering experience Completeness of project information Motivation Rules and regulations HSE (Health, Safety, Environment) competency Safety investment and cost Financial and productivity Resource and equipment Work pressure Work conditions Culture Safety program Unexpected changes in inflation rate Design errors Alterations in government laws, regulations, and policies impacting the project Weather conditions (continuous rainfall, snow, temperature, wind) Unpredicted adverse subsurface condition
Please specify any additional factors related to risk you have encountered:	
Root causes of quality	Continuous improvement Collaborative working Effective communication Availability of technical personnel ISO certification Procurement unit of the contractor Design management Communication management Field management Project scope management Project process management Active rework Project plan changes Subcontractor management Contract management Owner capability External environment
Please specify any additional factors related to quality you have encountered:	

French Version:

Comprendre les facteurs influençant les coûts, les délais, les risques et la qualité des projets de construction

Bienvenue à l'Enquête de Recherche sur les Méga Projets de Construction. Vos perspectives sont cruciales pour notre étude sur les facteurs qui impactent les méga projets de construction. Nous tenons à vous assurer que vos réponses seront strictement confidentielles. Cette enquête est conforme aux directives et à l'approbation du Comité Universitaire de l'ETS. Veuillez prendre quelques minutes pour partager votre expertise précieuse. Votre contribution nous permettra de mieux comprendre et d'améliorer l'industrie. Merci de votre participation.

Caractéristiques démographiques	
Niveau d'éducation	Lycée ou équivalent☒ Diploma☐ Certificat☐ Master☐Licence Doctorat (Ph.D.) ☐
expérience	Moins de 5 ans ☐ De 5 à 10 ans ☐ Plus de 10 ans ☐
Position	
Caractéristiques du projet	Public☐ Privé ☐
Type d'organisation	Client ☐ Entrepreneur ☐ Consultant☐

Dans la prochaine section, veuillez examiner les facteurs énumérés pour chaque dimension, puis ajouter tous les facteurs supplémentaires que vous avez rencontrés dans la zone de texte prévue à cet effet.

Causes fondamentales du dépassement/sous-dépassement des coûts	Changement de portée Planification et suivi du projet Gestion sur site Efficacité de la conception Communication Capacité technique des consultants Ordres de changement Compétence de l'équipe de projet Insuffisance de personnel, de main-d'œuvre, d'équipement, de matériaux, de temps ou de financement Matériaux ou main-d'œuvre défectueux Fourniture tardive d'informations Questions non assurables Lacunes et délais dans la couverture d'assurance Contraintes de financement

	Inflation Livraison retardée des matériaux (problèmes de chaîne d'approvisionnement) Biais d'optimisme parmi les responsables locaux Sous-estimation délibérée des coûts Prise de décision lente Gestion des délais Augmentation des prix des matériaux/machines Gestion des contrats Mauvaise conception Retard de conception Méthode d'estimation erronée Retravail en raison d'une mauvaise qualité Paiements retardés Planification financière Planification de la main-d'œuvre Mauvaise planification des matériaux Pénuries d'équipement Complexité du projet Biais d'optimisme Conditions météorologiques difficiles Conditions de sol imprévues
Veuillez spécifier tout facteur supplémentaire lié au dépassement/sous-dépassement des coûts que vous avez rencontré.	
Causes fondamentales du retard/ou de la livraison à temps	Communication Paiements retardés Planification financière Augmentation des prix Gestion de site Livraison retardée des matériaux (problèmes de chaîne d'approvisionnement) Compétences en gestion Surveillance et contrôle Planification de la main-d'œuvre Planification des matériaux Pénuries d'équipement Structures organisationnelles Procédures de processus Complexité du projet Durée du projet Biais d'optimisme, tromperie Défis liés aux conditions météorologiques Engagement de l'entrepreneur Gestion de site Coordination sur site Portée du projet Qualification des consultants, ingénieurs et personnel de projet Planification et ordonnancement par l'entrepreneur Modifications de conception
Veuillez spécifier tout facteur supplémentaire lié aux retards	

temporels que vous avez rencontré.	
Causes fondamentales des risques	Conséquences de la prise de décision Expérience en ingénierie Exhaustivité des informations sur le projet Motivation Règles et réglementations Compétence en HSE (Santé, Sécurité, Environnement) Investissement et coût de la sécurité Financier et productivité Ressources et équipement Pression de travail Conditions de travail Culture Programme de sécurité Changements inattendus dans le taux d'inflation Erreurs de conception Modifications des lois, règlements et politiques gouvernementales impactant le projet Conditions météorologiques (pluies continues, neige, température, vent) Conditions souterraines défavorables imprévues
Veuillez spécifier tout facteur supplémentaire lié aux risques que vous avez rencontré.	
Causes fondamentales de la qualité	Amélioration continue Travail collaboratif Communication efficace Disponibilité du personnel technique Certification ISO Unité d'approvisionnement de l'entrepreneur Gestion de la conception Gestion de la communication Gestion sur site Gestion de la portée du projet Gestion du processus du projet Retravail actif Changements dans le plan du projet Gestion des sous-traitants Gestion des contrats Capacité du propriétaire Environnement externe
Veuillez spécifier tout facteur supplémentaire lié à la qualité que vous avez rencontré.	

Survey part II

Dear Survey Participant,

We kindly request your participation in our research project aimed at improving the performance of construction projects concerning cost, time, quality, and risk, with a focus on the Channel Tunnel as our case study. Your valuable insights and expertise will contribute to the validation of our system dynamics model and its application.

Model Overview:

The model presented here illustrates the interaction and sequence of factors influencing time, cost, risk, and quality in construction projects, with a particular emphasis on the Channel Tunnel project connecting France and the UK. We conducted two scenarios using the model. The first scenario reflects the current state of the Channel Tunnel project, while the second scenario involves altering the quality of materials, impacting project time due to rework. This change results in increased project overhead costs and subsequent cost overruns, elevating project financial risks. This scenario demonstrates how altering quality affects all dimensions of projects - time, cost, quality, and risk, as represented in the four related graphs below. Please review the model and graphs before answering the questionnaire.

Survey link:

English version: https://forms.gle/HnB3j9gbFsWFpYKu5

French version: https://forms.gle/KXZY68RDJEgxx5Bz5

Best regards,

Amir Atariani

ETS University

Demographics				
Degree of education	High school☐	Diploma☐	Degree☐	Master☐
Year of experience				
Position				
Characteristic of project	Public☐	private☐		
Type of organization	Client ☐	Contractor ☐	Consultant☐	
Are you familiar with System Dynamics?	Yes ☐	No ☐		

System dynamics model:

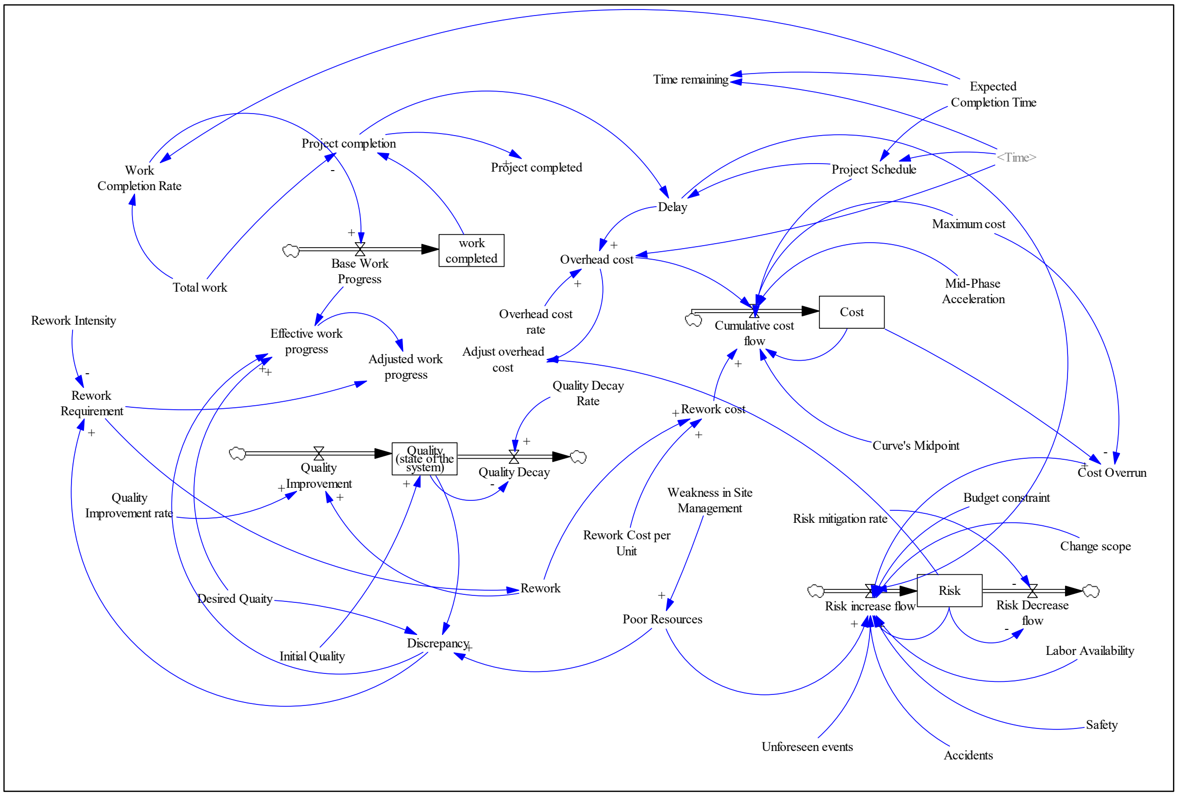

Figure 1- Presented model

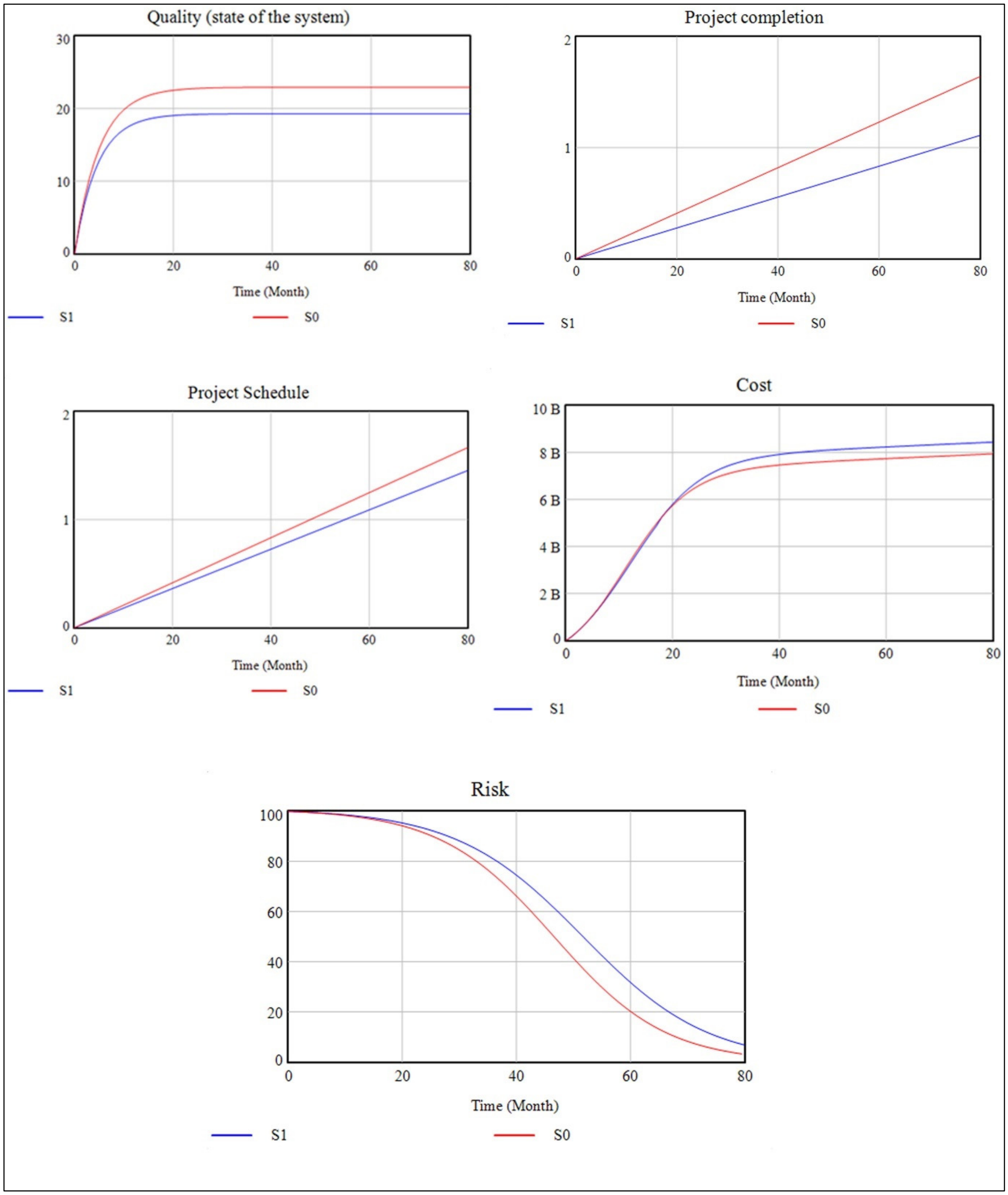

Figure 2 Change in risk augmented iron triangle in construction project

To what extent do you believe system dynamics can predict cost management in project management?

Very low ☐ Low ☐ Moderate ☐ High ☐ very high ☐

To what extent do you believe system dynamics can predict time management in project management?

Very low ☐ Low ☐ Moderate ☐ High ☐ very high ☐

To what extent do you believe system dynamics can predict risk management in project management?

Very low ☐ Low ☐ Moderate ☐ High ☐ very high ☐

To what extent do you believe system dynamics can predict quality management in project management?

Very low ☐ Low ☐ Moderate ☐ High ☐ very high ☐

To what extent are you interested in implementing System Dynamics model in the projects you are involved in?

Very low ☐ Low ☐ Moderate ☐ High ☐ very high ☐

Do you have any suggestions regarding the implementation or use of this method in project management?

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