EXPLORING AND MEASURING PROJECT COMPLEXITY IN METRORAIL PROJECTS

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SRUTHILAYA DARA
(Roll No. 701914)

Research Supervisor

Dr. ANEETHA VILVENTHAN

CONSTRUCTION TECHNOLOGY AND MANAGEMENT DIVSION
DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY WARANGAL
TELANGANA STATE, INDIA – 506004

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NATIONAL INSTITUTE OF TECHNOLOGY WARANGAL

CERTIFICATE

This is to certify that the thesis entitled **"EXPLORING AND MEASURING PROJECT COMPLEXITY IN METRORAIL PROJECTS"** being submitted by **Ms. SRUTHILAYA DARA** for the award of the degree of **DOCTOR OF PHILOSOPHY** in the Department of Civil Engineering, National Institute of Technology Warangal, is a record of bonfire research work carried out by her under my supervision and it has not been submitted elsewhere for the award of any degree.

Dr. ANEETHA VILVENTHAN

Thesis Supervisor
Assistant Professor
Department of Civil Engineering
NIT Warangal (T.S), India

NATIONAL INSTITUTE OF TECHNOLOGY WARANGAL

Dissertation Approval

This dissertation entitled **“Exploring and Measuring Project Complexity in Metrorail Projects”** by **Ms. Sruthilaya Dara** is approved for the degree of **Doctor of Philosophy.**

Examiners

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Supervisor(s)

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Chairman

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DECLARATION

This is to certify that the work presented in the thesis entitled **“Exploring and Measuring Project Complexity in Metrorail Projects”** is a bonafide work done by me under the supervision of Dr. Aneetha Vilventhan and was not submitted elsewhere for the award of any degree.

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D. Sruthilaya

(SRUTHILAYA DARA)

(Roll No: **701914**)

Date: 07-10-2024

Dedicated To My

Beloved Parents

Shri. Dara Janardhan Rao and Padmavathi

For their support and encouragement throughout my life

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Sruthilaya Dara
Roll No: 701914

ABSTRACT

Project complexity is one of the most common issues faced by metro rail projects due to its complex and interdependent characteristics. The challenging characteristics necessitate a study to identify and measure the impact of project complexity in metro rail projects. Hence, its strategic importance lies in enhancing project management and decision-making processes in the context of metro rail projects. This research provides valuable insights for the construction industry, effectively addressing and navigating complexity in metro rail projects.

Initially this research identifies and analyzes the interdependence of Project complexity factors (PCFs) in metro rail projects using the Decision-Making Trial and Evaluation Laboratory (DEMATEL). The study provides qualitative and quantitative analysis of project complexities factors and their relationships. This study employs a case-based method for identifying PCFs and a DEMATEL method for analyzing the interdependence of complexity factors in metro rail projects. Initially, PCFs were identified through an extensive literature review. To validate and refine these factors, semi-structured interviews were conducted with thirty experienced professionals, each having 5-20 years of experience in roles such as project management, engineering, and planning. Further, elevated, and underground metro rail projects were purposefully selected as cases, for identifying the similarities and differences in PCFs. A questionnaire survey was conducted with various technical experts in metro rail projects. These experts rated the impact of PCFs on a five-point Likert scale, for the evaluation of the interdependence of PCFs. The DEMATEL technique was used to analyze the interdependencies of the PCFs.

Later the study addresses the impact of project complexity on the performance parameters like time, cost, scope, quality, sustainability, and reliability. Machine learning (ML) was used as a powerful tool to predict the impact of project complexity. Despite the recognized challenges, there has been limited research utilizing ML models to assess the impact of project complexity in metro rail projects. An integrated predictive model was developed by combining three different ML algorithms: Support Vector Machine (SVM), Random Forest (RF), and Decision Tree (DT). This combined approach shows the unique strengths of each algorithm to create a more comprehensive and robust predictive model. This study aimed to analyze how project complexity influences key project performance parameters, including time, cost, scope, quality, sustainability, and reliability in metro rail projects. The integrated model showed improved performance compared to using each algorithm separately, indicating its potential for

delivering interactive results in predictive modeling. It accurately predicted time, scope, and cost, showcasing the model's robustness in predicting their impacts. However, challenges arose when predicting quality and sustainability, given their complex and multifactored influences. This model contributes to a better understanding and precise prediction of the impact of complexity in metro rail projects.

BWM, a robust Multi-Criteria Decision-Making technique, was used to prioritize key complexities, and a PCI model was developed. Further, the developed PCI was validated through case studies and sensitivity analysis was performed to check the accuracy and applicability of the developed PCI model. The analysis revealed that the location complexity exerted the most substantial influence on project performance, followed by the environmental, organizational, technological, and contractual complexities. Sensitivity analysis revealed the varying impacts of complexity indices on the overall project complexity. The existing studies on project complexity identification and quantification were limited to megaprojects other than metro rail projects. Efforts to quantitatively study and analyze the impact of project complexity in metro rail projects are left unattended. The developed PCI model and its validation contribute to the field by providing a definite method to measure and manage complexity in metro rail projects.

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ABBREVIATIONS

CAS	Characteristics of Complex Adaptive Systems
PCFs	Project Complexity Factors
TOE	Technical, organizational, and environmental
PCI	Project Complexity Index
DEMATEL	Decision-Making Trial and Evaluation Laboratory
ML	Machine Learning Models
SVM	Support vector machine
RF	Random Forest
DT	Decision Tree
MCDM	Multi Criteria Decision Making
BWM	Best and Worst Method
CR	Consistency Ratio

Chapter 1
Introduction

1.1 Overview

Megaprojects are characterized by their massive scale, significant impact, and complexity, which play a crucial role in shaping global and national development circumstances. The management of large-scale projects demands substantial investments, advanced technologies, and collaboration among diverse stakeholders, impacting economic growth, technological innovation, and societal well-being. However, megaprojects often face inherent challenges, and one of the key factors contributing to their complexity is the complex nature of their execution.

The study of complexity in megaprojects, especially in the context of metro rail projects, is necessary for several reasons. Firstly, understanding the unique challenges posed by project complexity is crucial for effective project management and successful outcomes. Metro rail projects, being multidisciplinary and multicultural projects, require detailed planning and a clear understanding of the interconnected factors influencing their complexity. Additionally, the identification and analysis of project complexity factors (PCFs) are essential for cost control, timely project delivery, risk mitigation, resource allocation, and stakeholder cooperation.

Metro rail projects often face specific problems due to project complexity. Issues such as scope changes, delays, cost overruns, and conflicts among stakeholders may arise. Factors influencing project complexity in the context of metro rail projects can be diverse, ranging from the definition of project goals and scope, internal and external politics, project management methods, type of contracts, technological uncertainties, and the number of stakeholders to the overall size and nature of the project. Project complexity may vary, encompassing technical, organizational, and environmental (TOE) aspects. For instance, an urban development-focused metro rail project might encounter complexity in managing stakeholders and minimizing disruption in densely populated areas. Conversely, an infrastructure-focused project may face complexity related to complex engineering, financial problems, and adherence to tight schedules.

1.2 Importance of Mega Projects and their Development in India

Megaprojects are large-scale projects characterized by various factors like size, type, significance, and project complexity (Flyvbjerg, 2014). These projects demand heavy investments, extraordinary expertise, resources, and capabilities (Morris, 1988). All megaprojects require substantial financial investments, necessitate intensive collaboration among project teams and stakeholders, employ cutting-edge technologies, and encompass extensive scopes far beyond the ordinary. The prominence of megaprojects is recognized by their impact on social development, economic growth, technological innovation, and urbanization. This phenomenon is not limited to developed nations like the United States, South Korea, the United Kingdom, and the Netherlands; it also extends to developing countries like China, Pakistan, and Indonesia. Megaprojects are traditionally evaluated based on the 'iron triangle' of timelines, budget adherence, and quality assurance, yet their success is mostly measured by long-term factors such as team and stakeholder satisfaction, sustainability of economic benefits, and community welfare. Unfortunately, many megaprojects fall short of their originally defined targets. The management of megaprojects is an inherently complex task, with characteristic project complexity being a leading factor in their occasional setbacks. The project complexity of megaprojects develops the number of involved individuals, costs, and project scopes, making the management of project complexity vital to their successful execution.

Notably, managing project complexity in developing countries presents even greater challenges. These nations often contend with economic, political, and social instability, unstable regulatory frameworks, distinct cultural backgrounds, and a shortage of skilled labor due to limited educational and professional training opportunities. Consequently, there is a lack of comprehensive studies on megaprojects, particularly regarding project complexity, within the context of developing countries (Flyvbjerg, 2014). India, as a rapidly developing nation, stands to benefit significantly from the strategic interest of megaprojects. With its diverse and ambitious projects in infrastructure, transportation, and urban development, India's embrace of megaprojects has the potential to drive economic growth, enhance technological capabilities, and improve the overall quality of life for its citizens. Hence, understanding the project complexity and its management in mega construction projects is not only crucial for avoiding failures but also for realizing India's vision of transformative development.

1.2.1 Types of megaprojects and their necessity

Megaprojects are recognized as a diverse variety of massive activities that have a global impact. They can be systematically categorized into distinct types, each characterized by its unique set of challenges and objectives. Infrastructure megaprojects, which form one prominent category, develop complex and large-scale structures like airports, bridges, tunnels, and highways (Flyvbjerg, 2014; Locatelli et al., 2023). These projects invariably demand significant capital investments and are characterized by their inherent complexity, necessitating experienced project management approaches. Urban development megaprojects, often considered a subset of infrastructure projects, focus on the development of modernization and urbanization strategies (Kennedy et al., 2014). Examples include transformative projects like the Delhi Metro Rail, the Hyderabad Metro, and the Mumbai Metro Rail projects, which enhance urban infrastructure and the quality of life in expanding cities. Energy megaprojects occupy another critical domain, containing a wide spectrum of activities related to energy generation, transmission, and distribution (Lessard et al., 2014). Nuclear power plants, massive hydroelectric dams, and expansive solar energy parks are examples of these megaprojects. The construction of India's Kudankulam Nuclear Power Plant exemplifies the construction and project complexity associated with these types of projects. Industrial megaprojects are necessary for industrial growth, and involve the creation of extensive manufacturing facilities, refineries, and expansive production units. The iconic Tata Nano manufacturing plant in India is a testament to the transformative power of industrial megaprojects (Bruzelius et al., 2002). Furthermore, environmental megaprojects deal with global challenges, such as large-scale environmental remediation projects, ambitious reforestation programs, and comprehensive efforts to combat climate change. These projects are key in helping for a more sustainable and environmentally conscious future (Anguelovski & Carmin, 2011).

All the megaprojects play a vital role both globally and in India for several reasons. Megaprojects drive economic growth by generating employment opportunities and fostering local industries (Flyvbjerg, 2014). They contribute significantly to a country's GDP. Many megaprojects involve cutting-edge technology and innovation, pushing the boundaries of what is technically feasible. This technological progress often has far-reaching benefits beyond the project itself. In rapidly urbanizing countries like India, megaprojects are critical for developing and upgrading essential infrastructure, including transportation networks and energy systems. Projects such as international airports, seaports, and cross-border transportation links enhance a country's connectivity with the global economy facilitating trade and tourism (Othman, 2014). Furthermore, urban development megaprojects enhance living standards by providing modern housing, better transportation, and improved public spaces (Lehtonen et al., 2016). Some megaprojects are also designed to address environmental issues, such as pollution control or renewable energy production, contributing to a more sustainable future. Megaprojects can also have strategic significance, particularly in countries with geopolitical interests, where they may enhance national security or geopolitical influence (Bruzelius et al., 2002).

In India, megaprojects are vital for addressing the infrastructure needs of its rapidly growing population and economy. The Delhi Metro, for example, has transformed urban transportation in the capital city and projects like the Mumbai Coastal Road aim to ease traffic congestion while enhancing the city's resilience to climate change-induced sea-level rise (Giezen, 2013). Therefore, megaprojects, with their diverse types and far-reaching impacts, are indispensable for driving economic growth, technological advancement, and improved living standards, both worldwide and particularly in countries like India, where the demand for infrastructure and development is high.

1.2.2 Significance and diversity of metro rail initiatives in India

Metro rail projects in India can be broadly categorized into two types: underground and elevated projects. Underground metro projects involve constructing tracks and stations below the ground level. For example, the Delhi Metro, one of India's largest and most advanced metro systems, has several underground lines. Similarly, partially underground systems, like those in Kolkata and Bangalore, have sections where the tracks and stations are below the surface while other parts remain elevated. Elevated metro rail projects, on the other hand, feature tracks and stations built above ground level, typically using viaducts. Examples include the Hyderabad Metro and Mumbai Metro Line 1 (Versova-Andheri-Ghatkopar line), which operate primarily as elevated systems (Rastogi et al., 2014).

India's first metro system, the Kolkata Metro, began operations in 1984 with an initial budget of USD 23 million for a 32-kilometer stretch. The project aimed to alleviate the severe traffic congestion in one of India's most densely populated cities, and its success paved the way for future metro projects across the country (Chatterjee, 1985). Following Kolkata, the Delhi Metro initiated its first phase in the late 1990s with a budget of USD 1.4 billion and a total planned length of 390 kilometers. Since then, the system has expanded across multiple phases, adding new lines and extensions that have helped reduce traffic congestion and improve air quality in the capital city (Bosch-Rekveldt et al., 2011). Mumbai Metro Line 1, which began operations in 2014 with a budget of approximately USD 576 million, spans 11.4 kilometers. This metro is intended to provide a faster and more efficient mode of transportation in one of India's most populous and congested cities. The Hyderabad Metro, which commenced in 2007 with a budget of USD 2.5 billion, spans 69.2 kilometers. It plays a critical role in improving connectivity in Hyderabad, a rapidly growing tech hub, reducing travel times, and promoting economic development (Rastogi et al., 2014). The Bangalore Metro project, also known as Namma Metro, began construction in the mid-2000s with a budget of USD 1.9 billion. It opened its first phase in 2011 and continues to expand. When fully completed, the system is expected to cover over 200 kilometers, addressing the transportation needs of the city's large IT workforce and alleviating congestion on its busy roads (Rastogi et al., 2014). Multiple phases and extensions are planned to ensure it meets the city's growing demand.

In conclusion, metro rail projects in India have evolved significantly over time, from the early days of the Kolkata Metro in the 1980s to the large-scale, ongoing projects in cities like Delhi, Mumbai, and Bangalore. These projects play a critical role in improving urban mobility, reducing traffic congestion, and promoting economic development across India's largest and fastest-growing cities.

1.2.3 Project complexity

Project complexity refers to the uncertain and difficult nature of a project, which can manifest in various dimensions and aspects. It involves the interdependence of numerous factors, making it challenging to manage and execute projects effectively (Baccarini, 1996; Geraldi et al., 2011). Project complexity is not uniform and can vary significantly from one project to another. Project complexity is not a one-size-fits-all concept; rather, it necessitates a contingent approach, considering the unique characteristics and contextual factors of each project (Donaldson, 2001).

In the context of metro rail projects, project complexity can be understood as a combination of diverse elements, containing technical, organizational, environmental, and socio-political factors (Bosch-Rekveldt et al., 2011). The characteristics and factors of complexity can differ from one metro rail project to another, influenced by factors such as project scope, technological novelty, time constraints, and the socio-political landscape. For instance, metro rail projects in developing countries often face socio-political complexities due to land acquisition issues and governmental regulations (Othman, 2014). The complexity of a metro rail project may evolve over its lifecycle as external contingencies change, demanding adaptability in project management (Geraldi et al., 2011).

Metro rail projects are diverse, ranging from urban development projects to large-scale infrastructure projects. The nature of complexity in these projects may vary accordingly. For example, an urban development metro rail project might face complexity in terms of managing stakeholders and minimizing disturbance to densely populated areas. In contrast, an infrastructure-focused project may face problems with complexity related to complex engineering, financial problems, and tight schedules (Bosch-Rekveldt et al., 2011; Othman, 2014).

The relationship between project complexity and project performance in metro rail projects is complex. While complexity can introduce risks such as cost overruns, delays, and reduced project success, it can also serve as a driver for innovation and progress (Flyvbjerg, 2014). In particular, the technical and socio-political complexities associated with metro rail projects may lead to both obstacles and opportunities for innovation (Geraldi et al., 2011). While complexity can present challenges and potential risks, it can also be helpful for innovation and progress (Flyvbjerg, 2014). However, complexity can sometimes lead to cost overruns, delays, and reduced project success. Therefore, frameworks such as the TOE complexity framework developed by Bosch-Rekveldt et al., (2011) are valuable tools for evaluating and understanding project complexity in metro rail projects. This framework considers various factors within the categories of TOE complexity, providing a comprehensive approach to assess the complex nature of metro rail projects. Project complexity in metro rail projects is a complicated concept that necessitates project-specific evaluation. Understanding the unique characteristics of complexity and its influence on project performance is crucial for effective project management in the context of metro rail projects, where each project presents a distinct set of challenges and opportunities (Donaldson, 2001; Bosch-Rekveldt et al., 2011).

1.2.4 Factors influencing project complexity

In construction projects, various factors influence project complexity, significantly impacting cost, time, and overall success. These factors are not isolated; they often interrelate, creating a complex web of challenges. Recognizing and managing these complexities is necessary for effective project management. Various PCFs affect the performance and progress of construction projects like metro rail projects. PCFs depend on characteristics such as project definition, scope, size, organizational problems, technological drawbacks, uncertainty, and interdependencies. For example, the degree of goal and scope definition influences the clarity of project objectives (Geraldi & Adlbrecht, 2007). These factors can lead to scope changes and delays, raising project costs. Organizational factors, including internal politics, can delay cooperation with partners (Geraldi & Adlbrecht, 2007), affecting transparency and potentially increasing costs. PCFs often interrelate (Geraldi & Adlbrecht, 2007), resulting in task dependencies and reliance on external departments or companies (Terry Williams, 1999). Mismanaging these interdependencies causes delays and increased expenses. The newness of a project (Geraldi & Adlbrecht, 2007) and novel technologies (He et al., 2014) can lead to technical uncertainties (Yunbo et al., 2015), which, when poorly managed, can cause delays and cost overruns. The number of locations and stakeholders affects project size (Müller & Turner, 2007), often necessitating more resources and time. Larger projects tend to be more complex to manage. A project's size can affect the stability of its environment (Geraldi & Adlbrecht, 2007), potentially introducing uncertainties and risks (Nguyen et al., 2015). Limited resources or skills (Thomas & Mengel, 2008) can delay project progress. This relates to the variety of project management methods and tools applied (Vidal & Marle, 2008). Uncertainty can affect a project's duration, potentially leading to resource strain or quality issues (Xia & Lee, 2005). Conflicts and delays can arise if stakeholder perspectives do not align with project goals (Geraldi & Adlbrecht, 2007). Understanding the interrelationships among PCFs is necessary. Neglecting these factors or their connections can result in inefficiencies, budget overruns, delays, and disputes. Effective project management necessitates recognizing and mitigating these complexities to ensure successful outcomes. Factors of complexity identified from the literature are shown in Table 1.1.

Table 1.1 Factors of complexity identified from literature

S. No	Indicator from literature	References
1	Information availability	Flyvbjerg, Bruzelius, et al. (2003), Brockmann & Girmscheid (2007), Aarseth et al. (2011)
2	Interface among people	Vidal & Marle (2008), Aarseth et al. (2011)
3	Physical resources availability	Flyvbjerg, Bruzelius, et al. (2003), Vidal & Marle (2008), Lokuge et al., (2019)
4	Change in economy	Flyvbjerg, Bruzelius, et al., (2003), Vidal & Marle (2008), Kardes et al. (2013)
5	Change in technologies	Bonner (1994), Flyvbjerg, Bruzelius, et al. (2003), Mohseni et al. (2019)
6	Effect of types of contracts	Geraldi & Adlbrecht (2007), Bosch-Rekveldt et al. (2011), F. Chen et al. (2020)
7	Cultural varieties and configuration	Wood (1986), Geraldi & Adlbrecht (2007), Vidal & Marle (2008), Rezvani & Khosravi (2019)
8	Differences in Culture	Wood (1986), Geraldi & Adlbrecht (2007), Vidal & Marle (2008)
9	Degree of attaining information	Brockmann & Girmscheid (2007), Merrow (2011)

10	Degree of transferring and processing the Information	Zhang et al. (2009), Tavakolan & Etemadinia (2017), Keers & van Fenema (2018)
11	Dependencies among schedules	Wood (1986), Thomé et al. (2016), Zhao et al. (2021)
12	Dependencies among tasks	Geraldi & Adlbrecht (2007), Vidal & Marle (2008), Merrow (2011), Bosch-Rekveldt et al. (2011), Zhao et al. (2021), Wang et al. (2023)
13	Duration of project	Flyvbjerg, Bruzelius, et al. (2003), Geraldi & Adlbrecht (2007)
14	Dynamic and developing team organization	Bui & Sivasankaran (1990), Bonner (1994), Rezvani & Khosravi (2019)
15	Experience of the parties involved	Geraldi & Adlbrecht (2007), Merrow (2011)
16	Experience with new technology	Baccarini (1996), Bosch-Rekveldt et al. (2011)
17	Geographical location	Greitzer (2005)
18	Interaction between external environment, technology system	Williams (1999), Vidal & Marle (2008)
19	Interdependence between departments, sites, and companies	Bonner (1994), Greitzer (2005), Nguyen et al. (2019)
20	Interdependence of information among organizations	Bonner (1994), Keers & van Fenema (2018), Rezvani & Khosravi (2019)
21	Levels of interrelation among phases in construction	Campbell (1988), Keers & van Fenema (2018)
22	Unpredictability and uncertainty of market	Vidal & Marle (2008), Merrow, (2011)
23	Local regulations and laws	Bonner (1994), Brockmann & Girmscheid (2007), F. Chen et al. (2020)
24	Emerging of new technologies	Flyvbjerg, Bruzelius, et al. (2003), Geraldi & Adlbrecht (2007), Vidal & Marle (2008), Merrow (2011), Kardes et al. (2013)
25	Coordination among teams	Bonner (1994), Rezvani & Khosravi (2019)
26	Coordination among number of system components	Baccarini (1996), Williams (1999), Geraldi & Adlbrecht (2007), Vidal & Marle (2008), Nguyen et al. (2019)
27	Involvement of a large number of tasks and activities	Brockmann & Girmscheid (2007), Zhang et al. (2009), Zhang et al. (2018), Zhao et al. (2021), Wang et al. (2023)
28	Deficiency of internal support from organization	Geraldi & Adlbrecht (2007), Bosch-Rekveldt et al. (2011)
29	Deficiency of degree of innovation in organization	Baccarini (1996), Rezvani & Khosravi (2019)
30	Influence of politics	Geraldi & Adlbrecht (2007), Brockmann & Girmscheid (2007), Kardes et al. (2013)

31	Interdependence among stakeholders and organization	Flyvbjerg, Bruzelius, et al. (2003)
32	Relationship problems with permanent organizations	Williams (1999), Baccarini (1996), F. Chen et al. (2020)
33	Reliability of information on platforms	Greitzer (2005), Wang et al. (2023)
34	Interdependencies of resource and raw material	Flyvbjerg, Bruzelius, et al. (2003)
35	Changing in scope	Flyvbjerg, Bruzelius, et al. (2003)
36	Consequence faced with public	Bonner (1994), Flyvbjerg, Bruzelius, et al. (2003)
37	Interdependencies among Specifications and laws	Baccarini (1996), Vidal & Marle (2008)
38	Stability in project environment	Geraldi & Adlbrecht (2007)
39	Lack of communication and team cooperation	Bui & Sivasankaran (1990), Bonner (1994), Rezvani & Khosravi (2019)
40	Impact of Technological degree of innovation	Wood (1986), Baccarini (1996), Bonner (1994), Flyvbjerg, Bruzelius, et al. (2003)
41	Interdependencies of technological process	Flyvbjerg, Bruzelius, et al. (2003), Peñaloza et al. (2020), Owolabi et al. (2020)
42	Transparency of objectives of the organization	Geraldi & Adlbrecht (2007), (Vidal & Marle (2008)
43	Uncertainty of scope and goals	Flyvbjerg, Bruzelius, et al. (2003), Peñaloza et al. (2020)
44	Uncertainty of the project management techniques and tools	Geraldi & Adlbrecht (2007), Brockmann & Girmschei (2007), Vidal & Marle (2008)
45	Unpredictability of activities	Bui & Sivasankaran (1990), Peñaloza et al. (2020), Owolabi et al. (2020)
46	Variability of investors and financial resources	Wood (1986), Brockmann & Girmscheid (2007)
47	Impact of hierarchy in organization	Campbell (1988), Siraj & Fayek (2019), Peñaloza et al. (2020)
48	Impact of large resources used	Campbell (1988), Baccarini (1996), Geraldi & Adlbrecht (2007)
49	Impact of involvement if large stakeholders interest and perspective	Geraldi & Adlbrecht (2007), Vidal & Marle (2008), Merrow (2011)
50	Deficiency in technological skills needed	Bonner (1994), Siraj & Fayek (2019), Erol et al. (2020), Owolabi et al. (2020)
51	Variation of the technologies used during the project	Flyvbjerg, Bruzelius, et al. (2003), Brockmann & Girmscheid (2007), Siraj & Fayek (2019)

1.2.5 Importance of identifying and analyzing project complexity factors

In the construction of metro rail projects, various complex factors impact the performance and progress of urban infrastructure projects like metro rail projects. These factors adversely impact the characteristics of projects in terms of time, cost, and technical management. Metro rail projects are naturally multidisciplinary and multicultural projects, necessitating detailed planning and clear goal alignment. Identifying and thoroughly analyzing PCFs in the context of metro rail projects in India is necessary. It facilitates cost control measures, ensuring that substantial investments are utilized carefully, and enables timely project delivery, preventing public inconveniences and economic losses due to delays. By proactively assessing and mitigating risks, project teams enhance project resilience, while understanding the diversity of stakeholder perspectives aids in gathering support and cooperation, expediting project approvals, and ensuring community acceptance. Effective allocation of resources and compliance with strict regulations are streamlined, leading to optimized planning, efficient execution, and improved project outcomes. Lastly, addressing social and political complexities promotes public trust and reduces problems, contributing to urban development, economic growth, and an enhanced quality of life for urban populations.

1.2.6 The necessity of developing a model for measuring project complexity

The need for analyzing project complexity in metro rail projects arises from the existing gap in research, which has traditionally focused on megaprojects without considering the unique aspects of metro rail systems (Othman, 2014; Flyvbjerg, 2017). While various complexity factors relevant to large-scale construction projects, often overlook the specific challenges faced by metro rail projects, particularly in urban settings. These projects not only face the complexity inherent in all megaprojects but also encounter additional difficulties related to land acquisition, densely populated areas, and the integration of advanced transportation technologies (Rothengatter, 2019). In contrast to other types of megaprojects, metro rail projects must navigate highly regulated urban environments, where complexities can have significant social, political, and economic implications. These unique challenges demand a more adapted approach to measuring complexity. Urban metro rail projects often involve working within existing infrastructure networks, which adds layers of complexity related to utilities, transportation systems, and minimizing the disruption to daily city life (Locatelli et al., 2023). In addition, the regulatory environment surrounding metro rail projects tends to be more rigid, involving multiple governmental and municipal bodies, which increases organizational complexity.

Another distinguishing feature of metro rail projects is the technological complexity associated with integrating modern signaling systems, automated fare collection, and ensuring the safety of underground or elevated structures (Giezen, 2013). Unlike conventional infrastructure projects, metro rail projects must also account for long-term sustainability and environmental impact, especially in densely populated urban areas. Therefore, while general megaproject studies provide valuable insights, the complexities identified in those studies cannot be directly applied to metro rail projects due to the unique socio-political, environmental, and technological constraints they face.

This research aims to bridge the gap by not only identifying project complexity and its influencing factors but also by developing a Project Complexity Index (PCI) model specific to metro rail projects. The PCI model goes beyond existing complexity indices by offering a quantifiable measure of how project complexity impacts the performance of metro rail projects. This distinction is important because metro rail projects are highly context-dependent, and the challenges they face in urban settings make them face challenges to delays, cost overruns, and stakeholder conflicts (Othman, 2014; Rothengatter, 2019).

The development of the PCI model is essential because it serves as a benchmark for measuring project complexity in similar metro rail projects. Moreover, it provides valuable insights into strategic project complexity management, which is crucial for optimizing project outcomes. Understanding project complexity and its specific influence on metro rail projects is essential for ensuring successful project execution, especially in cities where infrastructure demands are constantly growing. The significance of project complexity has grown in parallel with the increasing complexity of construction projects. However, the application of complexity science in metro rail projects is still relatively limited. For project managers, comprehending project complexity and its management is critical due to the decision-making processes and goal attainment associated with complexity. In metro rail projects, complexity exerts an influence on project planning and control, potentially delaying the identification of clear goals and objectives and shaping the selection of appropriate project organizational structures. Therefore, a comprehensive understanding of project complexity in metro rail projects can provide significant benefits to project managers.

In summary, while there has been substantial research on megaproject complexity, the unique challenges of metro rail projects particularly in urban environments require dedicated attention. The interdependence of factors such as regulatory approvals, stakeholder management, and technological innovation distinguishes metro rail projects from other megaprojects, making it necessary to develop an adapted complexity measurement model like PCI. This model not only addresses the distinct challenges posed by metro rail projects but also provides a strategic framework for managing complexity in future urban infrastructure projects.

1.3 Research Gap

Identification and analysis of project complexities in the Indian Metro Rail project is important, for identifying the challenges, optimizing resource allocation, and development stakeholder association. Despite existing research focusing on project complexity in megaprojects, conventional projects, and transportation projects, the factors of complexity, interdependence in metro rail construction have been inadequately addressed. While some studies have explored project complexity and its consequences in metro rail projects, there remains a gap in understanding the factors responsible for complexity occurrence and their interdependence. Furthermore, research on the similarities and differences in complexity factors between elevated and underground metro rail projects is lacking. Existing research has explored project performance in megaprojects, the impact of project complexity on performance parameters in metro rail projects remains unexplored. Although some studies have touched upon this issue, a detailed investigation into predicting the impact of complexity on parameters like time, cost, quality, scope, sustainability, and reliability using Machine Learning (ML) Models techniques such as Support Vector Machine (SVM), Decision Tree (DT), and Random Forest (RF) models has not been undertaken.

Furthermore, few studies have been conducted in measuring the impact of project complexity in megaprojects, but complexity assessment models in metro rail projects have not been thoroughly addressed. Previous studies on project complexity assessment are very limited, with most studies focusing on the conceptual framework of project complexity in megaprojects. The existing complexity measurement models often consider a limited number of complexity factors, falling short in identifying the impact of project performance caused by complexity in other projects like metro rail and similar projects and they are limited to megaprojects. The impact of such complexities on metro rail projects and the use of measurement methods to analyze the impact of project complexities in project performance in metro rail projects remains underexplored.

Hence, this research bridges the gap by identifying PCFs, interdependence, and developing a project complexity measurement model, i.e. PCI, to assess the level of impact on project performance for effective management of metro rail projects. By addressing these gaps, this study contributes to a better understanding of how complexity influences metro rail project success, enables the prediction of potential challenges, and facilitates better decision-making in project management.

1.4 Research Objectives

The primary objective of this study is to address the research questions and accomplish the following goals:

1. To identify factors influencing project complexity and their interrelationships.
2. To study and analyze the impact of project complexity on project performance parameters.
3. To develop a model for measuring project complexity.

Project parameters considered in the present study

- Time
- Cost
- Quality
- Scope
- Sustainability
- Reliability

By achieving these specific objectives, this research will advance the understanding of the complexity of metro rail projects and provide valuable tools for assessing and managing its influence on project performance.

1.5 Significance of the Research

This research holds considerable significance for the field of metro rail project management by addressing the broader challenge of managing complexity in large-scale infrastructure projects**.** Through the identification and analysis of PCFs in metro rail projects, this study contributes to an enhanced understanding of how complexity affects various performance parameters such as cost, time, and quality. By developing quantitative models and a complexity index, this research expands the methodological toolkit available to both academic researchers and industry professionals. From a practical perspective, this study addresses a critical need for metro rail organizations, offering insights that enable practitioners to better anticipate and mitigate complexity-related challenges. The predictive models developed in this research provide metro rail project managers with actionable tools to quantify and plan for complexity's impact on project performance, thereby increasing the likelihood of achieving successful project outcomes. Ultimately, this research promotes the development of professional expertise in managing the complexity of metro rail projects, helping practitioners navigate the challenges inherent in such complex infrastructure projects. Its broader significance lies in its potential to improve the strategic management of metro rail projects, contributing to the overall success of urban transportation initiatives and advancing the body of knowledge in project management, particularly in the domain of infrastructure megaprojects.

1.6 Research Contribution

This study makes specific and valuable contributions to the field of metro rail projects by introducing new insights into the nature and management of project complexity. The research goes beyond general complexity management to focus on the interdependencies among complexity factors unique to metro rail projects and their direct impact on project performance parameters. With both qualitative and quantitative methods, this study identifies and categorizes the types of complexities commonly encountered in metro rail projects, offering a detailed analysis of their underlying causes. Drawing from complexity theory, the study provides a comprehensive explanation of how these complexity factors interact, offering practitioners a clearer understanding of the root causes of project complexity and its potential impacts. A key contribution of this research is the development of a PCI, a model capable of predicting the level of complexity in metro rail projects. This model provides a quantitative measure that enables project managers to assess complexity early in the project lifecycle and take appropriate measures to mitigate risks. By introducing this model, the research enhances both the theoretical and statistical foundations of project complexity analysis, making a significant contribution to the field of project management. In practical terms, this research offers a constructive approach to measuring and managing project complexity in metro rail projects, thereby fostering competency development among professionals tasked with handling such projects. By bridging the gap between theory and practice, this study provides both scholars and practitioners with the tools to understand and manage the complexities of large-scale metro rail initiatives, thus contributing to the successful execution of future projects.

Chapter 2
Literature Review

2.1 Overview

The literature review focuses on gaining a comprehensive understanding of project complexity and its management. Extensive research has been conducted to explore the state of the art in project complexity, including relevant theories, methodologies, and project complexity structures in various fields. A wide range of scholarly journals and sources were consulted, comprising both practical and academic information.

2.2 Understanding Project Complexity

Project complexity refers to the unpredictable behavior of systems due to interactions among their components (Remington & Pollack, 2008). In transportation systems, the non-linear nature of project elements and the interrelationships between them contribute to emerging unexpected problems (Simons' theory). Although project parts or subprojects can be analyzed individually, predicting outcomes in megaprojects remains challenging because of the combined effect of multiple project characteristics (Gransberg et al., 2013).

Megaprojects, such as those in the construction industry, involve various interdependent activities, leading to an increase in complexity and risk (Baccarini, 1996). The growing complexity in megaprojects, especially in construction, is a major concern for project managers. According to Mills (2001), the construction industry faces a dynamic and demanding environment, making it susceptible to high levels of uncertainty and risk. Additionally, the industry has a poor record in risk management, often failing to meet schedules and cost targets (Mulholland & Christian, 1999).

The study of project complexity has been significant for decades, with Baccarini (1996) early work being one of the first attempts to address complexity in megaprojects. Researchers like Al Nahyan et al. (2012) and Maddaloni & Davis (2017) have further explored the complexity factors affecting projects, employing both qualitative and quantitative approaches. However, while qualitative evaluations have been more prevalent, quantitative assessments are limited, revealing a gap in the literature for more structured complexity measurement methods (Chapman, 2016). This is particularly important for metro rail projects, where specific complexity factors are not well-studied throughout the project life cycle.

2.3 Complexity in Megaprojects

Megaprojects have been recognized for their significant contribution to the economic development of countries, both directly and indirectly (Carr, 2019). These large-scale projects have been associated with improved global connectivity, access to natural resources, competitive markets, and increased job opportunities, which are key socio-economic benefits often highlighted (Shan et al., 2018). Evidence from studies conducted in industrialized and developing nations supports these claims (Omonyo, 2018). Notably, intense capital investments in megaprojects in China have played a crucial role in the country's remarkable economic growth and the upliftment of over half a billion people from poverty between 1980 and 2000 (Sears, 2019). While acknowledging the importance of these developmental advantages, it is important to note that megaprojects have a history of underperformance, as indicated by researcher Ashish Gupta (2015). Such underperformance has been attributed to various factors related to technology, finance, socioeconomics, and the environment (Siemiatycki, 2018). It is worth emphasizing that this underperformance undermines the potential socio-economic, political, and environmental benefits that megaproject expenditures could otherwise deliver (Siemiatycki, 2018). Developing nations face significant challenges in dealing with the repercussions of megaproject underperformance due to limited resources and capacity to absorb associated shocks (Sears, 2019). Therefore, it is imperative to identify the contributing factors to such underperformance and propose appropriate corrective actions to enhance the performance of megaprojects and maximize their developmental impacts. By doing so, the potential benefits of these projects can be realized more effectively, leading to positive socio-economic outcomes for the countries involved.

Since World War II, the construction of megaprojects has become increasingly complex (Baccarini, 1996). These projects now encompass a wide range of end-user requirements and incorporate sophisticated structural systems, advanced electrical and mechanical installations, and other complex features. Although the term "project complexity" lacks a clear definition (Corning, 1998; Williams, 1999) it is considered a critical project characteristic that influences the appropriate actions needed to achieve successful project outcomes (Baccarini, 1996). In recent years, the construction of megaprojects has experienced significant growth due to rapid urbanization (Flyvbjerg, Bruzelius, et al., 2003; Van Marrewijk et al., 2008). Megaprojects, which have become a popular project category, are typically characterized as large-scale and complex projects with an average cost exceeding $1 billion, as indicated by researchers, Merrow (2011) and Flyvbjerg (2017). Capka (2004) defines megaprojects as multimillion-dollar projects that face the challenges of massive delivery schedules, fixed budgets, and the management of numerous concurrent and complex activities. Megaprojects exhibit a diverse range of characteristics and significant variations in capital investment. Zhai et al. (2015) emphasize that megaprojects possess extreme complexity, substantial risks, involve long duration, and extensive impact on the community, economy, technological development, and environment of a region or even an entire country. According to Haidar & Ellis (2010) the concept of megaprojects should encompass both their magnitude and complexity. Van Marrewijk (2007) highlights stakeholder conflicts, high-risk technological innovation, and a high level of uncertainty as inherent features of megaprojects. Fiori & Kovaka (2005) describe mega projects as single or combined projects characterized by large costs, significant risk levels, great complexity, substantial societal impact, and additional obstacles for stakeholders. Zidane et al. (2013) suggest that megaprojects are large-scale undertakings with an average capital cost of $985 million, long durations, technological demands, and a multidisciplinary nature. Collectively, all these definitions converge to emphasize that the term "megaproject" applies to projects that are massive, expensive, and inherently challenging.

Currently, many developing, and even underdeveloped countries are undertaking mega projects across various sectors, including construction, infrastructure, and oil and gas industries. Notably, Flyvbjerg (2017) is a prominent researcher focusing on megaprojects and has authored a book titled "Managing Mega Projects" at Oxford University in London in 2017. Flyvbjerg, Bruzelius, et al. (2003) characterizes megaprojects as highly complex projects with broad scopes, distinguishing them from conventional projects in terms of investment, cost, process management, and duration (Flyvbjerg, 2017). Megaprojects like metro rail projects are characterized by their large scale, complexity, and transformative nature, with costs typically exceeding $1 billion and lengthy development and construction periods. They involve a diverse group of stakeholders from both the public and private sectors, ultimately impacting millions of people (Flyvbjerg, Bruzelius, et al., 2003; Van Marrewijk et al., 2008). Due to their unique factors in terms of aspirations, stakeholder engagement, lead times, complexity, and impact, megaprojects require specialized management approaches beyond traditional project management practices. Subject-matter experts who possess deep knowledge and thoughtful expertise are essential for effectively managing megaprojects (Tsai et al., 2019).

Megaprojects involve multiple actors and institutions with potentially conflicting interests, making it challenging to establish effective governance and management practices across different institutional cultures (Levitt et al., 2019). The presence of stakeholders, such as financiers, sponsors, subcontractors, investors, and suppliers, adds further complexity. Balancing the diverse goals and interests of these stakeholders and finding common ground can be difficult. Resource management is also a complex task in megaprojects due to the substantial number of resources required. Additionally, megaprojects often lack sufficient knowledge about costs, risks, and deadlines during the planning phase, leading to cost overruns, delays, and shortcomings during project execution (Flyvbjerg, 2017). These challenges need to be addressed while the project is already in progress, like "fixing the plane," which adds to installation difficulties. This management issue is fundamental and frequently contributes to the failure of megaprojects (Merrow, 2011).

The size and complexity of megaprojects have experienced significant growth in recent years, driven by global urbanization and substantial investments exceeding US$700 million per project (Hu et al., 2012; He et al., 2014). These projects are often characterized by their high level of complexity (Chan et al., 2004). Factors such as rapid environmental changes, increased material production, and lengthy schedules contribute to the increasing complexity of these projects (Williams, 1999). Numerous studies have demonstrated that project complexity influences the likelihood of project success and that conventional project management approaches are inadequate in dealing with this complexity (Remington & Pollack, 2008). Effective management of project complexity is crucial, necessitating a thorough understanding of its nature. Therefore, conducting a comprehensive review of recent literature is valuable for researchers to assess the current state and future trends in this field, as new researchers often build upon the findings of previous studies (Tsai & Wen, 2005).

The existing literature highlights the need to conceptualize complexity, a common characteristic of megaprojects, before developing management approaches to ensure project success (Ma & Fu, 2020). The specific concept of project complexity for megaprojects should be further examined, considering their unique characteristics and differences from other projects. Given the scarcity of specialized expertise in project complexity for megaprojects and their increasing complexity, a closer examination of complexity in the structures and dynamics of megaprojects is necessary.

The reviewed literature is categorized into the following key areas within the scope of this study:

1. ***Project Complexity Theory:*** This section represents the use and application of project complexity theory in the analysis of project complexity.
2. ***Definition of Project Complexity:*** This section provides literature insights about how project complexity is defined and conceptualized, identifying the key elements and characteristics that contribute to complexity.
3. ***Factors of Project Complexity:*** This section shows the various factors that influence project complexity, including organizational, environmental, technological, and contextual aspects.
4. ***Measuring and Assessing Project Complexity***: The literature explores different approaches, models, and methods employed for measuring and assessing project complexity, aiming to capture its multidimensional nature and provide quantitative or qualitative indicators.
5. ***Impact of Project Complexity:*** This section represents the effects of project complexity on project outcomes, performance parameters, and overall project success, considering aspects such as time, cost, quality, scope, sustainability, and reliability.

By synthesizing and summarizing the information from these literature sources, this study builds upon existing knowledge. It contributes to a deeper understanding of project complexity and its management in the context of metro rail projects.

2.4 Project Complexity Theory

Project complexity has emerged as a significant area of research within the field of project management. Baccarini (1996) was among the pioneers who conducted an early exploration of project complexity, defining it as the interdependency and differentiation of diverse project components. He classified project complexity into organizational and technological dimensions, recognizing that organizations exist within dynamic interdependence systems rather than in isolation from their environment.

According to Keene (2000) complexity theory goes beyond subjectivity and examines the interrelationships and interactions among organizations and the construction industry. Complexity science, originating in 1984, explores the behavior of complex systems using interdisciplinary concepts and focuses on nonlinear phenomena. In a complex system, activities interact within an organization to achieve a common goal. Interdependence among activities and elements is a key characteristic of complex systems. These systems exhibit unexpected and nonlinear behavior, as they comprise diverse components that generate unpredictable outcomes, which cannot be fully understood by studying individual activities alone. Moreover, complex systems are inherently unstable, as even slight modifications to their constituent parts can have profound effects on the entire system. By drawing on the principles of complexity theory, this research aims to deepen our understanding of project complexity and its implications for metro rail projects. It recognizes the interdependent nature of project components and the potential for non-linear dynamics, providing insights into how complexity can influence project outcomes and management approaches.

Project complexity is a complex concept that contains various dimensions and characteristics. The complexity of a project arises from the interdependence of different factors, making it essential to adopt a systems approach to understand and manage these project complexities. In the context of the project complexity systems approach, this study investigated the factors inherent in complex systems, characterized by the following properties:

- ***Complex Organization:*** An organization comprising numerous elements or activities exhibits diverse behaviors and functions.
- ***Uncertain Influences*:** The elements within the organization are primarily influenced by unpredictable activities, giving rise to inherent uncertainty.
- ***Interdependence factors:*** The factors within the system are interdependent due to numerous relationships, creating a network of interdependencies. Projects comprise numerous interrelated components, tasks, and processes. Changes or issues in one area can cause various effects throughout the entire project.
- ***Uncertainty:*** Uncertainty refers to the lack of clarity or precision in project requirements, goals, or constraints. Uncertain situations can lead to misunderstandings, differing interpretations, and difficulties in decision-making. Projects operate in dynamic environments where uncertainties occur. These uncertainties can arise from changes in requirements, technology, market conditions, or external factors, making it challenging to predict outcomes accurately.
- ***Dynamism:*** Project environments are often dynamic, with conditions and requirements evolving. Adapting to changes and staying responsive to evolving circumstances is a characteristic of complex projects.

- ***Non-linearity:*** Project activities and relationships are not always linear or straightforward. Non-linear relationships and dependencies can lead to unexpected interactions and outcomes that are difficult to predict.
- ***Diversity:*** Projects involve diverse stakeholders, team members, and skill sets. Managing a diverse set of resources and perspectives adds to the complexity, requiring the need for effective communication and coordination.
- ***Scale:*** The size and scope of a project contribute to its complexity. Larger projects often involve more elements, dependencies, and interactions, making them more complex.
- ***Technological Complexity:*** The use of advanced technologies or complex technical solutions can cause complexity. Managing and integrating complex technologies requires specialized knowledge and expertise.
- ***Human Factors:*** The involvement of people introduces a social dimension to project complexity. Team dynamics, communication challenges, and leadership issues can contribute significantly to the overall complexity of a project.
- ***Resource Constraints:*** Projects face problems in terms of time, budget, and other resources. Balancing these constraints while meeting project objectives adds another layer of complexity.
- ***Regulatory and Compliance Requirements:*** Projects in certain industries require specific regulations and compliance standards, adding complexity in terms of documentation, approvals, and quality assurance processes.
- ***Geographical Distribution:*** If team members, stakeholders, or components of the project are distributed across different locations, managing communication and coordination becomes more challenging, contributing to project complexity.

Understanding and addressing these characteristics of project complexity is necessary for effective project management. A systems approach involves considering the project, recognizing the interrelationship nature of its components, and implementing strategies to navigate and mitigate complexity. Over the past decade, complexity theory has found extensive applications in various domains such as astronomy, biology, physics, and finance, offering solutions to complex problems. While significant progress has been made in the theoretical and mathematical aspects of complex systems, there remains a scarcity of tools specifically designed to control and manage these complex systems in practical settings. This gap led to the development of complex project management, which aims to bridge the gap between theory and real-world application. Complex Project Management builds upon the foundations of complexity theory, which explores the interrelationships among nonlinear variables. It also draws inspiration from chaos theory, initially introduced by Edward Lorenz (1995), to examine how complex systems give rise to new patterns and structures. Researchers, Manson (2001) and (Cooke-Davies et al., 2007) are contributed to the development and understanding of complexity theory and its implications for project management.

Complexity theory encompasses various classifications and approaches for understanding complex systems. It can be classified into deterministic complexity, which draws upon chaos theory; cumulative complexity, which considers internal structure, change, evolution, and interrelationships; and complexity algorithms, which are rooted in information theory and mathematical complexity (Manson, 2001). Notably, complexity theory is characterized by its nonlinearity and unpredictability, as observed in study carried by Cooke-Davies et al. (2007). In the context of project management, complexity theory has evolved into Complex Adaptive Systems (CAS), which offers a temporary assessment of project complexities (Daniel & Daniel, 2019) and serves as an analytical approach in megaprojects. CAS is characterized by six key features: non-linearity, feedback, adaptivity, inter-relationships, and self-organization (Thiry & Deguire, 2007). These features provide insights into the behavior and dynamics of complex systems within the realm of complexity theory. Table 2.1 represents the characteristics of the CAS.

Table 2.1 Mapping characteristics of CAS with complexities

S. NO	CAS Characteristics	Type of Complexity	Complexity Theory
1	Differentiation, Modularity, Diversity, Technical factors, uncertainty, emergence, the high difference in integration development.	Technological	Tatikonda & Rosenthal (2000), Manson (2001), Cooke-Davies et al. (2007), Hanseth & Lyytinen (2010)
2	Emergence, Agent Cooperation, Strategic Leadership, Connectivity, Interdependence-Behavioral patterns, dynamic changes, social interaction, lack of transparency.	Organizational	Boal & Schultz (2007), Antonacopoulou & Chiva (2007), Aritua et al. (2009), Lauser (2010)
3	Requisite Variety, Continuous Varying Interactions, Interaction Interdependence, Nonlinear contract firm, Political and external influences.	Contractual	Tatikonda & Rosenthal (2000), Manson (2001), Warren (2002), Gidado (2004), Antonacopoulou & Chiva (2007), DeRosa et al. (2008), Borzillo & Kaminska-Labbé (2011)
4	Adaptability, Unpredictability, Continuous Varying Interactions, Uncertainty, changes in environmental conditions, unpredictable consequences.	Environmental	Aritua et al. (2009), Hammer et al. (2012)
5	Boundary Constraints, Landscape, Dissipative Structures, People Factors.	Location	Boal & Schultz (2007), Hammer et al. (2012)
6	Continuous Varying Interactions, Boundary Constraints.	Quality and Safety	Aritua et al. (2009), Hammer et al. (2012)

2.5 Literature Analysis

For a better understanding of complexities, the study is divided into five categories based on papers that have been analyzed. They include complexity definition, factors causing project complexity, classification of project complexities, complexities in different infrastructural sectors, and existing methods and framework models for qualitative and quantitative measurement of complexities in the megaproject. The framework for the study of complexities in megaprojects is represented in Figure 2.1.

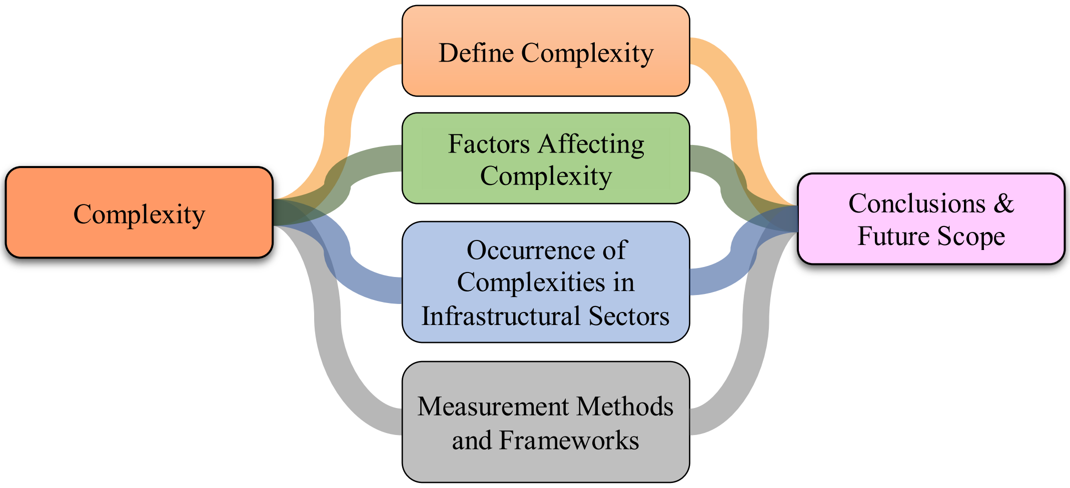


Figure 2.1 Framework for the Study of Complexity in Megaprojects (source: authors' own work)

Various research efforts on project complexities in megaprojects are explored in the existing literature and different research approaches are classified into theory, case studies, review, empirical, mathematical, and application frameworks. Different sectors in the reviewed articles include public-private-partnership projects (Ahmadabadi & Heravi, 2019), different infrastructure projects (Algarni et al., 2007) such as energy (Kian et al., 2015), telecommunication (Nandi & Banani, 2000), transportation (Al Nahyan et al., 2012), and environmental sectors projects (Raghuram et al., 2009).

2.6 Project Complexity Definition

There is no universally accepted definition of project complexity in literature. Researchers have approached it from various perspectives, considering unpredictability, interconnections, and uncertainty as key elements (Zhu & Mostafavi, 2017a; Dao et al., 2016). Project complexity can be understood as arising from factors that complicate management due to variability, non-linearity, and challenges related to outcomes. Table 2.2 explains the definition of project complexity identified from the literature.

Table 2.2 Project complexity definition identified from literature

Author & year	**Definition**
Qiu et al. (2019)	Complexity in megaproject associations comes from macro-level and micro-level parts, including regulatory, political, social complexity, cultural, social, and evolutionary complexity.
Bjorvatn & Wald (2018)	The adverse impact of the complex nature supersedes the alleviating impact of absorptive limits on project management successes.
Maylor & Turner (2016)	The term complex is if the project comprises interdependent parts, each of which can change in manners that are not predictable and which would then be able to have unpredictable impacts on different components that are themselves equipped for change.
Kermanshachi et al. (2016)	Project Complexity has been extensively investigated in the literature in its commitment to the disappointment of significant projects in terms of cost and time overruns
Nguyen et al. (2015)	Complexity comprises numerous associated parts and can be operationalized as far as differentiation and dependence.
Lessard et al. (2014)	Complexity is identified to be a developing concept that focuses on the interrelationship among various project features and properties related to non-linearity and outcome variability, difficulties, and (non) governability in the projects
Senescu et al. (2013)	Complexity is portrayed by a complicated or included arrangement of many interconnected components that it is difficult to comprehend or manage
Sedaghat-seresht et al. (2012)	Complexity is an expression of language that makes it difficult to formulate the whole behavior even after the availability of complete information regarding the components and interrelationships of the elements in the project.
Zolin et al. (2009)	A complex project demonstrates several characteristics to a degree, or level of severity, that make it difficult to predict project outcomes or manage the project.
Vidal & Marle (2008)	Project complexity is the property of a project, which makes it difficult to understand, foresee, and keep under control its overall behavior.
Brockmann & Girmscheid (2007)	The complexity is the degree of manifoldness, interrelatedness, and consequential impact of a decision field.
Remington & Pollack (2008)	These authors attribute project complexity to the "interrelationships and feedback between increasing numbers of areas of uncertainty and ambiguity."
Gidado (1996)	Project complexity is the measure of the difficulty of implementing a planned workflow concerning the project objectives.

Despite these definitions, the literature lacks a comprehensive framework for project complexity in specific sectors like metro rail projects. This creates challenges in predicting and managing complex projects, especially when complexity directly affects project performance

(Geraldi et al., 2011). A more refined understanding of project complexity, including both qualitative and quantitative analysis, is necessary to ensure the development of effective complexity management tools.

2.7 Project Complexity Dimensions and Factors

Megaprojects encompass a multitude of interdependent factors that exhibit varying levels of complexity, as highlighted in studies conducted by Si et al. (2018) and Kardes et al. (2013). The interrelationship among these factors is characterized by nonlinearity, where even minor changes in one factor can have inconsistent effects, leading to unexpected consequences and increased complexity. To address the challenges posed by complexity and uncertainty in such chaotic conditions, a sense analysis approach, involving the investigation, identification, analysis, and response to emerging patterns, is employed (Snowden & Boone, 2007; Oehmen et al., 2015). This approach aids in navigating the complexity and uncertainties inherent in megaprojects, facilitating effective decision-making and management.

The classification and identification of complexity factors in projects can vary across different studies, leading to some inconsistency and overlapping of complexity factors. The literature review reveals that research on project complexity and its factors can be categorized into two groups: theoretical models and qualitative models/frameworks based on complexity factors. Baccarini (1996) made initial attempts to introduce project complexity based on technological dimensions (interrelationships between various technologies used) and organizational dimensions (involvement of multiple stakeholders). Baccarini (1996) defined project complexity as the interdependence and differentiation of project elements. Williams (1999) later proposed structural complexity, which relates to the interdependence of project elements, and added characteristics of uncertainty to project complexity. Cicmil & Marshall (2005) identified PCFs as performance, unpredictability, ambiguity, and interface issues in their studies. Vidal & Marle (2008) focused on context-related factors such as PCFs, considering project size, type, and system. Using the Delphi technique, Vidal et al. (2011b) identified 18 PCFs, with most of them being related to organizational complexity. Bosch-Rekveldt et al. (2011) conducted semi-structured interviews with 18 individuals involved in six engineering projects and integrated their findings with the literature to identify 50 PCFs across technological, organizational, and environmental dimensions. Geraldi et al. (2011) expanded the dimensions of project complexity by adding socio-political factors (communication and interaction challenges imposed by people), dynamic factors (changes in project goals and specifications), and time-related factors (project delivery).

Overall, there is a range of PCFs identified in the literature, encompassing technological, organizational, environmental, socio-political, dynamic, and time-related dimensions. The specific factors and their classification may vary across studies, reflecting the complex nature of the project complexity and the diverse perspectives of researchers in understanding and defining it. Dunović et al. (2014) emphasize the significance of the environment and available resources as key factors contributing to project complexity. Botchkarev & Finnigan (2015) adopted the System of Systems (SoS) approach to identify multiple PCFs categorized under the product, project, and external environment systems. In one of the most comprehensive studies on complexity factors, Bakhshi et al. (2016) analyzed 423 articles from project management journals published between 1990 and 2015. They identified 127 complexity factors grouped into categories such as size, emergence, diversity, connectivity, belonging, autonomy, and context. Dao et al. (2016) conducted a statistical analysis of survey data from 44 projects and identified 34 complexity indicators across 11 categories. Their study aimed to differentiate between high-complexity projects and low-complexity efforts. The complexity factors were categorized as "factors related to the project," "factors related to the external environment," "factors related to an organization," and "factors related to the project manager and team members."

Although the specific factors identified may vary, Montequín et al. (2018) also researched project complexity and discovered 26 complexity factors. These factors were grouped into four categories: "factors related to the project," "factors related to the external environment," "factors related to an organization," and "factors related to the project manager and team members." These studies contribute to the understanding of project complexity by identifying and categorizing various complexity factors. By considering factors related to the project itself, the external environment, the organization, and the project team, researchers gain insights into the multidimensional nature of project complexity.

Megaprojects, including metro rail projects, encompass a multitude of interdependent factors that exhibit varying levels of complexity, as highlighted in studies conducted by (Si et al., 2018) and (Kardes et al., 2013). However, despite extensive research on project complexity, several gaps persist in the literature**.** The existing studies primarily focus on general megaprojects and large-scale construction projects but often fail to consider the unique complexities of metro rail projects, particularly those related to urban settings, regulatory environments, and advanced technological systems. These gaps underscore the necessity of this research, which aims to address the specific complexities inherent in metro rail projects. One key limitation of existing research is that many studies treat project complexity as a general concept without adequately addressing the unique factors relevant to metro rail systems. For instance, while Baccarini (1996) and Williams (1999) introduced the concepts of technological and organizational complexity, their frameworks do not fully account for the socio-political challenges specific to urban metro rail projects. These challenges include land acquisition, regulatory approvals, and the need to minimize disruptions in densely populated urban areas (Othman, 2014). This study seeks to fill this gap by focusing specifically on the interdependencies between technical, organizational, and socio-political factors in metro rail projects, which have been inadequately addressed in previous research.

Another overlooked aspect in the existing literature is the evolving nature of complexity over the lifecycle of metro rail projects. While Geraldi et al. (2011) and Bosch-Rekveldt et al. (2011) expanded the dimensions of project complexity to include dynamic and time-related factors, they did not delve into how these factors uniquely interact in the phased development of metro rail systems. For example, as metro rail projects move from the planning phase to construction and operational phases, complexity factors evolve, influenced by changing stakeholder expectations, technological advancements, and political pressures. This study introduces a PCI model designed to measure these evolving complexities over time, offering a more dynamic and adaptable tool for managing metro rail projects.

The literature also tends to emphasize complexity at the organizational and technical levels, often overlooking the environmental and contextual factors that uniquely affect metro rail projects. Vidal & Marle (2008) identified environmental dimensions as contributors to complexity, but their study primarily focused on generic construction projects. In metro rail projects, environmental factors such as the integration of sustainable technologies, urban space constraints, and the need for long-term environmental impact assessments are critical and require more attention. This research fills this gap by incorporating environmental complexity factors that are specifically relevant to urban metro rail systems. Additionally, most existing studies do not explore the socio-political dimensions of complexity in detail. Bosch-Rekveldt et al. (2011) introduced socio-political factors, but the research did not delve into the challenges posed by public opposition, local governance issues, and cross-agency coordination that are critical in metro rail projects (Giezen, 2013). This study expands on socio-political factors, particularly within the context of developing countries, where bureaucratic inefficiencies, lack of public support, and shifting political priorities further complicate metro rail projects (Othman, 2014). In summary, while existing research has made significant strides in identifying and categorizing PCFs, gaps remain, particularly in the context of metro rail projects**.** This study addresses these gaps by:

1. Developing a more focused and comprehensive model for metro rail project complexity, considering technical, organizational, socio-political, and environmental factors.
2. Introducing the PCI model, which is designed to capture the evolving nature of complexity throughout the lifecycle of metro rail projects.
3. Expanding the understanding of socio-political and environmental complexities, particularly those that are unique to urban metro rail projects, thus providing project managers with a more nuanced tool for anticipating and mitigating risks.

By addressing these gaps, this study contributes to a more holistic understanding of project complexity in metro rail projects and provides practical tools for improving project outcomes.

2.7.1 Type of project complexity

1. ***Uncertainty and unpredictability:*** Project outcomes may be influenced by various uncertainties, such as change of scope, new technology, shifting project deadlines, or socio-political disruptions (Geraldi & Adlbrecht, 2007; Harvey et al., 2008). Dealing with emergent complexity and effectively managing uncertainties is crucial to avoid disruption and inefficiency in projects (Maylor & Turner, 2016).
2. ***Interdependence and interface issues:*** The interdependence among project activities and challenges in managing interfaces between different project components contribute to complexity (Baccarini, 1996). Coordination and integration of these interdependent elements are essential for successful project execution.
3. ***Changes and dynamism:*** Complexity can arise from changes that occur over time, including design changes, scope changes, and the evolving nature of project goals (Harvey et al., 2008). Handling these changes effectively and communicating them to the project team is critical to minimize disruptions and rework.

4. ***Stakeholders and external factors***: Project complexity can be influenced by various external factors, such as legal, political, environmental, regulatory, social, and economic aspects (Rad & Ming, 2014). Managing the diverse interests and expectations of stakeholders adds another layer of complexity to projects.
5. ***Technological challenges:*** Projects involving new technologies or complex technical systems can introduce additional complexity (Xia & Chan, 2012; Gransberg et al., 2013). The utilization and integration of new technologies may require specialized expertise and coordination.
6. ***Organizational and structural complexity:*** The complexity of project delivery processes, project organization, and project features contribute to project complexity (Rad & Ming, 2014). Factors such as system rigidity, concurrent activities, trade interactions, geological conditions, and environmental conditions can also add to the complexity (Wood & Ashton, 2010).

It's worth noting that the occurrence and magnitude of complexity may vary depending on factors such as project size, type, stakeholders involved, and technology utilized (Bosch-Rekveldt et al., 2011; San Cristobal et al., 2018). Different studies may focus on different aspects of complexity, resulting in various classifications and perspectives on project complexity.

Based on the studies mentioned, the PCFs can be categorized into different dimensions like factors related to diverse design methods, cultural diversities, technological assistance, organizational interdependency, and the involvement of numerous stakeholders with different interests. Factors related to the scale of the project include the number of stakeholders involved, the number of deliverables, the complexity of structures and tools utilized, and the duration and scope of the project. Factors related to communication interface issues, interdependency among stakeholders, organizational and team cooperation, and the level of autonomy and decision-making authority granted to different entities involved in the project. Factors related to the uncertainty of project, include scope of the project, introduction of modern technologies, and the establishment of trust among stakeholders. These factors contribute to the emergence of complexity as the project progresses and evolves. The identified PCFs can serve as a basis for conducting case studies and further research on megaprojects and large-scale projects to better understand and define the concept of project complexity. It is important to consider these factors and dimensions to effectively manage and address complexity in project management practices.

Indeed, the literature highlights that dynamic, interaction and structural characteristics also contribute to project complexity. Whitty & Maylor (2009) and Cicmil & Marshall (2005) emphasize the importance of these characteristics in understanding project complexity. Dynamic characteristics refer to the ever-changing nature of projects, including the presence of uncertainties, evolving requirements, and the need for adaptability and flexibility in project management. The dynamic nature of projects can increase complexity as it introduces unpredictability and the potential for emergent challenges and changes.

Interaction characteristics affect the complexities arising from the interactions and relationships among project stakeholders, teams, and organizations involved. Interactions can involve communication challenges, coordination issues, conflicting interests, and the need to manage diverse perspectives, cultures, and expectations. These interactions can add layers of complexity to a project. Structural characteristics relate to the project's structural elements, such as its scope, scale, organizational setup, and technical components. The structural complexity of a project can be influenced by factors such as the number of components or subsystems, the interdependencies among them, the level of integration required, and the complexity of the project's physical or technical aspects. It is important to note that the impact and level of complexity attributed to specific characteristics or factors may change as the interrelations among them evolve throughout the project lifecycle. Projects are dynamic and complex systems, and the interactions and dependencies among various factors can influence the overall complexity and its impact at different stages. Understanding the dynamic, interactive, and structural characteristics of projects can provide valuable insights into managing complexity effectively. By recognizing and addressing these dimensions, project managers can better anticipate and navigate the challenges and uncertainties associated with project complexity. Table 2.3 explains the classification of project complexity in megaprojects.

Management of megaprojects requires highly robust strategies and methods as their decisions do not depend on a single aspect. For example, the design of a project depends on various factors like technical requirements, political agenda, public acceptance, changing legislations, and attracting private investments into the sector (Owens et al., 2012). The different types of project complexities are represented in Figure 2.2.

Table 2.3 Different types of complexities in megaprojects

Author & Year	Classification
Peñaloza et al. (2020)	Technical, organizational, and environmental complexity
Qiu et al. (2019)	Institutional, regulatory, political, and social complexity and cultural, evolutionary, and relational complexity
Gao et al. (2018)	Technical, organizational, and environmental complexity
Mirza & Ehsan (2017)	Schedule, Scope, Cost Quality, Resources, and Risk
Rad et al. (2017)	Economy, environment, Legal and regulations, Politics and Social (External); Organization, Process of Delivery, and Project Characteristics (Internal)
Chapman (2016)	Finance, Context, Management, Site, Task, and Delivery
Nguyen et al. (2015)	Socio-Political, Environmental, Organizational, Infrastructural, Technological and Scope Complexity
Brady et al. (2012)	Structural and Dynamic Complexity
Dunović et al. (2014)	Structural, uncertainty, and constraints
He et al. (2014)	The technological, organizational, goal, environmental, cultural, and information complexities
Hiroshi Tanaka (2014)	Political, Economic, Social, Technological, Legal, and Environmental
Gransberg et al. (2013)	Technical, Schedule, Cost, Context, and Financing
Senescu et al. (2013)	Product complexity, organization complexity, and process complexity
Bosch-Rekveldt et al. (2011)	Technical, Organizational, and Environmental
Puddicombe (2011)	Technical Complexity and Novelty
Gerhard & Christian (2008)	Task Complexity, Social Complexity, Cultural Complexity, Operative Complexity, and Cognitive Complexity
Geraldi & Adlbrecht (2007)	The complexity of Fact, Complexity of Faith, and Complexity of Interaction
Harvey Maylor (2003)	Organizational Complexity, Resource Complexity, and Technological Complexity

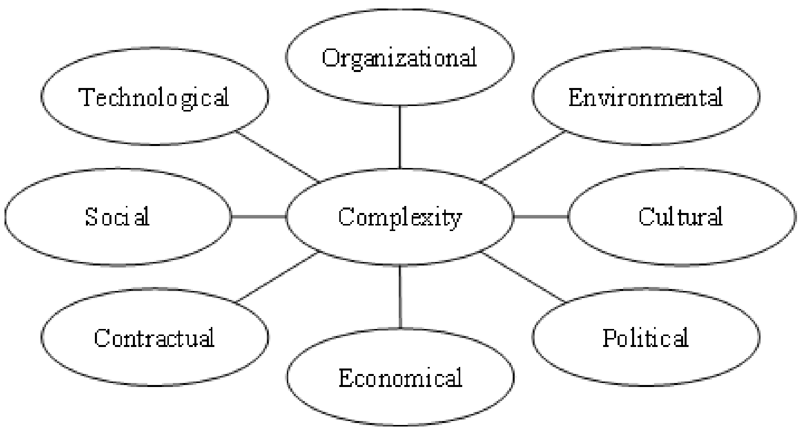


Figure 2.2 Types of complexities in megaprojects (source: authors' own work)

- ***Organizational Complexity:*** The construction of megaprojects involves the engagement of numerous project participants with separate organizational structures. This develops a temporary multi-organizational structure containing differentiated parts with operational interdependencies, which are complex to manage and coordinate during the execution of the project. This is caused by different parties and people involved in the project and occurs due to poor communication, lack of transparency, and internal strategic pressure (Bosch-Rekveldt et al., 2011).
- ***Environmental Complexity**:* Environmental complexities occur due to competition levels, prevailing market conditions, required local content, political influence, weather conditions, geographic conditions, natural environmental risks, strategic pressure, interference with the existing site, and varying needs of stakeholders involved in the project (Bosch-Rekveldt et al., 2011).
- ***Technological complexity:*** Projects comprise enormous investments, time, levels of process, and methodologies which are causes for failure of project due to high difficulty levels. This failure occurs due to the dependence on technological processes, diversity of technology in projects, risk in handling complex technology, and communication between the external environment and technology system (Baccarini, 1996; Maylor & Söderlund, 2016; Desai et al., 2018).
- ***Social complexity:*** Social complexities occur in megaprojects as many individuals such as contractors, clients, suppliers, managers, and laborers are involved, where problems like lack of communication, trust, and commitment are predominant. This complexity also occurs due to the poor leadership, lack of team coordination, modest exchange of information, and miscommunication between project stakeholders (San Cristobal et al., 2018).
- ***Economical complexity:*** Economic assessment of the huge projects is essential for stakeholders and other individuals participating in the successful completion of the megaproject. Heavy investments lead to greater impact on the environment of the project. These large investments attract the public and media and may lead to difficulties when the project goals are not achieved. The impact of the economy on the project, operation cost, investments, barrier effects, and time intended in the project are various kinds of economic complexity (Pitsis et al., 2018).
- ***Cultural complexity:*** They are caused by the diversity of cultural human mindsets or behavior (He et al., 2014). Megaprojects are progressively complex and involve

collaboration and coordination among various project participants. This may increase the issues of relations, and social interaction with their social reproductions. The diversity of the culture, language barrier, and multinational participants create an impact on the team, and flexibility of working on the project causes an impact on the productivity of the project.

- ***Political complexity:*** Mega-projects are recognized based on scale, difficulty, and necessity upon large measurements of economic, human, and material resources. These kinds of projects are generally involved with large policies, programs, and private and public stakeholders across numerous jurisdictions which leads to the chances for the execution of conflicts and political interests. Finance, foreign relations, contractual negotiation, political pressure, guidelines, financial risk and involvement of local political parties, and disputes among authorities and organizations are considered as other factors for the occurrence of political complexities (Maylor & Turner, 2016).
- ***Contractual complexity***: The realization of megaprojects involves the participation of various stakeholders to perform various tasks and requires huge amounts of investment and effective return policies to benefit all the parties involved in the project. Contracts play a major role in establishing relationships and degree of interface among the project participants (Wang et al., 2018) and tend to have complicated contractual agreements between the participants. Modification of the terms, contract elimination, disputes in the projects, insufficient contractual clarification, and low experience of the organization are reasons for contractual complexities in megaprojects. Figure 2.3 shows the percentage of complexities obtained from the literature.

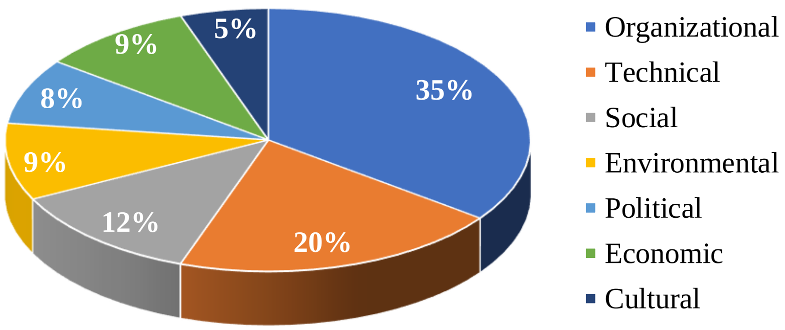


Figure 2.3 Percentage of types of complexities from literature (source: authors' own work)

2.8 Complexity in Different Sectors

The infrastructure industry comprises transportation sector, energy sector, telecommunication sector, and urban advancement sector (Rad et al., 2017). In India, around US$ 777.73 billion was dispensed for infrastructure projects, with US$ 22.04 billion was allotted for the development of metro rail projects alone (India Brand Equity Foundation, 2019). Studies indicate that over 40% of transportation megaprojects experience cost and schedule overruns due to various aspects of project complexities (Flyvbjerg, Bruzelius, et al., 2003; Ansar et al., 2014). Hence, there is a need for the management of megaprojects, which requires a new administration methodology (Gransberg et al., 2013; Chapman, 2016).

Complexities in projects should be comprehended for better administration (Yu Maemura et al., 2018; Mevada & Devkar, 2018). Hence an in-depth analysis of various aspects of complexities in different infrastructure sectors would help in overseeing issues and better management of infrastructure projects. It is observed that aspects of complexities may include cost and schedule overruns, however, the actual issues and their impacts differ from sector to sector, which strongly recommends sectoral analysis of complexities for a better understanding. In this study, the occurrence of complexity has been considered in the aspects of different sectors and is shown in Figure 2.4.

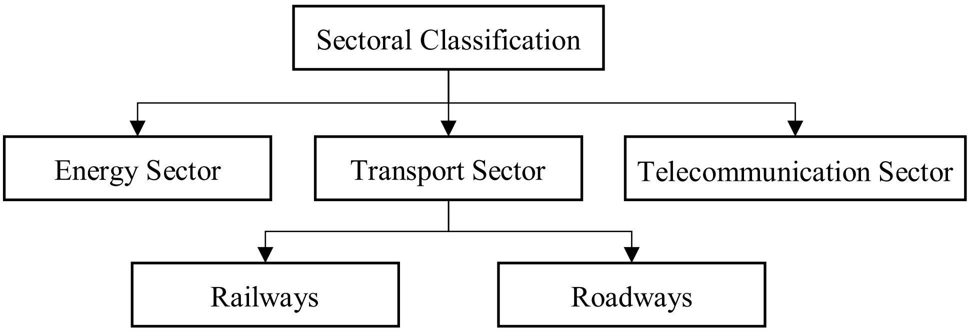


Figure 2.4 Classification of different sectors (source: authors' own work)

The types of project complexity in the phases of a project addressed in literature are presented in Table 2.4.

Where in Table 2.4, ***T****- Technological Complexity;* ***O****- Organizational Complexity;* ***C****- Contractual Complexity;* ***E****- Environmental Complexity;* ***L****-location Complexity.*
Context: MP*- Mega Projects;* ***CP****- Conventional Projects;* ***RP****- Rail Projects;* ***TP****- Transportation Projects.*

Table 2.4 Types of project complexity in the phases of a project

Phases of Project		Development					Planning /Designing					Construction /Execution					Operation					Context MP/CP/RP/ TP
		Types of Project Complexity																				
S. No	Author and Year	T	O	C	E	L	T	O	C	E	L	T	O	C	E	L	T	O	C	E	L	
1	Baccarini (1996)	✓	✓				✓	✓				✓	✓									**MP**
2	Williams (1999)			✓					✓					✓								**MP**
3	Flyvbjerg, Bruzelius, et al. (2003)						✓	✓		✓	✓				✓	✓						**MP**
4	Tah & Carr (2001)	✓			✓	✓																**CP**
5	Ghosh & Jintanapakanont (2004)			✓		✓			✓					✓				✓		✓		**RP**
6	Williams (2005)		✓	✓				✓	✓				✓									**MP**
7	Acharya et al. (2006)						✓				✓				✓		✓	✓				**CP**
8	Abdel Aziz (2007)			✓					✓													**CP**
9	Geraldi & Adlbrecht (2007)	✓	✓			✓	✓		✓	✓		✓	✓			✓	✓					**MP**
10	Müller & Turner (2007)	✓																				**MP**
11	Zou et al. (2007)		✓	✓																		**MP**
12	Zayed et al. (2008)	✓			✓	✓		✓					✓									**TP**
13	Vidal & Marle (2008)	✓			✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	**MP**
14	Gerhard & Christian (2008)		✓			✓																**MP**
15	Brockmann (2009)		✓	✓	✓														✓	✓		**MP**
16	Aritua et al. (2009)				✓	✓																**CP**
17	Raghuram et al. (2009)					✓																**MP**
18	Wood & Ashton (2010)		✓	✓		✓	✓			✓	✓		✓			✓	✓	✓			✓	**MP**
19	Hertogh & Westerveld (2010)						✓	✓				✓	✓									**CP**
20	Bosch-Rekveldt et al. (2011)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓						**MP**
21	Merrow (2011)							✓					✓									**MP**
22	Geraldi et al. (2011)			✓					✓					✓								**MP**
23	Yong & Mustaffa (2011)	✓	✓																			**CP**
24	Chen et al. (2018)											✓	✓		✓		✓	✓		✓		**CP**
25	Xia & Chan (2012)			✓	✓	✓			✓	✓	✓				✓	✓				✓	✓	**MP**
26	Hammer et al. (2012)				✓	✓				✓	✓				✓	✓	✓			✓	✓	**MP**
27	Johnsen & Veen (2013)																	✓				**RP**
28	Ribeiro et al. (2013)	✓						✓										✓				**CP**
29	Kardes et al. (2013)									✓					✓							**MP**
30	Kuo & Lu (2013)												✓		✓							**CP**
31	Babatunde et al. (2014)	✓	✓		✓	✓				✓				✓								**TP**
32	Nguyen et al. (2015)						✓	✓		✓	✓						✓			✓	✓	**TP**
33	Yunbo et al. (2015)			✓																		**CP**
34	Botchkarev & Finnigan (2015)									✓												**CP**
35	Brockmann et al. (2016)	✓						✓														**MP**
36	Chapman (2016)							✓														**RP**
37	Al-Saadi & Abdou (2016)							✓														**CP**
38	Luo et al. (2017)	✓					✓	✓				✓	✓				✓	✓				**MP**
39	Hu et al. (2015)						✓	✓	✓	✓	✓							✓				**MP**
40	Singh & Sarkar (2018)											✓	✓				✓	✓		✓	✓	**RP**
41	Sinesilassie et al. (2018)						✓			✓			✓		✓							**CP**
42	Zhang et al. (2021)		✓	✓			✓			✓	✓											**CP**
43	Ghosh & Bakshi (2020)							✓			✓		✓		✓		✓	✓				**CP**
44	Jia et al. (2022a)	✓		✓				✓				✓		✓								**MP**
45	Ashkanani & Franzoi (2023)			✓		✓								✓		✓			✓			**CP**
46	Jia et al. (2022b)				✓	✓	✓		✓						✓	✓				✓	✓	**TP**

47	Liu et al. (2024)		✓			✓				✓	✓									✓	✓	**RP**

2.8.1 Energy sector

Energy is the most invested sector all over the world. Of the overall energy sources like hydroelectricity, nuclear reactors, wind energy, and thermal, hydropower shares the maximum demand. It is predicted that by the end of 2030, cumulative investment in the energy sector will reach $17 trillion, with a significant portion targeting developing countries (Birol, 2006). Energy megaprojects often involve collaboration with multinational and transnational organizations. Hence, the megaprojects in energy sectors encounter environmental complexity, technical complexity, and financial, social, economic, political, organizational, and legal complexities (McCully, 2001; Scudder, 2005; Stone, 2011). Technical complexity and environmental complexity have a challenging role in the case of the energy sector because the techniques used, or the methodologies considered are quite challenging, and a higher number of risks are experienced while managing high-energy projects.

Along with the economy of nations, global climate changes in the environment have created a problem in energy usage which has led to problem for the generation and supply of energy in the sectors making the projects more complex. Rad et al. (2017) have identified issues in the energy sector such as cost and time overruns, capital costs, and technical, and organization processes in a project, etc.

2.8.2 Transportation sector

The transportation sector involves roadways, railways, metro rail, tunnels and bridges, airports, and ports. The megaprojects in this sector are increasingly complex. Factors such as cost, design, context, and financial factors are considered to be the key distributors for the occurrence of complexity in the transportation sector (Owens et al., 2012). Initially, technology, schedule, and cost have been considered as aspects of complexity, but later financing and context were also added to develop a five-dimensional project management framework to define complexities in transportation sectors (Gransberg et al., 2013). According to Nguyen et al. (2015), thirty-six complexity factors have been identified in the transportation sector to cause six main project complexities namely, environmental, socio-political, organizational, technological, infrastructural, and scope complexity. Among them the socio-political and organizational complexities have been considered the most defining components of the megaprojects in the transportation sector. Issues like land acquisition (Austin et al., 2002) utility relocation (Vilventhan & Kalidindi, 2016), stakeholder issues (Al Nahyan et al., 2012;

Erkul et al., 2016; Nazanin et al., 2018) were identified as predominant factors causing environmental complexities.

2.8.3 Roadways

Project type is also an essential factor for the complexities of megaprojects. Hence studies have been conducted specifically on roadways as part of the transportation sector. Quality issues and lack of funds were considered as main problems in developing countries like India and PPP (Public-Private-Partnership) was suggested as a better strategy to overcome both the problems (Sharma & Vohra, 2009). Thus, choosing the contract type becomes an essential task in high-investment projects like highways where many stakeholders are involved. Complexities and uncertainties of scope and processes, value for many, scheduling and others play a significant role in choosing the contract type, thereby developing contractual complexities in projects (Antoniou et al., 2013).

Management of stakeholders is considered a significant issue in highway projects, and, it is suggested that operation and maintenance phases contractors are also needed to be present during the pre-construction phase so that a better idea of the project can be obtained before the start of work (Nazanin et al., 2018). Political support and experience play a major role in projects' success when PPP is considered in highway projects (Ahmadabadi & Heravi, 2019). Utility relocation was also considered a major issue causing complexities in highway projects (Vilventhan & Kalidindi, 2016).

2.8.4 Railways

Rail projects are more prone to cost escalation when compared to roadways. In developing countries, rail projects have more cost escalation compared to developed countries like North America and Europe (Flyvbjerg, Bruzelius, et al., 2003; Huo et al., 2018). A study on Hong Kong transportation projects identifies project type, size, and duration as factors that affect project cost overruns and reports that rail projects are prone to more cost escalation compared to other types of megaprojects (Huo et al., 2018). Another important aspect of complexity in rail projects is difference of opinion in stakeholder perspectives. Different stakeholders have different roles and forming a common conclusion over two or more choices becomes a difficult decision (Cedergren, 2012).

In a study on metro projects in China, 48 safety factors were identified as causing project complexities, over which the approach of participants involved in safety, site safety measures, government supervision, and task unpredictability were considered predominant factors of project complexities, knowledge sharing, service delivery, and organizational issues are considered as major drawbacks of the project for successful delivery The rail projects mostly experience technical and organizational complexities with their expectations and performance (Chapman, 2016).

2.8.5 Telecommunication sector

Telecommunication sector is gaining importance in many countries as communication infrastructure is seen to be critical for economic and social development (Nandi & Banani, 2000). Telecommunication industry is quite different from the other kinds of industries, which are characterized by product life cycles, the demand for deliveries, vendors, and operators. This sector is a business process for cloud computing, IT sources, and telecom sectors and partnering with third parties providing services.

Unlike the transportation sector, telecommunication does not have sustained investments in budgets, legal and regulatory issues (Touray et al., 2013), and technological limitations (Jaura & Michailova, 2014), which thereby causes complexities in the telecom sector. Insufficient facilities in the telecom industry are the root cause of the occurrence of technological and organizational issues and these areas need to be focused on the sustainability of projects mostly in developing countries like India (Raman & Chadee, 2011). Political influence, managing capabilities, financial resources, and pressure of competition were also considered as impacting factors for the successful delivery of projects (Alizadeh, 2017).

2.9 Measurement of Project Complexity

Numerous studies have demonstrated that project complexity significantly impacts project performance and success (Molenaar et al., 2000; Austin et al., 2002; Chan & Wu, 2002; Chan et al., 2004; Levitt et al., 2019). However, there are limited objective approaches available for quantifying project complexity. This is primarily because complexity and perception are intertwined (Corning, 1998). Different stakeholders, such as clients, designers, project managers, and construction managers, may perceive building complexity differently. Leung et al. (2014) argues for the need to develop an objective tool for quantitatively assessing project complexity in megaprojects. Nevertheless, due to the inherent challenges in quantifying project complexity, many researchers have focused on identifying and explaining its various dimensions. Efforts have been made to assess the complexities of projects, as it has a significant impact on project outcomes. Empirical studies in the construction field have found that project complexity influences project duration, cost, and quality (Hahn et al., 1990; Gidado & Millar, 1992; Tatikonda & Rosenthal, 2000; Chang et al., 2013; Levitt et al., 2019). It is widely accepted that project complexity should be objectively quantified to provide consistent input for effective project development and process control (Baccarini, 1996; Calinescu et al., 1998; Sinha et al., 2006; Nassar & Hegab, 2006; Yu & Leung, 2015). To identify and reduce the impacts of complexities in megaprojects, various measurement methods and frameworks have been presented in the literature. These approaches aim to provide tools and techniques for assessing and managing project complexity effectively.

2.9.1 Frameworks for analyzing the project complexity.

1. ***Complexity Index**:* Complexity index is a quantitative measure that assesses the level of complexity in a project based on specific criteria. It involves assigning weights to different complexity factors and calculating an overall complexity score. This index helps in comparing and benchmarking the complexities of different projects (Geraldi & Adlbrecht, 2007; Thomas & Mengel, 2008).
2. ***Complexity Matrix:*** The complexity matrix is a visual representation that maps complexity factors against project stages or dimensions. It provides a comprehensive view of the project's complexity profile and helps identify areas of high complexity that require special attention and mitigation strategies (Crawford et al., 2006; He et al., 2014).
3. ***Complexity Assessment Models**:* Complexity assessment models provide structured frameworks for evaluating project complexity. These models typically involve a set of criteria or dimensions that capture various aspects of complexity, such as technological complexity, organizational complexity, environmental complexity, and stakeholder complexity. By assessing the project against these criteria, managers can gain insights into the specific complexities involved and develop appropriate management approaches (Vidal et al., 2011a; Nguyen et al., 2015).
4. ***Qualitative Approaches:*** Qualitative approaches involve subjective assessments and expert judgment to understand project complexity. These methods rely on the expertise and insights of project stakeholders, including project managers, team members, and external experts, to identify and evaluate complexity factors. Techniques such as

interviews, surveys, and workshops can be employed to gather qualitative data and insights (Baccarini, 1996; Shenhar et al., 2002).

5. ***System Dynamics Modeling*****:** System dynamics modeling is a simulation-based approach that helps analyze the behavior of complex systems, including megaprojects. It involves creating a dynamic model of the project that captures the interdependencies among various factors and their impact on project outcomes. System dynamics modeling enables the exploration of different scenarios and the assessment of complex dynamics over time (Luo et al., 2016; Wang et al., 2021).

These measurement methods and frameworks provide valuable tools for project managers and researchers to assess, understand, and manage the complexities of megaprojects. By employing these approaches, project stakeholders can make informed decisions, develop appropriate strategies, and mitigate the risks associated with project complexity, ultimately increasing the likelihood of project success.

2.9.2 Types of qualitative and quantitative approaches for the analysis of project complexity

Researchers have proposed various measurement methods to analyze the impact of project complexity in megaprojects. (Qureshi & Kang, 2015) proposed using project network analysis and graph theory to measure project complexity based on the connectivity of activities and the structure of the project network. Nassar & Hegab (2006) developed a complexity measure for schedules, focusing on the connectivity of activities in project timelines. Cicmil & Marshall (2005) introduced a project complexity framework specifically for construction projects, considering factors such as complexity, social interaction, and procurement mechanisms. Hass (2009) identified project complexity features and developed a model for visualizing complexity using a spider diagram. The model aimed to capture the complexity of business tasks. Xia & Chan (2012) proposed a linear and additive method for assessing complexity in Chinese construction projects, considering six complexity variables. Vidal et al. (2011b) questioned the validity of existing complexity assessment models and suggested combining the Delphi approach and the Analytical Hierarchy Process (AHP) for assessing project complexity. Luo et al. (2016) employed six complexity variables to measure project complexity: information, tasks, technology, organization, environmental, and goal-oriented complexity. San Cristobal et al. (2018) focused on engineering complexity characteristics in naval shipbuilding projects and established a conceptual framework for their detection and support. Ward & Chapman (2003) identified a number of influencing elements and their interdependence as components of project complexity, emphasizing the importance of understanding and managing these factors. Samimpey & Saghatforoush (2024) discussed constructability requirements and their impact on project complexity, highlighting issues such as poor implementation plans, design decision-making, and lack of experience in the design team. Chadee et al. (2022) analyzed factors contributing to delays and cost overruns in construction projects, proposing a technique to estimate and measure optimism bias in project planning.

These studies provide insights into the diverse approaches and perspectives on assessing and measuring project complexity. By considering different dimensions and factors of complexity, researchers and practitioners can develop more effective strategies for managing complexity and improving project outcomes. Vidal et al. (2011b) developed a method for evaluating project complexity characteristics based on interconnection, diversity, context, and size. The Analytic Hierarchy Process (AHP) is employed to weigh the importance of complexity variables for potential solutions. However, this approach is not suitable for assessing the complexity of individual projects, and there is no assessment of pairwise comparison consistency. Owens et al. (2012) proposed a five-dimensional model to assess project complexity in transportation projects, focusing on cost, duration, and design aspects. However, the model primarily emphasizes the project's delivery dimension, and there are no defined weights for the dimensions, leading to unpredictability in evaluation. Xia & Chan (2012) suggested a project complexity evaluation technique for construction projects utilizing six complexity factors, such as environmental conditions, project scope and size, construction structure, and geological conditions. Factor weights are calculated using a Likert scale based on the ranking index. However, this method is more suitable for assessing the complexity of simpler projects. The study "Measuring the Complexity of Mega Construction Projects in China: A Fuzzy Analytic Network Process Analysis" introduced a project complexity assessment model consisting of 28 complexity factors categorized into six major categories: organizational, technical, economic, social, environmental, and cultural. The fuzzy analytic network process (FANP) and two rounds of the Delphi method were used to establish criteria such as environmental, technological, informational, objective, and cultural. The approach was demonstrated through a case study of a large construction project. These studies contribute to the development of frameworks and methodologies for assessing project complexity, considering various dimensions and factors and are represented in Table 2.5. However, it's important to note that each approach has its limitations and applicability depending on the project context and scope.

Table 2.5 Representation of qualitative and quantitative analysis from the literature

Model/Framework/Methodology	Author and Year
Safety Performance of Management Systems (SPMS)	Peñaloza et al. (2020)
Social Network Analysis (SNA)	Lee et al. (2018)
Project Execution Complexity Index (PECI)	Mirza & Ehsan (2017)
Fuzzy Analytical Hierarchy Process (FAHP)	Işik & Aladağ (2017)
Expected Value Method (EVM)	Gerrits & Verweij (2016)
Analytical Hierarchy Process (AHP)	He et al. (2014)
Qualitative Comparative Analysis (QCA)	Gerrits & Verweij (2016)
Project Sim Software (PSS)	Yunbo et al. (2015)
Project Complexity Assessment and Management (PCAM)	Kermanshachi et al. (2020)
Project Complexity Assessment (PCA)	Al Nahyan et al. (2012)
Delphi Analysis Method	Grisham (2009)
Analytic Network Process (ANP)	He et al. (2014)
Fuzzy Analytic Network Process (FANP)	He et al. (2014)
Visual Design Team (VDT)	Jin & Levitt (1996)

Analytical Hierarchy Process (AHP): AHP is a multi-criteria decision-making method that helps in selecting the most suitable alternative among a set of options. In the context of project complexity, AHP has been used to measure the complexity index of different project alternatives based on individual complexity levels. This method aids in decision-making by considering the various aspects of project complexity (He et al., 2014). Fuzzy Analytical Hierarchy Process (FAHP): FAHP is an extension of AHP that incorporates fuzzy logic to handle uncertainty and imprecision in decision-making. It is used to evaluate measures and indicators related to project performance and cost. In the assessment of project complexity, FAHP has been applied to weigh complexity parameters and components, enabling the identification of the most significant factors contributing to project complexity in transportation projects (Nguyen et al., 2015). Fuzzy Analytic Network Process (FANP): FANP combines fuzzy logic with Analytic Network Process (ANP) to address complex decision-making problems. FANP has been utilized to develop complexity measurement models that quantify the level of project complexities. This approach enhances the decision-making process in the construction of megaprojects by considering the interdependencies and interactions among different complexity factors (He et al., 2014). These methods provide systematic approaches to evaluate and measure project complexity, considering multiple criteria and factors. By incorporating techniques such as AHP, FAHP, and FANP, researchers and practitioners can better understand and manage the complexities associated with projects, leading to improved decision-making and project outcomes.

Social Network Analysis (SNA) is used to analyze and manage networks, including the uncertainty and dynamic changes present in complex projects (Lee et al., 2018). It helps in understanding social and non-social structures, improving efficiency, and enhancing interactions in complex projects. SNA can be applied alongside methods like the Critical Path Method (CPM) to identify critical activities and facilitate strategic planning (Lee et al., 2018). Delphi Analysis is a research method that involves a series of discussions and questionnaires among a group of experts. It is used to identify complex issues in mega projects and achieve consistent results. Delphi Analysis is particularly useful in projects where quantitative analysis plays a significant role (Grisham, 2009). The Analytic Network Process (ANP) is a decision-making research metho d that addresses interdependencies and uncertainties among complex projects. It defines the interrelationships among complexity factors and provides a realistic representation of decision-making processes and network structures in projects (He et al., 2014). Qualitative Comparative Analysis (QCA) is a statistical method that is used to analyze complex projects and gain knowledge of specific cases. It helps researchers understand and explain project complexity, providing insights for project improvement. QCA is considered a valuable evaluation method for analyzing complexity in megaprojects (Gerrits & Verweij, 2016). Project Sim Software (PSS) is an organizational simulation model which is used to visualize the structure and work processes within an organization. It has been employed to measure complexities in megaprojects by mapping task and organization measures. PSS aids in understanding the hidden workload and its impact on project factors such as schedule, quality, and cost (Yunbo et al., 2015).

Visual Design Team (VDT) is a tool used to assess the hidden workload in megaprojects, which can have an impact on various project aspects. It focuses on task and organizational perspectives, providing insights into project complexity and its implications for project performance (Jin & Levitt, 1996). Project Complexity Assessment (PCA) is a tool used for quantitatively measuring complexity levels in megaprojects, particularly in the energy sector. It integrates methods such as AHP and Delphi to quantify complexity indicators and develop numerical ratings for identifying complexity levels (Al Nahyan et al., 2012). Project Execution Complexity Index (PECI) is a tool used to assess the impact of project complexity on project performance. It quantifies various project complexities and compares them with project schedule and cost performance indices to evaluate the influence of complexity on project outcomes (Mirza & Ehsan, 2017). Expected Value Method (EVM) is a method used to evaluate the impact of risk factors in megaprojects. It helps in recognizing, assembling, computing, and evaluating project risks, with a focus on determining the impact factors and likelihood of risks in each project activity (Gerrits & Verweij, 2016). Project Complexity Assessment and Management (PCAM) is a tool used to identify and verify complexity indicators in a project and guide the selection of resources required for project completion. It enables the identification and differentiation of complexity levels at different stages of the project, facilitating effective management (Kermanshachi et al., 2020). Safety Performance of Management Systems (SPMS) is a method used to investigate and monitor complexity and resilience levels in construction projects, particularly in terms of safety performance. It helps in managing complexity-related challenges and ensuring project safety (Peñaloza et al., 2020).

The key aspects of the above-mentioned measurement methods are summarized. Indeed, the measurement of complexity plays a crucial role in enabling effective decision-making and addressing uncertainties in projects. The tools and methods mentioned are utilized to analyze and manage various complexities and risks associated with technical, organizational, environmental, and goal-related factors. They provide insights into project uncertainties, cost, and time overruns, and help overcome these challenges. Methods such as FANP, FAHP, project sim software, ANP, and EVM are commonly used to analyze and assess risks caused by different dimensions of complexity. These methods aid in evaluating the impact of complexity on project outcomes and guide decision-making processes. On the other hand, methods like Markov analysis, PSO (Particle Swarm Optimization), and multi-regression analysis are employed to analyze and address project uncertainties, specifically focusing on mitigating cost and time overruns.

QCA serves as a comparative analysis method, particularly in the transportation sector, to understand complexities related to tasks and organizational structures. PCA, PCAM, SPMS, and Delphi methods are utilized to determine and assess complexity levels arising from technical, organizational, social, and environmental factors in projects. These methods help in quantifying and managing complexities to ensure project success. Overall, these measurement methods and tools provide valuable insights into project complexities and uncertainties, enabling project managers and stakeholders to make informed decisions and effectively manage projects.

2.10 Impact of Project Complexity

Since the late 1990s, extensive research has been conducted to understand the concept of project complexity. Despite ongoing efforts to define complexity, there remains a lack of consensus on its specific characteristics due to the challenges associated with identification and quantification. Consequently, the notion of complexity continues to be uncertain in the field. Project complexity is primarily defined by the interdependence and differentiation of various project elements, as proposed by Baccarini (1996). Differentiation refers to the division of responsibilities, expert components, and elements within a project, while interdependency captures the extent of interdependence among these elements. Williams (1999) characterized project complexity as structural complexity, which encompasses both the quantity and interdependence of project components, as well as the uncertainty surrounding goals and methods. Additionally, researchers have recognized project complexity dynamism as the tendency for complex project components to interact with each other in unpredictable ways, further contributing to the complex nature of complexity (Baccarini, 1996).

The development of mega-construction projects has experienced rapid growth worldwide, encompassing sectors such as transportation, energy, telecommunications, and urban development (Lam, 1999; Rad et al., 2017). The substantial investments and scale of these mega-construction projects have gathered significant public attention and interest. Research on transportation projects has revealed occurrences of cost and budget failures, with nine out of ten projects experiencing cost and schedule overruns, particularly in metro projects which exhibit a higher rate compared to road, water, and airway projects (Flyvbjerg, Holm, et al., 2003; Ansar et al., 2014). Consequently, the growing demand for effective megaproject management has necessitated the development of new management strategies that can effectively address the unique characteristics and challenges posed by mega projects (Gransberg et al., 2013). To achieve better management outcomes, a comprehensive understanding of the complexities involved in these projects is crucial. Identifying the key complexity factors becomes essential for improving project management practices (Park et al., 2017; Mevada &

Devkar, 2018; Yu Maemura et al., 2018). A thorough evaluation of the various factors of project complexity is necessary for enhancing the effectiveness of managing mega construction projects like metro rail projects.

Authors (Williams, 1999; Puddicombe, 2011; Senescu et al., 2013; Liu et al., 2024) have thoroughly investigated the complex relationship between project complexity and project performance. The research studies represent the significant influence of project complexity on outcomes, manifesting in cost overruns, schedule delays, and increased uncertainty (Floricel & Miller, 2001; Shenhar et al., 2002; Qazi et al., 2016; Mirza & Ehsan, 2017). Project complexity is commonly identified as a primary cause of risk and uncertainty in projects, resulting in increased costs throughout the entire project life cycle (Williams, 1999; Floricel et al., 2016). The empirical evidence consistently shows an inverse correlation between complexity and project performance, with more complex projects facing significant challenges in achieving project goals (Antoniadis et al., 2011). Floricel et al. (2016) studied the impact of complexity specifically in the context of construction projects, and Senescu et al. (2013) highlighted the positive association between complexity and interface issues in the Architecture, Engineering, and Construction (AEC) industries. Technical complexity, as explained by Floricel et al. (2016) emerges as a key factor impacting project performance, particularly in construction projects. Puddicombe (2012) contributes to this study by explaining a collective and negative relationship between complexity characteristics and project performance across various sectors, encompassing energy, transportation, and water infrastructure. Understanding and accurately managing project complexity emerge as critical prerequisites for ensuring successful outcomes (Floricel et al., 2016).

Researchers, Luo et al. (2016) have employed diverse methodologies, including web-based questionnaires and simulation techniques, to examine deeper into the complex dynamics between project complexity and performance. The utilization of simulation, coupled with opinion-based data like surveys and interviews, shows the necessity for such approaches due to the lack of empirical project data. Lebcir (2011), employing system dynamics modeling, and Kennedy et al. (2011) utilizing Monte Carlo simulations, show how factors such as project uncertainty, new technology, interdependence, and project size influence project cycle time and team communication and performance in megaprojects.

Moreover, empirical evidence from the literature illustrates the significant impact of these challenges on project performance, resulting in substantial cost overruns, delays, and failure to achieve project objectives (Williams, 1999; Williams, 2005; Flyvbjerg, Bruzelius, et al., 2003; Lessard et al., 2014). While a considerable proportion of large and complex projects are completed within scope, financial, and schedule constraints, many megaprojects, particularly those involving novel technical applications, experience shortcomings in one or more dimensions of success (Hartman & Ashrafi, 2002). It is generally acknowledged among scholars that megaprojects tend to fall short in this regard. Consequently, gaining a comprehensive understanding of the dynamic, challenging, and complex nature of megaprojects becomes crucial. Given that complexity is a fundamental characteristic of megaprojects, and the vague nature of complexity influences how these projects are perceived and managed, hence a deeper examination of complexity in the study of megaprojects like metro rail projects is necessary. Scholars (Capka, 2004; Van Marrewijk & Smits, 2016; Pitsis et al., 2018) define that megaprojects are inherently complex projects. Megaprojects exhibit increased complexity due to a multitude of uncertainties and their interdependence, along with various underlying aspects such as people, components, tasks, and budget (Mihm, Loch, & Huchzermeier, 2003). Van Marrewijk et al. (2008) identify several key factors that contribute to the complexity of megaprojects, including size, duration, escalating costs, the number of participants, the range of technological aspects involved, stakeholder interests, multinational collaboration, sponsor interests, high levels of political or public interest, uncertainty, and country risk. The scope of megaprojects contributes to their complexity. Given their lengthy durations, changes in the legal system, political landscape, and economic conditions can occur throughout the project lifecycle (Kolltveit & Grønhaug, 2004).

The complex nature of cause-effect relationships and the evaluation of project effectiveness is challenging due to various factors that can influence specific actions in megaprojects (Flyvbjerg, 2017). In summary, the complexity of megaprojects is increased by the presence of numerous uncertainties and their interactions, as well as various factors such as project size, duration, costs, participants, technological specialization, stakeholder interests, multinational aspects, political/public interest, uncertainty, and country-specific risks. The vast scale and long timeframes of megaprojects also contribute to their complexity, making it challenging to assess cause-effect relationships and project performance. The complexity of megaprojects arises from the presence of numerous distinct and interdependent activities. Moreover, the use of innovative technology and non-standard designs in megaprojects makes it challenging to learn from past mistakes (Prencipe & Tell, 2001). The occurrence of multiple distinct and interdependent activities contributes to complexity, while the use of innovative technology and unconventional designs delays the ability to draw lessons from previous experiences (Prencipe & Tell, 2001). With technology constantly evolving, it is difficult to accurately predict its behavior and performance.

The impact of megaprojects like metro rail projects extends beyond financial aspects and affects the economy, scientific advancements, culture, and the community at large (Pitsis et al., 2018). Scholars have emphasized the association between cost and complexity in mega projects, which often involve multimillion or billion-dollar budgets (Flyvbjerg, Bruzelius, et al., 2003; Hu et al., 2015). The inherent uncertainty in managing these projects significantly contributes to their complexity and can lead to project failures, as these projects encounter unexpected cost overruns and scheduling issues due to their size and scope (Eriksson et al., 2017). The contractual structure of these projects is often related to multiple claims and local challenges. The literature reveals various characteristics of complexity that are present in megaprojects. Key factors such as size, budget, duration, impact, uniqueness, and complexity contribute to the overall understanding of megaproject complexity. Size is often emphasized as megaprojects that are characterized by their immense scale and magnitude (Flyvbjerg, Bruzelius, et al., 2003; Zidane et al., 2013). While megaprojects are frequently high-cost projects, typically exceeding one billion dollars (Erol et al., 2018), the definition of "one billion or more U.S. dollars" in terms of cost can vary between emerging and industrialized nations. Additionally, megaprojects are associated with lengthy construction periods, requiring significant human, technological, and financial resources over extended periods (Capka, 2004).

Uniqueness and originality are also highlighted in the literature regarding metro rail projects. Some studies focus on the technological aspects (Addae-Boateng et al., 2015), while others consider operational, temporal, financial, quality, and human resource variables to explain the distinctiveness of megaprojects (Zidane et al., 2013). The large-scale, expensive, and long-term nature of these can have significant direct and indirect effects on the state, the environment, and various stakeholders (Zidane et al., 2013). These characteristics demonstrate the complex nature of megaprojects, which face numerous challenges, including decision-making in the presence of risk and uncertainty (Atkinson-Palombo, 2010) and potential conflicts of interest among stakeholders from the public and private sectors (Clegg et al., 2006; Alderman & Melanie, 2012). In summary, the existing literature robustly establishes a bridge between project complexity and performance, particularly in the construction of metro rail projects, emphasizing the critical need for comprehensive understanding and effective management of complexity for successful project outcomes.

2.11 Literature Findings

The definitions of project complexity were identified from the literature review, but there was no commonly accepted definition of project complexity. The authors have different perspectives on defining complexity. It was also observed that project complexity was not studied in the metro rail projects. Although studies represented the occurrence of project complexity in megaprojects, there were only limited studies on the identification and analysis of project complexity in metro rail projects. Therefore, this research identified and analyzed the impact of project complexity in metro rail projects using a literature survey, focus groups, multiple case studies, and questionnaire surveys. Project complexity is defined as the degree of differentiation of project factors, their interdependence among project factors, and their impact on project decisions. A detailed study of the impacts of project complexity and its factors may help practitioners understand, analyze, and manage the project complexity. In addition, the literature shows that project complexity is measured by measuring complexity facts. Therefore, an approach for identifying PCFs and measuring PCFs would help stakeholders and practitioners thoroughly understand the complexity of a project and its impact on the project.

Chapter 3

Research Methodology

3.1 Overview

The chapter focuses on addressing the gaps in understanding project complexity specifically in the context of metro rail projects within the transportation sector of megaproject construction. To gather comprehensive insights, a mixed research methodology that combines qualitative and quantitative approaches was employed for data collection and analysis.

3.2 Background

The literature on megaprojects has extensively examined the characteristics, features, and analysis methods which are used to identify and understand project complexity. With the increasing number of construction projects, the concern surrounding project complexity has also grown. The literature reveals a focus on the characteristics, features, and analysis of project complexity in megaprojects. However, there is a lack of literature on the definition of project complexity, specific factors that contribute to project complexity, and their corresponding analysis methods. Additionally, there is a lack of studies on the project complexity of metro rail projects and their associated measurement methods. Based on the literature, there is a consensus among authors that project complexity should be studied, evaluated, and approached with more practice-oriented strategies. This literature gap led to the necessity for a specific measurement model to measure and assess project complexity, which is currently lacking in the construction sector of metro rail projects.

The research methodology for this study was shaped by the questions and gaps identified in existing literature, particularly in the context of metro rail projects. The study aimed to thoroughly investigate the complexity of these projects and evaluate the current methods used for assessing them. Metro rail projects pose unique challenges within the transportation sector, and understanding their complexity is crucial. However, the existing literature does not adequately address this aspect, leaving a noticeable gap in research. To fill this gap, the study focused on understanding the characteristics and factors that contribute to project complexity in metro rail projects, their impact on project outcomes, and the stages at which complexity becomes most evident. The research methodology was strategically designed to define and measure project complexity, identify the factors causing it, explain their effects on project success, and determine when and how project complexity can be recognized.

This chapter outlines the methodological framework used in the study, which integrates both qualitative and quantitative approaches to gather and analyze significant data. The research began with a thorough literature review to establish the study's rationale and identify key challenges and complexity factors in metro rail projects. Data collection involved semi-structured interviews and a questionnaire survey to understand contemporary perspectives on project complexity and identify the key contributing factors. Additionally, comprehensive case studies were conducted to explore these factors in detail and evaluate their significance. The study employed a modeling approach to develop practical methods for evaluating project complexity. These models were applied to case studies for validation and recommendations, with sensitivity analysis performed to check the reliability of the findings. This chapter details the various methods used and the approach to data collection in this research. The overall methodology of the research work is presented in Figure 3.1.

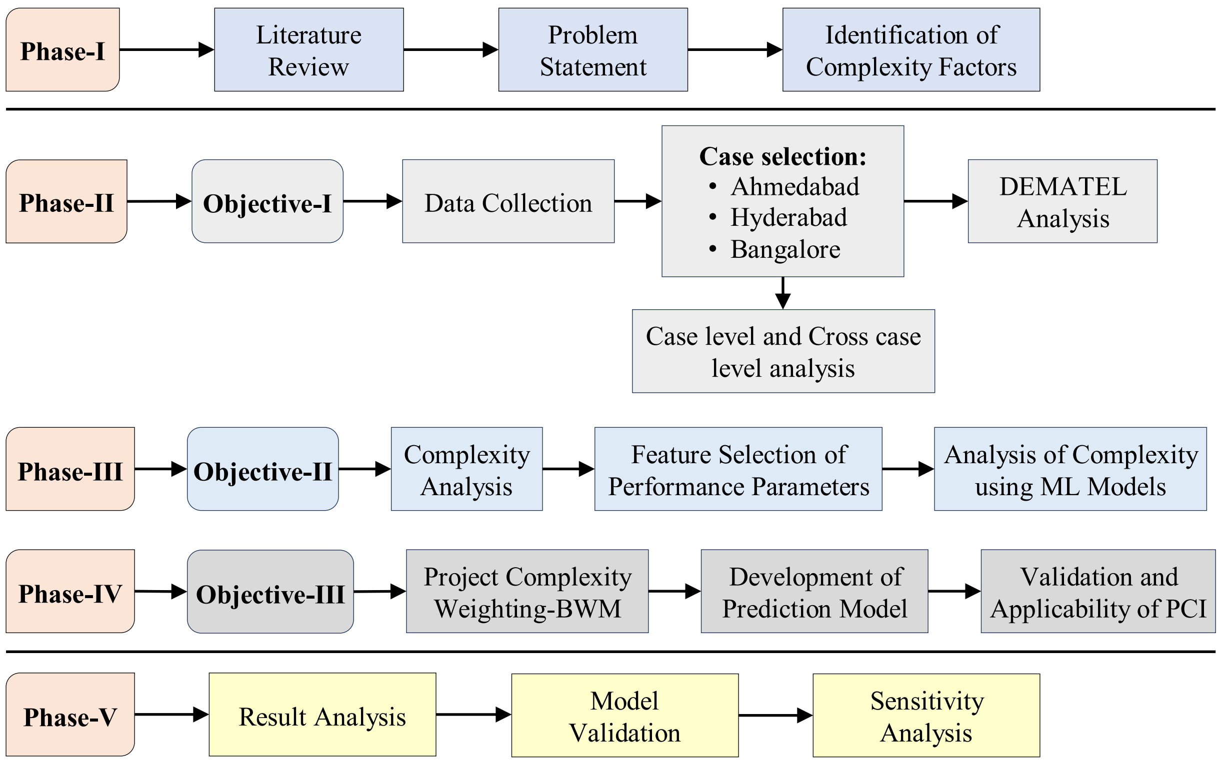


Figure 3.1 Overall research methodology of the research (source: authors' own work)

A mixed-method approach was used, combining both qualitative and quantitative techniques for gathering and analyzing data. This approach, based on ideas from Robson & McCartan (2011) and Bryman Alan (2012) helps researchers understand complex topics. Different methods are used confirm the findings, with qualitative methods providing deeper context and helping to generate ideas, while quantitative methods, like surveys, helped us gather and analyze numerical data effectively. By combining structured approaches with more flexible ones, the study was able to explore both the big-picture and detailed aspects of the research, balancing the views of both the researcher and the participants. This combination also made it possible to generalize some findings and better explain the relationships between different factors. Overall, the use of mixed methods helps to get a fuller understanding of the research topic by using the right approach at each stage of the study. In summary, gaps identified in the literature include the lack of determination of project complexity and interrelation among complexity factors, limited studies on the impact of project complexity on performance parameters in metro rail projects, and the absence of a comprehensive and specific complexity measurement method for the project type. Addressing these gaps through further research would contribute to a better understanding and management of project complexity in metro rail projects. The objective of the research study is to address the gaps in the literature on project complexity in metro rail projects and to develop a comprehensive model for measuring project complexity.

3.3 Objectives of the Research

1. To identify factors influencing project complexity and their interrelationships.
2. To study and analyze the impact of project complexity on project performance parameters.
3. To develop a model for measuring project complexity.

Project parameters considered in the present study

- Time
- Cost
- Quality
- Scope
- Sustainability
- Reliability

The scope of the study focuses on investigating and quantifying the complexity of metro rail projects within the Indian context. Despite its specific application to India, the underlying concepts and methodology are universally applicable and extendable to other sectors or countries. The study is limited to the identification and analysis of project complexity within the domain of metro rail projects, which are considered megaprojects in the transportation sector. The study was limited to metro rail projects because of its construction procedures, budget, and schedules.

3.4 Research Methodology

A framework was developed to identify and assess the PCFs and represented below:

3.4.1 Phase 1: Literature review and identification of PCF's

The first phase of the research is to comprehensively review the current literature on project complexity to build a robust understanding of the concept of project complexity. This step also involves gathering background information and experiences related to the metro rail project. This phase also outlines the approach to identify project complexity and factors that impact the performance and progress of metro rail projects. Focus groups and semi-structured interviews were conducted to finalize the project's complexity and its factors.

The process of identifying PCFs in the study of metro rail projects involved a systematic approach. Initially, various complexity factors were identified from the existing literature. Later, to validate and refine these factors, semi-structured interviews were conducted with experienced professionals. This research employs a purposive sampling technique for participant selection and identification of PCFs within metro rail projects. The purposive sampling technique was employed in this study to ensure that the participants selected for the semi-structured interviews had the necessary expertise and experience in metro rail projects. The selection criteria were based on the professionals' in-depth knowledge, ranging from 5 to 20 years of experience, in roles such as project management, engineering, and planning. This approach ensured that participants brought diverse perspectives and specialized insights into the complexity factors affecting metro rail projects. By prioritizing participant expertise, the study gathered robust and relevant data, enhancing the validity and reliability of the identified PCFs. This empirical approach ensures the robustness of the collected data for understanding and identifying the PCFs in metro rail projects.

To validate and finalize PCFs from the literature, an interview protocol was prepared. This protocol contains project details, contract types, technology used, design methods, organizational and environmental factors, existing complexities, stakeholder concerns, and complexity factors in metro rail projects. Semi-structured interviews with open-ended questions were conducted with 30 professionals each having 5-20 years of experience in metro rail projects. Interviews were conducted with two project managers (>30 years of experience), eight project engineers (>10 years of experience), seven planning engineers (>7 years of experience), and eleven assistant executive engineers. Moreover, the interview questions for the participants were thoughtfully designed, incorporating descriptive queries, project-specific characteristics, and understandings from existing literature. They were interviewed for 60 to 120 minutes, with recordings for further analysis. As interviews progressed, it became evident that no new complexity factors were identified, signifying data saturation. This ensured that the factors identified were finalized, eliminating the need for further interviews. A total of 17 major complexity factors were finalized from the interviews and are shown in Figure 3.2. These factors were systematically categorized into distinct groups, namely, technological, environmental, organizational, locational, and contractual complexities. This categorization provided a structured framework for analyzing the interrelationships among the factors. Later, underground, and elevated metro rails projects were purposefully selected as case studies to identify the similarities and differences among PCFs. To maintain data credibility and dependability, computer-assisted qualitative analysis software, Nvivo 11, was employed.

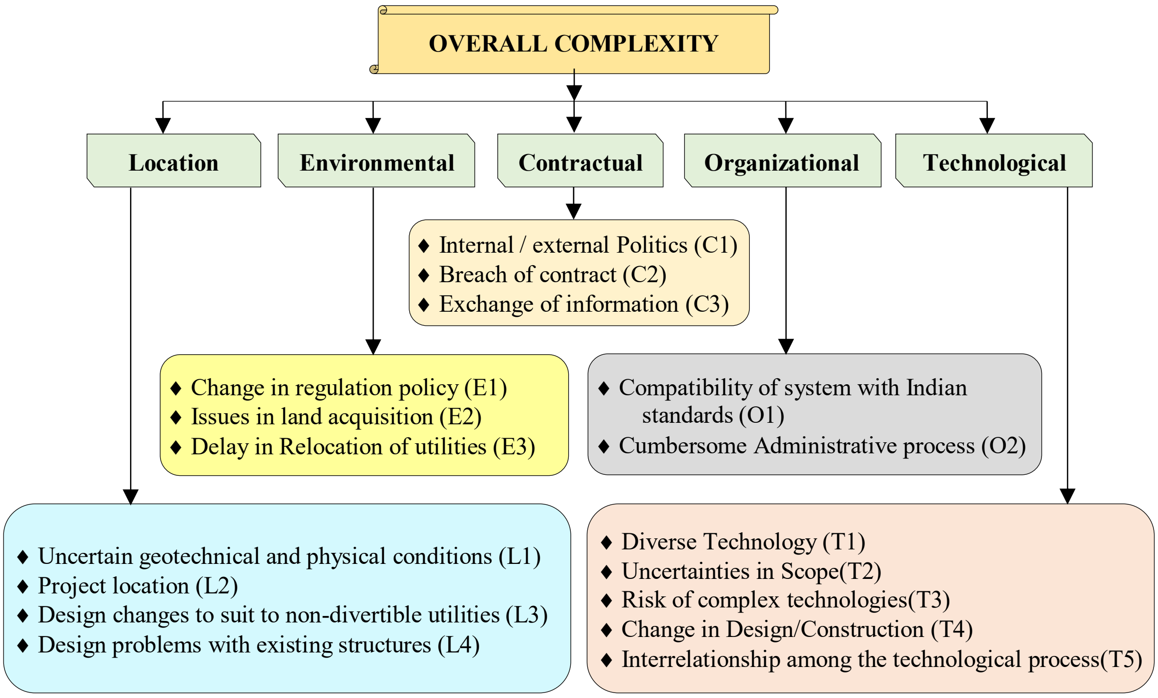


Figure 3.2 Identified project complexity factors from literature (source: authors' own work)

3.4.2 Phase-2: Analysis of project complexity factors and their relationships in metro rail projects

Questionnaires were developed based on the Likert scale and were electronically distributed to the participants who had a minimum of 5 years of experience in metro rail projects. The questionnaires are represented in the appendix. The survey requested the respondent to complete two surveys, one for the impact of project complexity on project performance parameters and the other for the impact of project complexity on the overall project. To improve the ease of responding to the survey and to maximize the number of survey responses, Likert scale was used for the questions as a basis for assessing project complexity and its factors. Following the development of the questionnaire, a pilot survey was conducted to ensure that the survey questions were suitable. Metro rail experts with over 15 years of expertise assessed the questionnaire's reliability. The survey responses were collected and checked to ensure that no incorrect questions or material remained in the survey. This pilot survey assists in identifying any questionnaire difficulties as well as prospective statistical analysis that could be managed with the data collected for survey distribution. The implementation of a questionnaire survey was the next step in the data collection process for identifying and analyzing PCFs. A large sample size was used for an electronic questionnaire survey. To collect data, the questionnaire was distributed to members of several metro rail projects. The questionnaires were distributed through emails and WhatsApp. The questionnaire was sent to metro rail experts having more than seven years of experience.

A multiple case study was used to identify the project complexity and the factors impacting metro rail projects. The case study analysis helps to study a real-time problem (Robert K. Yin, 2009) and was considered an approach for identifying in-depth information for complex construction projects (Sutrisna & Barrett, 2007). The use of multiple case studies helps in the representation of comparisons within and between cases to provide similarities and differences among the cases (Blair & Lacy, 1993; Sutrisna & Barrett, 2007). In this study, the complexity theory principle was used to understand the uncertainty and non-linearity of project complexity and the impacting factors in metro projects. Therefore, the use of the case study methodology was considered an appropriate approach for gaining in-depth knowledge of project complexity and its influencing factors in various metro rail projects. The cases studies were purposefully selected based on specific criteria to ensure they were representative of the complexities inherent in metro rail projects. Choosing these cases included their scale, the complexity of the challenges they presented, and their relevance to the research objectives.

Projects were selected from different regions to capture a diverse range of socio-political and environmental contexts, which allowed for a more comprehensive understanding of how these factors influence project complexity. Additionally, the availability of detailed data and the opportunity for site visits were important factors in the selection process, ensuring that the cases could provide robust and meaningful insights for the study.

Decision-Making Trial and Evaluation Laboratory (DEMATEL) is a method used for analyzing the interdependence of complexity factors in metro rail projects. The study applies complexity theory principles to understand the uncertainty and non-linearity in project complexity and its influencing factors within metro projects. This approach is well-suited for acquiring in-depth knowledge about these aspects in various metro rail projects. The DEMATEL method was chosen to analyze the interdependence of complexity factors in metro rail projects due to its effectiveness in handling complex and interrelated issues (Wu & Chang, 2015). This is a methodology that allows for the exploration of interdependencies and the assessment of the influence of PCFs on one another. This approach facilitates the construction of a structured model, which visually represents the complex causal relationships among the PCFs (Ahsan & Paul, 2018). This method analyses cause-and-effect relationships using matrix-based analysis and helps in problem understanding and solution identification (Wu & Chang, 2015). This method is effective for achieving statistically significant results with a limited sample size, making it suitable for situations where finding many experts in a particular field is challenging (Chang & Chen, 2018). The analysis of interdependence among PCFs was based on the insights and opinions provided by the participating technical experts. This characteristic justifies the use of this method for collecting data through a questionnaire survey with a small sample size. To collect the necessary data, an electronic questionnaire was sent to experienced professionals in metro rail projects with 5-20 years of experience. These professionals who participated in the survey are site engineers (26%), planning engineers (16%), associate engineers (14%), project managers (10%), project engineers (14%), assistant engineers (10%), and field supervisors (10%). These experts rated the impact of PCFs on a five-point Likert scale for the evaluation of the interdependence of PCFs in metro rail projects. A rating of five indicated an extremely critical impact, while a rating of one indicated a very low criticality level. This survey aimed to gather insights into the significance and interrelationship of PCFs in metro rail projects based on the perspectives of the participating experts. 173 responses were obtained, of which 150 were suitable for in-depth analysis. This quantitative approach was used for the analysis of interrelationships among the identified complexity factors in metro rail projects.

3.4.3 Phase-3: Analysis of impact of project complexity on the performance of the project

The project data was evaluated to provide a basis for development models. The DEMATEL approach, used in the study, helps in identifying the interdependence among PCFs. This dependency shows the identification of causes and effects of PCFs. Later ML models, SVM, RF, and DT algorithms were employed together to create a prediction model that identifies the impact of project complexity in metro rail projects. To predict the impact of project complexity on PPP, three prominent ML models- SVM, RF, and DT were employed together as an integrated model. Data related to project complexity and its impact on PPP were collected from different metro rail projects through a questionnaire survey. The survey consisted of two sections: the first section gathered general information about the respondents, while the second section focused on complexity factors that could affect PPP. Respondents were asked to rate the impact of complexity on performance criteria using a Likert scale from "Extremely High (5)" to "Extremely Low (1)." The questionnaire was distributed electronically to various stakeholders involved in metro rail projects, such as project managers, senior and junior engineers, contractors, and other relevant stakeholders. In total, 315 responses were collected, out of which 278 were suitable for the analysis. The collected data was preprocessed to ensure its quality and usability. Data imputation and outlier detection were performed to handle missing values and ensure accurate analysis. Feature selection was carried out to enhance the predictive power of the model. The input PCFs were scaled and encoded to make them compatible and meaningful for the model. The dataset was split into a training set (80% of the data) to build regression models and a testing set (20% of the data) to independently evaluate the model's performance. Regression models from the scikit-learn library in Python were utilized for the analysis. A multilayer regression model was created, incorporating the selected input PCFs to improve its effectiveness. To assess the performance of the model, various evaluation metrics such as accuracy score, Mean Absolute Error (MAE), Mean Squared Error (MSE), and Mean Absolute Squared Error (MASE) were used. These metrics provided insights into the accuracy and precision of the model's predictions on the testing dataset, indicating its overall performance. The reliability of the data set was also assessed using Cronbach's alpha, which measures the internal consistency of the questionnaire survey. The reliability of the data obtained was found to be 0.89, indicating that it is considered reliable for further analysis. By analyzing the data, the researchers aimed to understand how project complexity influences the performance parameters in metro rail projects.

Exploratory Data Analysis (EDA) is necessary for understanding dataset patterns and relationships. Data visualization, summary statistics, and correlation analysis, missing values, outliers, and complexity factors, preparing data for analysis. Correlation analysis measures relationships between complexity factors and performance parameters, and its coefficient ranges from -1 to 1, with values near -1 or 1 representing negative or positive correlations and values close to 0 indicating weak or negligible correlations. This analysis was employed to examine the relationship between project complexity and PPP, ensuring a robust and accurate analysis. For feature selection, correlation analysis was performed to assess the relationship between predictors and the target variable, checking for multicollinearity. It retains relevant complexity factors, enhancing model interpretability and reducing overfitting. The study used a correlation matrix test to identify and remove redundancies.

3.4.4 Phase-4: Development of project complexity model

Finally, the study employed to develop a PCI model for the metro rail projects. BWM is used as a primary technique to quantitatively analyze the project complexities in metro rail projects and prioritize them based on their impact. BWM was used to prioritize the identified PCFs. BWM is a robust MCDM technique that involves comparing the best and worst factors, ensuring an efficient prioritization process. Following this the PCI model was developed to quantify the overall complexity of metro rail projects. This approach is particularly effective for scenarios where decision makers need to evaluate and rank multiple criteria based on expert judgement. Survey respondents were asked to identify the most significant(best) and least significant(worst)complexity factors from the list of PCFs. The respondents then compared the other factors to the best and worst factors to assign a relative importance score. Using the pairwise comparison results, weights were assigned to each complexity factor, reflecting their relative importance in the overall complexity of metro rail projects. To ensure the robustness and accuracy of the model, case studies of real-world metro rail projects were used for validation. These case studies provided empirical data to compare the predicted complexity index with actual project performance. A sensitivity analysis was performed to evaluate the reliability of the PCI model under different scenarios. By varying the input data and examining the model’s responses, the study ensured that the PCI model is adaptable to a wide range of metro rail project contexts. Sensitivity analysis also provided insights into the most critical factors affecting the complexity index, further validating the model's practical relevance.

3.5 Conclusions

In conclusion, this research methodology was designed to address gaps in understanding project complexity, particularly in the context of metro rail projects in the transportation sector. The mixed research methodology, combining qualitative and quantitative approaches, was employed for comprehensive data collection and analysis. The literature review reveals a lack of specific studies on project complexity in the context of metro rail projects, necessitating the need for a measurement model, particularly in metro rail projects. The gaps identified include the absence of a comprehensive complexity measurement method, limited studies on interrelationships among complexity factors, and a lack of research on the impact of complexity on performance parameters.

The objectives of the research include identifying factors influencing project complexity, studying its impact on performance parameters, and developing a model for measuring project complexity. The parameters considered in the study are time, cost, quality, scope, sustainability, and reliability. The research approach involves a phased process, including literature review, data collection, analysis, and model development. Qualitative methods such as interviews and focus groups are used alongside quantitative methods like surveys. Triangulation, providing a holistic picture, balancing structure, and process, and linking macro and micro levels are key aspects of the mixed research methodology. The questionnaire development process includes a pilot survey to ensure reliability. The main survey was distributed electronically to metro rail experts, and data analysis involved both qualitative and quantitative methods. The developed models, including DEMATEL and ML algorithms, contribute to the creation of a PCI. In summary, this research aims to fill gaps in the literature, provide a comprehensive understanding of project complexity in metro rail projects, and develop a practical model for measuring and managing complexity. The findings aim to contribute to effective project management strategies in the transportation sector.

Chapter 4

Analysis of Project Complexity Factors and their Interdependencies in Metro Rail Projects

4.1 Overview

This chapter explains in detail the first objective i.e., to identify and analyze the interdependence of PCFs in metro rail projects using DEMATEL. The study provides both qualitative and quantitative analysis of PCFs and their relationships. The results of the study will help in facilitating more effective project planning, proactive risk management, and better-informed decision -making deliverables for stakeholders. To achieve this, the study employed a case-based approach to identify PCFs and used the DEMATEL technique to evaluate the interdependence of these factors specifically within metro rail projects. Initially, PCFs were identified through an extensive and comprehensive literature review. To validate and refine these factors, semi-structured interviews were conducted with thirty experienced professionals. These professionals each had 5 to 20 years of experience in roles such as project management, engineering, and planning. Further, elevated, and underground metro rail projects were purposefully selected as case studies, allowing the study to examine similarities and differences in PCFs between different types of metro rail projects. The case selection ensured that insights were drawn from diverse project settings, adding depth to the analysis. Additionally, a questionnaire survey was conducted with various technical experts involved in metro rail projects. These experts rated the impact of PCFs on a five-point Likert scale, allowed for a a structured evaluation of the interdependence of PCFs. The DEMATEL technique was employed to map out and analyze these interdependencies, providing a clearer understanding of the key complexity drivers in metro rail projects.

Metro rail projects are inherently influenced by numerous PCFs, which significantly impacts their performance. The analysis reveals that "design problems with existing structures," "change in design or construction," and "land acquisition issues" are among the key factors contributing to project complexity. The study of project complexity within metro rail projects is currently limited because most of the studies have features examining complexity in mega projects. The existing literature lacks adequate data in identifying project complexity and its effects on metro rail project performance. This research aims to bridge this gap by examining project complexity and interdependencies in metro rail projects.

4.2 Introduction

Megaprojects are defined as complex projects with budgets exceeding US$156 million by the Ministry of Statistics and Program Implementation (MoSPI) in India. Within the transportation sector, metro rail projects are designated as megaprojects due to their extensive infrastructure, significant investments, and profound local and international significance. Notably, India's metro rail projects exhibit this characteristic with an average cost of approximately $22.04 billion (India Brand Equity Foundation, 2019). These projects play a fundamental role in urban development by enhancing mobility, dealing with traffic congestion, and offering sustainable solutions for generating economic and social benefits (Symbroj Media, 2022). Substantially 40% of these projects are characterized by complexity, imposing considerable challenges and complexities that impact their execution and performance (Flyvbjerg, Bruzelius, et al., 2003; Ansar et al., 2014).

In metro rail projects, complexity results from complex interrelationships and non-linear project characteristics, significantly impacting project performance (Mevada & Devkar, 2018). Maylor & Turner (2016) and Kardes et al. (2013) have focused on the theoretical aspects of project complexity whereas Chapman (2016) explored the practical dimensions by studying how complexity characteristics influence project performance. Additionally, Niu et al. (2019) analyzed the complexities of task complexity. Cantarelli (2020) investigated the relationship between innovation and project complexity in megaprojects through a cross-case study approach. Mohseni et al (2019) explored complexities in megaproject management with a specific focus on environmental, technological, and organizational dimensions. Damayanti et al. (2021) focused on addressing the lack of a common definition of complexity in the context of megaprojects, especially in developing countries. While these studies have contributed valuable insights, there is a need for a comprehensive and systematic investigation of factors contributing to project complexity and their interdependence within the context of metro rail projects. From the literature, it is observed that the Indian metro rail projects face significant challenges like high capital costs, land acquisition problems, and complex construction difficulties leading to delays and budget overruns. For example, the estimated cost of the Mumbai metro line 3 amounts to approximately $3.2 billion, while Delhi's phase-III project necessitates a vast area of 1,821 hectares of land. Kolkata's East-West project, initially scheduled for completion in 2012, faced multiple delays, ultimately inflating costs from $677 million to $1.2 billion, completed in 2015. It is also evident that interface issues, political influence, and funding problems delay progress. Nagpur's metro project experienced delays primarily due to local farmers' issues. Additionally, research has shown that metro rail projects across India frequently face various common challenges. These involve land acquisition, effective management of stakeholders, technical complexities, financial support, urban congestion, and the management of project schedules and costs.

The motivation for conducting this research stems from the existing gap in understanding and addressing project complexity in metro rail projects. While some studies have investigated the theoretical aspects of this complexity, there's been a noticeable lack of attention exploring the specific factors that contribute to the complexity and their interdependencies. This knowledge gap is a significant concern considering the increasing prominence of metro rail projects in the construction industry.

The study adopts a practical approach, conducting an in-depth investigation involving three case studies. It uses DEMATEL technique to analyze complexity factors and their interdependencies. Metro rail projects are witnessing rapid expansion and growth within the Indian construction industry, making them a focal point of investigation. Despite being an emerging sector, the metro rail construction industry operates in a systematic and process-oriented manner. The utilization of the DEMATEL technique further supports metro construction project managers in devising strategies to address each complexity factor based on a hierarchical or prioritized order. This approach ensures that efforts are focused on minimizing the impact of critical complexity factors and maximizing project performance. By considering the interdependencies and relationships between complexity factors, project managers can allocate resources and implement targeted measures to mitigate challenges and optimize project outcomes. However, it is important to note that the scope of this study is limited to metro rail projects in India. While the findings and methodologies presented in this research have broader applicability, their specific implications may vary when applied to projects in different geographical locations or within different cultural contexts. Hence, further research is encouraged to explore and validate the findings in diverse project environments to enhance the generalizability of the study's outcomes.

4.3 Research Objective

Project complexity refers to the level of interdependence among uncertain events in construction projects and is a common characteristic (Flyvbjerg, Bruzelius, et al., 2003). In metro rail projects, complexity arises primarily from unpredictable interrelationships and non-linear project characteristics (Park et al., 2017; Yu Maemura et al., 2018) leading to a significant impact on project performance (Augustine et al., 2005; Thomas & Mengel, 2008).

The motivation for conducting this research stems from the existing gap in understanding and addressing project complexity in metro rail projects. While previous studies have touched upon the theoretical aspects of project complexity in this context, there has been limited attention given to exploring the specific factors that contribute to the complexity and their interdependencies. This knowledge gap is a significant concern considering the increasing prominence of metro rail projects in the construction industry.

Research on Indian Metro Rail PCFs helps in identifying challenges, optimizing resource allocation, and development stakeholder association. Understanding interrelations shows effective management practices, enhancing project success. Investigating stakeholder opinions finds potential conflicts, improving outcomes. Examining phase-specific complexity differences in decision-making, refining project management strategies. This research advances project management knowledge, benefiting infrastructure development and transportation systems in India. For instance, Kardes et al. (2013) and Maylor & Söderlund (2016) have primarily focused on the theoretical aspects of project complexity in metro rail projects. Chapman (2016) analyzed complexity characteristics and their influence on project performance, while Niu et al. (2019) examined task complexity in metro rail projects. While these studies have contributed valuable insights, there is a clear need for a more comprehensive and systematic investigation into the factors that give rise to project complexity and their interdependence in the specific context of metro rail projects. The metro network in India currently has over 980 km under construction in 27 cities, according to the Union Minister for Housing and Urban Affairs, Hardeep Puri. Among these, the Delhi Metro stands as the largest operational network, having completed 20 years of service on December 25, 2022. In recent years, the Indian Metro Rail sector has experienced significant growth, with numerous ongoing and planned projects across various cities and regions. As of 2021, more than 20 metro rail projects are either in the construction phase or in the planning phase throughout the country. The primary objectives of these projects are to enhance urban transportation infrastructure, tackle escalating traffic congestion, and provide efficient and sustainable modes of transportation for the rapidly expanding urban population. The financial investments dedicated to these metro rail projects are substantial, with billions of dollars allocated for their development and implementation. These investments are anticipated to have a transformative impact on urban transportation, enhancing connectivity, reducing travel time, and promoting economic growth in regions where these projects are being executed.

From the literature survey, it is evident that the Indian metro rail projects face significant challenges like high capital costs, land acquisition and right of way issues, and construction complexities that result in delays and cost overruns. For example, the estimated cost of the Mumbai metro line 3 amounts to approximately $3.2 billion. The execution of the Delhi metro rail phase -III project requires a substantial 1,821 hectares of land. The Kolkata East-west project was initially scheduled to be completed by 2012 and experienced multiple delays while finally getting completed in 2015, leading to a budget escalation from $677 million to $1.2 billion. From the literature, it is also evident that interface issues, political impacts, and funding problems have hampered the project's progress. Notably the Nagpur metro rail project faced delays due to challenges posed by local farmers. Additionally, from the literature, it is also evident that the Indian metro rail projects encounter significant complexities such as land acquisition, stakeholder management, technical and engineering challenges, economic assistance, urban congestion, and time and cost management. The statistics of Indian metro rail are represented in Figure 4.1.

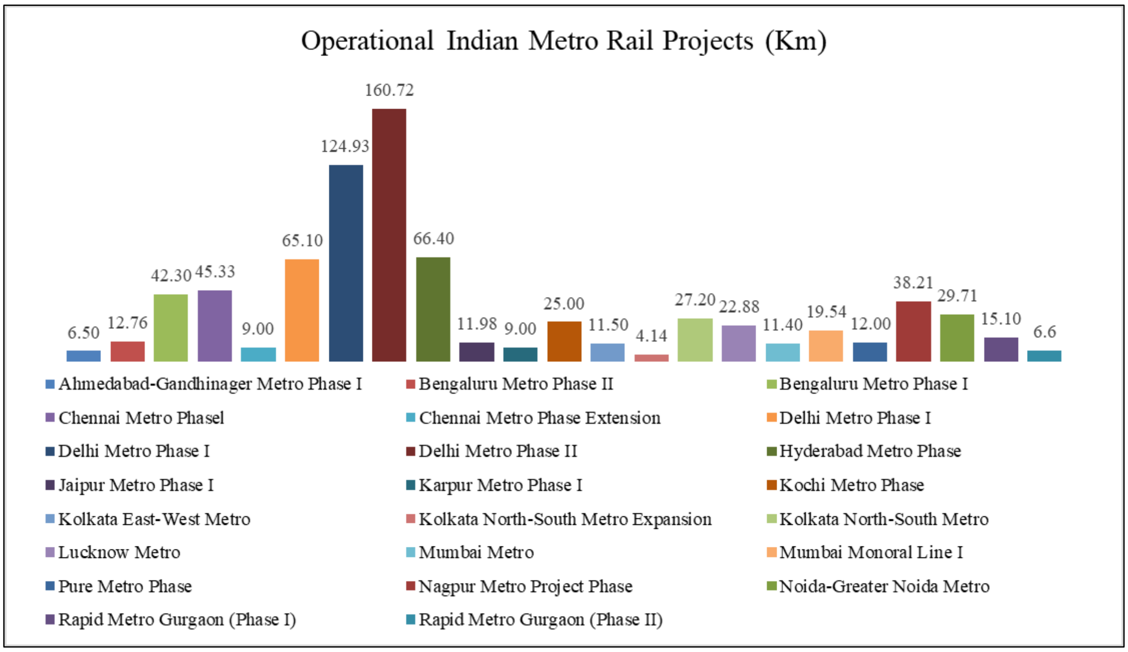


Image Source: https://indianinfrastructure.com/2022/08/19/key-statistics-402/

Figure 4.1 Statistics of operation Indian metro rail projects in kms.

To bridge this research gap, this study aims to identify project complexity and influencing factors in metro rail projects, specifically focusing on their interdependencies. The study adopts a practical-oriented approach and presents three case studies. The analysis utilizes DEMATEL technique, followed by a discussion of the findings, implications, recommendations, and limitations of the study. To gain a comprehensive understanding of the complexity and interdependence of metro rail projects, an extensive literature review was conducted. The aim was to identify any existing gaps in knowledge and explore the specific characteristics of complexity in the context of metro rail construction. These projects are witnessing rapid expansion and growth within Indian construction industry, making them a focal point of investigation. Despite being an emerging sector, the metro rail construction industry operates in a systematic and process-oriented manner.

This study plays a crucial role in assisting metro organizations by shedding light on the occurrence of complexity, identifying complexity factors, and analyzing the relationships between these factors. By examining the complexity and interdependencies within metro rail projects, the research methodology developed in this study can also be applied to other megaprojects in the construction sector. It enables project management to prioritize complexity or risk factors based on their significance, providing a foundation for making effective and agile decisions to reduce the overall impact on project outcomes.

The utilization of DEMATEL technique further supports metro construction project managers in devising strategies to address each complexity factor based on a hierarchical or prioritized order. This approach ensures that efforts are focused on minimizing the impact of critical complexity factors and maximizing project performance. By considering the interdependencies and relationships between complexity factors, project managers can allocate resources and implement targeted measures to mitigate challenges and optimize project outcomes. However, it is important to note that the scope of this study is limited to metro rail projects in India. While the findings and methodologies presented in this research have broader applicability, their specific implications may vary when applied to projects in different geographical locations or within different cultural contexts. Hence, further research is encouraged to explore and validate the findings in diverse project environments to enhance the generalizability of the study's outcomes.

4.4 Literature Review

4.4.1 Overview of metro rail projects globally and in India

The global metro rail geography has approximately 148 cities with 540 metro lines covering 11,000 kilometers and 9,000 stations. The London metro project, which started in 1890, was the world's first underground metro system, of urban transportation (Verma et al., 2021). At present, Shanghai claims to be the world's most extensive metro network, covering over 500 kilometers. Other cities like New York, Moscow, Madrid, and Paris have also significantly expanded their metro systems (Rahul & Tiwari, 2014). In the Indian context, metro projects have gained priority in urban transport planning due to their ability to manage increasing traffic congestion. These systems offer greater comfort, speed, and efficiency in comparison to bus networks (Alam & Ahmed, 2013). They also play a major role in promoting low-carbon transport, aligning with India's National Action Plan for Climate Change. Kolkata Metro initiated the modern metro system era, and the Delhi Metro, operations, have transformed urban transportation in India since 2002 (Rahul & Tiwari, 2014). Now, India has over 320 kilometers of operational metro rails. These metro constructions aim to provide efficient, eco-friendly, and affordable transportation, significantly reducing road congestion (Symbroj Media, 2022).

4.4.2 Complexity in megaprojects

Megaprojects are characterized by their large scale, high risk, and complexity (Raghuram et al., 2009; Zhai et al., 2009; Hu et al., 2013). These projects differ from traditional ones in terms of investment, time, cost, and execution, and their complexity directly impacts various aspects of a country, including the economy, technology, culture, and community (Flyvbjerg, 2017; Pitsis et al., 2018). Since the 1990s, researchers have been studying project complexity, especially in the context of megaprojects, and have offered different perspectives on its definition (Zhu & Mostafavi, 2017a). The underlying principle of project complexity refers to activities with interdependent characteristics within a project (Bakhshi et al., 2016). Adeleke et al. (2018) define project complexity as the outcome of various project characteristics interacting in complex ways, without a specific method for managing these complex actions. Vidal & Marle (2008) note the absence of a single, universally accepted definition of project complexity and its factors. While conventional projects have defined notions of complexity, megaprojects present challenges due to their indefinite boundaries, uncertainty, ambiguity, and interdependencies (Bakhshi et al., 2016). Despite the increasing number of studies on project complexity, there is still ongoing debate regarding its definition and quantification methods.

Consequently, multiple definitions of project complexity exist, influenced by the type of project, organization, and sector involved.

4.4.3 Project complexity and factors

Project complexity in megaprojects can be classified into different categories, including environmental, socio-political, organizational, technological, infrastructural, and scope complexity (Owens et al., 2012; Nguyen et al., 2015). Factors such as project change, project size, scheduling, different types of contracts, work packages, overlap of construction elements, uncertainty, technological difficulties, numerous stakeholders, new construction methods, new technologies, lack of knowledge, difficulty in achieving project goals, interdependence among project participants, lack of trust, previous work experience, lack of internal support, involvement of multiple languages and cultures, organizational interdependence, different levels of hierarchy, political influence, frequent changes in laws and regulations, bad weather, cost overruns, delays, environmental conditions, unpredictable geological and market conditions, land acquisition, utility relocation, and stakeholder issues contribute to project complexity (Baccarini, 1996; Geraldi & Adlbrecht, 2007; Remington & Pollack, 2008; Bosch-Rekveldt et al., 2011; Owens et al., 2012; Vilventhan & Kalidindi, 2016; Nazanin et al., 2018). While researchers have employed various methodologies to assess project complexity, there is still a need for further research to identify and analyze project complexity and factors impacting it (Vidal et al., 2011b; Botchkarev & Finnigan, 2015; Bakhshi et al., 2016). While researchers have employed various methodologies to assess project complexity, there is still a need for further research to identify and analyze project complexity and factors impacting it (Botchkarev & Finnigan, 2015; Bakhshi et al., 2016). A list of PCFs identified from the literature is shown in Table 4.1. Despite the identification of factors causing complexity for several megaprojects, the study of project complexity, impacting factors, and their interdependence in metro rail projects remains largely unexplored. Previous research has primarily focused on project complexity in construction projects, including megaprojects, conventional projects, transportation, and rail projects.

Table 4.1 List of project complexity factors identified from the literature (source: authors' own work)

Type of Complexity	Code	Complexity Factors	References
Techno-logical	T1	Diverse Technology	Baccarini (1996), Bosch-Rekveldt et al. (2011)
	T2	Uncertainties in Scope	Flyvbjerg, Bruzelius, et al. (2003)
	T3	Risk of Complex Technologies	Vidal & Marle (2008)
	T4	Change in Design / Construction	Vidal & Marle (2008)
	T5	Interrelationships among the technological process	Baccarini (1996), Vidal & Marle (2008)
Environ-mental	E1	Change in regulation policy	Baccarini (1996), Vidal & Marle (2008)
	E2	Issues in land acquisition	Baccarini (1996), Vidal & Marle (2008)
	E3	Delay in Relocation of utilities	Vilventhan & Kalidindi (2016)
Organizational	O1	Compatibility of system with required standards	Vidal & Marle (2008), Botchkarev & Finnigan (2015)
	O2	Cumbersome administrative Process	Geraldi & Adlbrecht (2007)
Location	L1	Uncertain geotechnical and physical conditions	Vilventhan & Kalidindi (2016)
	L2	Project location	Vidal et al. (2011b)
	L3	Design changes to suit non-divertible utilities	Vilventhan & Kalidindi (2016)
	L4	Design problems with existing structures	Vidal et al. (2011b), Botchkarev & Finnigan (2015)
Contractual	C1	Breach of contract	Geraldi & Adlbrecht (2007), Bosch-Rekveldt et al. (2011)
	C2	Exchange of information	Botchkarev & Finnigan (2015)
	C3	Internal/external Politics	Geraldi & Adlbrecht (2007)

4.4.4 Gap in literature

Existing research has focused on the studies of project complexity in the construction of megaprojects, conventional projects, and transportation projects, but studies on project complexity have not been adequately addressed in metro rail construction. Though some studies in the literature have addressed the issue of project complexity and its consequences in metro rail projects, a detailed study to explore the factors responsible for the occurrence of project complexity and its interdependence has not yet been explored. Qazi et al. (2016) developed a new process called "Project Complexity and Risk Management (ProCRiM)" to identify the interdependence between project complexity and risk management in the construction industry. Dara & Vilventhan (2023) focused on identifying project complexity in a metro rail project, and Dara et al. (2023) focused on identifying the interrelationship of complexity factors in a metro rail project. These PCFs were identified and analyzed on a single metro rail project. The PCFs and their interdependencies differ based on the type of metro rail project. The study on the similarities and differences of the PCFs in elevated and underground metro rail projects is lacking. Hence this research bridges the gap by identifying and analyzing the PCFs and interdependencies in both elevated and underground metro rail projects.

4.5 Case Study Description

Three metro rail projects were chosen as case studies to identify the complexity factors. The demographic information of the considered cases is shown in Table 4.2 below and Figure 4.2 shows the interaction matrix of project complexities observed in the metro rail projects from the case study analysis.

Table 4.2 Details of the case area and their description (source: authors' own work)

S.No	Case Area (CA)	Case Area Description
1	**CA: Ahmedabad metro rail project** ***State:*** Gujarat ***Budget:*** USD 1619.3 million-2012 ***Data Source:*** Interviews, archival records, documents	The Ahmedabad Metro Rail Project is an underground construction project with AFCON PVT. Ltd. as the contractor for the construction of two stations and a tunnel length of 2.2 kilometers.
2	**CA: Hyderabad metro rail project** ***State:*** Telangana ***Budget:*** USD 2.36 billion- 2017 ***Data Source:*** Interviews, archival records, documents	The Hyderabad metro rail project is one of the largest elevated high-density traffic corridors in India, with L&T as the contractor for the construction of the 72-kilometer-long high-density traffic corridor. This corridor is divided as follows: Corridor-I is from Miyapur to L.B. Nagar, 29 km; Corridor-II is from Jubilee Bus Station to Falaknuma, 15 km; and Corridor-III is from Nagole to Raidurg, 28 km.
3	**CA: Bangalore RT-03 metro rail project** ***State:*** Karnataka ***Budget:*** USD 17 Million -2017 ***Data Source:*** Interviews, archival records, documents.	The Bangalore Metro Rail Project is an underground construction with a 2.8 km tunnel and two stations, built by L&T Company. This is the first phase of the RT 02 Reach 6 Line project in Bangalore.

Based on the information gathered from interviews, case-level analysis was performed and a descriptive story for each case was developed.

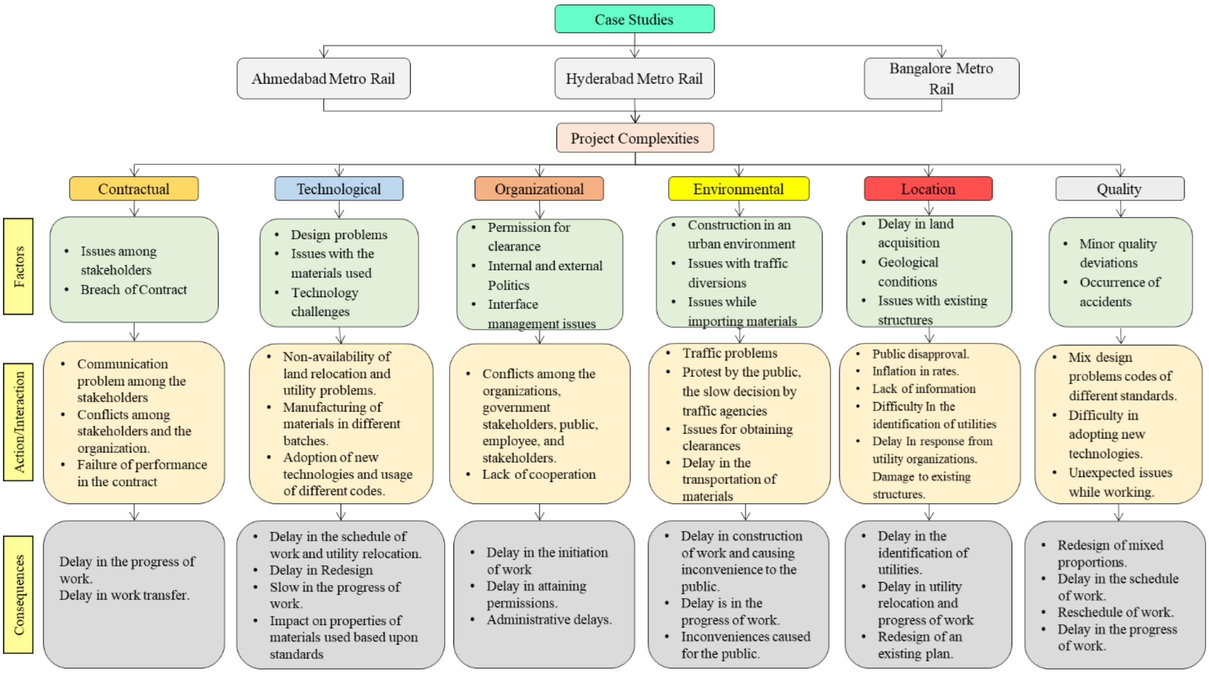


Figure 4.2 Interaction matrix of project complexities observed in the metro rail projects from the case study analysis (source: authors' own work)

The PCFs identified in Hyderabad metro rail projects are traffic congestion during construction, problems with existing infrastructure, challenges during excavation and foundation work, and the difficulty of construction near rail over bridges. As Bangalore is an underground construction project, seepage, and excavation problems due to mixed geological conditions, and problems with grouting machines for underground tunneling are observed. Land acquisition challenges, political issues, clearance permissions, and design changes were the PCFs observed in the Ahmedabad metro rail project. A descriptive story for each case was developed using the data collected from the interviews. This formed the basis for case-level and cross-case-level analysis.

4.5.1 Case-level analysis of Ahmedabad metro rail

The case study focuses on Ahmedabad, an Indian metropolitan city, where a Mass Rapid Transit System (MRTS) spanning 68.28 kilometers was undertaken. This project encountered three primary complexities: environmental, technological, and organizational. Environmental complexity stemmed from challenges related to land acquisition, building demolition permits, utility relocation, and traffic diversion. These issues led to reduced land availability for stations, causing delays and necessitating design modifications. These factors have led to a reduction in land availability for the first station from 260 to 214 meters and for the second station to 220 meters. Consequently, this caused a three-month delay and necessitated design modifications.

Construction presented significant challenges, including utility relocation at depths of 3 to 5 meters and tunneling at depths of 16 to 18 meters. Vibrations from the Tunnel Boring Machine (TBM) resulted in project delays and public inconveniences. To manage tunneling heat, foam was employed, leading to rescheduling and quality deviations, including design flaws and segmental cracks, leading to technological complexity.

Organizational complexity contributed to internal stakeholder conflicts and difficulties in securing permissions for traffic diversions and material transportation, causing construction delays and cost overruns.

4.5.2 Case level analysis of Hyderabad metro rail

In Hyderabad, a rapidly growing city, the implementation of a Mass Rapid Transit System (MRTS) encountered several layers of complexity. This metro project follows the Design Build Finance Operate and Transfer (DBFOT) model and spans a high-density traffic corridor covering 72 kilometers. Environmental complexity is notably influenced by the challenges associated with land acquisition due to surging land costs, resulting in a substantial one-year project delay. The relocation of utilities in an ancient city with incomplete records has also caused delays and design adaptations. Excavation near the Musi River and the relocation of a century-old stormwater pipeline presented further complexities. Unforeseen geological conditions necessitated design revisions. Interference with existing structures, such as government buildings and religious sites, public resistance to land acquisition, and internal political issues also led to project redesigns. Additionally, the need for traffic diversions, clearances, and permission contributes to location complexity. Safety complexity is heightened by near-miss accidents, traffic incidents, and worker injuries or casualties among workers.

4.5.3 Case-level analysis of Bangalore metro rail

The Bangalore Metro Rail RT-03 project, executed as a design-and-build contract, encountered significant environmental complexity due to challenges related to land acquisition. These challenges caused a significant 20-month delay in project completion. The unavailability of utility drawings and documents posed significant difficulties in construction detailing and design in utility relocation. Obtaining permission for traffic diversion and utility relocations is a challenging task, due to a lack of inter-organizational coordination and communication. Additionally, obtaining necessary permissions for traffic diversion and utility relocations has proven to be a challenging task, primarily due to a lack of coordination and communication among the organizations involved. Moreover, the project's location presents diverse geological conditions, developing location complexity. These geological challenges have notably affected tunnel excavation, necessitating the adoption of distinct tunneling techniques. Additionally, the need for frequent modifications in mix design due to intermittent supply of chemicals and admixtures by manufacturers has further complicated quality control aspects.

4.5.4 Cross-case-level analysis

A comparative analysis was conducted among the three selected cases to identify project complexity and factors impacting project execution in both elevated and underground metro rail projects. Among the various complexity factors, land acquisition and utility relocation emerged as the most common environmental complexities observed in all three cases. These factors led to public inconvenience and delays in acquiring the necessary Right of Way (ROW) for road construction.

Technological complexity, attributed to the adoption of new construction technologies and insufficient knowledge about them, was primarily observed in the Bangalore and Ahmedabad metro rail projects. Organizational complexity factors, such as internal politics, stakeholder management issues, interface management problems, construction in urban environments, and clearance permissions, were prevalent in all three metro rail projects. These factors contributed to project delays, redesigns, and administrative bottlenecks. Contractual complexity factors, including contract breaches, political issues (both internal and external), and stakeholder difficulties, were also identified as impacting project performance. They resulted in delays in obtaining approvals, hindered work progress, and complicated the delegation of work to other contractors.

Location complexity factors, such as interference between metro rail alignment and existing infrastructures, material transportation challenges, traffic diversion, adverse geological conditions, and delays in obtaining permissions and clearances, were commonly observed across the case studies. Among these, location complexities, and geological conditions had a significant impact, particularly in the underground metro projects of Bangalore and Ahmedabad. Minor deviations in quality, accidents, and near-miss incidents were factors that contributed to complexities related to quality and safety in the projects.

4.6 Interdependence of Complexity Factors Using the DEMATEL Technique

The review of existing literature revealed a research gap regarding quantitative analysis of the relationships between PCFs in metro rail projects. To address this gap, DEMATEL method was employed to analyze the interdependence among PCFs in metro rail projects, enabling informed decision-making to enhance project performance.

Given the multifaceted nature of complexity in metro rail projects, it was crucial to identify the relationships between project complexity and the factors influencing it to develop effective strategies within organizations. DEMATEL method served as a comprehensive approach for constructing a structural model that elucidated the interdependencies among the PCFs, identified as well as their relative significance, through a visual representation.

The DEMATEL method is widely used for tackling complex problems and assessing, comparing, and improving the effectiveness of each complexity factor by categorizing them into cause-and-effect groups. Leveraging graph theory, this method facilitates the identification and formulation of interdependent factors within any given structural model. Notably, its application in MCDM enables the establishment of relationships between project complexity and factors, dearth the outcome, thereby aiding in problem resolution both visually and theoretically. Figure 4.3 illustrates a step-by-step process for implementing the DEMATEL method, offering guidance in performing this analysis.

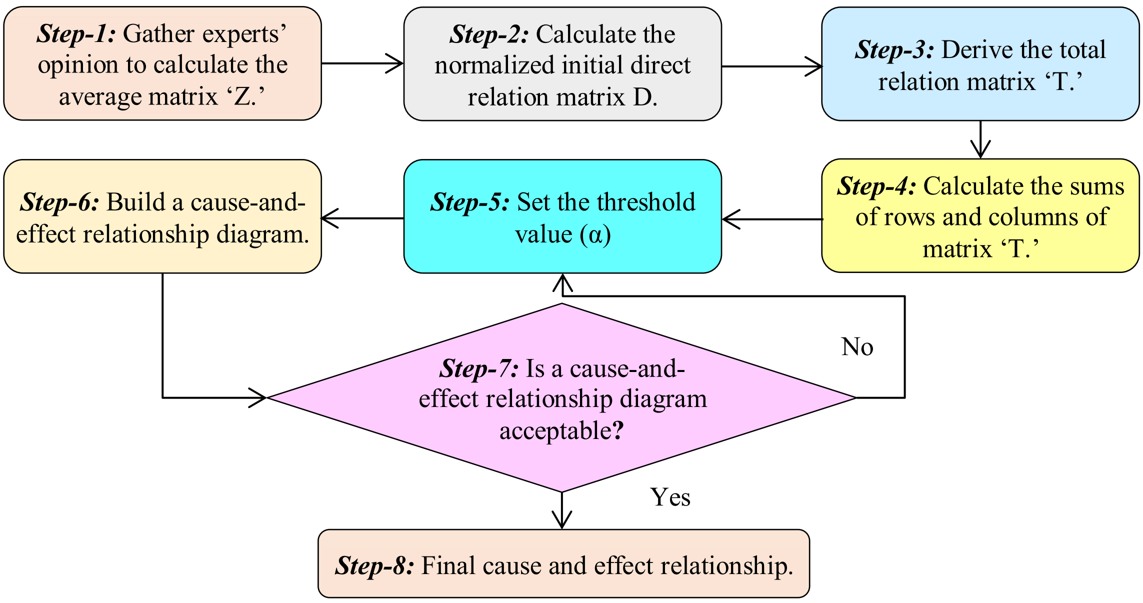


Figure 4.3 The step-by-step process for DEMATEL analysis (source: authors' own work)

First, a direct relationship (Average) matrix is constructed using the responses from the questionnaire survey, indicating the influence of each complexity factor on a scale ranging from 0 (no influence) to 4 (very high influence). Subsequently, this matrix is normalized (Y) by dividing each value by the highest average sum of rows.

Next, the total relation matrix is determined by employing identity matrix (I) and the formula T=Y(I-Y)-1. The sum of rows and columns is utilized to calculate the D and R values in the subsequent step. Ultimately, based on the mean of Total Relations Matrix, a threshold value (p) of 0.721 is selected to elucidate the structural relationship between the factors.

The outcomes of Total Relations Matrix, indicating the interrelationships among complexity factors, are presented in Table 4.3. Using the findings from Table 4.2, a complexity map for elevated, underground, and overall metro rail projects is developed. Figures 4.4(a), 4.4(b), and 4.4(c) display these complexity maps, respectively.

4.7 Analysis and Discussions of Results

DEMATEL method was used to identify the interdependencies of PCFs of underground and elevated metro rail projects. This method was widely used for complex problem-solving, categorizes factors into cause-and-effect groups, and uses graph theory to identify and formulate interdependencies. This MCDM model helps to analyze the relationships between PCFs of various metro rail projects. To obtain the data for analysis questionnaires were used. In the questionnaire, a pair-comparison scale with a five-level rating system was used to assign scores of 0, 1, 2, 3, and 4, signifying "no influence," "low influence," "medium influence," "high influence," and "very high influence," respectively. Respondents were asked to rank the influence of PCFs on a five-point Likert scale, from "no influence" to "very high influence." The obtained scores were used to quantitatively evaluate the relationships among various complexity factors. Specifically, they indicated the level of influence one factor (i) had on another (j), denoted as xij. It's significant that the diagonal elements (i = j) consistently held a value of zero. To ensure understanding and consistency among all survey participants, an example was provided, to fill in the questionnaire explaining how one factor influenced another. Throughout the survey process, open discussions were facilitated to help with uncertainties or questions arising during the pairwise comparisons. The resulting dataset was used in creating matrix X, from which a normalized initial direct-relation matrix, Y, was derived. A total relation matrix was generated using T=Y(I-Y)-1. D and R values were calculated based on row and column sums. A threshold value of 0.721 was chosen to determine structural relationships. Table 4.3 shows the Total Relation Matrix (T).

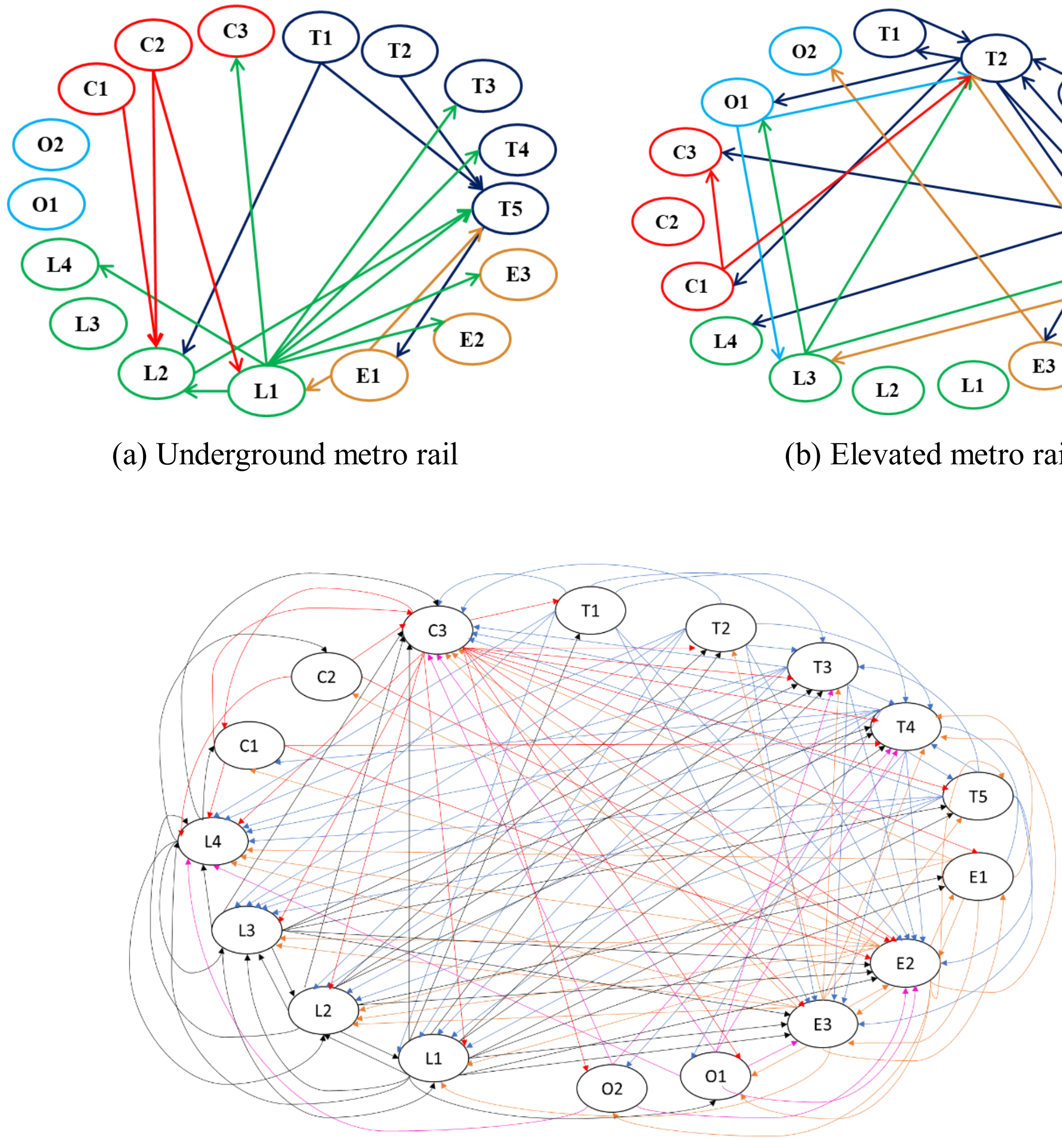
Complexity maps for elevated, underground, and overall metro rail projects as shown in Figs. 4.4(a), 4.4(b), and 4.4(c) were developed based on the results in Table 4.3, which demonstrates the interdependence of PCFs.

Table 4.3 Total Relation Matrix (T) (source: authors' own work)

Code	T1	T2	T3	T4	T5	E1	E2	E3	O1	O2	L1	L2	L3	L4	C1	C2	C3
T1	0.62	0.70	0.74*	0.76*	0.70	0.68	0.75*	0.71	0.69	0.64	0.71	0.70	0.72	0.75*	0.65	0.63	0.75*
T2	0.68	0.64	0.73*	0.75*	0.70	0.69	0.76*	0.73*	0.69	0.65	0.71	0.74*	0.71	0.76*	0.67	0.65	0.76*
T3	0.70	0.70	0.68	0.76*	0.70	0.69	0.76*	0.72	0.70	0.65	0.72	0.73*	0.73*	0.75*	0.67	0.64	0.75*
T4	0.75*	0.76*	0.81*	0.76*	0.77*	0.75*	0.83*	0.81*	0.76*	0.74*	0.79*	0.79*	0.79*	0.82*	0.74*	0.71	0.82*
T5	0.68	0.70	0.73*	0.76*	0.66	0.70	0.76*	0.75*	0.70	0.67	0.72	0.71	0.72	0.76*	0.68	0.66	0.75*
E1	0.66	0.68	0.71	0.73*	0.70	0.63	0.76*	0.72	0.67	0.67	0.71	0.74*	0.70	0.74*	0.67	0.66	0.75*
E2	0.73*	0.76*	0.79*	0.82*	0.76*	0.75*	0.76*	0.79*	0.74*	0.72	0.78*	0.79*	0.77*	0.82*	0.73*	0.71	0.81*
E3	0.70	0.73*	0.76*	0.79*	0.76*	0.72	0.80*	0.71	0.72	0.70	0.75*	0.76*	0.76*	0.80*	0.70	0.69	0.80*
O1	0.67	0.68	0.73*	0.75*	0.70	0.67	0.74*	0.71	0.63	0.65	0.71	0.70	0.71	0.74*	0.68	0.64	0.73*
O2	0.63	0.65	0.69	0.73*	0.68	0.67	0.73*	0.70	0.65	0.59	0.67	0.69	0.68	0.74*	0.64	0.63	0.72
L1	0.71	0.72	0.76*	0.79*	0.74*	0.72	0.79*	0.76*	0.72	0.68	0.69	0.76*	0.74*	0.79*	0.70	0.67	0.79*
L2	0.67	0.71	0.74*	0.76*	0.70	0.72	0.77*	0.74*	0.68	0.67	0.74*	0.68	0.72	0.77*	0.68	0.67	0.77*
L3	0.69	0.70	0.75*	0.77*	0.71	0.69	0.77*	0.75*	0.70	0.66	0.72	0.73*	0.67	0.77*	0.68	0.64	0.76*
L4	0.74*	0.77*	0.79*	0.81*	0.77*	0.75*	0.83*	0.81*	0.75*	0.74*	0.78*	0.79*	0.78	0.77*	0.75*	0.71	0.83*
C1	0.65	0.68	0.70	0.73*	0.69	0.68	0.74*	0.71	0.68	0.65	0.70	0.70	0.70	0.75*	0.61	0.64	0.73*
C2	0.64	0.66	0.68	0.71	0.68	0.68	0.73*	0.70	0.66	0.64	0.69	0.70	0.67	0.72	0.65	0.58	0.72
C3	0.72	0.75*	0.77*	0.80*	0.74*	0.75*	0.81*	0.79*	0.73*	0.72	0.78*	0.78*	0.76*	0.81*	0.72	0.69	0.75*

Note: * indicates the value of an element greater than the threshold value (α)

Codes: T1- Diverse Technology; **T2**- Uncertainties in Scope; **T3**- Risk in complex Technologies; **T4**-Change in design construction; **T5**-Interrelationships among technological processes; **E1**- Change in regulation policy; **E2**-Issues in land acquisition; **E3**-Delay in the relocation of utilities; **O1**- Compatibility of system with the standards; **O2**-Cumbersome administrative process; **L1**-Uncertain geotechnical and physical conditions; **L2**-Project Location; **L3**-Design changes to suit non-divertible utilities; **L4**- Design Problems with existing structures; **C1**-Breach of contract; **C2**-Exchange of information; **C3**-Internal/external politics



(a) Underground metro rail

(b) Elevated metro rail

(c) Overall complexity

Figure 4.4 Complexity maps (Interdependence of complexity factors) for metro rails (source: authors' own work)

The values of "D" and "R," obtained from the rows and columns of the total relation matrix, are presented in Table 4.4. "D" represents the sum of the rows, while "R" represents the sum of the columns. The sum of (D+R) was used to represent the overall impact of the cause-and-effect derived from the complexity maps of the DEMATEL method, showing the importance of each PCF in metro rail projects and their impact on other PCFs. The difference (D - R) shows the net impact of each PCF in metro rail projects. A PCF was classified into the effect group if its (D – R) value was negative, and as a net cause if its (D + R) value was positive. Figure 4.5 shows the causal influence diagram which illustrates the cause-and-effect relationships between different PCFs.

Table 4.4 Degree of significance (source: authors' own work)

Code	D	R	D+R	Rank	D-R	Impact
T1	11.90	11.64	23.54	14	0.26	*Cause*
T2	12.04	11.97	24.01	11	0.07	*Cause*
T3	12.05	12.55	24.60	8	-0.50	*Effect*
T4	13.20	12.98	26.18	2	0.22	*Cause*
T5	12.12	12.16	24.28	10	-0.04	*Effect*
E1	11.88	11.97	23.85	12	-0.09	*Effect*
E2	13.00	13.09	26.09	3	-0.09	*Effect*
E3	12.66	12.62	25.28	5	0.04	*Cause*
O1	11.86	11.87	23.73	13	-0.01	*Effect*
O2	11.48	11.44	22.92	16	0.04	*Cause*
L1	12.53	12.37	24.90	6	0.16	*Cause*
L2	12.20	12.51	24.71	7	-0.31	*Effect*
L3	12.16	12.31	24.47	9	-0.15	*Effect*
L4	13.18	13.07	26.25	1	0.11	*Cause*
C1	11.71	11.62	23.33	15	0.09	*Cause*
C2	11.54	11.22	22.76	17	0.32	*Cause*
C3	12.87	13.00	25.87	4	-0.13	*Effect*

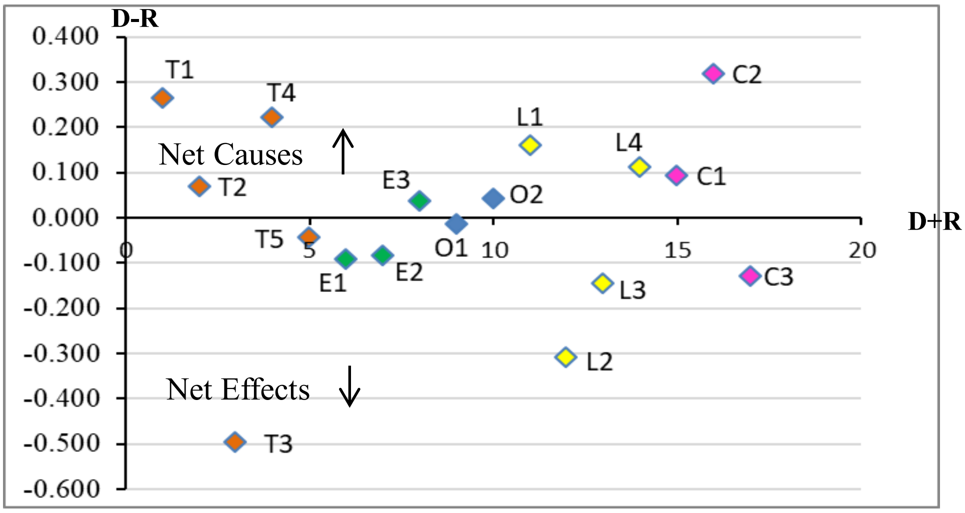


Figure 4.5 Cause and effect influence diagram (source: authors' own work)

With the highest D+R (26.25), "Design problems with existing structures (L4)" shown to have a major impact on metro rail projects. "Exchange of information (C2)" showed the lowest D+R (22.76) and the least impact. The following describes how seventeen PCFs were prioritized according to their D+R values: L4 > T4 > E2 > C3 > E3 > L1 > L2 > T3 > L3 > T5 > T2 > E1 > O1 > T1 > C1 > O2 > C2.

4.7.1 Cause group

The examination of cause group complexities in metro rail projects has indicated that a positive D-R value signifies a net cause, exerting a direct influence on other PCFs. PCFs with higher D-R values hold greater influence over other factors. The analysis has identified the 'exchange of information' (C2) as the most critical complexity factor in metro projects, with a value of 0.32. Thus, it becomes imperative to prioritize efforts to mitigate its impact on other PCFs in metro rail projects.

Several other significant cause group complexity factors have also been identified. These include 'diverse technology' (T1), 'change in design and construction' (T4), 'uncertain geotechnical and physical conditions' (L1), 'design problems with existing structures' (L4), 'breach of contract' (C1), and 'uncertainty in scope' (T2), with values of 0.26, 0.22, 0.16, 0.11, and 0.09, respectively. On the other hand, 'utility relocation delay' (E3) and 'cumbersome administrative process' (O2) were found to have the lowest values of 0.04. Special attention should be given to PCFs to minimize their impact on the effect group. By considering and addressing these PCFs, project stakeholders can effectively manage and mitigate complexities in metro rail projects.

4.7.2 Effect group

A negative D-R value indicates the net effect group, which is greatly influenced by the cause group PCF. It has been observed that the 'risk in complex technologies' (T3) exhibits the highest D-R value (-0.50), signifying its strong influence. Conversely, the 'system's compatibility with standards' (O1) holds the least significance with a value of -0.01. Additionally, other PCFs in the net effect group include 'project location' (L2), 'design changes to accommodate non-divertible utilities' (L3), 'delay in utility relocation' (C3), 'change in regulation policy' (E1), 'issues in land acquisition' (E2), and 'interrelationships among technological processes' (T5), with respective values of -0.31, -0.15, -0.13, -0.09, -0.09, and -0.04.

Based on the cause and net groups, the PCFs exhibiting positive D-R values are T1, T2, T4, E3, O2, L1, L4, C1, and C2. These factors exert greater influence on other factors and are categorized as "net cause groups." Conversely, the PCFs with negative D-R values include T3, T5, E1, E2, O1, L2, L3, and C3. These factors are referred to as the "net effect group" since they are influenced by complexity factors within the cause group. Consequently, the complexity factors within the effect group need to be more concentrated, considering the influence of the cause-group factors.

For instance, an examination of the cause-and-effect groups reveals that metro rail projects encounter challenges related to land acquisition, site clearances, and administrative procedures. These challenges stem from the regulations that govern the available time and space for executing construction activities. Additionally, limited access to existing data and information has resulted in financial and technical issues at certain locations. Communication among stakeholders within the organization is another crucial factor that significantly impacts project performance. Factors such as trust in contractors and project teams, task interdependence, and other PCFs contribute to the overall complexity of the project. However, cultural differences and language barriers have a minor effect since technical language serves as the common barrier among project managers, contractors, site engineers, and other stakeholders, while a common language is used to communicate with different hierarchical levels of the organization. Consequently, the metro rail organization should prioritize attention to the cause group PCFs to minimize the impact of the effect group factors and enhance the overall project performance.

Based on the literature analysis, urban areas encounter challenges when dealing with metro rail projects (Nguyen et al., 2015). Project access limitations in remote locations result in technical and financial issues, leading to an increase in project complexity (Xia & Chan, 2012; Nguyen et al., 2015). In metro rail projects, specific PCFs such as project location (L2), design problems with existing structures (L4), and clearance permissions have an impact on project performance. The complexity of stakeholder communication is influenced by the diversity and dependencies of project activities, trust in project teams and contractors, and the varying perspectives of stakeholders (Bosch-Rekveldt et al., 2011). Changes in regulation policy (E1), cumbersome administrative processes (O2), and communication among stakeholders, contractors, and project teams are identified as critical complexity factors in metro rail projects. Political influence also significantly affects the administrative procedures of metro rail projects. The involvement of both domestic and international cultures in construction projects introduces challenges related to linguistic and cultural barriers, although, in metro construction, these barriers have relatively little impact on project performance. Stakeholders speak at least one common language and cultural adaptation has become a shared factor due to the project's extended duration (He et al., 2014; Nguyen et al., 2015).

Underground metro rail constructions are typically proposed in densely populated areas where elevated rail alignments would require extensive demolition of existing structures. Elevated metro rail projects often follow the alignment of existing roads, making the acquisition of land outside the right of way (ROW) and obtaining permission for demolishing existing structures crucial (Somnath Nandan, 2020). Consequently, underground metro rail construction is chosen in such circumstances to minimize disruption to above-ground infrastructure. The increasing need for space has led to a significant reliance on underground space. However, underground construction projects face various challenges, including ensuring the safety of existing buildings within tunnel construction zones, navigating water bodies, dealing with deep foundation work and unpredictable geological conditions, managing construction overlapping with existing utilities, and obtaining tunneling permissions. These challenges, which are typically less severe in elevated projects, increase the complexity of underground constructions. Underground construction of metro rail projects also incurs exceptionally high-power consumption due to tunnel ventilation systems, environmental control systems, and the usage of tunnel boring machines (TBM) (Somnath Nandan, 2020). Underground projects are known for their riskiness due to susceptibility to design problems, making them more challenging to manage compared to other types of construction projects. Elevated projects, while less technically challenging, still require careful management of land acquisition and permissions, which can significantly delay the project. Hence, effective project complexity management is crucial in underground metro rail construction. Project management plays a vital role in resolving complexity factors such as technical incompetence, professional diversity, uncertainty, inequity, and other unexpected events during the construction process. Project managers of metro rail projects require innovation, adaptability, and flexibility to overcome project complexity in construction (Remington & Pollack, 2008). Each type of metro project (underground and elevated) presents unique complexities, from technical challenges in tunneling to land acquisition for elevated tracks, all of which need adapted management strategies.

It is necessary to conduct a reliable assessment of project complexity before implementing effective management solutions (Austin et al., 2002; Augustine et al., 2005; Thomas & Mengel, 2008). Recent research has focused on examining project complexity in megaprojects (Geraldi et al., 2011). While the importance of project complexity in mega projects has been acknowledged in studies (Remington & Pollack, 2008), there is a lack of research specifically addressing the identification of project complexity and PCFs s in metro rail projects. To bridge this research gap, this study utilizes multiple case studies and the DEMATEL approach to identify project complexity, PCFs, and their interdependence. This method is particularly useful in both underground and elevated projects, where different PCFs have varying degrees of influence. This method enhances the study by providing a comprehensive framework for understanding project complexity, PCFs, and their interrelationships. Additionally, the study develops cause and effect diagrams and a complexity map that differ significantly from existing literature, enabling the practical application of this approach for quantitatively assessing project complexity in metro rail projects.

Project complexity assessment is essential in construction project planning and management. Reliable assessments are crucial for implementing effective management solutions (Austin et al., 2002; Augustine et al., 2005; Thomas & Mengel, 2008; Singh & Gupta, 2015). The increasing demand for underground structures like utility tunnels and subterranean stations due to urban population growth has led to considerations of both underground and overground construction in metro rail projects (Baziar et al., 2014). Underground construction is preferred in densely populated areas to avoid extensive demolition, while elevated projects align with existing roads, necessitating land acquisition and demolition permissions (Somnath Nandan, 2020). Underground projects come with their challenges, including ensuring building safety, navigating water bodies, managing unpredictable geological conditions, dealing with utilities, and handling ventilation and environmental systems. These complexities demand innovative, adaptable, and flexible project management. These complexities greatly impact planning and coordination. While there is existing research on project complexity in megaprojects, there's a gap in understanding project complexity in metro rail projects. This study addresses this gap through multiple case studies and the DEMATEL approach, offering a unique quantitative assessment framework with cause-and-effect diagrams and a complexity map. The findings of this study can serve as a benchmark for assessing similar projects. Identifying project complexity, PCFs, and their interdependence assists managers and engineers in evaluating the complexity of construction projects such as metro rail systems. Understanding project complexity aids in predicting challenges, risks, and uncertainties, thereby facilitating effective resource allocation within metro organizations. Furthermore, this study supports the strategic management of project complexity by demonstrating the interdependence among PCFs. Therefore, gaining an understanding of how to identify complexity and its interdependencies is crucial for effective complexity management.

The study identified two primary complexities, location, and environmental, that significantly impact metro project performance with delays. To mitigate these issues, completing land acquisition before project commencement is crucial, ensuring efficient operations (Dara & Vilventhan, 2023). Contracts should include specific land procurement terms to address interface concerns. Availability of essential data from utility companies and government agencies, along with coordination with specialized officials, is vital to prevent delays. Provisions in contracts for accessing existing data, managing traffic diversions, and material transportation reduce delays. Intra-organizational coordination is key for information access. Precise sensor technology and modeling for geological conditions and underground utilities improve understanding and design implementation. Application of BIM, and RS&GIS enhances planning and management accuracy. Workplace monitoring tools identify improvements and reduce delays. Incorporating time constraints in contracts simplifies meeting deadlines. These methods aid in reducing complexities and enhancing overall metro project outcomes.

4.7.3 Sensitivity analysis

A sensitivity analysis was carried out which assessed the robustness of PCF rankings by altering their weights by 5%, 10%, and 15%, while other weights remained constant. The objective of this analysis was to gauge the sensitivity of the results and determine the extent to which altering weights influences the significance of the PCFs. To conduct sensitivity analysis, the weights of the highest and lowest-ranked PCFs were adjusted by 5%, 10%, and 15%, while keeping the weights of the remaining PCFs constant. This enabled an examination of how modifications in the weights of specific PCFs impacted their significance levels and overall ranking. Figure 4.6 illustrates the causal diagram depicting the sensitivity analysis with varying weight percentages, while Table 4.5 presents the significance levels of the PCFs obtained from the analysis. PCF significance levels and rankings remained unchanged with a 5% weight adjustment, indicating their robust influence on metro rail project complexity. However, at 10% and 15% PCFs, T1, T2, E3, and L1 have transitioned from being categorized as net cause to net effect factors.

The sensitivity analysis offers valuable insights into the stability and robustness of the PCFs, identified PCFs, thereby enhancing the reliability of the findings. It emphasizes the importance of considering different scenarios and weight variations when assessing project complexity and underscores the need for a comprehensive understanding of the interdependence among PCFs to effectively manage project complexity in metro rail projects.

Table 4.5 Degree of Significance Obtained from Sensitivity Analysis (source" authors' own work)

Project Complexity Code	5% Variation		10% Variation		15% Variation	
	Ri+Ci	*Ri-Ci*	*Ri+Ci*	*Ri-Ci*	*Ri+Ci*	*Ri-Ci*
T1	30.37	0.07	42.44	-0.27	69.53	-1.03
T2	31.01	-0.19	43.38	-0.63	71.16	-1.63
T3	31.74	-0.93	44.36	-1.69	72.70	-3.39
T4	34.53	0.84	49.28	1.92	82.41	4.34
T5	31.37	-0.34	43.90	-0.85	72.04	-2.01
E1	30.82	-0.39	43.15	-0.91	70.84	-2.09
E2	34.44	0.43	49.20	1.35	82.35	3.41
E3	32.67	-0.24	45.73	-0.72	75.07	-1.81
O1	30.66	-0.28	42.93	-0.76	70.47	-1.83
O2	30.32	0.53	43.41	1.40	72.80	3.34
L1	32.14	-0.08	44.95	-0.50	73.71	-1.46
L2	31.92	-0.67	44.66	-1.32	73.27	-2.77
L3	31.60	-0.48	44.20	-1.05	72.49	-2.34
L4	34.66	0.69	49.52	1.72	82.88	4.01
C1	30.83	0.60	44.08	1.50	73.85	3.52
C2	30.07	0.88	42.99	1.87	72.01	4.10
C3	33.40	-0.46	46.73	-1.04	76.65	-2.35

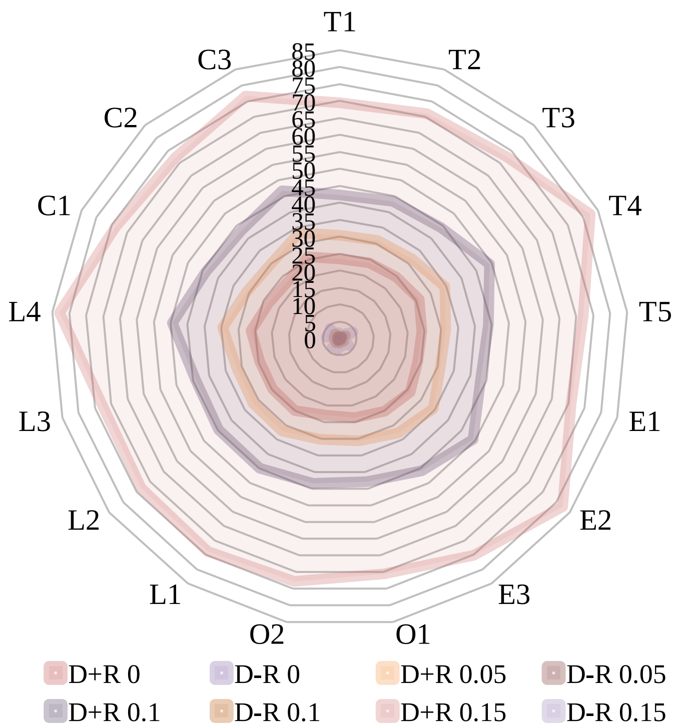


Figure 4.6 Casual influence diagram of sensitivity analysis (source: authors' own work)

During the sensitivity analysis, it was observed that when the weights were varied by 5%, the significance levels and rankings of the PCFs remained unchanged. This indicates that the identified PCFs exhibited robustness and consistency in their influence on project complexity in metro rail projects. However, when the weights were adjusted by 10% and 15%, certain PCFs experienced a shift in their influence from the cause group to the effect group. Specifically, PCFs T1, T2, E3, and L1 transitioned from being categorized as net cause factors to becoming net effect factors. This suggests that the interdependence and impact of these PCFs on other complexity factors were affected by changes in weights. It is important to note that despite these changes, the majority of the PCFs maintained their significance and rankings across different weight variations. This validates the appropriateness of the identified PCFs and their interdependence in metro rail projects, as they consistently demonstrated influence even when subjected to variations in weight assignments. The sensitivity analysis offers valuable insights into the stability and robustness of the PCFs identified, thereby enhancing the reliability of the findings. It emphasizes the importance of considering different scenarios and weight variations when assessing project complexity and underscores the need for a comprehensive understanding of the interrelationships among PCFs to effectively manage project complexity in metro rail projects.

4.8 Conclusion

The study of project complexity in Indian metro rail construction holds significant importance due to the complex nature of these projects. This research specifically focuses on identifying PCFs and the interrelationships among these factors in metro rail projects in India. Real-time metro rail projects were considered case studies to gain insights into the occurrence of PCFs. DEMATEL method was applied to analyze the interdependencies of complexity factors. Design and construction changes, land acquisition issues, utility relocation delays, structural design problems, information exchange, and unpredictable geological conditions are highly interrelated PCFs. These factors were categorized into cause-and-effect groups, emphasizing their interdependence. This study presents a novel approach to project complexity assessment, identifying PCFs and analyzing their interdependence. The methodology assists metro organizations and project managers in formulating strategies to reduce the effects of complexity. These findings can serve as a benchmark for similar projects and extend to various metro rail and construction projects, particularly those sharing common complexity factors such as large-scale infrastructure needs, extensive stakeholder involvement, and urban location challenges.

The suitability of the findings for benchmarking across similar projects stems from the detailed identification and analysis of key complexity factors that are common to many large-scale infrastructure projects. For instance, challenges like land acquisition, regulatory delays, and interdependencies between technical and organizational elements are not exclusive to metro rail projects but are also prevalent in other transportation, urban development, and infrastructure construction projects. Thus, projects that exhibit similar interrelated complexity factors such as highways, airports, or even large-scale urban developments can adopt the DEMATEL-based approach used in this study to understand and prioritize their own complexity factors. The categorization of PCFs into cause-and-effect groups offers a generalizable framework that project managers in different sectors can adapt, allowing them to focus on critical issues early in the project lifecycle.

In addition, the practical insights and guidance offered by this study are especially useful for transportation projects and other infrastructure-related endeavors. The methodology used, such as identifying the root causes of delays (e.g., land acquisition or utility relocation) and understanding how these affect downstream activities, can be applied to other types of projects where similar technical and organizational challenges exist. For example, projects in urban environments that require careful coordination with multiple stakeholders such as public utilities, regulatory bodies, and community organizations can benefit from this approach to manage complexity and mitigate risks. However, the findings are most applicable to projects that share specific characteristics with metro rail constructions such as large-scale transportation infrastructure projects or construction efforts involving significant urban development. For these projects, the complexity factors related to land use, environmental constraints, and stakeholder coordination are similar enough that the methodologies developed in this study can be directly applied. In contrast, projects in more rural or less regulated environments, or those that do not face such high levels of interdependency between complexity factors, may need to adapt the findings more cautiously. Under these conditions, the complexity factors might not play as significant a role, and thus, the methodology may require modification.

In conclusion, the generalizability of the findings depends on the presence of key complexity factors that are shared across large-scale infrastructure and urban transportation projects. The DEMATEL approach and insights derived from this study are most applicable to projects that face interdependent technical, organizational, and socio-political challenges, particularly in densely populated or regulated environments.

4.9 Implications of the study

Theoretical Implications

The study shows the application of complexity theory in metro rail projects. The identification of complexity factors and the analysis of interdependencies between complexity factors in underground and elevated metro rail projects is limited. As a result, this study shows the use of case-based research and the DEMATEL method to identify the PCFs and their interdependencies. This methodology is generic and can be applied to any kind of project. The case and cross-case level analysis depicts the similarities and differences of PCFs in underground and elevated metro rail projects.

Practical Implications

The results of this study can be used by government organizations and project stakeholders involved in metro rail projects for project management. Understanding the interrelationships between various PCFs specific to metro rail projects can help them develop effective management strategies. The application of DEMATEL method can help in effective distribution of work, cost control, and resource allocation for project activities. The research approach can be applied to metro rail projects or any construction projects as many developing nations are facing similar challenges in mega projects. Therefore, project managers can use the research findings as a benchmark for complexity management. The study's findings can be used by researchers for analysis and research on metro rail projects.

Chapter 5

Analyzing the Impact of Project Complexity on the Performance Parameters of Metrorail Project Using Machine Learning Models

5.1 Overview

Project complexity is one of the most common issues faced by metro rail projects due to the complex and interdependent characteristics. The challenging characteristics necessitate a study to measure the impact of project complexity in metro rail projects. ML emerges as a robust tool to identify the impact of complex challenges. However, there has been little research using ML models to determine the impact of project complexity in metro rail projects. As a result, a prediction model was developed in this study using ML models to identify the impact of project complexity on project performance parameters (PPP). For analyzing project complexity, the key factors influencing complexity were first identified. Furthermore, SVM, RF, and DT were employed together as an integrate model. This model evaluates the impact of project complexity on PPP (time, cost, scope, quality, sustainability, and reliability) in metro rail projects. The study's results demonstrate the effectiveness of this ML model in predicting the impact of project complexity on various parameters in metro rail projects. Time, scope, and cost are accurately predicted, highlighting the model's robust performance in predicting the impact. However, challenges arise in predicting quality and sustainability, due to their complex nature and multifactorial influences. This model, integrating insights from different algorithms, provides a comprehensive view of complexity's impact, enhancing overall prediction accuracy. This outcome helps in the model's strategic application for improved project management and decision-making in metro rail projects, offering valuable insights for the construction industry.

5.2 Introduction

Project complexity is a fundamental characteristic of project management, influencing the success and outcomes of construction projects (Flyvbjerg, Bruzelius, et al., 2003). However, the type and characteristics of complexity in projects have been subjected to significant debate, leading to a lack of well-defined terms and frameworks in existing literature. Despite identifying complexity as a significant factor, limited research has been conducted on defining and effectively managing complexity in construction projects. To optimize project performance, it is necessary to accurately define and measure project complexity and its relationship with project outcomes (Turner & Muller, 2005). In particular, the construction of large-scale and highly complex projects, known as "megaprojects," establishes unique challenges beyond conventional construction projects (Flyvbjerg, Bruzelius, et al., 2003). Megaprojects involve the construction of major infrastructure and utilities that significantly impact society, the environment, and the economy (Flyvbjerg, Bruzelius, et al., 2003; Koppenjan & Leijten, 2005). As they are involved in large investments and collaborations between private companies and governments, the management of megaprojects becomes politically sensitive and requires careful consideration of uncertainty, evolving interfaces, and timelines (Floricel & Miller, 2001). However, despite its importance, there is a lack of studies concerning the definition and characterization of complexity in the context of metro rail projects. Metro rail projects, being significant to urban transportation infrastructure, present complex challenges and interrelationships between various project factors (Floricel & Miller, 2001).

ML is an essential model with cognitive analytics, focusing on predicting problems and operations with thorough instructions (Jordan & Mitchell, 2015). It can also adapt existing methodologies for analyzing complex tasks (Shalev-Shwartz & Ben-David, 2014). Recent advancements have led to the emergence of innovative machine-learning models applied across sectors. In construction, it aids in virtual reality-based building information modeling and construction site monitoring through risk prediction (Rahimian et al., 2020; Sanni-Anibire et al., 2020). Likewise, it's also used in consumer services and transportation sectors to enhance experiences and reduce complexities (Jordan & Mitchell, 2015; Cong et al., 2022; Li et al., 2022). Classification, regression, ranking, clustering, and dimensionality reduction (Mohri, Rostamizadeh, & Talwalkar, 2018) are recent applications developed in ML. Studies have been conducted specifically on the management of construction projects to understand how enormous amounts of project data can be analyzed (Whyte et al., 2016). Pre-existing ML algorithms have only rarely been used to predict building cost overruns (Soman & Whyte, 2020). They have mostly concentrated on applications to speed up design processes in the construction industry (Chen & Whyte, 2022). From the literature, it is evident that various quantitative measures are used to analyze the project complexity of various construction projects. The Earned Value Method (EVM) is commonly used for assessing project performance and cost estimation (Cheng et al., 2006). The time series analysis method in construction projects is utilized to predict project needs like time and cost (Cheng et al., 2006; Joukar & Nahmens, 2016). The fuzzy logic method combined with EVM is used mostly for the prediction of progress analysis (Naeni et al., 2014; Yu et al., 2021). The outcomes of engineering projects are predicted using the integration of EVM and Montecarlo simulation (Bonato et al., 2019).

Zhang et al. (2018) introduced a comprehensive framework for evaluating the resilience of extensive and complex metro networks. Batselier & Vanhoucke (2015), in their studies, compared the accuracy of the project cost and time using EVM and simulation methods. A social network theory-based model was used to explore risks associated with stakeholders and their relationships in complex green building projects (Yang & Zou, 2014). Uddin (2017) suggested a social network analytics relationship framework for analyzing project stakeholders' networks and interactions.

The literature lacks a standardized framework for understanding and managing complexity in metro rail projects. Despite the significant application of various quantitative methods in construction projects, there exists a distinguished gap in employing ML models to understand the complex relationship between project complexity and performance parameters in metro rail projects. While EVM and time series analysis (Cheng et al., 2006), and fuzzy logic (Yu et al., 2021) have been applied to assess project performance, predict future needs, and manage uncertainty, they primarily focus on singular aspects and often lack the holistic understanding offered by ML. These conventional methods lack the tools/techniques to identify the complex relationships between diverse complexity factors and multiple performance parameters. Few researchers have been able to comprehensively describe the interrelationships and causal relations from the perspective of metro rail projects (Floricel & Miller, 2001). However, the existing literature lacks adequate studies on predicting the impact of project complexity on PPP like schedule, budget, scope, and quality performance, which are essential for assessing project performance in metro rail projects.

Consequently, the potential to show hidden patterns, significant impacts, and unforeseen correlations within the context of project complexity in metro rail projects, remains unexplored. The application of ML models, known for their capability to process complex data and identify complex patterns, could bridge this gap, and provide a more comprehensive insight into how project complexity impacts various performance parameters in metro rail projects. To bridge the existing gap in identifying the impact of project complexity on PPP and optimizing project complexity within metro rail projects, there is a requirement for developing advanced analytical methods, particularly using ML models, as they are highly effective in handling complex and multidimensional data and predicting outcomes in various domains. Application of the ML model in this research helps to understand the complex relationships between project parameters and predict potential challenges in metro rail projects.

The primary objective of this study is to develop a robust prediction model employing ML models to predict the impact of project complexity on PPP. This study aims to discover the project complexity impact on PPPs in metro rail projects by developing a prediction model using ML. Through an in-depth analysis of data, project characteristics, and diverse performance factors, this model seeks to predict the impact of project complexity on PPP like time, cost, scope, quality, sustainability, and reliability.

This study extensively reviews the literature on project complexity in metro rail projects, identifying various complexity factors through literature analysis and expert discussions. The study also includes a review of the latest machine-learning models and techniques applicable to metro rail projects. The methodology for developing the prediction model is outlined, using a comprehensive dataset from metro rail projects containing key project complexity and performance factors. In conclusion, this research aims to improve the understanding and management of project complexity in metro rail projects through ML models.

5.3 Literature Review

Project performance analysis is an important requirement for project success in achieving its objectives (Kagioglou et al., 2001). In the domain of construction engineering and management, various analytical methods have been utilized to predict complex processes (Molenaar et al., 2000; Mohamed, 2003; Dikmen & Birgonul, 2004). These methods are designed for specific research goals and data requirements. Statistical methods, particularly multiple regression analysis, have gained popularity for establishing cause-and-effect relationships for identifying project complexity (Chan et al., 2001; Han et al., 2007). Megaprojects, known for their complexity and risks, are considered successful when their complexity is effectively managed (Ashkanani & Franzoi, 2023). However, there is still a need for more research to gain a deeper understanding of the complexity associated with megaprojects like metro rail projects. Several researchers have emphasized the requirement of further investigation into abstracting and measuring complexity in the context of megaprojects, particularly the increasing number and scale of such projects worldwide (Gidado, 1996; Xia & Lee, 2004; Gransberg, 2013; Bakhshi et al., 2016). The existing research on project complexity shows varying perspectives among researchers (Dao et al., 2016; Zhu & Mostafavi, 2017b). Researchers, Whitty & Maylor (2009), argue that the term "complexity" lacks practicality without proper measures. In response, project management experts have identified complexity indicators and proposed descriptive models to measure them (Bosch-Rekveldt et al., 2011; Geraldi et al., 2011; Vidal et al., 2011b; He et al., 2014). Researchers have used multiple case studies, qualitative and quantitative studies, questionnaire surveys, systematic literature surveys, and comparative case studies to identify and assess project complexity (Vidal et al., 2011b; Botchkarev & Finnigan, 2015). Despite these efforts, there is still no common understanding or method to define and measure project complexity (Mikkelsen, 2021). This lack of clarity delays project managers' ability to optimize performance on complex projects. While individual factors related to megaprojects have been identified in the literature, there is a need for quantitative methods and frameworks that explain the interrelationships among the factors (Chapman, 2016). There is also a need for researchers to emphasize the importance of incorporating the experiences of practitioners in understanding complexity (Geraldi & Adlbrecht, 2007; Mikkelsen, 2021). According to Crawford et al. (2006), reflective practice, where practitioners learn from past experiences and apply practical knowledge in decision-making, can be seen as valuable input in dealing with complexity. According to Patanakul et al. (2016), the conventional description of project performance, represented by the "iron triangle," concentrates on time, cost, scope, and quality, and its description is limited. In the opinion of Golini et al. (2015) and Young et al. (2020), the studies of megaproject performance, internal performance from the project management perspective, and external performance from the stakeholders' viewpoint are to be considered.

5.3.1 Project complexity theory

The management of project complexity is necessary for ensuring the successful completion of projects (Manson, 2001; Cooke-Davies et al., 2007). Understanding the relationship between project conditions and success is essential for effective project implementation (Thiry & Deguire, 2007; Aritua et al., 2009). Complexity in projects is often unpredictable and arises from the interactions within and between organizations. To mitigate the impact of unpredictability, it is vital to measure and manage project complexity levels, minimizing the activation of risks and increasing the chances of project success. This research paper employs the concept of a Complex Adaptive System (CAS) as a framework to understand project complexity. The CAS model is used as the foundation for defining complexity theory in the context of megaprojects, large infrastructure projects, and organizations (Remington & Pollack, 2008). Complexity theory is significant in metro rail projects due to the inherent complexity and uncertainty involved in such large-scale infrastructure projects. By applying complexity theory, project managers can better understand the interdependencies and dynamics within the project, enabling them to identify potential challenges and address them proactively. It provides a holistic approach to understanding the various factors affecting project performance and successful project delivery.

5.3.2 Project complexity factors

Project complexity is an essential aspect influenced by dynamic, structural, and unpredictable factors (Luo & Wood, 2017). Despite efforts to categorize and assess complexity, accurately quantifying it remains challenging (Gransberg et al., 2013; He et al., 2014). Various authors have classified complexity based on their research. Harvey et al. (2008) pointed to stakeholders, delivery, team, and organization as primary factors of organizational complexity. Gerhard & Christian (2008) listed society, operation, task, consciousness, and culture as complexity factors. Meanwhile, He et al. (2014) developed a six-dimensional framework encompassing information, technological, cultural, organizational, goal, and environmental complexity.

Construction projects tend to be more complex due to uncertainty and interdependence factors such as project size, interdependencies, scope, stakeholder management, technology, diversity, and ambiguity (Patanakul et al., 2016; San Cristobal et al., 2018; Sridarran et al., 2017). Dao et al. (2016) examined project complexity from diverse perspectives, including its relationship to project management, project risk, and difficulty. (Bosch-Rekveldt et al., 2011) developed the TOE framework to offer insights into technology adoption, organizational change, and performance. He et al. (2014) expanded this framework to include the complexity of culture, acknowledging the diverse backgrounds of employees involved in construction projects. Nguyen et al. (2015) expanded the framework further to include infrastructural complexity, socio-political complexity, and scope complexity, in addition to TOE. While previous research has recognized the impact of project complexity in mega construction projects, there is limited empirical evidence exploring the relationship between complexity factors and their performance in the context of complex construction projects like metro rail projects.

5.3.3 Relationship between performance and project complexity in projects

The relationship between project complexity and project performance has been extensively studied in the literature (Puddicombe, 2011; Senescu et al., 2013; Qazi et al., 2016; Mirza & Ehsan, 2017; Liu et al., 2024). Various research studies have shown that project complexity has a significant impact on project performance, leading to cost overruns, schedule delays, and increased uncertainty (Floricel & Miller, 2001; Shenhar et al., 2002; Qazi et al., 2016; Mirza & Ehsan, 2017). Complexity is often considered a key source of risk and uncertainty in projects, resulting in additional costs throughout the project life cycle (Floricel et al., 2016). Studies have demonstrated an inverse relationship between complexity and project performance, with more complex projects facing greater challenges in meeting project goals (Antoniadis et al., 2011). Floricel et al. (2016) demonstrated the inverse relationship between complexity and project performance on construction projects. Senescu et al. (2013) discovered a positive association between complexity and interface issues in the AEC (Architecture, Engineering, and Construction) industries. Technical complexity has a major impact on project performance in construction projects (Floricel et al., 2016). Puddicombe (2012) discovered that complexity characteristics were collectively and negatively related to project performance in various sectors (energy, transportation, water infrastructure, etc.).

Overall, understanding and effectively managing project complexity is essential for ensuring successful project outcomes (Floricel et al., 2016). Luo et al. (2016) used a web-based questionnaire to acquire a deeper understanding of the relationship between project complexity and performance. To assess the relationship between complexity and project performance, researchers used simulation in addition to opinion-based data (e.g., surveys and interviews) due to a lack of project empirical data**.** Another study by Lebcir (2011) used system dynamics modeling to show that factors like project uncertainty, new technology, interdependence, and project size influenced project cycle time. Lebcir (2011) and Kennedy et al. (2011) used Monte Carlo simulations to demonstrate the impact of complexity on team communication and performance in building projects. From literature, it is observed that researchers have identified a strong relationship between complexity and project performance in various mega projects.

5.3.4 Research gap

The existing research has focused on studies of project performance in megaprojects, but studies on the impact of project complexity on the performance parameters of metro rail projects remain unexplored. Though few studies in the literature address the issue of project complexity on project performance, a detailed study to predict the impact of project complexity on PPP (project performance parameters) in metro rail using ML has not yet been explored. To address this gap, this study aims to predict the impact of project complexity on various PPPs, such as time, cost, quality, scope, sustainability, and reliability in metro rail projects. SVM, DT, and RF ML models are employed together as an integrated model for developing a prediction model. By filling this research gap, the study contributes to a better understanding of how complexity can influence the success of metro rail projects, predict potential challenges, and enable the stakeholders to make better decisions.

ML regression models, such as SVM, DT, and RF, are used in metro rail projects to identify the complex relationships between project complexity and its impact on PPP. These models excel at capturing non-linear dependencies and patterns from diverse data sets. SVM clarifies how complexity affects parameters, DT identifies complex interactions, and RF provides a holistic view. SVM's ability to handle high-dimensional and non-linear data patterns makes it a promising approach for assessing project complexity as an important factor impacting project performance. Construction professionals use SVM to gain valuable insights, facilitating better project management and decision-making for successful outcomes (Dip et al., 2024). RF is a collective method that combines multiple decision trees to accurately predict and handle complex data patterns. It offers robustness and generalizability, making it suitable for assessing project complexity. On the other hand, DT models provide a transparent and interpretable representation of decision-making processes. DT models partition data into hierarchical structures, making them suitable for understanding and analyzing PCFs (Zheng et al., 2021). By employing three ML models, metro rail projects gain insights to guide decision-making, ensure optimal resource distribution, and adopt risk management. This practical approach leads to improved project outcomes, streamlined operations, and successful project delivery. Considering the complex nature of construction processes and uncertainties in metro rail projects, the study developed an integrated prediction model that integrates RF, SVM, and DT models. This model analyzed data from both underground and elevated metro rail projects. The performance of the three models was statistically evaluated and discussed. To validate the effectiveness of the proposed project complexity prediction model, it was compared with Traditional RF model.

5.4 Results and Discussions

In this study, ML models were used to identify the impact of project complexity on various PPPs and show complex relationships. SVM, DT, and RF ML models were used as statistical methods for prediction. SVM was employed to predict and analyze the impact of project complexity on PPP because of its expertise in handling high-dimensional data and identifying complex relationships among complexity factors. The DT model was used to determine the linear relationship between PCFs and to highlight the most influential complexity factor that impacts PPP. RF was used because it combines insights from multiple decision trees for high accuracy and stability and effectively addresses overfitting issues by combining all the predictions. Furthermore, RF accurately manages missing or incomplete project data for robust predictions when certain factors are unavailable. By examining complexity factors and their impact, these models help identify critical factors that impact project outcomes. The analysis of the three models is represented in Table 5.1.

Table 5.1 Analysis of the performance of three evaluation models (source: authors' own work)

Performance Parameter	Performance Evaluation	Support Vector Machine	Random Forest	Decision Tree
Time	Training Accuracy	0.544	0.565	0.529
	R^2 Score	0.544	0.510	0.532
	MAE	0.460	0.453	0.448
	MSE	0.370	0.406	0.388
	RMSE	0.615	0.637	0.623
	Average accuracy	0.826	0.820	0.824
Cost	Training Accuracy	0.535	0.764	0.770
	R^2 Score	0.607	0.686	0.690
	MAE	0.443	0.411	0.414
	MSE	0.412	0.335	0.325
	RMSE	0.642	0.579	0.570
	Average accuracy	0.807	0.826	0.828
Quality	Training Accuracy	0.802	0.516	0.728
	R^2 Score	0.597	0.575	0.536
	MAE	0.284	0.421	0.325
	MSE	0.354	0.373	0.408
	RMSE	0.595	0.611	0.639
	Average accuracy	0.831	0.827	0.819
Scope	Training Accuracy	0.567	0.230	0.375
	R^2 Score	0.383	0.349	0.291
	MAE	0.400	0.485	0.486
	MSE	0.365	0.385	0.419
	RMSE	0.604	0.620	0.647
	Average accuracy	0.815	0.809	0.801
Sustainability	Training Accuracy	0.614	0.314	0.358
	R^2 Score	0.437	0.416	0.425
	MAE	0.392	0.468	0.493
	MSE	0.393	0.408	0.402
	RMSE	0.627	0.638	0.634
	Average accuracy	0.821	0.817	0.819
Reliability	Training Accuracy	0.106	0.108	0.146
	R^2 Score	0.162	0.096	0.103
	MAE	0.586	0.598	0.583
	MSE	0.473	0.443	0.449
	RMSE	0.687	0.668	0.670
	Average accuracy	0.802	0.808	0.807

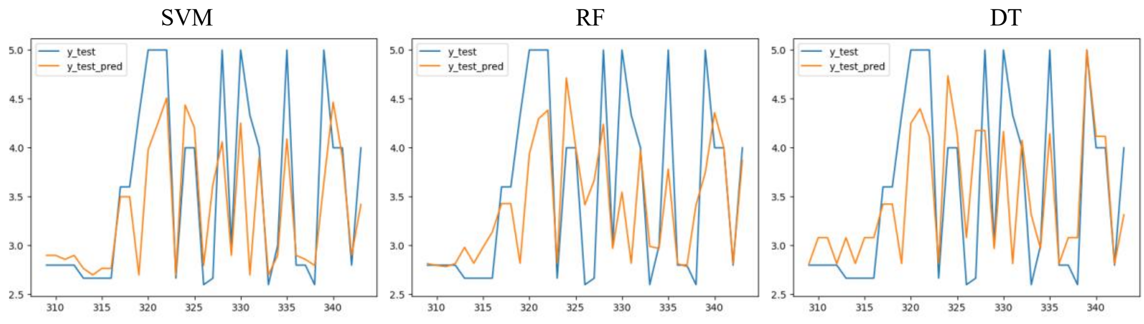
5.4.1 Impact of project complexity on performance parameters

The influence of project complexity on performance parameters in metro rail projects is a complex relationship. The prediction models, illustrated in Table 5.2 and Figures 5.1 (a) to (f), show how project complexity impacts PPP.

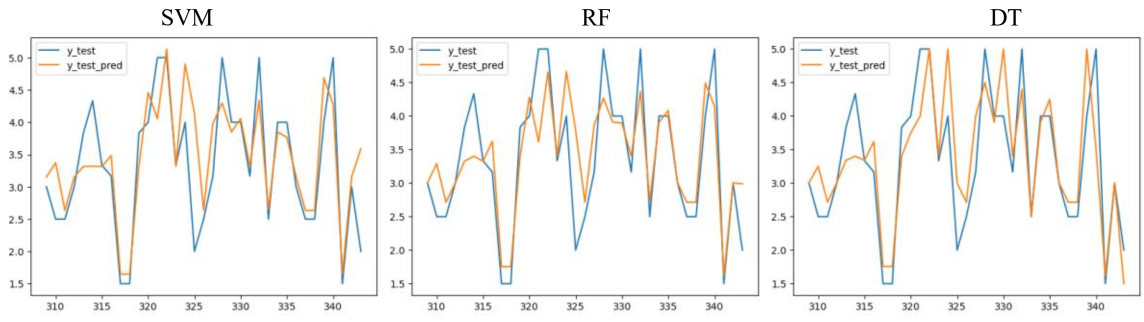
Table 5.2 The significance of prediction models of project complexity (source: authors' own work)

PP	Significance of Project Complexity
Time	The SVM model demonstrates a training accuracy of 54.4% and an R^2 score of 0.544, ensuring precise project completion time prediction with an MAE of 0.46 and RMSE of 0.615. Its average accuracy of 82.67% effectively forecasts metro rail project time. The SVM's low training accuracy, R^2 score, and average accuracy moderately impact overall complexity, primarily driven by time-related complexities from scheduling constraints and delays. The RF model achieves a training accuracy of 56.5% and an R^2 score of 0.51, indicating reasonably accurate estimations with an MAE of 0.453 and RMSE of 0.637. RF's low training accuracy and R^2 score suggest moderate complexity impact due to complex timelines caused by delays. The DT model attains a training accuracy of 52.9% and an R^2 score of 0.532 for predicting completion time, with an MAE of 0.448 and an RMSE of 0.623. Its moderate training accuracy and R^2 score denote moderate complexity impact influenced by scheduling complexities. These findings align with complexity factor analysis attributing the high impact of project complexity to time.
Cost	In the context of metro rail projects, the SVM model delivers a training accuracy of 54.4% and an R^2 score of 0.544, indicating its proficiency in predicting project completion time. The MAE of 0.46 and RMSE of 0.535 denote relatively minor deviations and error magnitudes. With an average accuracy of 82.67%, the model effectively forecasts project cost. Its high impact on overall complexity, driven by time-related complexities due to scheduling constraints and delays, aligns with the complexity factor analysis assigning a high impact on cost. Similarly, the RF model demonstrates good accuracy for cost predictions, obtaining a high training accuracy of 0.764 and an R^2 score of 0.686. For cost complexities, the model's high values highlight their substantial influence on project complexity, by the complexity factor analysis. The DT model exhibits varying accuracies across cost parameters, underscoring the need to consider parameter-specific complexities for effective decision-making in metro rail projects.
Scope	In scope analysis, the SVM model achieves a 56.7% training accuracy, capturing a 56.7% variance in metro rail project scope prediction with an R^2 score of 0.383, signifying moderate accuracy. A 0.4 MAE and 0.604 RMSE indicate deviations and error magnitude. Its 81.5% average accuracy implies 81.5% precision. SVM's low values suggest a moderate impact on complexity, tied to scope complexities shaping the project. RF shows moderate accuracy with 0.23 training accuracy and 0.349 R^2 score, reflected in 0.485 MAE, 0.385 MSE, and 0.62 RMSE. RF's low values imply a minor impact of complexity on the scope parameter. DT attains 0.375 training accuracy and 0.291 R^2 score, reflected in 0.486 MAE, 0.419 MSE, and 0.647 RMSE. DT's low values indicate a moderate complexity impact on the scope.

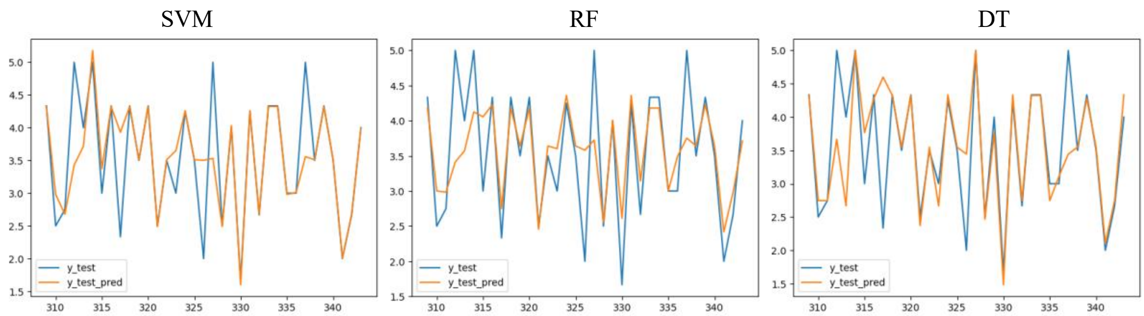
Quality	In quality prediction, SVM demonstrates excellence with an 80.2% training accuracy and 0.597 R^2 score, explaining an 80.2% variance. A 0.284 MAE implies a mere 0.284-unit deviation from actual quality, and 0.354 MSE signifies accurate predictions. The RMSE of 0.595 represents the error magnitude. Its 83.17% average accuracy underscores reliable quality estimation. SVM's high values signify a significant complexity impact. For RF, a 0.516 training accuracy and 0.575 R^2 score reflect moderate accuracy. A 0.421 MAE and 0.373 MSE imply moderate accuracy in quality predictions, while 0.611 RMSE indicates error magnitude. Its 82.72% average accuracy suggests a reasonably accurate quality assessment. DT excels in quality predictions with 0.728 training accuracy and 0.536 R^2 score. A 0.325 MAE means 0.325 average deviations from actual quality, while 0.408 MSE indicates moderate accuracy. The RMSE of 0.639 represents the error magnitude. Its 81.94% average accuracy implies satisfactory quality prediction. DT's moderate values signify a moderate impact on complexity.
Sustainability	In sustainability prediction, SVM exhibits moderate performance with a 61.4% training accuracy and 0.437 R^2 score, capturing significant variance. A 0.392 MAE suggests relatively precise predictions, with 0.393 MSE indicating reasonable accuracy. RMSE of 0.627 signifies error magnitude. Its 82.1% average accuracy showcases satisfactory sustainability estimation. For RF, a 0.314 training accuracy and 0.416 R^2 score reflect moderate accuracy. A 0.468 MAE and 0.408 MSE imply moderate sustainability prediction accuracy, while 0.638 RMSE indicates error magnitude. DT excels in sustainability prediction with 0.358 training accuracy and 0.425 R^2 score. A 0.493 MAE signifies a 0.493 average deviation from actual sustainability values, while 0.402 MSE suggests moderate accuracy. RMSE of 0.634 represents error magnitude. DT's high values indicate a significant complexity impact. Complexity factor analysis aligns, attributing high impact to sustainability.
Reliability	SVM faces challenges in predicting metro rail project reliability, evident in its 10.6% training accuracy and 0.162 R^2 score, with 0.586 MAE and 0.473 MSE indicating higher errors and limited accuracy. RF's 0.108 training accuracy and 0.096 R^2 score suggest lower reliability prediction accuracy, with 0.598 MAE and 0.443 MSE signifying lesser accuracy. DT's 0.146 training accuracy and 0.1033 R^2 score reflect limited reliability prediction, with a 0.583 MAE and 0.449 MSE implying deviations and moderate accuracy. Despite variations in model performance, reliability-related complexities have a marginal influence on overall complexity, supported by low complexity Factor analysis impact attributions.



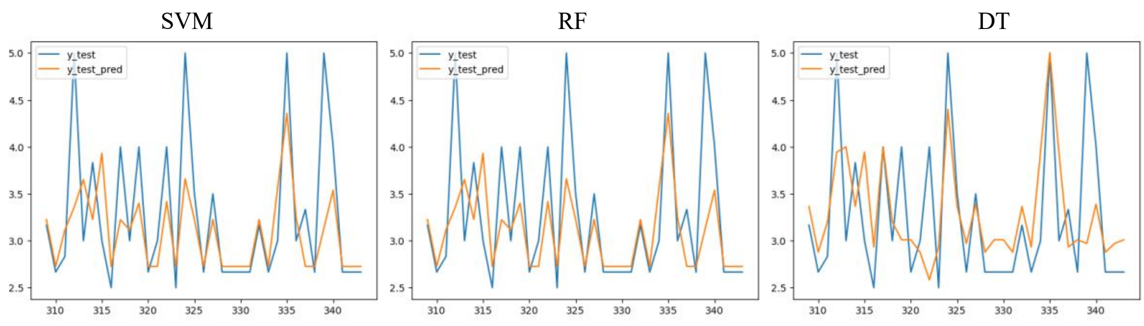
(a) Time models



(b) Cost models



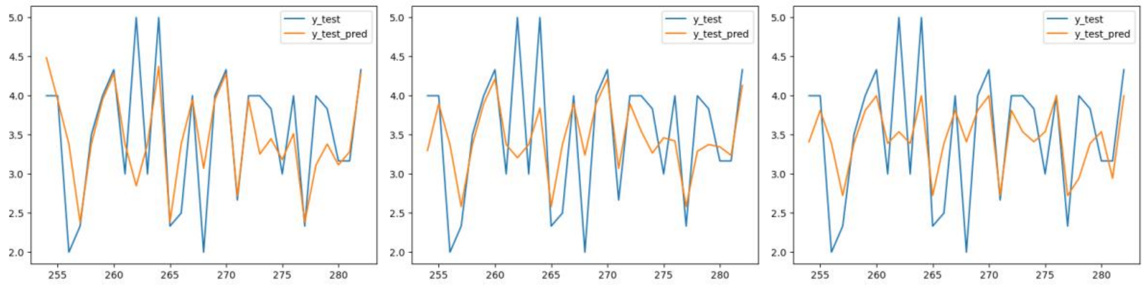
(c) Quality models



(d) Scope models

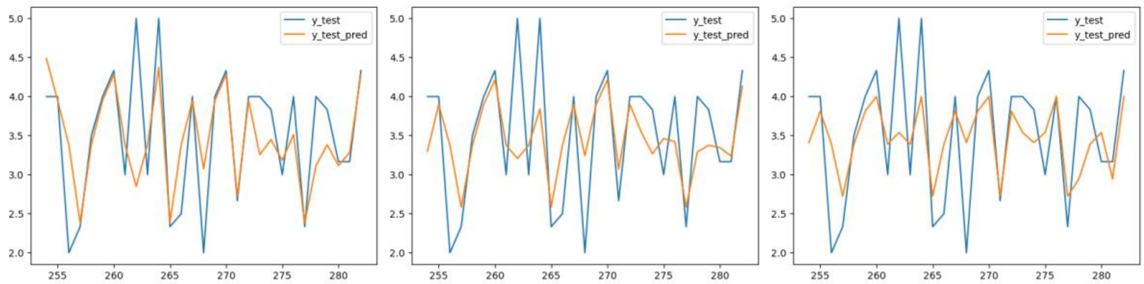
SVM RF DT

Figure Continues…



(e) Sustainability models

SVM RF DT



(f) Reliability models

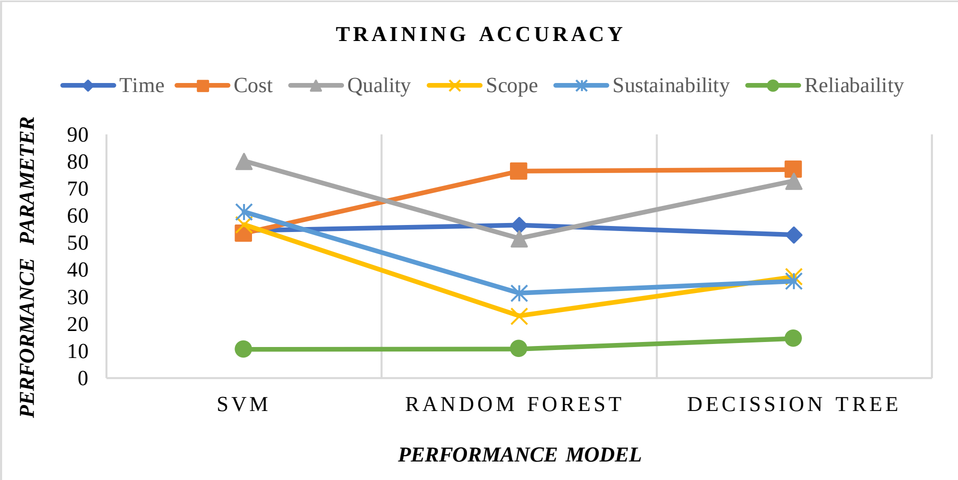
Figure 5.1 Prediction models (source: authors' own work)

In the graph, the orange line represents the predicted values, and the blue line represents the actual values, illustrating the impact of PCFs on each performance parameter. In terms of time and cost performance, the predicted and actual values exhibit a high level of similarity across all three models. The model accurately predicts time and cost performance parameters for metro rail projects, showing strong alignment with observed outcomes. For the scope, SVM and RF models demonstrate similarities between predicted and actual values, with a minor difference in DT. SVM and RF perform well in predicting scope-related outcomes, while DT shows slight inconsistency. In the quality model, the three models show minor changes between the predicted and actual values, indicating partial similarity in predictions. The model provides reasonably accurate predictions for quality parameters, with some variations among the models. In the sustainability model, the three models show differences between the predicted and actual values, suggesting a deviation in the model and a necessity for adjustments. The models were not able accurately predict sustainability-related outcomes, indicating a need for improvements or adjustments. Finally, the reliability model shows a divergent relationship between the predicted and actual values, representing model drift and the model's failure to adapt to changes. The reliability model exhibits a significant difference between predicted and actual values, indicating a need for model adaptation to maintain accuracy as performance factors change over time.

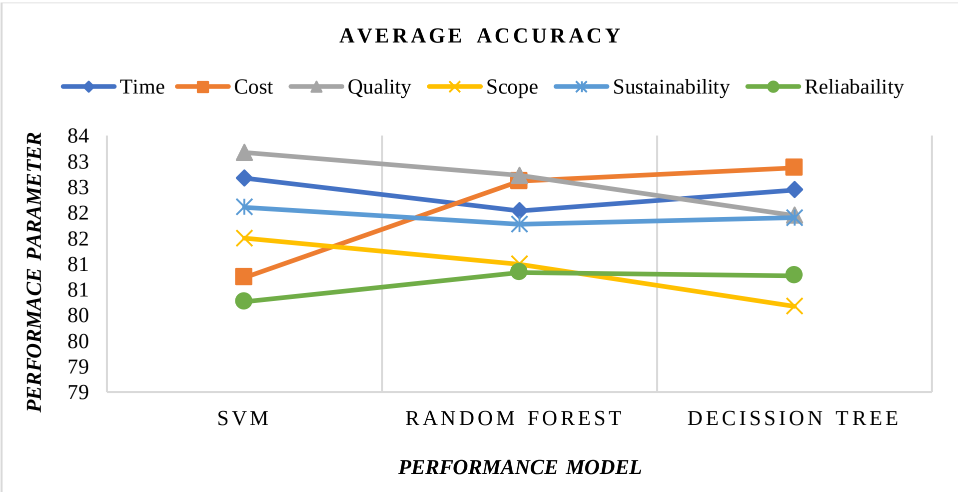
5.4.2 Results for the comparison of SVM, RF, and DT on the performance of PPP

The average accuracy and training accuracy of the models are represented in Figs. 5.2(a) and 5.2(b). SVM performs moderately well for most parameters, with relatively higher accuracy for quality predictions and moderate accuracy for time, cost, and sustainability predictions. It shows limited accuracy for scope and reliability predictions, indicating challenges in capturing the variance of these parameters. Overall, SVM demonstrates varying levels of accuracy across different project parameters in metro rail projects. RF exhibits good performance for cost predictions and reasonably accurate predictions for quality and time parameters. It shows moderate accuracy for sustainability and reliability predictions. However, the model's accuracy is relatively lower for scope predictions, indicating limitations in capturing the complexity of the project scope. Overall, RF performs well in certain areas but shows mixed results for different project complexity parameters. DT achieves reasonably good accuracy for cost predictions and moderate accuracy for quality and time predictions. It demonstrates moderate performance for sustainability and reliability predictions. However, the model's accuracy is relatively lower for scope predictions suggesting challenges in capturing the complexity of the project scope. Overall, DT exhibits mixed performance across various project complexity parameters.

In conclusion, SVM, RF, and DT ML models display varying performance in predicting the impact of project complexity on performance parameters in metro rail projects. SVM shows moderate to high accuracy across parameters, except for scope and reliability. RF excels in cost predictions but has mixed results elsewhere. DT performs well in predicting costs but not with scope parameters. These results highlight the impact of project complexity in metro rail projects, emphasizing the importance of this approach for effective assessment and management.



(a) Training accuracy of the prediction model.



(b) Average accuracy of the prediction model.

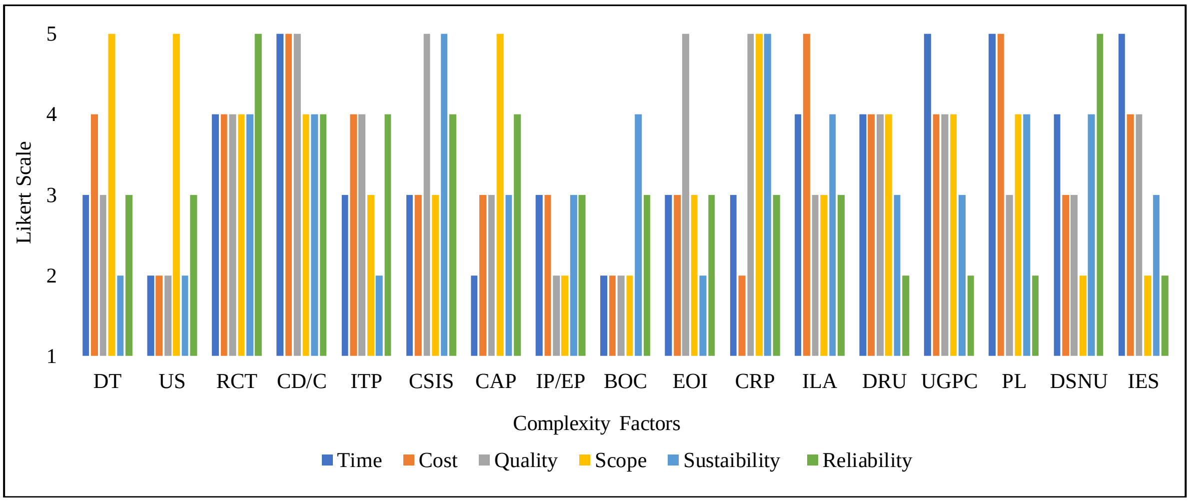
Figure 5.2 (a) and (b) Graphs representing training accuracy and average accuracy of prediction models (source: authors' own work)

5.4.3 Prediction of the project complexity impact on the project parameters (time, cost, quality, scope, sustainability, and reliability) in metro rail projects

The complex nature of underground and elevated construction leads to delays in metro rail projects. Changes in Design/Construction (CD/C) have a very high impact on time, cost, and quality parameters due to the complex challenges caused by the construction of metro rail projects. This complexity factor impacts both project types, emphasizing the need for structural reliability and safety in underground tunnels and durability in elevated structures. Uncertainties in Scope (US) cause a moderate impact on metro rail projects due to rigid project timelines, the use of advanced technologies, and uncertainties related to geological conditions. While

Cumbersome Administrative Processes (CAP) significantly delay progress in the projects due to delays in decision-making and interface and hierarchical problems, Breach of Contract (BOC) causes impact due to interrupted schedules, inflated costs, thereby compromising on overall project quality. Uncertainties in Scope (US) result in cost overruns due to uncertainties in the structural planning of the project, while Change in Regulation Policy (CRP) necessitates additional expenditures to align with new policies. Project Location (PL) and Issues in Land Acquisition (ILA) cause challenges demanding ample space for underground structures and land for elevated pillars and stations, causing a high impact on cost parameter. Uncertainties in Scope (US) and Internal/External Politics (IP/EP) impact quality, and BOC further raise concerns about quality problems.

Uncertain Geotechnical and Physical Conditions (UGPC) cause significant risks for underground projects, potentially causing delays and quality issues. Scope modifications and challenges arise from Internal/External Politics (IP/EP), BOC, Design Changes to Suit Non-Divertible Utilities (DSNU), and Interference with Existing Structures (IES). The exchange of information (EOI) highly impacts the quality parameter. Change in Regulation Policy (CRP) causes challenges in approvals and adapting to regulatory changes, adversely impacting project scope, quality, and sustainability. Compatibility of the System with Indian Standards (CSIS) has an impact on quality and sustainability parameters due to inadequate safety standards for tunneling and structural works. Sustainability faces challenges from Diverse Technology (DT), Uncertainties in Scope (US), Interrelationship among Technological Processes (ITP), and Exchange of Information (EOI). Reliability issues occur due to Delay in the Relocation of Utilities (DRU), Uncertain Geotechnical and Physical Conditions (UGPC), and Project Location (PL), causing an impact on the project's robustness and performance. Risk of Complex Technologies (RCT) and Design Changes to Suit Non-Divertible Utilities (DSNU) cause reliability challenges, emphasizing the need to mitigate risks associated with complex technologies and accommodate utilities in designs. The impact of PCFs on PPP is shown in Figure 5.3.



Codes: DT- Diverse Technology; **US**- Uncertainties in Scope; **RCT**- Risk in complex Technologies; **CD/C**-Change in design construction; **ITP**-Interrelationships among technological processes; **CSIS**- Compatibility of system with the standards; **CAP**-Cumbersome administrative process; **IP/EP**-Internal/external politics; **BOC**-Breach of contract; **EOI**-Exchange of information; **CRP**-Change in regulation policy; **ILA**-Issues in land acquisition; **DRU**-Delay in the relocation of utilities; **UGPC**-Uncertain geotechnical and physical conditions; **PL**-Project Location; **DSNU**-Design changes to suit non-divertible utilities; **IES**-Interference with existing structures. (Likert Scale 1-Very Low; 2-Low; 3-Moderate; 4-High; 5-Very High)

Figure 5.3 Graph representing the impact of project complexity factors on project performance parameters (source: authors' own work)

According to overall analysis, the CD/C and UGPC have higher impact on the time parameter, but the US and BOC have a lower impact. In terms of cost, CD/C and UGPC have a greater impact on cost, while factors such as US and BOC have lower impact. ITP and EOI have a moderate impact on quality, indicating the need for further focused investigation. CD/C and CRP complexity factors have a moderate impact on scope, sustainability, and reliability. Factors such as ITP and BOC have a limited impact on project scope, sustainability, and reliability. DT has a high impact on time, cost, reliability, and quality, but a moderate impact on scope and low impact on sustainability. The complexity factor US has a low impact on cost and sustainability, moderate impact on quality, and a high impact on scope. RCT has a minor impact on time, cost, and scope but higher impact on sustainability and reliability. CD/C has a moderate impact on time, cost, and scope, a higher impact on quality, and low impact on sustainability and reliability. ITP has a moderate impact on time and cost, as well as a high impact on quality and reliability, but has lower impact on scope and sustainability. The CSIS factor has higher impact on quality, sustainability, and reliability, and the CAP factor has moderate impact on quality, sustainability, and reliability. The overall findings show the impact of PCFs on performance parameters in metro rail projects. While complexity correlates with longer schedules and higher costs, it also has varied degrees of impact on quality, scope, sustainability, and reliability parameters. Understanding the impact is necessary for informed decision-making in metro rail project design and execution.

The overall complexity of the metro rail project is significantly impacted by various complexity factors. The high impact of project complexity on time and cost parameters results in complex scheduling, budget allocation, and potential delays. The moderate impact on quality parameters results in the need for specialized expertise and adjustments. The moderate impact on scope and sustainability results in defining boundaries and coordinating tasks. A Low impact on reliability implies that project complexity has minimal effect.

5.5 Conclusions

The application of ML models in construction projects is still in the nascent stages. However, the application is limited to design, time, and cost prediction in construction projects. Therefore, this study develops a prediction model to identify the impact of project complexity on various project performance parameters. An integrated ML model combining (SVM, RF and DT) was used to predict the impact of project complexity on project performance parameters in metro rail projects. Performance parameters' quality, scope, and sustainability have significant variations and a moderate impact on project complexity while other parameters, such as time, and cost, predict a high impact on project complexity. Reliability poses challenges in predicting the impact of project complexity and is observed to have low impact. Furthermore, this holistic approach combined the strengths of different models and led to more comprehensive and accurate predictions in the context of project complexity in metro rail projects.

Performance parameters like time, scope, and cost are predicted quite accurately by all three models. This means that these models can effectively understand and anticipate how these factors will behave in metro rail projects. However, other factors, such as quality and sustainability, are more challenging to predict accurately. This is because these factors are more complex and can be influenced by a variety of factors that are not as easy to attain using these models. To deal with this variability, it's important to take a comprehensive approach. Therefore, instead of relying solely on one model, it's beneficial to consider the accuracy of all three. This way, the study represented a comprehensive understanding of the impact of complexity on metro rail projects, allowing for more informed decisions. The study suggests that combining insights from different models can provide a more holistic view of how project complexity affects different performance parameters of metro rail projects, leading to better project management and decision-making.

In summary, each ML model has strengths and weaknesses in predicting different project parameters. SVM tends to perform moderately well with linear trends; RF is effective in predicting certain non-linear patterns; and DT shows mixed prediction. Therefore, the choice of this model can be applied to predict the impact of project complexity on a specific project parameter. The integrated model strategically employs domain-specific developments and can make more comprehensive predictions in metro rail project management. The results of this study offer valuable insights into the prediction and management of project complexity in metro rail projects, providing a valuable tool for improving project outcomes and decision-making in the construction industry.

5.5.1 Project complexity management strategies

To optimize performance and minimize complexities in metro rail projects, strategic approaches are vital and are suggested below: Comprehensive planning, guided by essential tools like Work Breakdown Structure (WBS) and the use of Project Management Body of Knowledge (PMBOK) guidelines, serves as the foundational blueprint, preventing scope creep and ensuring task clarity. Robust stakeholder engagement and clear communication channels minimize conflicts and promote collaboration and advancing decision-making. A skilled workforce, empowered through continuous training, reduces errors and strengthens decision-making. Application of BIM in metro rail projects streamlines collaboration, enhances visualization, detects clashes, manages lifecycles, enables data-driven decisions, reduces complexity, and improves efficiency. Structured change management ensures modifications that align with project goals, minimizing disturbances and developing flexibility. Regular performance assessments offer real-time insights for continual project optimization and success. These strategies offer a holistic approach to metro rail project management, resulting in timely, cost-effective, and high-quality outcomes, meeting stakeholder expectations, and contributing to sustainable urban infrastructure development.

5.5.2 Future scope

In the future, enhancing ML models for metro rail projects holds potential. Customized models could address complexities more accurately. Also, refining the integrated approaches that combine model strengths may yield reliable predictions. Integrating real-time data from sensors and weather forecasts can enhance responsiveness to dynamic changes. Moreover, expanding models to predict maintenance needs based on usage patterns would enable proactive maintenance planning, minimizing downtime effectively. These advancements can significantly improve project management and decision-making in metro rail projects.

5.5.3 Practical implications

Real-time data integration facilitates prompt decision-making and efficient adaptation to unexpected challenges. Predictive models for maintenance planning minimize interruptions, ensuring smoother operations. Accurate predictions foster transparent communication with stakeholders, promoting collaboration. Real-time insights enable adaptive planning, effectively addressing changes in metro rail projects. These practical implications enhance project resilience and success.

Chapter 6

Development of a Project Complexity Measurement Model for Metro Rail Projects

6.1 Overview

The purpose of the study is to develop a PCI model using the BWM to quantitatively analyze the impact of project complexities on the performance of metro rail projects. This study employed a two-phase research methodology. The first phase identifies complexities through literature review and expert discussions and categorizes different types of complexities in metro rail projects. In the second phase BWM, a robust Multi-Criteria Decision-Making technique, was used to prioritize key complexities, and a PCI model was developed. Further, the PCI model developed was validated through case studies and sensitivity analysis was performed to check the accuracy and applicability of the PCI developed model. The analysis revealed that location complexity exerted the most substantial influence on project performance, followed by environmental, organizational, technological, and contractual complexities. Sensitivity analysis revealed varying impacts of complexity indices on overall project complexity. Existing studies on project complexity which involve identification and quantification were limited to megaprojects other than metro rail projects. Efforts to quantitatively study and analyze the impact of project complexity in metro rail projects have not been adequate. The PCI model that was developed and its validation contribute to the field by providing a definitive method to measure and manage complexity in metro rail projects.

6.2 Introduction

Metro rail projects are classified as one of the megaprojects within the transportation sector due to their complexity and uncertainty. According to the definition provided by the Ministry of Statistics and Program Implementation (MoSPI) in India, megaprojects are characterized by their complexity and budgets exceeding US$156 million. Metro rail projects align with these criteria due to their significant infrastructure requirements and large financial investments. Megaprojects exhibit distinct features in terms of their size, cost, complexity, duration, technology, uncertainty, interface, and risk characteristics when distinguished from conventional projects (Van Marrewijk et al., 2008; Brockmann, 2009). Similarly, metro rail projects, as part of the megaproject category, exhibit specific differences in terms of construction, technology-encompassing challenges, features, and uncertainty. Research indicates that over 40% of transportation projects encounter cost and schedule overruns attributed to PCFs such as risk, uncertainty, complexity itself, time overruns, and cost overruns (Baccarini, 1996; Sedaghat-seresht et al., 2012). These complexities significantly impact the economies of both developed and developing countries (Baccarini, 1996; Mulholland & Christian, 1999) causing management challenges for transportation projects in nations at various stages of development (Baccarini, 1996). Understanding project complexity and its factors for transportation projects is crucial for successful and effective project management (Mevada & Devkar, 2017; Yu Maemura et al., 2018). Metro rail projects are complex and unpredictable and face various challenges during construction. Therefore, addressing the complexities and developing for measuring project complexities is essential. According to Baccarini (1996), assessing and controlling project complexity in the developing construction industry is difficult. Identifying project complexity problems is important as they often lead to drastic changes due to uncertainties (Bosch-Rekveldt et al., 2011). Project complexity plays a significant role in project development therefore, understanding the importance of measuring project factors and their relationships is necessary (Grisham, 2009; Dao et al., 2016). Vidal & Marle (2008) developed a conceptual framework for measuring project complexity and uncertainty. Bosch-Rekveldt et al. (2011) focused on process engineering complexity, while Wood & Ashton (2010) introduced a pre-construction complexity evaluation technique.

However, the methods were conceptual and utilized as decision-making frameworks and quantitative models to measure the occurrence of project complexity only in megaprojects. While they effectively assessed the relative importance of complexity factors in megaprojects, they lacked in identifying the direct impact of complexity on project performance in projects specific to metro rail projects. Moreover, existing methods do not adequately address the dynamic nature of complexity and its evolving impact throughout project lifecycles. Hence, there is a need for a method that quantitatively and comprehensively measures the impact of project complexity on performance in metro rail projects. Therefore, to address this gap, this study aims to develop a complexity measurement model to measure the impact of project complexity on the performance of metro rail projects.

6.3. Literature Review

6.3.1 Complexity and its factors in megaprojects

Complexity measurement plays a significant role in project management. Researchers have identified the importance of complexity measurement in megaprojects (Baccarini, 1996).

Project complexity depends on characteristics like project type, size, stakeholders, technological, contractual, and environmental factors (Bosch-Rekveldt et al., 2011). The literature identifies several complexity factors, such as lack of trust in contractors, lack of internal and external support, and managing diverse nationalities and languages (Geraldi & Adlbrecht, 2007). Organizational complexity occurs due to large team sizes, numerous hierarchical levels, diversity of organizational interdependencies, uncertainty in project outcomes, and difficulties in achieving project goals (Bosch-Rekveldt et al., 2011). Contractual complexity is caused due to contractual terms, the number of contracts, work packages, and stakeholder management (He et al., 2014). Environmental complexity factors are environmental risks, remote site locations, adverse weather conditions, lack of awareness regarding health, safety, security, and uncertain market conditions (He et al., 2014). Technological complexity factors are design changes, interdependence among construction activities, interface problems, and challenges associated with new technologies (Geraldi & Adlbrecht, 2007).

Rapid urbanization has increased the complexity of metro rail projects. These megaprojects are becoming complex due to the interdependence among complexity factors (Bosch-Rekveldt et al., 2011). Project managers are facing significant challenges due to an increase in project complexity in these projects (Baccarini, 1996; Bosch-Rekveldt et al., 2011). Several key factors contribute to the increased complexity of metro rail projects, including the need for extensive land acquisition, managing construction in densely populated urban areas, coordinating with multiple stakeholders (government bodies, contractors, and local communities), and addressing technical challenges such as tunneling, utility relocation, and dealing with unpredictable geological conditions.

Metro rail projects are also highly susceptible to socio-political factors, such as regulatory approvals, public opposition, and delays due to political changes, which add another layer of complexity to the project management process. Additionally, the scale and duration of metro rail projects, often spanning several years and requiring large-scale coordination, contribute to their complexity. These projects often require complex integration of technology, such as the installation of signaling systems, energy-efficient infrastructure, and maintaining safety standards, all of which further complicate the execution of such projects. Therefore, metro rail projects are more challenging due to the interrelatedness of these factors and the inherent uncertainties involved. The combination of technical challenges, socio-political influences, and long-term operational requirements make it necessary to have a systematic approach to assess and evaluate the complexity of metro rail projects. Although numerous studies have attempted to measure the complexity of megaprojects, many of these methods have shown limitations in assessing complexity (Vidal et al., 2011a). A more targeted approach that takes into account the unique characteristics of metro rail projects is needed to better manage and mitigate the complexity involved.

6.3.2 Project complexity measurement methods

Various measurement methods of project complexity from the literature are as follows: Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process (FAHP) are multi-criteria decision-making methods to address project performance and cost factors (Işik & Aladağ, 2017). The fuzzy Analytic Network Process (FANP) and Analytic Network Process (ANP) use fuzzy techniques to identify and analyze the interdependencies of project complexity (He et al., 2014). Social Network Analysis (SNA) helps in understanding team dynamics and productivity (Lee et al., 2018). Delphi analysis is used to identify and quantify complexities in megaprojects using expert judgments (Grisham, 2009). Gerrits & Verweij (2016) used qualitative comparative analysis (QCA) to compare the relationship between project complexities. To measure complexity, Project Sim Software (PSS) is used to visually display an organization's structure and work processes (Yujie et al., 2015). Al Nahyan et al. (2012) describe Project Complexity Assessment (PCA) as a tool for determining project complexity and assisting in decision-making. The Project Execution Complexity Index (PECI) evaluates the influence of project complexity on project performance, focusing on schedules and cost (Mirza & Ehsan, 2017). The Expected Value Method (EVM) is used to identify and quantify project risks (Gerrits & Verweij, 2016). Project Complexity Assessment and Management (PCAM) helps in the identification and verification of complexity indicators, guiding resource allocation for project completion (Kermanshachi et al., 2020; Peñaloza et al., 2020).

6.3.3 Gap in literature

The existing research has focused on studies measuring the impact of project complexity in megaprojects, but complexity assessment models in metro rail projects have not been thoroughly addressed. Previous studies on project complexity assessment are very limited, with most studies focusing on the conceptual framework of project complexity in megaprojects. Therefore, studies on assessing the impact of project complexity on metro rail projects are lacking. Hence, this research bridges the gap by developing a project complexity measurement model, i.e., PCI, to measure the impact of project complexity on the performance of metro rail projects.

However, the existing complexity measurement models often consider a limited number of complexity factors, falling short of identifying the impact of project performance caused by complexity in other projects like metro rail and similar projects and they are limited to megaprojects. The impact of such complexities on metro rail projects and the use of measurement methods to analyze the impact of project complexities in project performance in metro rail projects, remains underexplored. Hence, to fill this research gap, this study identifies project complexity and factors impacting metro rail projects, and subsequently develops the complexity measurement model to assess the level of impact on project performance for effective management of metro rail projects using BWM approach.

BWM is a highly effective and efficient approach that employs a linear scale to compare the overall complexity by considering the best (most significant) and worst (least significant) criteria (Rezaei, 2015). This approach was used to compute the weights of project complexities and their factors for the development of the PCI model. To evaluate and validate the applicability of the PCI model developed, real-time metro rail projects were considered case studies. Additionally, sensitivity analysis was performed to assess the robustness and reliability of the PCI. These validation measures ensured the accuracy and applicability of the PCI model in evaluating project complexity in metro rail projects. The step-by-step procedure of BWM is shown in Figure 6.1. A nine-point linear scale was used to determine the best (most significant) and worst (least significant) complexity factors resulting in a linear vector of $A_B = (a_{B1}, a_{B2}, a_{B3} \ldots, a_{Bn,})$; where $A_B =$ Best to Others (BO) and $A_W = (a_{W1}, a_{W2}, a_{W3} \ldots, a_{nW,})^T$; where $A_W =$ others to worst (OW) and consistency ratio (CR) is calculated to determine consistency using Equation 1. The result of the analysis is presented in Table 6.1 and Table 6.2.

$$\text{Consistency ratio (CR)} = \frac{\xi *}{Consistency\ Index} \qquad (1)$$

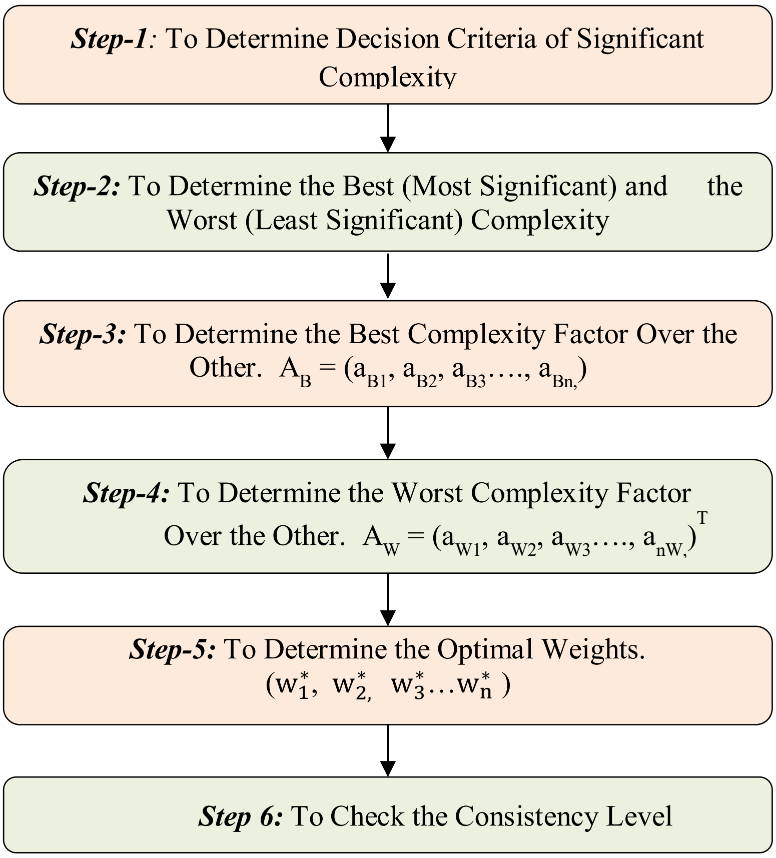


Figure 6.1 Flow chart of the BWM (source: authors' own work)

Table 6.1 Pairwise comparison of project complexities (source: authors' own work)

Best to others	TC	OC	CC	EC	LC
Best Criteria: Location	5	3	1	1	1
Others to Worst					Worst Criteria: Contractual
TC					4
OC					8
CC					1
EC					3
LC					2

Table 6.2 Pairwise comparisons of complexity factors (source: authors' own work)
(a) Comparison of technological complexity factors

Best to others	DT	US	RCT	CDC	ITP
Best Criteria: DT	5	3	1	1	1
Others to Worst					Worst Criteria: CDC
DT					5
US					1
RCT					1
CDC					1
ITP					1

(b) Comparisons of organizational complexity factors

Best to others	CSIS	CAP
Best Criteria: CAP	1	5
Others to Worst		Worst Criteria: CSIS
CSIS		5
CAP		1

(c) Comparisons of contractual complexity factors

Best to others	EOI	BOC	IPEP
Best Criteria: IPEP	1	2	1
Others to Worst			Worst Criteria: EOI
EOI			1
BOC			7
IPEP			1

(d) Comparisons of environmental complexity factors

Best to others	CRP	ILA	DRU
Best Criteria: ILA	2	1	1
Others to Worst			Worst Criteria: CRP
CRP			1
ILA			2
DRU			3

(d) Comparison of location complexity factors

Best to others	UGPC	PL	DSNU	IES
Best Criteria: UGPC	1	3	2	7
Others to Worst				Worst Criteria: PL
UGPC				3
PL				1
DSNU				1
IES				6

As per the findings of Rezaei (2015), the CR value should range between 0 and 1. A CR value closer to 0 indicates a higher level of consistency, while a value closer to 1 signifies inconsistency in the results. In this study, the CR value determined is less than 0.5, suggesting consistent results. Table 6.3 provides an overview of the calculated weights, global weights, and the consistency ratio for project complexity other factors impacting factors in metro rail projects. It presents a comprehensive summary of weight values obtained through the analysis. For a visual representation of the results, Figure 6.2 illustrates the graphical depiction of the individual key project complexity weights and factor weights, respectively.

Table 6.3 Weights of key project complexities and their influencing factors on metro rail projects (source: authors' own work)

Key factor	Weight of Key Project Complexity Factors	consistency ratio of the Key factor	Project Complexity factors	Weight of Project complexity factors	Consistency ratio of subfactor	Local rank	Global weights	Rank
Technology	0.07	0.31	DT	0.55	0.23	1	0.08	8
			US	0.15		2	0.03	13
			RCT	0.11		3	0.06	10
			CDC	0.16		4	0.01	15
			ITP	0.13		5	0.009	16
Organizational	0.12		CSIS	0.71	0.15	1	0.09	7
			CAP	0.17		2	0.02	14
Contractual	0.05		EOI	0.11	0.48	3	0.006	17
			BOC	0.29		2	0.04	12
			IPEP	0.59		1	0.05	11
Environmental	0.37		CRP	0.16	0.05	1	0.12	5
			ILA	0.38		2	0.15	3
			DRU	0.44		3	0.11	6
Location	0.38		UGPC	0.47	0.28	1	0.19	1
			PL	0.06		4	0.13	4
			DSNU	0.34		2	0.17	2
			IES	0.10		3	0.07	9

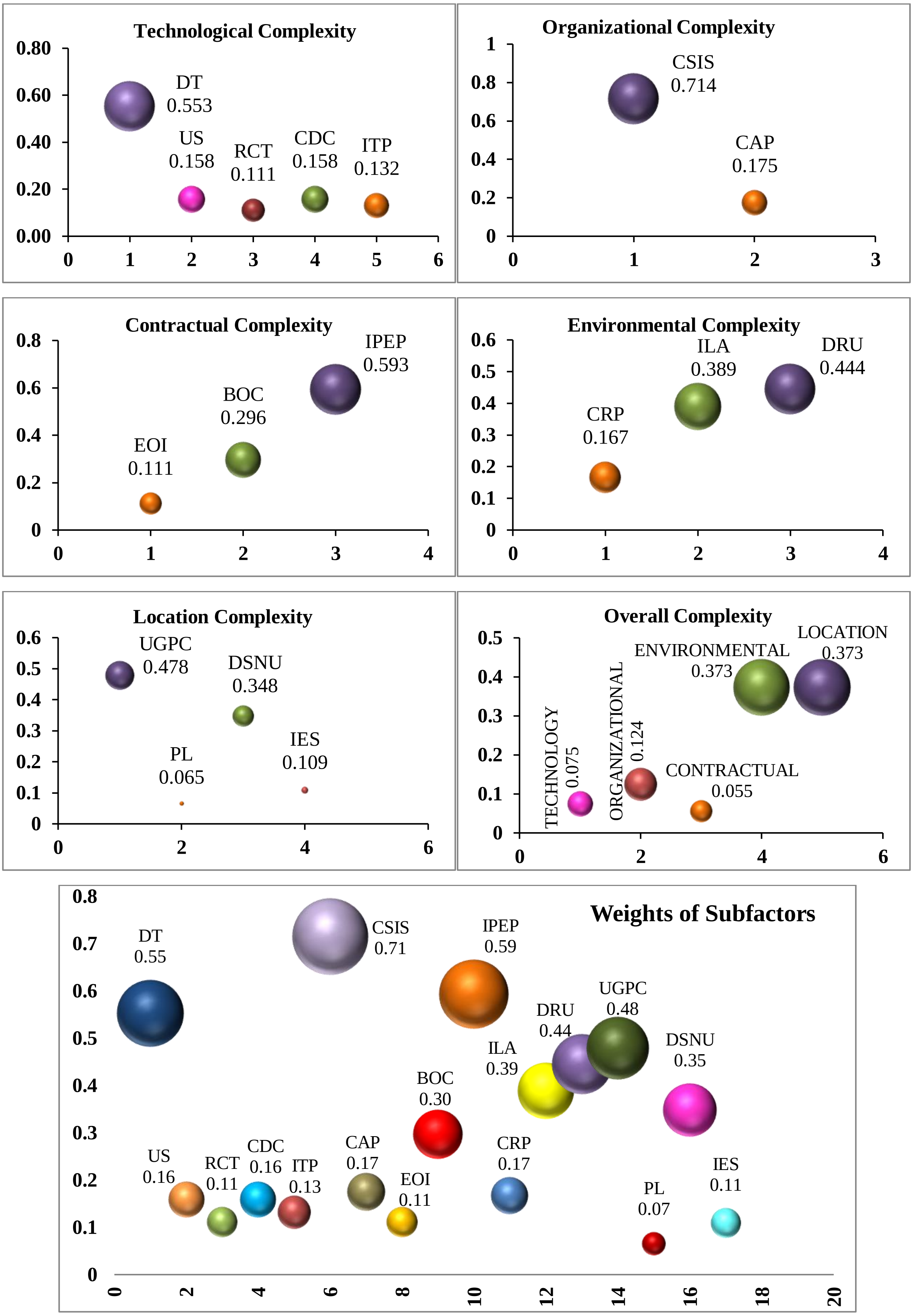


Figure 6.2 Graphical representation of project complexity factors weights (source: authors' own work)

Figure 6.2 presents a comparison of complexity factors based on their weights, where the size of each bubble represents the weight assigned to the corresponding PCF. A larger bubble indicates a higher weight, indicating that the complexity factor has a greater influence on the overall project complexity. It can be identified that CSIS (0.71) has the highest value suggesting that it is considered the most significant complexity factor and IPEP (0.592) indicates its relatively high importance. UGPC (0.47) is positioned as the third most important complexity factor. DRU (0.44) and ILA (0.38) are represented to be at a moderate level of importance in comparison to the top three complexity factors. DSNU (0.34), BOC (0.29), and CAP (0.17) have relatively lower-level significance compared to the top-weighted complexity factors. CRP, US, CDC, ITP, RCT, EOI, and IES have values ranging from 0.16 to 0.10, suggesting that they have lower importance or relevance. Finally, PL (0.06) has the lowest value, indicating that it is considered the least significant complexity factor among the listed ones. By comparing the values, we can gain an understanding of the relative priority of each complexity factor of metro rail projects. This helps in determining the level of attention to be given to each complexity factor and its corresponding aspects.

6.4. Development and Validation of PCI Model on Metro-Rail Projects

The PCI model is a comprehensive linear model that incorporates individual key complexity weights and factor weights and is used to quantify the impact of project complexity. To evaluate the effectiveness of this model, a correlation matrix was constructed. The values in the matrix range from "-1" to "+1," indicating negative and positive relationships, respectively, while "0" indicates no relationship between variables (Israel, 2008). Table 6.4 presents the correlation matrix with a significance level of 5%. After determining the weights and validating the linear model, Equation 2, referred to as PCI model, was derived. This equation serves as a tool to assess the degree of complexity in metro rail projects.

$$\boldsymbol{Project\ Complexity\ Index} = 0.07X\ \sum(0.55X\ DT) + (0.15X\ US) + (0.11X\ RCT) + (0.16XCDC) + (0.13X\ ITP) + 0.12X\sum(0.71XCSIS) + (0.17X\ CAP) + 0.05\sum\ (0.11X\ EOI) + (0.29X\ BOC) + (\ 0.59X\ IPEP) + 0.37\sum(0.16X\ CRP) + (0.38X\ ILA) + (0.44X\ DRU) + 0.38\sum\ (0.47X\ UGPC) + (0.06X\ PL) + (0.34X\ DSNU) + (0.10X\ IES) \quad (2)$$

The PCI model designed was applied to three metro rail projects: Ahmedabad, Hyderabad, and Bangalore metro rail projects. A purposeful sample of ongoing and completed metro rail projects was chosen based on size, cost, type of project (underground or elevated), and location. These criteria aimed to capture various complexities in both underground and elevated metro rail projects.

The Ahmedabad Metro Rail is an underground project located in the state of Gujarat, which commenced in 2012 with a budget of USD 1.619 billion. The Hyderabad Metro Rail is an elevated project situated in Telangana state that started in 2017 with a budget of USD 2.36 billion. Lastly, the Bangalore metro rail is an underground project located in Karnataka state which began in 2017 with a budget of USD 17 million. For each of these metro construction sites, on-site visits were conducted to collect relevant information for demonstrating the practical implementation of PCI. Table 6.5 provides an overview of the PCI levels observed in case studies, while Figure 6.3 visually presents the key complexity weights and corresponding to PCI values. These findings offer insights into the level of complexity associated with each project and allow for a comparative analysis of complexity factors among different metro rail projects.

Table 6.4 Correlation matrix among the complexity factors (source: authors' own work)

Correlation Matrix	DT	US	RCT	CDC	ITP	CSIS	CAP	EOI	BOC	IPEP	CRP	ILA	DRU	UGPC	PL	DSNU	IES
DT	1																
US	0.36	1															
RCT	-0.08	-0.07	1														
CDC	0.528*	-0.23	0.05	1													
ITP	0.31	0.08	0.19	0.45*	1												
CSIS	-0.06	0.11	0.25	0.08	-0.42	1											
CAP	0.18	0.07	0.21	-0.03	-0.17	0.36	1										
EOI	0.09	0.21	0.52*	0.22	-0.01	0.55*	0.27	1									
BOC	0.05	0.01	0.40	0.35	-0.30	0.66**	0.12	0.68**	1								
IPEP	-0.11	-0.37	0.40	0.05	-0.13	-0.02	0.14	0.43	0.28	1							
CRP	-0.16	-0.25	-0.09	-0.28	-0.37	-0.15	0.24	-0.12	0.07	0.37	1						
ILA	-0.01	-0.30	0.05	-0.12	-0.26	0.10	0.38	0.05	0.07	0.32	0.72**	1					
DRU	-0.15	-0.60**	0.12	0.18	-0.11	-0.10	0.15	-0.11	0.14	0.32	0.52*	0.33	1				
UGPC	-0.59**	-0.35	-0.18	-0.22	-0.28	-0.26	-0.11	-0.30	-0.02	0.08	0.26	-0.17	0.50*	1			
PL	0.10	0.01	0.56**	0.17	0.15	-0.04	0.38	0.59**	0.28	0.65**	0.32	0.38	0.33	-0.09	1		
DSNU	-0.03	0.27	-0.17	-0.46*	-0.24	0.08	0.40	-0.09	-0.26	-0.33	0.10	-0.13	-0.04	0.14	-0.20	1	
IES	0.25	0.01	-0.08	0.06	0.06	0.22	0.46*	0.33	-0.07	0.06	0.22	0.61**	0.01	-0.42	0.26	0.23	1

Note: ** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

Table 6.5 Determination of the project complexity index (source: authors' own work)

Type of Complexity	Weight of Main Factors	Complexity Factors	Mean	Weights of sub-Factors	Level of Sub-Factors	Project complexity Index
Technology	0.074	**DT**	5.90	0.55	3.25	
		US	4.00	0.15	0.62	
		RCT	4.75	0.11	0.52	
		CDC	3.75	0.15	0.58	
		ITP	4.25	0.13	0.55	
		Factors Complexity Level			5.55	0.41
Organizational	0.124	**CSIS**	5.35	0.71	3.81	
		CAP	4.70	0.17	0.81	
		Factors Complexity Level			4.63	0.57
Contractual	0.055	**EOI**	3.35	0.11	0.37	
		BOC	4.30	0.29	1.27	
		IPEP	4.55	0.59	2.69	
		Factors Complexity Level			4.33	0.23
Environmental	0.370	**CRP**	4.45	0.16	0.73	
		ILA	4.55	0.38	1.76	
		DRU	5.05	0.44	2.24	
		Factors Complexity Level			4.74	1.76
Location	0.372	**UGPC**	5.10	0.47	3.40	
		PL	5.25	0.06	0.34	
		DSNU	4.20	0.34	1.45	
		IES	3.95	0.10	0.42	
		Factors Complexity Level			5.62	2.09
Overall Project Complexity Index						**5.09**

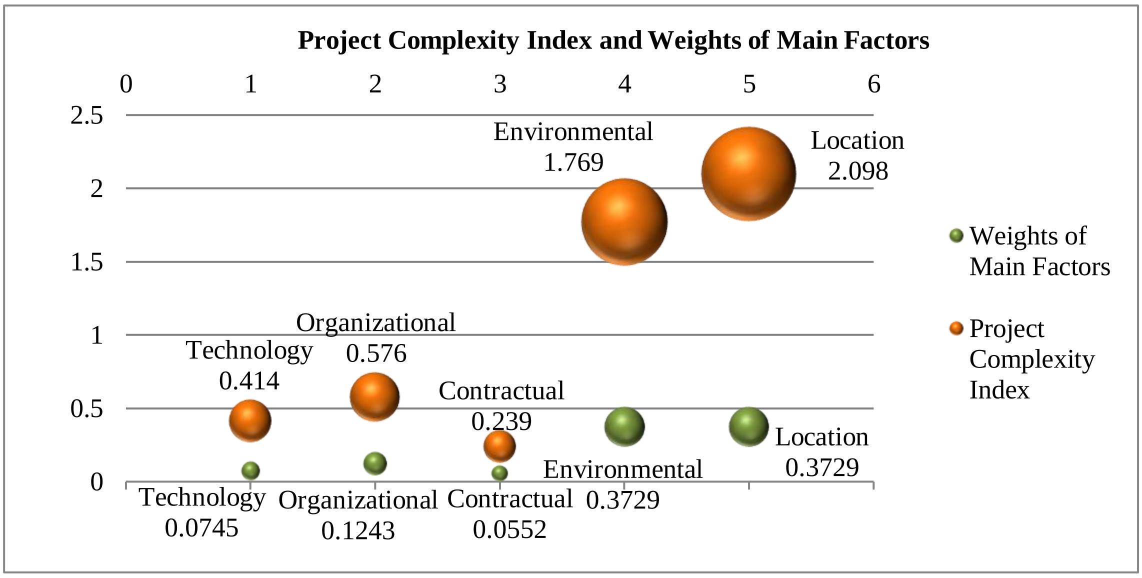


Figure 6.3 Graph representing the project complexity index and weights of key project complexities (source: authors' own work)

The results obtained from the analysis show that location complexity is identified as the most significant factor influencing metro rail projects followed by environmental, organizational, technological, and contractual complexity.

6.5 Sensitivity Analysis

The PCI derived from the study was subjected to sensitivity analysis to assess its reliability and applicability. This analysis enables estimating the effectiveness of PCI across different percentage variations to evaluate project performance. Three distinct levels, 5%, 30%, and 50% were considered during sensitivity analysis. By using diverse percentage values, the analysis sought to examine how project complexities varied under various assumptions and the impact they exercised on overall performance. To gain a comprehensive understanding of the obtained PCI and its implications, the percentages of project complexity values were systematically adjusted while maintaining other values constant. The resulting project complexity indices, corresponding to varying percentages, are presented in Figure 6.4.

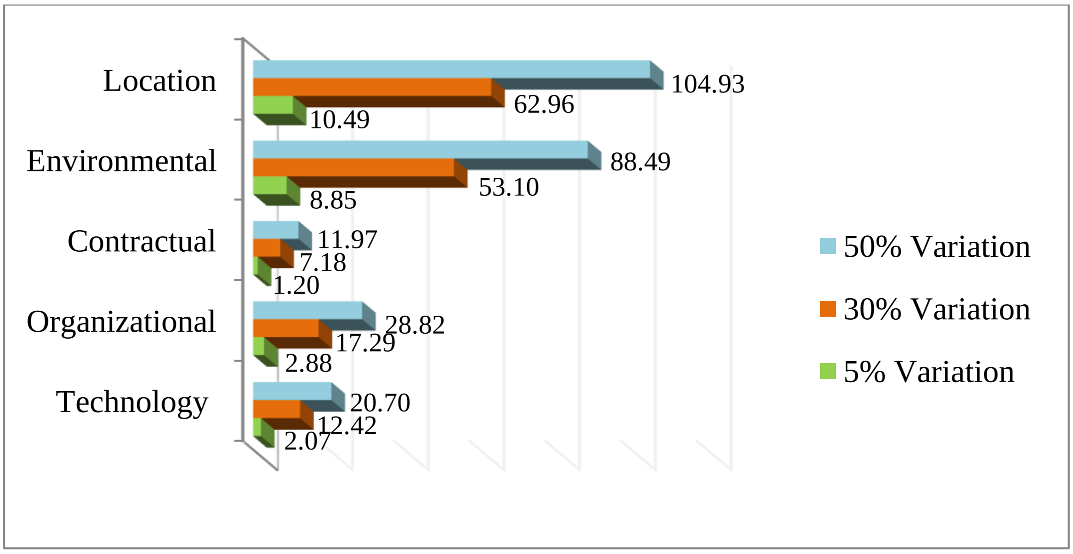


Figure 6.4 Comparison of the PCI for 5%,30%, and 50% Variation with Overall PCI (source: authors' own work)

From both PCI and sensitivity analysis it is apparent that location (2.09) and environmental (1.76) complexities exerted the most substantial influence on project performance, followed by, organizational (0.57), technological (0.41), and contractual (0.23) complexities respectively.

6.6 Discussions

The PCI model developed was considered a novel index in project complexity measurement models. In comparison to other measurement models like EVM, which were used to identify and quantify project risks (Gerrits & Verweij, 2016), PCI addresses complexity providing a broader perspective of understanding the challenges posed by various PCFs. While PCAM and PECI evaluate the complexity's influence on time, costs, and resource allocation (Mirza & Ehsan, 2017; Kermanshachi et al., 2020), PCI acts as the best measurement model in decision-making and resource allocation in various projects. Furthermore, the existing frameworks excel in specific domains, but PCI is superior in that it functions by integrating diverse complexity characteristics, making it a robust and adaptable model for assessing project complexity by considering various PCFs specific to underground and elevated metro rail projects. The developed model shows the impact of project complexity and how the degree of complexity changes based on influence of project characteristics.

From the analysis, it was certain that uncertain geological conditions and government approvals contribute to the location complexity of the Hyderabad metro rail. Originally it was planned for a 120-foot road widening, but faced delays as it was revised to 60 feet due to lack of approvals. Bangalore metro rail encountered similar challenges during excavation, with varying geological conditions and trench cleaning issues. The Ahmedabad metro rail project experienced delays due to clearance and land acquisition approvals, necessitating a redesign. Limited land acquisition before contracts caused delays in both Hyderabad and Bangalore metro projects. Relocating utilities in the old city of Hyderabad, with limited utility records, became a major complexity factor impacting project cost, time, and quality. Alignment issues and differences among government and stakeholders caused delays in Hyderabad and Ahmedabad. Political issues, contract breaches, and challenges in information exchange caused contractual complexity.

Theoretical Implications

The existing literature has focused primarily on assessing the impact of complexity in megaprojects, showing a gap in the analysis of the impact of project complexity in metro rail projects. Previous studies have focused on the conceptual framework of complexity in megaprojects, but the analysis of project complexity's impact on the performance of metro rail has been limited. This study bridges that gap by identifying PCFs inherent in metro rail projects and developing a PCI model. This model determines the impact of project complexity by considering a wide range of PCFs specific to metro rail projects. It allows for a detailed analysis of how complexity affects project performance and is used as a measurable tool for assessing and managing complexity, enhancing decision-making processes, and strategic management.

PCI can be used effectively in projects to determine the level of complexity's impact on project performance. The project complexity indices can assist managers in developing management strategies for dealing with project complexity issues. The PCI is generic and can be used for any type of project.

Practical Implications

The results of this study can be used efficiently by managers in construction projects to identify the level of impact of complexity on the project performance. Assessing the impact of project complexity is necessary for project managers, stakeholders, and metro organizations to deal with the project complexity of metro rail projects. The utilization of the PCI model can effectively measure the complexity levels of various metro projects, identifying challenges, risks, and uncertainties for managing project complexity. This model helps to make strategic and data-driven decisions about the allocation of technological, human, and financial resources to increase project performance. This index can also be used to compare different metro rail projects, assisting with other metro organization management decisions. The PCI model developed can be applied to different metro rail projects. Therefore, project managers can use the research findings as a benchmark for project complexity assessment.

Recommendations

To mitigate complexities, the following recommendations are provided: advanced geotechnical techniques can be used to understand underground geological conditions. Drones can assist in land surveys to assess environmental complexity. Organizational coordination can be improved via real-time monitoring, digital platforms, and project management tools. Contract management software, blockchain for transparency, and e-signatures for faster processes can all help reduce contract complexity.

6.7 Conclusion

The study of project complexity measurement in metro rail projects plays an important role in identifying major complexities for the development of project management strategies. This research mainly focuses on developing a measurement model by identifying significant PCFs and their impact on the performance of metro rail projects. A PCI model was developed using BWM for measuring the impact of complexity and real-time metro projects were used as case studies to apply and validate the measurement model designed for the purpose.

The PCI model analysis indicates that underground metro rail project exhibits the highest levels of technological and organizational complexity, with a mean score of 5.90. On the other hand, the over-ground metro project shows a relatively lower complexity with a mean score of 4.00. Location, environmental, and contractual complexity for elevated metro rail projects represent the highest level of complexity with mean scores of 5.25, 5.05, and 4.55, respectively. This suggests that elevated projects involve complex contractual arrangements and environmental obligations. The sensitivity analysis conducted further strengthens the robustness of the results by considering different percentages and uncertainties related to project complexity.

This research contributes to the field of construction project management by developing an applicable model for assessing and managing project complexity, enabling stakeholders to make informed decisions and improve project performance in transportation industry. The PCI model integrates empirical evidence from case studies, offering practical insights and guidance specific to metro rail and other transportation projects. By adopting the technical insights and leveraging generic implications of PCI model, the management of complexities in construction projects can be improved and enhance decision-making. However, it is important to acknowledge the limitations of this study, which focuses primarily on metro rail projects and employs a specific method for weight calculation. Future research should expand the scope to encompass diverse construction projects and explore correlations among complexity factors across different sectors. Additionally, further investigations into the development of alternative mathematical models would enhance the understanding and management of complexity in metro rail on similar projects.

Chapter 7
Conclusions of the Research

7.1 Conclusions

The study of project complexity in Indian metro rail construction has significant implications stakeholders connected with the project. This research specifically focuses on identifying PCFs and the interrelationships among these factors in metro rail projects in India. Real-time metro rail projects were considered case studies to gain insights into the occurrence of PCFs. DEMATEL method was applied to analyze the interdependencies of complexity factors, which allows for better decision-making regarding resource prioritization. Design and construction changes, land acquisition issues, utility relocation delays, structural design problems, information exchange, and unpredictable geological conditions are highly interrelated PCFs. These factors are interrelated because each one can directly or indirectly influence the occurrence or resolution of the others. For example, delays in land acquisition often cause a domino effect, leading to delays in utility relocation and subsequent construction delays. Similarly, unpredictable geological conditions can lead to structural design modifications, which may also cause delays in construction and utility relocation. Each of these factors impacts another in the project's lifecycle, creating a web of cause-and-effect relationships. These factors were categorized into cause-and-effect groups, emphasizing their interdependence. Understanding these interdependencies is crucial because it helps project managers pinpoint which factors trigger other problems and need to be addressed first. By understanding these cause-and-effect relationships, project managers can identify the root causes of problems and prioritize resources to address the most critical factors early on. This study presents a novel approach to project complexity assessment, identifying PCFs and analyzing their interdependence. The methodology assists metro organizations and project managers to formulate strategies and reduce complexity effects. These findings can serve as a benchmark for similar projects and extend to various metro rail and construction projects.

DEMATEL approach does not directly solve workforce allocation or resource utilization problems, it provides a clear map of which complexity factors have the most significant impact on others. For instance, if land acquisition delays are identified as a primary cause of multiple downstream problems (such as construction delays and increased costs), project managers can allocate additional workforce or resources early in the process to mitigate these effects. The insight gained through DEMATEL helps in determining which issues need immediate attention and where resources should be concentrated to minimize overall project delays or cost overruns. Therefore, DEMATEL indirectly supports workforce allocation and resource utilization by helping project managers prioritize key tasks and allocate resources efficiently to resolve critical issues. It offers clarity on the cascading effects of different complexity factors, allowing for better forecasting of where resources will be most needed. For example, focusing resources on resolving land acquisition delays early can prevent a chain reaction of delays across multiple project areas, leading to more efficient use of workforce and materials in later stages. The study highlights the importance of identifying complexity factors and analyzing interdependencies among PCFs for developing effective complexity management strategies.

The application of ML models in construction projects is still in its nascent stages. However, the application is limited to design, time, and cost prediction in construction projects. Therefore, this study develops a prediction model to identify the impact of project complexity on various project performance parameters. An integrated ML model combining (SVM, RF and DT) was used to predict the impact of project complexity on project performance parameters in metro rail projects. Performance parameters' quality, scope, and sustainability have significant variations and have a moderate impact on project complexity whereas other parameters, such as time, and cost, predict a high impact on project complexity. Performance parameters such as quality, scope, and sustainability experience significant variations due to project complexity. Rather than these performance parameters influencing complexity, it is the complexity of the project that exerts a direct impact on these factors**.** Project complexity influences how well project quality, scope, and sustainability are managed, making these parameters more susceptible to variation. Complex interdependencies, unexpected changes, and uncertainties in project scope can lead to deviations from planned quality standards and sustainable practices, highlighting the moderate impact of project complexity on these performance aspects. Project complexity has a high impact on parameters like time and cost**.** It often leads to delays due to unforeseen challenges such as design changes, coordination issues, or technical uncertainties, significantly extending project timelines. The effect of complexity on project timelines consequently impacts costs, as longer project durations increase labor, material, and overhead costs. Additionally, unforeseen challenges often require unplanned expenditures, directly contributing to budget overruns. Therefore, project complexity creates significant strain on maintaining both time and cost parameters**,** which are more sensitive to complex project dynamics compared to parameters like quality, scope, and sustainability.

Project complexity influences performance parameters such as time and cost more severely, while it has a moderate impact on quality, scope, and sustainability. The more complex a project becomes, the greater its potential to disrupt timelines, escalate costs, and introduce variations in other performance parameters. Understanding these relationships allows for better planning and resource allocation to mitigate the negative effects of complexity on project performance. Reliability poses challenges in predicting the impact of project complexity and is observed to have a low impact. Furthermore, this holistic approach combines the strengths of different models and leads to more comprehensive and accurate predictions in the context of project complexity in metro rail projects. The study suggests that combining insights from different models can provide a more holistic view of how project complexity affects different performance parameters of metro rail projects, leading to better project management and decision-making. In summary, each ML model has strengths and weaknesses in predicting different project parameters. SVM tends to perform moderately well with linear trends; RF is effective in predicting certain non-linear patterns; and DT shows mixed prediction. Therefore, the choice of this integrated model can be applied to predict the impact of project complexity on a specific project parameter. This model strategically employs domain-specific developments and can make more comprehensive predictions in metro rail project management. The results of this study offer valuable insights into the prediction and management of project complexity in metro rail projects, providing a valuable tool for improving project outcomes and decision-making in the construction industry.

The study of project complexity measurement in metro rail projects plays an important role in identifying major complexities for the development of project management strategies. A PCI model was developed using the BWM method for measuring the impact of complexity and real-time metro projects were used as case studies to apply and validate the developed measurement model. The PCI model analysis indicates that the underground metro rail project exhibits the highest levels of technological and organizational complexity. On the other hand, elevated metro project shows a relatively lower complexity. Location, environmental, and contractual complexity for elevated metro rail projects represent the highest level of complexity respectively. This suggests that the elevated project involves complex contractual arrangements and environmental obligations. The sensitivity analysis conducted further strengthens the robustness of the results by considering different percentages and uncertainties related to project complexity.

The findings from this study offer a robust framework for benchmarking across similar infrastructure projects due to their focus on PCFs that are commonly encountered in large-scale construction endeavors. The PCI and the application of the DEMATEL method can be generalized and applied to a range of megaprojects, such as highway systems, bridge constructions, airport developments, and urban infrastructure projects, where interdependencies, regulatory challenges, and coordination across multiple stakeholders are prominent. The suitability of these findings for benchmarking arises from the universal nature of the complexity factors identified, including land acquisition challenges, regulatory constraints, structural and design changes, utility relocation, and stakeholder engagement, which are not exclusive to metro rail projects but also apply to other large-scale projects in the transportation and infrastructure sectors.

These findings can be generalized or adapted to other types of projects by considering the specific contextual factors relevant to each project type. For instance, in projects where environmental or contractual complexity may play a more significant role, such as in bridge or energy infrastructure, the weight of these complexity factors in the PCI model can be adjusted accordingly. The geographical location, regulatory frameworks, and project size further influence the adaptability of the findings, allowing for their application to projects with similar urban settings, regulatory challenges, and stakeholder dynamics. This ensures that the methodological framework developed in this research, while tailored to metro rail projects, can be extended to similar construction projects, where managing complexity is a critical component of project success. Thus, this research provides practical tools for assessing and managing complexity in a wide range of infrastructure projects, offering generalizable insights that can enhance project planning, resource allocation, and overall project management across various sectors.

7.2 Limitations of the Study

While this research makes significant contributions to the field of construction project management by developing an applicable model for assessing and managing project complexity, it is important to recognize several limitations that may influence the interpretation of the findings and their broader application. A detailed exploration of these limitations can provide context for the conclusions drawn and guide future research in this domain.

1. **Focus on Metro Rail Projects**: This study specifically examines metro rail projects in India, which limits the generalizability of the findings to other types of infrastructure projects. While the PCI model and the DEMATEL method provide valuable insights into complexity factors, these results are based on the unique characteristics of metro rail construction, such as urban density, regulatory challenges, and transportation-specific complexities. The findings may not be fully applicable to infrastructure projects like highways, airports, or power plants, where different sets of complexity factors could dominate. Future research could test and adapt the PCI model for broader application across diverse project types to enhance its versatility.

2. **Case Study-Based Evidence:** The empirical evidence supporting the PCI model is drawn from real-time case studies of Indian metro rail projects. While these case studies offer practical insights into project complexity, the sample size is limited to a few selected projects, which may not capture the full spectrum of complexity across various regions or project environments. Different geographic locations, legal frameworks, and project sizes could yield different results. Thus, the conclusions drawn from this study should be applied cautiously in other contexts until further research is conducted to validate the model across a broader range of projects and regions.

3. **Methodology and Weight Calculation:** The study employs the Best-Worst Method (BWM) for calculating the weights of complexity factors in the PCI model. While BWM is a robust technique for multi-criteria decision-making, it is based on subjective judgments from project stakeholders. As such, the results could be influenced by the personal experiences and biases of the participants involved in the study. This subjectivity may affect the reliability of the model's output when applied to different projects or stakeholders with varying perspectives. To mitigate this limitation, future research could explore alternative weighting methods, such as Analytic Hierarchy Process (AHP) or Fuzzy Logic, to improve objectivity and test the sensitivity of the model under different assumptions.

4. **Static Nature of Complexity Assessment:** The PCI model provides a snapshot of project complexity at a specific point in time, which may not fully reflect the dynamic nature of construction projects. As projects evolve, new complexity factors may emerge, while others may diminish in importance. The static nature of the complexity assessment could limit its effectiveness in long-term projects where continuous

reassessment is necessary to capture changes in complexity over time. Future studies could explore dynamic complexity models that allow for ongoing evaluation and adjustment of complexity factors throughout the project lifecycle.

5. **Limited Exploration of Performance Parameters:** While this research explores how project complexity impacts key performance parameters like time, cost, quality, scope, sustainability, and reliability, the study's analysis may not encompass all the factors that influence these parameters in metro rail projects. For example, external factors such as political influence, market conditions, and technological advancements are not explicitly incorporated into the model, yet they could significantly affect project outcomes. Further research is needed to incorporate a wider range of variables that could affect project performance under complex conditions.

By acknowledging these limitations, this research sets the stage for future investigations to refine and extend the PCI model. While the study offers a solid foundation for understanding and managing project complexity in metro rail projects, further work is required to adapt and enhance the model for broader applications across different project types and contexts.

7.3 Theoretical Contribution from the Thesis

- **Novel Methodology:** The research introduces a novel approach and provides a theoretical understanding of project complexity assessment employing the DEMATEL method to identify and analyze complexity factors in real-time metro rail projects.
- **Interdependencies Analysis*:*** The study goes beyond merely identifying complexity factors; and provides an understanding of how different factors interact, contributing to the development of complexity management frameworks.
- **Cause and Effect Group Differentiation**: The research categorizes complexity factors into cause-and-effect groups, offering a framework that distinguishes between factors requiring enhanced managerial attention for mitigation strategies and those emphasizing the need for improved project management to reduce overall complexity.
- **Comprehensive Model Integration:** The research expands theoretical insights and provides a comprehensive approach to understanding the impact of project complexity on various performance parameters.

7.4 Practical Contribution from the Thesis

- **Strategic Decision-Making Tool:** The findings of the research offer a practical tool for metro organizations and project managers. The insights gained from the complexity analysis can be utilized to formulate targeted strategies, optimize workforce allocation, and predict and manage complexity in real-time metro rail projects.
- **Predictive Analysis:** The application of DEMATEL method facilitates predictive analysis, enabling proactive measures to be taken in response to potential challenges. The prediction ensures that project managers can anticipate and address complexity issues before they increase.
- **Integrated Machine Learning Model for Prediction:** This ML model acts as a valuable practical tool for predicting the impact of project complexity on various performance parameters supporting effective decision-making in metro rail project management.
- **Construction of a Project Complexity Index:** The PCI model serves as a benchmark for assessing and quantifying project complexity. This can be used by metro organizations to prioritize and allocate resources efficiently, considering the distinct challenges associated with underground and elevated metro rail projects.

7.5 Scope for Future Work

- Enhancing ML models for metro rail projects is important, involving customization for accurate complexity assessment and refining approaches.
- Integration of real-time data from sensors and weather forecasts promises improved responsiveness. While expanding models to predict maintenance needs based on usage patterns could facilitate proactive planning.
- Additionally, diversifying research focus to encompass various construction projects and exploring correlations among complexity factors across sectors is an area that can be researched.
- Investigating alternative mathematical models would enhance understanding and management of complexity in metro rail and similar projects, offering innovative approaches to project planning and decision-making.

Bibliography

Aarseth, W., Rolstadås, A., & Andersen, B. (2011). Key factors for management of global projects: a case study. *International Journal of Transitions and Innovation Systems*, *1*(4), 326. https://doi.org/10.1504/ijtis.2011.044905

Abdel Aziz, A. M. (2007). Successful Delivery of Public-Private Partnerships for Infrastructure Development. *Journal of Construction Engineering and Management*, *133*(12), 918–931. https://doi.org/10.1061/(asce)0733-9364(2007)133:12(918)

Acharya, N. K., Lee, Y. D., & Kim, J. K. (2006). Critical Construction Conflicting Factors Identification Using Analytical Hierarchy Process. *KSCE Journal of Civil Engineering*, *10*(3), 165–174. https://doi.org/https://doi.org/10.1007/BF02824057

Addae-Boateng, S., Wen, X., & Brew, Y. (2015). Contractual Governance, Relational Governance, and Firm Performance: The Case of Chinese and Ghanaian and Family Firms. *American Journal of Industrial and Business Management*, *05*, 288–310. https://doi.org/10.4236/ajibm.2015.55031

Adeleke, A. Q., Bahaudin, A. Y., Kamaruddeen, A. M., Bamgbade, J. A., Salimon, M. G., Khan, M. W. A., & Sorooshian, S. (2018). The Influence of Organizational External Factors on Construction Risk Management among Nigerian Construction Companies. *Safety and Health at Work*, *9*(1), 115–124. https://doi.org/10.1016/j.shaw.2017.05.004

Ahmadabadi, A. A., & Heravi, G. (2019). The effect of critical success factors on project success in Public-Private Partnership projects: A case study of highway projects in Iran. *Transport Policy*, *73*, 152–161. https://doi.org/10.1016/j.tranpol.2018.07.004

Ahsan, K., & Paul, S. K. (2018). Procurement Issues in Donor-Funded International Development Projects. *Journal of Management in Engineering*, *34*(6), 04018041(1-13). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000648.

Al-Saadi, R., & Abdou, A. (2016). Factors critical for the success of public–private partnerships in UAE infrastructure projects: experts' perception. *International Journal of Construction Management*, *16*(3), 234–248. https://doi.org/http://dx.doi.org/10.1080/15623599.2016.1146110

Al Nahyan, M. T., Sohal, A. S., Fildes, B. N., & Hawas, Y. E. (2012). Transportation infrastructure development in the UAE: Stakeholder perspectives on management practice. *Construction Innovation*, *12*(4), 492–514. https://doi.org/10.1108/14714171211272234

Alam, M. A., & Ahmed, F. (2013). Smarter Congestion Relief in Asian Cities -Win-Win Solutions to Urban Transport Problems. In T. Litman (Ed.), *Transport and Communications Bulletin for Asia and the Pacific* (pp. 1–18). United Nations publication. Retrieved from https://www.unescap.org/sites/default/files/bulletin82_Article-1.pdf

Alderman, L., & Melanie, L. (2012). How to Meet Stakeholders' Expectations, not Manage Them? In *Australasian Higher Education Evaluation Forum (AHEEF) 2012*. Rockhampton, Australia: University of Southern Queensland.

Algarni, A. M., Arditi, D., & Polat, G. (2007). Build-Operate-Transfer in Infrastructure Projects in the United States. *Journal of Construction Engineering and Management*, *133*(10), 728–735. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:10(728)

Alizadeh, T. (2017). An investigation of IBM's Smarter Cites Challenge:What do participating cities want? *Cities*, *63*, 70–80. https://doi.org/10.1016/j.cities.2016.12.009

Anguelovski, I., & Carmin, J. A. (2011). Something borrowed, everything new: innovation and institutionalization in urban climate governance. *Current Opinion in Environmental Sustainability*, *3*(3), 169–175. https://doi.org/10.1016/j.cosust.2010.12.017

Ansar, A., Flyvbjerg, B., Budzier, A., & Lunn, D. (2014). Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy*, *69*, 43–56. https://doi.org/10.1016/j.enpol.2013.10.069

Antonacopoulou, E., & Chiva, R. (2007). The Social Complexity of Organizational Learning: The Dynamics of Learning and Organizing. *Management Learning*, *38*(3), 277–295. https://doi.org/10.1177/1350507607079029

Antoniadis, D. N., Edum-Fotwe, F. T., & Thorpe, A. (2011). Socio-organo complexity and project performance. *International Journal of Project Management*, *29*(7), 808–816. https://doi.org/10.1016/j.ijproman.2011.02.006

Antoniou, F., Aretoulis, G. N., Konstantinidis, D., & Kalfakakou, G. P. (2013). Complexity in the Evaluation of Contract Types Employed for the Construction of Highway Projects. In *Procedia - Social and Behavioral Sciences-26th IPMA World Congress, Crete, Greece, 2012* (Vol. 74, pp. 448–458). Elsevier B.V. https://doi.org/10.1016/j.sbspro.2013.03.048

Aritua, Bernard, Smith, N. J., & Bower, D. (2009). Construction client multi-projects – A complex adaptive systems perspective. *International Journal of Project Management*, *27*(1), 72–79. Retrieved from http://dx.doi.org/10.1016/j.ijproman.2008.02.005

Ashish Gupta, B. E. (2015). *Successful Delivery of Mega-projects*. The University of Texas at Austin. Retrieved from http://hdl.handle.net/2152/31766

Ashkanani, S., & Franzoi, R. (2023). Gaps in Megaproject Management System Literature: A Systematic Overview. *Engineering, Construction and Architectural Management*, *30*(3), 1300–1318. https://doi.org/10.1108/ECAM-12-2021-1113

Atkinson-Palombo, C. (2010). Comparing the Capitalisation Benefits of Light-rail Transit and Overlay Zoning for Single-family Houses and Condos by Neighbourhood Type in Metropolitan Phoenix, Arizona. *Urban Studies Journal Limited*, *47*(11), 2409–2426. https://doi.org/10.1177/0042098009357963

Augustine, S., Payne, B., Sencindiver, F., & Woodcock, S. (2005). Agile Project Management: Steering From the Edges. *Communications of the ACM*, *48*(12), 85–89. https://doi.org/https://doi.org/10.1145/1101779.1101781

Austin, S., Newton, A., Steele, J., & Waskett, P. (2002). Modelling and managing project complexity. *International Journal of Project Managementmenet*, *20*(3), 191–198. https://doi.org/https://doi.org/10.1016/S0263-7863(01)00068-0

Babatunde, S. O., Perera, S., Udeaja, C., & Zhou, L. (2014). Challenges of Implementing Infrastructure Megaprojects through Public-Private Partnerships in Nigeria: A Case Study of Road Infrastructure. *International Journal of Architecture, Engineering and Construction*, *3*(2), 142–154. https://doi.org/10.7492/ijaec.2014.012

Baccarini, D. (1996). The Concept of Project Complexity - A Review. *International Journal of Project Management*, *14*(4), 201–204. https://doi.org/10.1016/0263-7863(95)00093-3

Bakhshi, J., Ireland, V., & Gorod, A. (2016). Clarifying the project complexity construct: Past, present and future. *International Journal of Project Management*, *34*(7), 1199–1213. https://doi.org/10.1016/j.ijproman.2016.06.002

Batselier, J., & Vanhoucke, M. (2015). Empirical Evaluation of Earned Value Management Forecasting Accuracy for Time and Cost. *Journal of Construction Engineering and Management*, *141*(11), 05015010 (1-13). https://doi.org/10.1061/(asce)co.1943-7862.0001008

Baziar, M. H., Moghadam, M. R., Kim, D. S., & Choo, Y. W. (2014). Effect of underground tunnel on the ground surface acceleration. *Tunnelling and Underground Space Technology*, *44*, 10–22. https://doi.org/10.1016/j.tust.2014.07.004

Birol, F. (2006). World Energy Prospects and Challenges. *The Australian Economic Review*, *39*(2), 190–195.

Bjorvatn, T., & Wald, A. (2018). Project complexity and team-level absorptive capacity as drivers of project management performance. *International Journal of Project Management*, *36*(6), 876–888. https://doi.org/10.1016/j.ijproman.2018.05.003

Blair, J., & Lacy, M. G. (1993). Educating Prospective Managers in the Complexity of Organizational Life. *Management Learning*, *30*(3), 321–342. https://doi.org/https://doi.org/10.1177/1350507699303004

Boal, K. B., & Schultz, P. L. (2007). Storytelling, time, and evolution: The role of strategic leadership in complex adaptive systems. *Leadership Quarterly*, *18*(4), 411–428. https://doi.org/10.1016/j.leaqua.2007.04.008

Bonato, F. K., De Albuquerque, A. A., & Da Paixão, M. A. S. (2019). An application of Earned Value Management (EVM) with Monte Carlo Simulation in Engineering Project Management. *Gestão & Produção*, *26*(3), 1–15. https://doi.org/10.1590/0104-530X4641-

19

Bonner, S. E. (1994). A Model of the Effects of Audit Task Complexity. *Accounting, Organizations and Society*, *19*(3), 213–234. https://doi.org/10.1016/0361-3682(94)90033-7

Borzillo, S., & Kaminska-Labbé, R. (2011). Unravelling the dynamics of knowledge creation in communities of practice though complexity theory lenses. *Knowledge Management Research and Practice*, *9*(4), 353–366. https://doi.org/10.1057/kmrp.2011.13

Bosch-Rekveldt, M., Jongkind, Y., Mooi, H., Bakker, H., & Verbraeck, A. (2011). Grasping project complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework. *International Journal of Project Management*, *29*(6), 728–739. https://doi.org/10.1016/j.ijproman.2010.07.008

Botchkarev, A., & Finnigan, P. (2015). Complexity in the Context of Information Systems Project Management. *Organisational Project Management*, *2*(1), 15. https://doi.org/10.5130/opm.v2i1.4272

Brady, T., Davies, A., & Nightingale, P. (2012). Dealing with uncertainty in complex projects: revisiting Klein and Meckling. *International Journal of Managing Projects in Business*, *5*(4), 718–736. https://doi.org/10.1108/17538371211269022

Brockmann, C. (2009). Mega Projects: Getting the Job Done. In *Proceedings-LEAD 2009 Conference* (Vol. 14, pp. 1–12).

Brockmann, C., Brezinski, H., & Erbe, A. (2016). Innovation in Construction Megaprojects. *Journal of Construction Engineering and Management*, *142*(11), 04016059. https://doi.org/10.1061/(asce)co.1943-7862.0001168

Brockmann, C., & Girmscheid, G. (2007). Complexity of Megaprojects. In *CIB World Building Congress* (pp. 219–230). https://doi.org/https://doi.org/10.3929/ethz-a-005997850

Bruzelius, N., Flyvbjerg, B., & Rothengatter, W. (2002). Big decisions, big risks. Improving accountability in mega projects. *Transport Policy*, *9*(2), 143–154. https://doi.org/10.1016/S0967-070X(02)00014-8

Bryman Alan. (2012). *Social Research Methods* (Fifth). US, Newyork: Oxford University Press. Retrieved from http://www.oxfordtextbooks.co.uk/orc/brymansrm5e/

Bui, T., & Sivasankaran, T. R. (1990). Relation between GDSS use and Group Task Complexity: An Experimental Study. In *Twenty-Third Annual Hawaii International Conference on System Sciences* (Vol. 3, pp. 69–78). Retrieved from https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=205329

Calinescu, A., Efstathiou, J., Schirn, J., & Bermejo, J. (1998). Applying and Assessing Two Methods for Measuring Complexity in Manufacturing. *The Journal of the Operational Research Society*, *49*(7), 723–733.

https://doi.org/https://doi.org/10.1057/palgrave.jors.2600554

Campbell, D. J. (1988). Task Complexity: A Review and Analysis. *Academy of Management Review*, *13*(1), 40–52. https://doi.org/10.5465/amr.1988.4306775

Cantarelli, C. C. (2020). Innovation in megaprojects and the role of project complexity. *Production Planning and Control*, *33*(9–10), 943–956. https://doi.org/https://doi.org/10.1080/09537287.2020.1837934

Capka, J. R. (2004). Megaprojects: Managing a Public Journey. Retrieved from https://highways.dot.gov/public-roads/julyaugust-2004/megaprojects-managing-public-journey

Carr, A. (2019). Community Economic Development Strategies in the New Millennium: KeyAdvantages of Community Benefits Agreements in Urban Mega-Projects. *Hastings Race and Poverty Law Journal*, *16*(2), 263–312. Retrieved from https://heinonline.org/HOL/License

Cedergren, A. (2012). Designing resilient infrastructure systems: a case study of decision-making challenges in railway tunnel projects. *Journal of Risk Research*, *16*(5), 563–582. https://doi.org/10.1080/13669877.2012.726241

Chadee, A. A., Martin, H. H., Mwasha, A., & Otuloge, F. (2022). Rationalizing Critical Cost Overrun Factors on Public Sector Housing Programmes. *Emerging Science Journal*, *6*(3), 647–666. https://doi.org/10.28991/ESJ-2022-06-03-016

Chan, A. P. C., Ho, D. C. K., & Tam, C. M. (2001). Design and Build Project Success Factors: Multivariate Analysis. *Journal of Construction Engineering and Management*, *127*(2), 93–100. https://doi.org/https://doi.org/10.1061/(ASCE)0733-9364(2001)127:2(93)

Chan, A. P. C., Scott, D., & Chan, A. P. L. (2004). Factors Affecting the Success of a Construction Project. *Journal of Construction Engineering and Management*, *130*(1), 153–155. https://doi.org/10.1061/(asce)0733-9364(2004)130:1(153)

Chan, L. K., & Wu, M.-L. (2002). *Quality function deployment: A literature review*. *European Journal of Operational Research* (Vol. 143). https://doi.org/10.1016/S0377-2217(02)00178-9

Chang, A. Y., Hu, K. J., & Hong, Y. L. (2013). An ISM-ANP approach to identifying key agile factors in launching a new product into mass production. *International Journal of Production Research*, *51*(2), 582–597. https://doi.org/10.1080/00207543.2012.657804

Chang, C. C., & Chen, P. Y. (2018). Analysis of critical factors for social games based on extended technology acceptance model: a DEMATEL approach. *Behaviour and Information Technology*, *37*(8), 774–785. https://doi.org/10.1080/0144929X.2018.1480654

Chapman, R. J. (2016). A framework for examining the dimensions and characteristics of complexity inherent within rail megaproject. *International Journal of Project Management*, *34*(6), 937–956. https://doi.org/10.1016/j.ijproman.2016.05.001

Chatterjee, S. k. (1985). *Calcutta Statistical Association Bulletin*. *Sage Publications* (Vol. 76). https://doi.org/https://doi.org/10.1177/0008068319850314

Chen, F., Wang, H., Xu, G., Ji, H., Ding, S., & Wei, Y. (2020). Data-driven safety enhancing strategies for risk networks in construction engineering. *Reliability Engineering and System Safety*, *197*, 106806. https://doi.org/10.1016/j.ress.2020.106806

Chen, H., H.L.Chiang, R., & C. Storey, V. (2018). Business Intelligence and Analytics: From Big Data To Big Impact. *MIS Quarterly*, *36*(4), 1165–1188. Retrieved from http://www.jstor.org/stable/41703503

Chen, L., & Whyte, J. (2022). Understanding design change propagation in complex engineering systems using a digital twin and design structure matrix. *Engineering, Construction and Architectural Management*, *29*(8), 2950–2975. https://doi.org/https://doi.org/10.1108/ECAM-08-2020-0615

Cheng, C. H., Chang, J. R., & Yeh, C. A. (2006). Entropy-based and trapezoid fuzzification-based fuzzy time series approaches for forecasting IT project cost. *Technological Forecasting and Social Change*, *73*(5), 524–542. https://doi.org/10.1016/j.techfore.2005.07.004

Cicmil, S., & Marshall, D. (2005). Insights into collaboration at the project level: Complexity, social interaction and procurement mechanisms. *Building Research and Information*, *33*(6), 523–535. https://doi.org/10.1080/09613210500288886

Clegg, S. R., Courpasson, D., & Phillips, N. (2006). *Power and organizations*. *SAGE Publications Ltd*. https://doi.org/10.4135/9781446215715

Cong, J., Zheng, P., Bian, Y., Chen, C.-H., Li, J., & Li, X. (2022). A machine learning-based iterative design approach to automate user satisfaction degree prediction in smart product-service system. *Computers & Industrial Engineering*, *165*, 107939. https://doi.org/https://doi.org/10.1016/j.cie.2022.107939

Cooke-Davies, T., Cicmil, S., Crawford, L., & Richardson, K. (2007). We’re not in kansas anymore,Toto- Mapping the Strange Landscape of complexity theory,and its relationship to project Management. *Project Management Journal*, *38*(2), 50–61. https://doi.org/https://doi.org/10.1177/875697280703800206

Corning, P. A. (1998). The synergism hypothesis: On the concept of synergy and its role in the evolution of complex systems. *Journal of Social and Evolutionary Systems*, *21*(2), 133–172. https://doi.org/10.1016/s1061-7361(00)80003-x

Crawford, L., Morris, P., Thomas, J., & Winter, M. (2006). Practitioner development: From trained technicians to reflective practitioners. *International Journal of Project*

Management, *24*(8), 722–733. https://doi.org/10.1016/j.ijproman.2006.09.010

Damayanti, R. W., Hartono, B., & Wijaya, A. R. (2021). Clarifying megaproject complexity in developing countries: A literature review and conceptual study. *International Journal of Engineering Business Management*, *13*, 1–25. https://doi.org/https://doi.org/10.1177/18479790211027414

Daniel, E., & Daniel, P. A. (2019). Megaprojects as complex adaptive systems: The Hinkley point C case. *International Journal of Project Management*, *37*(8), 1017–1033. https://doi.org/10.1016/j.ijproman.2019.05.001

Dao, B., Kermanshachi, S., Shane, J., Anderson, S., & Hare, E. (2016). Identifying and Measuring Project Complexity. In *Procedia Engineering-International Conference on Sustainable Design, Engineering and Construction Identifying* (Vol. 145, pp. 476–482). Elsevier B.V. https://doi.org/10.1016/j.proeng.2016.04.024

Dara, S., & Vilventhan, A. (2023). Complexities in Metrorail Project- A Case Study of Hyderabad Metro Rail. In *Towards a Sustainable Construction Industry: The Role of Innovation and Digitalisation* (pp. 392–401). Cham: Springer International Publishing. https://doi.org/https://doi.org/10.1007/978-3-031-22434-8_39

Dara, S., Vilventhan, A., & Gopal, P. R. C. (2023). Mapping the Project Complexity of Metro Rail Project Using DEMATEL Technique. In *Advances in Construction Materials and Management. ACMM 2022* (pp. 15–26). Singapore: Springer Nature Singapore. https://doi.org/https://doi.org/10.1007/978-981-99-2552-0_2

DeRosa, J. K., Grisogono, A. M., Ryan, A. J., & Norman, D. O. (2008). A research agenda for the engineering of complex systems. *2008 IEEE International Systems Conference Proceedings, SysCon 2008*, 1–8. https://doi.org/10.1109/SYSTEMS.2008.4518982

Desai, J. S., Pathak, V. B., & Yadav, N. B. (2018). Evaluation of Design-Construction Interface Problems in Building Construction Projects. *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, *6*(Iv), 242–247.

Dikmen, I., & Birgonul, M. T. (2004). Neural Network Model to Support International Market Entry Decisions. *Journal of Construction Engineering and Management*, *130*(1), 59–66. https://doi.org/10.1061/(asce)0733-9364(2004)130:1(59)

Dip, S., Islam, M., & Rahman, H. (2024). Artificial intelligence and machine learning applications in the project lifecycle of the construction industry : A comprehensive review. *Heliyon*, *10*(5), e26888. https://doi.org/10.1016/j.heliyon.2024.e26888

Donaldson, L. (2001). *The contingency theory of organizations*. Sage.

Dunović, I. B., Radujković, M., & Škreb, K. A. (2014). Towards a New Model of Complexity – The Case of Large Infrastructure Projects. In *Procedia - Social and Behavioral Sciences-27th IPMA World Congress Towards* (Vol. 119, pp. 730–738).

https://doi.org/10.1016/j.sbspro.2014.03.082

Edward Lorenz. (1995). *The Essence Of Chaos*. University of Washington Press.

Eriksson, P. E., Larsson, J., & Pesämaa, O. (2017). Managing complex projects in the infrastructure sector — A structural equation model for flexibility-focused project management. *International Journal of Project Management*, *35*(8), 1512–1523. https://doi.org/10.1016/j.ijproman.2017.08.015

Erkul, M., Yitmen, I., & Çelik, T. (2016). Stakeholder Engagement in Mega Transport Infrastructure Projects. In *Procedia Engineering-World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium 2016, WMCAUS 2016* (Vol. 161, pp. 704–710). The Author(s). https://doi.org/10.1016/j.proeng.2016.08.745

Erol, H, Dikmen, I., Atasoy, G., & Birgonul, M. T. (2018). Contemporary Issues in Mega Construction Projects. In *5th International Project and Construction Management Conference* (pp. 1022–1035).

Erol, Huseyin, Dikmen, I., Atasoy, G., & Birgonul, M. T. (2020). Exploring the Relationship between Complexity and Risk in Megaconstruction Projects. *Journal of Construction Engineering and Management*, *146*(12), 1–14. https://doi.org/10.1061/(asce)co.1943-7862.0001946

Fiori, C., & Kovaka, M. (2005). Defining megaprojects: Learning from construction at the edge of experience. *Construction Research Congress 2005: Broadening Perspectives - Proceedings of the Congress*, (480), 715–724. https://doi.org/10.1061/40754(183)70

Floricel, S., Michela, J. L., & Piperca, S. (2016). Complexity, uncertainty-reduction strategies, and project performance. *International Journal of Project Management*, *34*(7), 1360–1383. https://doi.org/10.1016/j.ijproman.2015.11.007

Floricel, S., & Miller, R. (2001). Strategizing for anticipated risks and turbulence in large-scale engineering projects. *International Journal of Project Management*, *19*(8), 445–455. https://doi.org/10.1016/S0263-7863(01)00047-3

Flyvbjerg, B. (2014). What You Should Know About Megaprojects and Why: An Overview. *Project Management Journal*, *45*(2), 6–19. https://doi.org/DOI: 10.1002/pmj.21409

Flyvbjerg, B. (2017). Introduction: The Iron Law of Megaproject Management. In *The Oxford Handbook of Megaproject Management (Oxford: Oxford University Press)* (pp. 1–18).

Flyvbjerg, B., Bruzelius, N., & Rothengatter, W. (2003). *Megaprojects and Risk: An anatomy of ambition. Cambridge University Press*. United Kingdom. https://doi.org/10.1017/cbo9781107050891

Flyvbjerg, B., Holm, M. K. S., & Buhl, S. L. (2003). How common and how large are cost overruns in transport infrastructure projects? *Transport Reviews*, *23*(1), 71–88. https://doi.org/10.1080/01441640309904

Gao, N., Chen, Y., Wang, W., & Wang, Y. (2018). Addressing Project Complexity: The Role of Contractual Functions. *Journal of Management in Engineering*, *34*(3), 1–12. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000613

Geraldi, J. G., & Adlbrecht, G. (2007). On Faith,Fact and Intercation in Projects. *Project Management Journal*, *38*(1), 32–43. https://doi.org/https://doi.org/10.1177/875697280703800104

Geraldi, J., Maylor, H., & Williams, T. (2011). Now, let's make it really complex (complicated): A systematic review of the complexities of projects. *International Journal of Operations and Production Management*, *31*(9), 966–990. https://doi.org/10.1108/01443571111165848

Gerhard, G., & Christian, B. (2008). The Inherent Complexity of Large Scale Engineering Projects. *Project Perspectives*, *29*, 22–26. https://doi.org/https://doi.org/10.3929/ethz-a-005994701

Gerrits, L. M., & Verweij, S. (2016). Qualitative comparative analysis as a method for evaluating complex cases: An overview of literature and a stepwise guide with empirical application. *Zeitschrift Fur Evaluation*, *15*(1), 7–22.

Ghosh, S., & Jintanapakanont, J. (2004). Identifying and assessing the critical risk factors in an underground rail project in Thailand: A factor analysis approach. *International Journal of Project Management*, *22*(8), 633–643. https://doi.org/10.1016/j.ijproman.2004.05.004

Ghosh, T., & Bakshi, B. R. (2020). Designing hybrid life cycle assessment models based on uncertainty and complexity. *International Journal of Life Cycle Assessment*, *25*(11), 2290–2308. https://doi.org/10.1007/s11367-020-01826-5

Gidado, K. (2004). Enhancing the prime contractor's pre-construction planning. *Journal of Construction Research*, *5*(1), 87–106.

Gidado, K. ., & Millar, A. . (1992). The Effect of Simple Overlap of The Stages of Building Construction on The Project Complexity and Contract Time. In *Proceedings of the 8 th Annual Conference, Association of Researchers in Construction Management* (pp. 307–317).

Gidado, K. I. (1996). Project complexity: The focal point of construction production planning. *Construction Management and Economics*, *14*(3), 213–225. https://doi.org/10.1080/014461996373476

Giezen, M. (2013). Adaptive and strategic capacity: navigating megaprojects through uncertainty and complexity. *Environment and Planning B: Planning and Design*, *40*(4), 723–741. https://doi.org/10.1068/b38184

Golini, R., Kalchschmidt, M., & Landoni, P. (2015). Adoption of project management practices: The impact on international development projects of non-governmental organizations.

International Journal of Project Management, *33*(3), 650–663. https://doi.org/10.1016/j.ijproman.2014.09.006

Gransberg, D. D. (2013). Early contractor design involvement to expedite delivery of emergency highway projects. *Transportation Research Record*, *2347*(1), 19–26. https://doi.org/https://doi.org/10.3141/2347-03

Gransberg, D. D., Shane, J. S., Strong, K., & del Puerto, C. L. (2013). Project Complexity Mapping in Five Dimensions for Complex Transportation Projects. *Journal of Management in Engineering*, *29*(4), 316–326. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000163

Greitzer, F. L. (2005). Toward the development of cognitive task difficulty metrics to support intelligence analysis research. In *Fourth IEEE Conference on Cognitive Informatics 2005, ICCI 2005* (pp. 315–320). https://doi.org/10.1109/COGINF.2005.1532647

Grisham, T. (2009). The Delphi technique: a method for testing complex and multifaceted topics. *International Journal of Managing Projects in Business*, *2*(1), 112–130. https://doi.org/10.1108/17538370910930545

Hahn, C. K., Watts, C. A., & Kim, K. Y. (1990). The Supplier Development Program : A Conceptual Model. *Journal of Purchasing and Materials Management*, *26*(2), 2–7.

Haidar, A., & Ellis, R. D. J. (2010). Analysis and Improvement of Megaprojects Performance. *Engineering Project Organizations Conference*, 22.

Hammer, J., R., Edwards, J. S., & Tapinos, E. (2012). Examining the strategy development process through the lens of complex adaptive systems theory. *Journal of the Operational Research Society*, *63*(7), 909–919. https://doi.org/10.1057/jors.2011.97

Han, S. H., Kim, D. Y., & Kim, H. (2007). Predicting Profit Performance for Selecting Candidate International Construction Projects. *Journal of Construction Engineering and Management*, *133*(6), 425–436. https://doi.org/10.1061/(asce)0733-9364(2007)133:6(425)

Hanseth, O., & Lyytinen, K. (2010). Design theory for dynamic complexity in information infrastructures: The case of building internet. *Journal of Information Technology*, *25*(1), 1–19. https://doi.org/10.1057/jit.2009.19

Hartman, F., & Ashrafi, R. A. (2002). Project Management in the Information Systems and Information Technologies Industries. *Project Management Journal*, *33*(3), 5–15. https://doi.org/10.1177/875697280203300303

Harvey, M., Richard, V., & Stephen, C. (2008). Managerial Complexity in Project- Based Operations: A Grounded Model and Its Implications for Practice. *Project Management Journal*, *39*(1), S15–S26. https://doi.org/10.1002/pmj.20057

Harvey Maylor. (2003). *Project Management* (Third Edit). London, UK: Pearson Education.

Hass, K. B. (2009). *Managing Complex Projects. A New Model. Management Concepts*. USA: Managementconcepts.

He, Q., Luo, L., Hu, Y., & Chan, A. P. C. (2014). Measuring the complexity of mega construction projects in China-A fuzzy analytic network process analysis. *International Journal of Project Management*, *33*(3), 549–563. https://doi.org/10.1016/j.ijproman.2014.07.009

Hertogh, M., & Westerveld, E. (2010). *Playing With Complexity. Management and Organisation of Large Infrastructure Projects*. *Erasmus University Rotterdam*. Retrieved from https://repub.eur.nl/pub/18456

Hiroshi Tanaka. (2014). Toward Project and Program Management Paradigm in the Space of Complexity: A Case Study of Mega and Complex Oil and Gas Development and Infrastructure Projects. In *Procedia - Social and Behavioral Sciences-27th IPMA World Congress Toward* (Vol. 119, pp. 65–74). Elsevier B.V. https://doi.org/10.1016/j.sbspro.2014.03.010

Hu, Y, Chan, A., & Le, Y. (2012). Conceptual frameowrk of program organisation for managing construction megaprojects-Chinese clients' perspective. In *Engineering Project Organizations Conference* (pp. 1–24).

Hu, Yi, Chan, A. P. C., & Le, Y. (2015). Pragmatic framework of programme organizational capability for delivering megaprojects at design and construction phases: a Chinese client perspective. *Engineering Project Organization Journal*, *5*(2–3), 49–62. https://doi.org/10.1080/21573727.2015.1014804

Hu, Yi, Chan, A. P. C., Le, Y., & Jin, R. (2013). From Construction Megaproject Management to Complex Project Management: Bibliographic Analysis. *Journal of Management in Engineering*, *31*(4), 1–18. https://doi.org/10.1061/(asce)me.1943-5479.0000254

Huo, T., Ren, H., Cai, W., Shen, G. Q., & Liu, B. (2018). Measurement and Dependence Analysis of Cost Overruns in Megatransport Infrastructure Projects : Case Study in Hong Kong. *Journal of Construction Engineering and Management*, *144*(3), 1–10. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001444.

India Brand Equity Foundation. (2019). INFRASTRUCTURE. *An Initiative of the Ministry of Commerce and Industry , Government of India.* India. Retrieved from https://www.ibef.org

Işik, Z., & Aladağ, H. (2017). A fuzzy AHP model to assess sustainable performance of the construction industry from urban regeneration perspective. *Journal of Civil Engineering and Management*, *23*(4), 499–509. https://doi.org/10.3846/13923730.2016.1210219

Israel, D. (2008). *Data analysis in business research: A step-by-step nonparametric approach*. *Sage Publications*. United Kingdom: Sage Publications India Pvt Ltd. https://doi.org/DOI: https://doi.org/10.4135/9788132108405

Jaura, M., & Michailova, S. (2014). Cognition and knowledge sharing in post-acquisition integration: Insights from Indian IT acquiring firms. *Journal of Asia Business Studies*, *8*(2), 146–167. https://doi.org/10.1108/JABS-05-2012-0027

Jia, Fuyuan, Xiang, P., & Chen, D. (2022a). A two-dimensional complexity evaluation model of megaprojects based on structure and attributes. *Ain Shams Engineering Journal*, *14*(2), 101852. https://doi.org/10.1016/j.asej.2022.101852

Jia, Fuyuan, Xiang, P., & Chen, D. (2022b). Prioritizing the Operation and Maintenance Complexity of Mega Transportation Projects Based on Systems Thinking. *Journal of Construction Engineering and Management*, *148*(2), 05021014 (1-17). https://doi.org/10.1061/(asce)co.1943-7862.0002220

Jin, Y., & Levitt, R. E. (1996). The Virtual Design Team : A Computational Model of Project Organizations. *Computational and Mathematical Organization Theory*, *2*(3), 171–196. https://doi.org/https://doi.org/10.1007/BF00127273

Johnsen, S. O., & Veen, M. (2013). Risk assessment and resilience of critical communication infrastructure in railways. *Cognition, Technology and Work*, *15*(1), 95–107. https://doi.org/10.1007/s10111-011-0187-2

Jordan, M. I., & Mitchell, T. M. (2015). Machine learning: Trends, perspectives, and prospects. *Science*, *349*(6245), 255–260. https://doi.org/10.1126/science.aaa8415

Joukar, A., & Nahmens, I. (2016). Volatility Forecast of Construction Cost Index Using General Autoregressive Conditional Heteroskedastic Method. *Journal of Construction Engineering and Management*, *142*(1), 04015051. https://doi.org/10.1061/(asce)co.1943-7862.0001020

Kagioglou, M., Cooper, R., & Aouad, G. (2001). Performance management in construction: a conceptual framework. *Construction Management and Economics*, *19*(1), 85–95. https://doi.org/10.1080/01446190010003425

Kardes, I., Ozturk, A., Cavusgil, S. T., & Cavusgil, E. (2013). Managing global megaprojects: Complexity and risk management. *International Business Review*, *22*(6), 905–917. https://doi.org/10.1016/j.ibusrev.2013.01.003

Keene, A. (2000). Complexity theory: The changing role of leadership. *Industrial and Commercial Training*, *32*(1), 15–18. https://doi.org/10.1108/00197850010311121

Keers, B. B. M., & van Fenema, P. C. (2018). Managing risks in public-private partnership formation projects. *International Journal of Project Management*, *36*(6), 861–875. https://doi.org/10.1016/j.ijproman.2018.05.001

Kennedy, D. M., McCombb, S. A., & Vozdolska, R. R. (2011). An investigation of project complexity's influence on team communication using Monte Carlo simulation. *Journal of Engineering and Technology Management*, *28*(3), 109–127.

https://doi.org/10.1016/j.jengtecman.2011.03.001

Kennedy, L., Robbins, G., Bon, B., Takano, G., Varrel, A., & Andrade, J. (2014). *Megaprojects and Urban Development in Cities of the South*. *Thematic Report*. https://doi.org/https://doi.org/10.13140/2.1.2344.4163

Kermanshachi, S., Dao, B., Rouhanizadeh, B., Shane, J., & Anderson, S. (2020). Development of the Project Complexity Assessment and Management Framework for Heavy Industrial Projects. *International Journal of Construction Education and Research*, *16*(1), 24–42. https://doi.org/10.1080/15578771.2018.1499568

Kermanshachi, S., Dao, B., Shane, J., & Anderson, S. (2016). Project Complexity Indicators and Management Strategies - A Delphi Study. In *Procedia Engineering-International Conference on Sustainable Design, Engineering and Construction Project* (Vol. 145, pp. 587–594). Elsevier B.V. https://doi.org/10.1016/j.proeng.2016.04.048

Kian, M. R. E., Sun, M., & Bosché, F. (2015). A Consistency-checking Consensus-building Method to Assess Complexity of Energy Megaprojects. In *Procedia - Social and Behavioral Sciences, 29th World Congress International Project Management Association (IPMA) 2015* (Vol. 226, pp. 43–50). https://doi.org/10.1016/j.sbspro.2016.06.160

Kolltveit, B. J., & Grønhaug, K. (2004). The importance of the early phase: The case of construction and building projects. *International Journal of Project Management*, *22*(7), 545–551. https://doi.org/10.1016/j.ijproman.2004.03.002

Koppenjan, J., & Leijten, M. (2005). Privatising Railroads: The Problematic Involvement of the Private Sector in Two Dutch Railway Projects. *Asia Pacific Journal of Public Administration*, *27*(2), 181–199. https://doi.org/10.1080/23276665.2005.10779307

Kuo, Y. C., & Lu, S. T. (2013). Using fuzzy multiple criteria decision making approach to enhance risk assessment for metropolitan construction projects. *International Journal of Project Management*, *31*(4), 602–614. https://doi.org/10.1016/j.ijproman.2012.10.003

Lam, P. T. I. (1999). A sectoral review of risks associated with major infrastructure projects. *International Journal of Project Management*, *17*(2), 77–87. https://doi.org/https://doi.org/10.1016/S0263-7863(98)00017-9

Lauser, B. (2010). Post-merger integration and change processes from a complexity perspective. *Baltic Journal of Management*, *5*(1), 6–27. https://doi.org/10.1108/17465261011016531

Lebcir, M. R. (2011). *Impact of project complexity factors on new product development cycle time*. United Kingdom. Retrieved from https://uhra.herts.ac.uk/dspace/handle/2299/6040

Lee, C. Y., Chong, H. Y., Liao, P. C., & Wang, X. (2018). Critical Review of Social Network Analysis Applications in Complex Project Management. *Journal of Management in Engineering*, *34*(2), 04017061. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000579

Lehtonen, M., Joly, P.-B., & Aparicio, L. (2016). *Socioeconomic Evaluation of Megaprojects: Dealing with uncertainties*. *Earthscan* (1st Editio). London: Routledge. https://doi.org/10.4324/9781315622125

Lessard, D., Sakhrani, V., & Miller, R. (2014). House of Project Complexity—understanding complexity in large infrastructure projects. *Engineering Project Organization Journal*, *4*(4), 170–192. https://doi.org/10.1080/21573727.2014.907151

Leung, M., Yu, J., & Chan, Y. S. (2014). Focus Group Study to Explore Critical Factors of Public Engagement Process for Mega Development Projects. *Journal of Construction Engineering and Management*, *140*(3), 04013061. https://doi.org/10.1061/(asce)co.1943-7862.0000815

Levitt, R. E., Scott, W. R., & Garvin, M. J. (2019). *Public–private partnerships for infrastructure development: Finance, stakeholder alignment, governance*. *Edward Elgar Publishing*. US, Newyork. https://doi.org/10.4337/9781788973182

Li, F., Chen, C.-H., Lee, C.-H., & Feng, S. (2022). Artificial intelligence-enabled non-intrusive vigilance assessment approach to reducing traffic controller's human errors. *Knowledge-Based Systems*, *239*, 108047. https://doi.org/https://doi.org/10.1016/j.knosys.2021.108047

Liu, K., Liu, Y., Kou, Y., & Yang, X. (2024). Study on dissipative structure of mega railway infrastructure project management system. *Engineering, Construction and Architectural Management*, *31*(9), 3599–3621. https://doi.org/https://doi.org/10.1108/ECAM-10-2022-1021

Locatelli, G., Ika, L., Drouin, N., Müller, R., Huemann, M., Söderlund, J., … Clegg, S. (2023). A Manifesto for Project Management Research. *European Management Review*, *20*(1), 3–17. https://doi.org/10.1111/emre.12568

Lokuge, S., Sedera, D., Grover, V., & Dongming, X. (2019). Organizational readiness for digital innovation: Development and empirical calibration of a construct. *Information and Management*, *56*(3), 445–461. https://doi.org/10.1016/j.im.2018.09.001

Luo, J., & Wood, K. L. (2017). The growing complexity in invention process. *Research in Engineering Design*, *28*(4), 421–435. https://doi.org/10.1007/s00163-017-0266-3

Luo, L., He, Q., Jaselskis, E. J., & Xie, J. (2017). Construction Project Complexity: Research Trends and Implications. *Journal of Construction Engineering and Management*, *143*(7), 04017019 (1-10). https://doi.org/10.1061/(asce)co.1943-7862.0001306

Luo, L., He, Q., Xie, J., Yang, D., & Wu, G. (2016). Investigating the Relationship between Project Complexity and Success in Complex Construction Projects. *Journal of Management in Engineering*, *33*(2), 04016036. https://doi.org/10.1061/(asce)me.1943-5479.0000471

Ma, L., & Fu, H. (2020). Exploring the influence of project complexity on the mega construction project success: a qualitative comparative analysis (QCA) method. *Engineering, Construction and Architectural Management*, *27*(9), 2429–2449. https://doi.org/10.1108/ECAM-12-2019-0679

Maddaloni, F. Di, & Davis, K. (2017). The influence of local community stakeholders in megaprojects: Rethinking their inclusiveness to improve project performance. *International Journal of Project Management*, *35*(8), 1537–1556. https://doi.org/10.1016/j.ijproman.2017.08.011

Manson, S. M. (2001). Simplifying complexity: a review of complexity theory. *Geoforum*, *32*(3), 405–414. https://doi.org/https://doi.org/10.1016/S0016-7185(00)00035-X

Maylor, H., & Söderlund, J. (2016). Project management research: Addressing integrative challenges. In *Designs, Methods and Practices for Research of Project Management* (pp. 41–48). Routledge. https://doi.org/10.4324/9781315270197-12

Maylor, H., & Turner, N. (2016). Understand, reduce, respond: project complexity management theory and practice. *International Journal of Operations and Production Management*, *37*(8), 1076–1093. https://doi.org/10.1108/IJOPM-05-2016-0263

McCully, P. (2001). Silenced rivers: the ecology and politics of large dams. *Journal of Political Ecology*, *11*(2004), 25–28. https://doi.org/10.2307/2624501

Merrow, E. (2011). *Industrial Megaprojects: Concepts, Strategies, and Practices for Success*. Wiley.

Mevada, J., & Devkar, G. (2017). Analysis of reasons for cost and time overrun in Indian megaprojects. *MATEC Web of Conferences- ASCMCES-17*, *120*(02018), 1–10. https://doi.org/10.1051/matecconf/201712002018

Mevada, J., & Devkar, G. (2018). Analysing Complexities and Uncertainties in Indian Megaprojects. In *The 7th World Construction Symposium 2018: Built Asset Sustainability: Rethinking Design, Construction and Operations* (pp. 44–53). Sri Lanka. Retrieved from https://www.researchgate.net/publication/326149073

Mihm, J., Loch, C., & Huchzermeier, A. (2003). Problem-solving oscillations in complex engineering projects. *Management Science*, *49*(6), 733–750. https://doi.org/10.1287/mnsc.49.6.733.16021

Mikkelsen, M. F. (2021). Perceived project complexity: a survey among practitioners of project management. *International Journal of Managing Projects in Business*, *14*(3), 680–698. https://doi.org/10.1108/IJMPB-03-2020-0095

Mills, A. (2001). A systematic approach to risk management for construction. *Structural Survey*, *19*(5), 245–252. https://doi.org/10.1108/02630800110412615

Mirza, E., & Ehsan, N. (2017). Quantification of Project Execution Complexity and its Effect on Performance of Infrastructure Development Projects. *Engineering Management*

Journal, *29*(2), 108–123. https://doi.org/10.1080/10429247.2017.1309632

Mohamed, S. (2003). Performance in International Construction Joint Ventures: Modeling Perspective. *Journal of Construction Engineering and Management*, *129*(6), 619–626. https://doi.org/10.1061/(asce)0733-9364(2003)129:6(619)

Mohri, M., Rostamizadeh, A., & Talwalkar, A. (2018). *Foundations of Machine Learning* (Second Edi). Cambridge, Massachusetts London, England: The Massachusetts Institute of Technology Press. Retrieved from https://dlib.hust.edu.vn/bitstream/HUST/24963/1/OER000003225.pdf

Mohseni, M., Tabassi, A. A., Kamal, E. M., Bryde, D. J., & Michaelides, R. (2019). Complexity Factors In Mega Projects: A Literature Review. In *The European Proceedings of Multidisciplinary Sciences - 4th International Conference on Rebuilding Place* (Vol. 2, pp. 54–67). https://doi.org/https://doi.org/10.15405/epms.2019.12.6

Molenaar, K., Washington, S., & James Diekmann. (2000). Structural Equation Model of Construction Contract Dispute Potential. *Journal of Construction Engineering and Management*, *126*(4), 268–277. https://doi.org/https://doi.org/10.1061/(ASCE)0733-9364(2000)126:4(268)

Montequín, V. R., Villanueva Balsera, J., Cousillas Fernández, S. M., & Ortega Fernández, F. (2018). Exploring Project Complexity through Project Failure Factors: Analysis of Cluster Patterns Using Self-Organizing Maps. *Complexity*, *2018*. https://doi.org/10.1155/2018/9496731

Morris, P. W. G. (1988). Lessons in Managing Major Projects Successfully in a European Context. *Technology in Society*, *10*(1), 71–98. https://doi.org/10.1016/0160-791X(88)90026-7

Mulholland, B., & Christian, J. (1999). Risk Assesement In construction Schedules. *Journal of Construction Engineering and Management*, *125*(1), 8–15. https://doi.org/https://doi.org/10.1061/(ASCE)0733-9364(1999)125:1(8)

Müller, R., & Turner, R. (2007). The Influence of Project Managers on Project Success Criteria and Project Success by Type of Project. *European Management Journal*, *25*(4), 298–309. https://doi.org/10.1016/j.emj.2007.06.003

Naeni, M. L., Shadrokh, S., & Salehipour, A. (2014). A fuzzy approach for the earned value management. *International Journal of Project Management*, *32*(4), 709–716. https://doi.org/10.1016/j.ijproman.2013.02.002

Nandi, M. I., & Banani, N. (2000). Telecommunications infrastructure and economic development. In *Traditional Telecommunications Networks* (pp. 1–36). https://doi.org/10.4337/9781781950630.00019

Nassar, K. M., & Hegab, M. Y. (2006). Developing a Complexity Measure for Project

Schedules. *Journal of Construction Engineering and Management*, *132*(6), 554–561. https://doi.org/10.1061/(asce)0733-9364(2006)132:6(554)

Nazanin, K. G., Ehsan, S., Athari Nikooravan, H., & Preece, C. (2018). Evaluating solutions to facilitate the presence of operation and maintenance contractors in the pre-occupancy phases: a case study of road infrastructure projects. *International Journal of Construction Management*, *21*(2), 140–152. https://doi.org/10.1080/15623599.2018.1512027

Nguyen, A. T., Nguyen, L. D., Le-Hoai, L., & Dang, C. N. (2015). Quantifying the complexity of transportation projects using the fuzzy analytic hierarchy process. *International Journal of Project Management*, *33*(6), 1364–1376. https://doi.org/10.1016/j.ijproman.2015.02.007

Nguyen, T. H. D., Chileshe, N., Rameezdeen, R., & Wood, A. (2019). External stakeholder strategic actions in projects: A multi-case study. *International Journal of Project Management*, *37*(1), 176–191. https://doi.org/10.1016/j.ijproman.2018.12.001

Niu, K., Fang, W., & Guo, B. (2019). A team task complexity measure for emergency procedures in fully automatic metro. *Concurrency and Computation: Practice and Experience*, *31*(10), 1–21. https://doi.org/10.1002/cpe.4753

Oehmen, J., Thuesen, C., Parraguez, P., & Geraldi, J. (2015). *Complexity Management for Projects, Programmes, and Portfolios: An Engineering Systems Perspective*. *Project Management Institute*. Retrieved from http://www.pmi.org/~/media/PDF/learning/project-complexity/complexity-management-engineering-systems.ashx

Omonyo, A. B. (2018). Moderating Role of Project Leadership on the Influence of Complexity on Success of Public Infrastructural Megaprojects in Kenya. *International Journal of Project Management*, *36*(22), 181–187.

Othman, A. (2014). A conceptual model for overcoming the challenges of mega construction projects in developing countries. *African Journal of Engineering Research*, *2*(4), 73–84.

Owens, J., Ahn, J., Shane, J. S., Strong, K. C., & Gransberg, D. D. (2012). Defining Complex Project Management of Large U.S. Transportation Projects: A Comparative Case Study Analysis. *Public Works Management and Policy*, *17*(2), 170–188. https://doi.org/10.1177/1087724X11419306

Owolabi, H. A., Oyedele, L. O., Alaka, H. A., Ajayi, S. O., Akinade, O. O., & Bilal, M. (2020). Critical Success Factors for Ensuring Bankable Completion Risk in PFI/PPP Megaprojects. *Journal of Management in Engineering*, *36*(1), 04019032. https://doi.org/10.1061/(asce)me.1943-5479.0000717

Park, K., Woo, H., Kunhee, L., Seung, C., & Lee, H. (2017). Project Risk Factors Facing Construction Management Firms. *International Journal of Civil Engineering*, *17*, 305–321. https://doi.org/10.1007/s40999-017-0262-z

Patanakul, P., Kwak, Y. H., Zwikael, O., & Liu, M. (2016). What impacts the performance of large-scale government projects? *International Journal of Project Management*, *34*(3), 452–466. https://doi.org/10.1016/j.ijproman.2015.12.001

Peñaloza, G. A., Saurin, T. A., & Formoso, C. T. (2020). Monitoring complexity and resilience in construction projects: The contribution of safety performance measurement systems. *Applied Ergonomics*, *82*, 102978. https://doi.org/10.1016/j.apergo.2019.102978

Pitsis, A., Clegg, S., Freeder, D., Sankaran, S., & Burdon, S. (2018). Megaprojects redefined-complexity versus cost- and social imperatives. *International Journal of Managing Projects in Business*, *11*(1), 7–34. https://doi.org/https://doi.org/10.1108/ IJMPB-07-2017-0080

Prencipe, A., & Tell, F. (2001). Inter-project learning: Processes and outcomes of knowledge codification in project-based firms. *Research Policy*, *30*(9), 1373–1394. https://doi.org/10.1016/S0048-7333(01)00157-3

Puddicombe, M. S. (2011). The Contingencies of Project Management: A Factor Analytic Approach to Complexity and Novelty. *International Journal of Construction Education and Research*, *7*(4), 259–275. https://doi.org/10.1080/15578771.2011.595474

Puddicombe, M. S. (2012). Novelty and Technical Complexity: Critical Constructs in Capital Projects. *Journal of Construction Engineering and Management*, *138*(5), 613–620. https://doi.org/10.1061/(asce)co.1943-7862.0000459

Qazi, A., Quigley, J., Dickson, A., & Kirytopoulos, K. (2016). Project Complexity and Risk Management (ProCRiM): Towards modelling project complexity driven risk paths in construction projects. *International Journal of Project Management*, *34*(7), 1183–1198. https://doi.org/10.1016/j.ijproman.2016.05.008

Qiu, Y., Chen, H., Sheng, Z., & Cheng, S. (2019). Governance of institutional complexity in megaproject organizations. *International Journal of Project Management*, *37*(3), 425–443. https://doi.org/10.1016/j.ijproman.2019.02.001

Qureshi, S. M., & Kang, C. (2015). Analysing the organizational factors of project complexity using structural equation modelling. *International Journal of Project Management*, *33*(1), 165–176. https://doi.org/10.1016/j.ijproman.2014.04.006

Rad, E. K. M., & Ming, S. (2014). Taxonomy of project complexity indicators in energy megaprojects. In *International Scientific Conference People, Buildings and Environment 2014*.

Rad, E. K. M., Sun, M., & Bosche, F. (2017). Complexity for Megaprojects in the Energy Sector. *Journal of Management in Engineering*, *33*(4), 1–13. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000517

Raghuram, G., Bastian, S., & Sundaram, S. S. (2009). *Mega projects in India Environmental* *and Land Acquisition Issues in the Road Sector*. *Indian institute of managment*.

Rahimian, F. P., Seyedzadeh, S., Oliver, S., Rodriguez, S., & Dawood, N. (2020). On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Automation in Construction*, *110*(October 2019), 103012. https://doi.org/10.1016/j.autcon.2019.103012

Rahul, G., & Tiwari, G. (2014). *Promoting Low Carbon Transport in India: Case Study of Metro Rails in Indian Cities*. *United Nations Environment Programme*. Retrieved from https://unepccc.org/wp-content/uploads/2014/08/case-study-of-metro-final.pdf

Raman, R., & Chadee, D. (2011). A comparative assessment of the information technology services sector in India and China. *Journal of Contemporary Asia*, *41*(3), 452–469. https://doi.org/10.1080/00472336.2011.582714

Rastogi, P., Khushalani, S., Dhawan, S., Goga, J., Hemanth, N., Kosi, R., … Rao, V. (2014). Understanding clinician perception of common presentations in South Asians seeking mental health treatment and determining barriers and facilitators to treatment. *Asian Journal of Psychiatry*, *7*(1), 15–21. https://doi.org/10.1016/j.ajp.2013.09.005

Remington, K., & Pollack, J. (2008). *Tools for Complex Projects* (1st Editio). London: Routledge. https://doi.org/https://doi.org/10.4324/9781315550831

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega (United Kingdom)*, *53*, 49–57. https://doi.org/10.1016/j.omega.2014.11.009

Rezvani, A., & Khosravi, P. (2019). Identification of failure factors in large scale complex projects: An integrative framework and review of emerging themes. *International Journal of Project Organisation and Management*, *11*(1), 1–21. https://doi.org/10.1504/IJPOM.2019.098723

Ribeiro, P., Paiva, A., Varajão, J., & Dominguez, C. (2013). Success evaluation factors in construction project management - some evidence from medium and large Portuguese companies. *KSCE Journal of Civil Engineering*, *17*(4), 603–609. https://doi.org/10.1007/s12205-013-0019-4

Robert K. Yin. (2009). *Case Study Research Design and Methods* (4th Editio). Sage Publications, London, England.

Robson, C., & McCartan, K. (2011). *Real World Reserach: A Resource for Users of Social Research Methods in Applied Settings* (Fourth). UK: Wiley.

Rothengatter, W. (2019). Megaprojects in transportation networks. *Transport Policy*, *75*, A1–A15. https://doi.org/10.1016/j.tranpol.2018.08.002

Samimpey, R., & Saghatforoush, E. (2024). Practical Framework to Facilitate Constructability Implementation Using Building Information Modeling Approach: A Case Study. *International Journal of Innovation and Technology Management*, *21*(1).

https://doi.org/10.1142/S0219877024500044

San Cristobal, J. R., Luis, C., Emma, D., Jose A, F., & Gregorio, I. (2018). Complexity and project management: A general overview. *Hindawi Complexity*, *2018*(Article ID 4891286), 1–10. https://doi.org/10.1155/2018/4891286

Sanni-Anibire, M. O., Zin, R. M., & Olatunji, S. O. (2020). Machine learning model for delay risk assessment in tall building projects. *International Journal of Construction Management*, *22*(11), 2134–2143. https://doi.org/10.1080/15623599.2020.1768326

Scudder, T. T. (2005). *The future of large dams: Dealing with social, environmental, institutional and political costs* (1st Editio). London, UK: Taylor & Francis. https://doi.org/https://doi.org/10.4324/9781849773904

Sears, C. (2019). What Counts as Foreign Aid: Dilemmas and Ways Forward in Measuring China's Overseas Development Flows. *Professional Geographer*, *71*(1), 135–144. https://doi.org/10.1080/00330124.2018.1479971

Sedaghat-seresht, A., Fazli, S., & Mozaffar, M. M. i. (2012). Using DEMATEL Method to Modeling Project Complexity Dimensions. *Journal of Basic and Applied Scientific Research*, *2*(11), 11211–11217.

Senescu, R. R., Aranda-Mena, G., & Haymaker, J. R. (2013). Relationships between project complexity and communication. *Journal of Management in Engineering*, *29*(2), 183–197. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000121

Shalev-Shwartz, S., & Ben-David, S. (2014). *Understanding machine learning: From theory to algorithms*. *Cambridge University Press*. New York, USA: Cambridge university press. https://doi.org/https://doi.org/10.1017/CBO9781107298019

Shan, S., Lin, Z., Li, Y., & Zeng, Y. (2018). Attracting Chinese FDI in Africa: The role of natural resources, market size and institutional quality. *Critical Perspectives on International Business*, *14*(2–3), 139–153. https://doi.org/10.1108/cpoib-11-2016-0055

Sharma, A. K., & Vohra, E. (2009). Critical evaluation of road infrastructure in India: A cross-country view. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/09699980910927903

Shenhar, A. J., Tishler, A., Dvir, D., Lipovetsky, S., & Lechler, T. (2002). Refining the search for project success factors: A multivariate, typological approach. *R and D Management*, *32*(2), 111–126. https://doi.org/10.1111/1467-9310.00244

Si, S., You, X., Liu, H., & Zhang, P. (2018). DEMATEL Technique : A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications. *Mathematical Problems in Engineering*, *2018*(1), 1–33. https://doi.org/https://doi.org/10.1155/2018/3696457

Siemiatycki, M. (2018). The making and impacts of a classic text in megaproject management:

The case of cost overrun research. *International Journal of Project Management*. https://doi.org/10.1016/j.ijproman.2016.07.003

Sinesilassie, E. G., Tabish, S. Z. S., & Jha, K. N. (2018). Critical factors affecting cost performance: a case of Ethiopian public construction projects. *International Journal of Construction Management*, *18*(2), 108–119. https://doi.org/10.1080/15623599.2016.1277058

Singh, B., & Gupta, A. (2015). Recent trends in intelligent transportation systems: a review. *The Journal of Transport Literature*, *9*(2), 30–34. https://doi.org/10.1590/2238-1031.jtl.v9n2a6

Singh, M., & Sarkar, D. (2018). Project risk management by fuzzy EVM for elevated metro rail corridor projects. In *Technology Drivers: Engine for Growth* (1st Editio, pp. 73–78). CRC Press.

Sinha, S., Kumar, B., & Thomson, A. (2006). Measuring project complexity: A project manager's tool. *Architectural Engineering and Design Management*, *2*(3), 187–202. https://doi.org/10.1080/17452007.2006.9684615

Siraj, N. B., & Fayek, A. R. (2019). Risk Identification and Common Risks in Construction: Literature Review and Content Analysis. *Journal of Construction Engineering and Management*, *145*(9), 03119004. https://doi.org/10.1061/(asce)co.1943-7862.0001685

Snowden, D. J., & Boone, M. E. (2007). A Leader ' s Framework for Decision Making. *Harvard Business Review*. Retrieved from www.hbrreprints.org

Soman, R. K., & Whyte, J. K. (2020). Codification Challenges for Data Science in Construction. *Journal of Construction Engineering and Management*, *146*(7), 04020072. https://doi.org/10.1061/(asce)co.1943-7862.0001846

Somnath Nandan. (2020). Underground or Elevated Metrorail -Which one is better? *Article*. Retrieved from https://www.linkedin.com/pulse/underground-elevated-metro-rail-which-better-india-somnath-nandan

Sridarran, P., Keraminiyage, K., & Herszon, L. (2017). Improving the cost estimates of complex projects in the project-based industries. *Built Environment Project and Asset Management*, *7*(2), 173–184. https://doi.org/10.1108/BEPAM-10-2016-0050

Stone, R. (2011). The Legacy of the Three Gorges Dam. *Science*, *333*(6044), 817. https://doi.org/https://doi.org/10.1126/science.333.6044.817

Sutrisna, M., & Barrett, P. (2007). Applying rich picture diagrams to model case studies of construction projects. *Engineering, Construction and Architectural Management*, *14*(2), 164–179. https://doi.org/10.1108/09699980710731281

Symbroj Media. (2022). *METRO RAIL NEWS EDITORIAL BOARD*. *Symbroj media pvt. ltd.* New Delhi. Retrieved from www.symbrojmedia.com

Tah, J. H. M., & Carr, V. (2001). Knowledge-Based Approach To Construction Project Risk Management. *Journal of Computing In Civil Engineering*, *15*(3), 170–177. https://doi.org/https://doi.org/10.1061/(ASCE)0887-3801(2001)15:3(170)

Tatikonda, M. V., & Rosenthal, S. R. (2000). Technology Novelty, Project Complexity, and Product Development Project Execution Success: A Deeper Look at Task Uncertainty in Product Innovation. *IEEE Transactions on Engineering Management*, *47*(1), 74–87. https://doi.org/10.1109/17.820727

Tavakolan, M., & Etemadinia, H. (2017). Fuzzy Weighted Interpretive Structural Modeling: Improved Method for Identification of Risk Interactions in Construction Projects. *Journal of Construction Engineering and Management*, *143*(11), 04017084. https://doi.org/10.1061/(asce)co.1943-7862.0001395

Terry Williams. (1999). *Modelling Complex Projects*. Baffins Lane, Chichester, West Sussex PO19 1UD, UK: John Wiley & Sons, Ltd.

Thiry, M., & Deguire, M. (2007). Recent developments in project-based organisations. *International Journal of Project Management*, *25*(7), 649–658. https://doi.org/10.1016/j.ijproman.2007.02.001

Thomas, J., & Mengel, T. (2008). Preparing project managers to deal with complexity - Advanced project management education. *International Journal of Project Management*, *26*(3), 304–315. https://doi.org/10.1016/j.ijproman.2008.01.001

Thomé, A. M. T., Scavarda, L. F., Scavarda, A., & Thomé, F. E. S. de S. (2016). Similarities and contrasts of complexity, uncertainty, risks, and resilience in supply chains and temporary multi-organization projects. *International Journal of Project Management*, *34*(7), 1328–1346. https://doi.org/10.1016/j.ijproman.2015.10.012

Touray, A., Salminen, A., & Mursu, A. (2013). ICT barriers and critical success factors in developing countries. *Electronic Journal of Information Systems in Developing Countries*, *56*(7), 1–17. https://doi.org/10.1002/j.1681-4835.2013.tb00401.x

Tsai, C.-L., Wong, C.-P., & Chou, C.-C. (2019). The Moderating/Mediating Effect of Relationships among Citizenship Behavior, Social Reflection, and Safety Behavior. *Open Journal of Social Sciences*, *07*(08), 241–261. https://doi.org/10.4236/jss.2019.78017

Tsai, C. C., & Wen, M. L. (2005). Research and trends in science education from 1998 to 2002: A content analysis of publication in selected journals. *International Journal of Science Education*, *27*(1), 3–14. https://doi.org/10.1080/0950069042000243727

Turner, J. R., & Muller, R. (2005). The Project Manager's Leadership Style as a Success Factor on Projects: A Literature Review. *Project Management Journal*, *36*(1), 49–61. https://doi.org/https://doi.org/10.1177/875697280503600206

Uddin, S. (2017). Social Network Analysis in Project Management-A Case Study of Analysing

Stakeholder Networks. *Journal of Modern Project Management*, *5*(1), 106–113. https://doi.org/10.19255/JMPM01310

Van Marrewijk, A. (2007). Managing project culture: The case of Environ Megaproject. *International Journal of Project Management*, *25*(3), 290–299. https://doi.org/10.1016/j.ijproman.2006.11.004

Van Marrewijk, A., Clegg, S. R., Pitsis, T. S., & Veenswijk, M. (2008). Managing public-private megaprojects: Paradoxes, complexity, and project design. *International Journal of Project Management*, *26*(6), 591–600. https://doi.org/10.1016/j.ijproman.2007.09.007

Van Marrewijk, A., & Smits, K. (2016). Cultural practices of governance in the Panama Canal Expansion Megaproject. *International Journal of Project Management*, *34*(3), 533–544. https://doi.org/10.1016/j.ijproman.2015.07.004

Verma, A., Harsha, V., & Subramanian, G. H. (2021). Evolution of Urban Transportation Policies in India: A Review and Analysis. *Transportation in Developing Economies*, *7*(25), 1–15. https://doi.org/10.1007/s40890-021-00136-1

Vidal, L. A., & Marle, F. (2008). Understanding project complexity: Implications on project management. *Kybernetes*, *37*(8), 1094–1110. https://doi.org/10.1108/03684920810884928

Vidal, L. A., Marle, F., & Bocquet, J. C. (2011a). Measuring project complexity using the Analytic Hierarchy Process. *International Journal of Project Management*, *29*(6), 718–727. https://doi.org/10.1016/j.ijproman.2010.07.005

Vidal, L. A., Marle, F., & Bocquet, J. C. (2011b). Using a Delphi process and the Analytic Hierarchy Process (AHP) to evaluate the complexity of projects. *Expert Systems with Applications*, *38*(5), 5388–5405. https://doi.org/10.1016/j.eswa.2010.10.016

Vilventhan, A., & Kalidindi, S. N. (2016). Interrelationships of factors causing delays in the relocation of utilities: A cognitive mapping approach. *Engineering, Construction and Architectural Management*, *23*(3), 349–368. https://doi.org/http://dx.doi.org/10.1108/ECAM-10-2014-0127

Wang, J., Luo, L., Sa, R., Zhou, W., & Yu, Z. (2023). A Quantitative Analysis of Decision-Making Risk Factors for Mega Infrastructure Projects in China. *Sustainability*, *15*(21), 15301. https://doi.org/10.3390/su152115301

Wang, T., Chan, A. P. C., & He, Q. (2021). Identification of Critical Factors for Construction Megaprojects Success (CMS). In *Collaboration and Integration in Construction , Engineering , Management and Technology-Proceedings of the 11th International Conference on Construction in the 21st Century, London 2019* (pp. 83–88). London. https://doi.org/https://doi.org/10.1007/978-3-030-48465-1_14

Wang, W., Chen, Y., Zhang, S., & Wang, Y. (2018). Contractual Complexity in Construction

Projects: Conceptualization, Operationalization, and Validation. *Project Management Journal*, *49*(3), 46–61. https://doi.org/10.1177/8756972818770589

Ward, S., & Chapman, C. (2003). Transforming project risk management into project uncertainty management. *International Journal of Project Management*, *21*(2), 97–105. https://doi.org/10.1016/S0263-7863(01)00080-1

Warren, L. (2002). Rational analysis for a problematic world revisited: Problem structuring methods for complexity, uncertainty and conflict. In Jonathan Rosenhead and John Mingers (Ed.), *Systems Research and Behavioral Science* (Vol. 19, pp. 383–387). John Wiley & Sons.

Whitty, S. J., & Maylor, H. (2009). And then came Complex Project Management (revised). *International Journal of Project Management*, *27*(3), 304–310. https://doi.org/10.1016/j.ijproman.2008.03.004

Whyte, J., Stasis, A., & Lindkvist, C. (2016). Managing change in the delivery of complex projects: Configuration management, asset information and "big data." *International Journal of Project Management*, *34*(2), 339–351. https://doi.org/10.1016/j.ijproman.2015.02.006

Williams, T. (2005). Assessing and moving on from the dominant project management discourse in the light of project overruns. *IEEE Transactions on Engineering Management*, *52*(4), 497–508. https://doi.org/10.1109/TEM.2005.856572

Williams, T. M. (1999). The need for new paradigms for complex projects. *International Journal of Project Management*, *17*(5), 269–273. https://doi.org/10.1016/S0263-7863(98)00047-7

Wood, H. L., & Ashton, P. (2010). The Factors of Project Complexity. In *18th CIB World Building Congress* (pp. 69–80).

Wood, R. E. (1986). Task complexity: Definition of the construct. *Organizational Behavior and Human Decision Processes*, *37*(1), 60–82. https://doi.org/https://doi.org/10.1016/0749-5978(86)90044-0

Wu, H. H., & Chang, S. Y. (2015). A case study of using DEMATEL method to identify critical factors in green supply chain management. *Applied Mathematics and Computation*, *256*, 394–403. https://doi.org/10.1016/j.amc.2015.01.041

Xia, B., & Chan, A. P. C. (2012). Measuring complexity for building projects : a Delphi study. *Engineering, Construction and Architectural Management*, *19*(1), 7–24. https://doi.org/10.1108/09699981211192544

Xia, W., & Lee, G. (2004). Grasping the complexity of IS development projects. *Communications of the ACM*, *47*(5), 68–74. https://doi.org/10.1145/986213.986215

Xia, W., & Lee, G. (2005). Complexity of information systems development projects:

Conceptualization and measurement development. *Journal of Management Information Systems*, *22*(1), 45–83. https://doi.org/10.1080/07421222.2003.11045831

Yang, R. J., & Zou, P. X. W. (2014). Stakeholder-associated risks and their interactions in complex green building projects: A social network model. *Building and Environment*, *73*, 208–222. https://doi.org/10.1016/j.buildenv.2013.12.014

Yong, Y. C., & Mustaffa, N. E. (2011). Clients, consultants and contractors' perception of critical success factors for construction projects in Malaysia. In *Association of Researchers in Construction Management, ARCOM 2011 - Proceedings of the 27th Annual Conference* (Vol. 2, pp. 735–744). Retrieved from https://www.arcom.ac.uk/-docs/proceedings/ar2011-0735-0744_Yong_Mustaffa.pdf

Young, R., Chen, W., Quazi, A., Parry, W., Wong, A., & Poon, S. K. (2020). The relationship between project governance mechanisms and project success: An international data set. *International Journal of Managing Projects in Business*, *13*(7), 1496–1521. https://doi.org/10.1108/IJMPB-10-2018-0212

Yu, F., Chen, X., Cory, C. A., Yang, Z., & Hu, Y. (2021). An Active Construction Dynamic Schedule Management Model: Using the Fuzzy Earned Value Management and BP Neural Network. *KSCE Journal of Civil Engineering*, *25*(7), 2335–2349. https://doi.org/10.1007/s12205-021-1041-6

Yu, J., & Leung, M. (2015). Exploring factors of preparing public engagement for large-scale development projects via a focus group study. *International Journal of Project Management*, *33*(5), 1124–1135. https://doi.org/10.1016/j.ijproman.2015.01.015

Yu Maemura, Kim, E., & Ozawa, D. E. K. (2018). Root Causes of Recurring Contractual Conflicts in International Construction Projects: Five Case Studies from Vietnam. *Journal of Construction Engineering and Management*, *144*(8), 1–15. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001523

Yujie, L., Li, Y., Pang, D., & Zhang, Y. (2015). Organizational network evolution and governance strategies in megaprojects. *Construction Economics and Building*, *15*(3), 19–33. https://doi.org/10.5130/AJCEB.v15i3.4609

Yunbo, L., Luo, L., Wang, H., Le, Y., & Shi, Q. (2015). Measurement model of project complexity for large-scale projects from task and organization perspective. *International Journal of Project Management*, *33*(3), 610–622. https://doi.org/10.1016/j.ijproman.2014.12.005

Zayed, T., Amer, M., & Pan, J. (2008). Assessing risk and uncertainty inherent in Chinese highway projects using AHP. *International Journal of Project Management*, *26*(4), 408–419. https://doi.org/10.1016/j.ijproman.2007.05.012

Zhai, L., Xin, Y., & Cheng, C. (2009). Understanding the Value of Project Management From a Stakeholder's Perspective: Case Study of Mega-project managment. *Project*

Management Journal, *40*(1), 99–109. https://doi.org/DOI: 10.1002/pmj.20099

Zhai, X., Joan Puigcerver, Kolesnikov, A., Ruyssen, P., Carlos Riquelme, Lucic, M., & Josip Djolonga. (2015). A large-scale study of representation learning with the visual task adaptation benchmark. *Computer Science- Computer Vision Pattern Recognition*. https://doi.org/https://doi.org/10.48550/arXiv.1910.04867

Zhang, D., Du, F., Huang, H., Zhang, F., Ayyub, B. M., & Beer, M. (2018). Resiliency assessment of urban rail transit networks: Shanghai metro as an example. *Safety Science*, *106*, 230–243. https://doi.org/https://doi.org/10.1016/j.ssci.2018.03.023

Zhang, Yan, Wei, H.-H., Zhao, D., Han, Y., & Chen, J. (2021). Understanding innovation diffusion and adoption strategies in megaproject networks through a fuzzy system dynamic model. *Frontiers of Engineering Management*, *8*(1), 32–47. https://doi.org/10.1007/s42524-019-0082-8

Zhang, Yijing, Li, Z., Wu, B., & Wu, S. (2009). A spaceflight operation complexity measure and its experimental validation. *International Journal of Industrial Ergonomics*, *39*(5), 756–765. https://doi.org/10.1016/j.ergon.2009.03.003

Zhao, N., Fan, D., & Chen, Y. (2021). Understanding the Impact of Transformational Leadership on Project Success: A Meta-Analysis Perspective. *Computational Intelligence and Neuroscience*, *2021*(1), 12. https://doi.org/10.1155/2021/7517791

Zheng, X., Chen, J., Han, Y., Ren, L., & Shi, Q. (2021). Unveiling complex relational behavior in megaprojects : A qualitative-quantitative network approach. *International Journal of Project Management*, *39*(7), 738–749. https://doi.org/10.1016/j.ijproman.2021.07.001

Zhu, J., & Mostafavi, A. (2017a). Discovering complexity and emergent properties in project systems: A new approach to understanding project performance. *International Journal of Project Management*, *35*(1), 1–12. https://doi.org/10.1016/j.ijproman.2016.10.004

Zhu, J., & Mostafavi, A. (2017b). Performance Assessment in Complex Engineering Projects Using a System-of-Systems Framework. *IEEE Systems Journal*, *12*(1), 262–273. https://doi.org/10.1109/JSYST.2017.2671738

Zidane, Y. J.-T., Johansen, A., & Ekambaram, A. (2013). Megaprojects-Challenges and Lessons Learned. In *Procedia - Social and Behavioral Sciences* (Vol. 74, pp. 349–357). Elsevier B.V. https://doi.org/10.1016/j.sbspro.2013.03.041

Zolin, R., Remington, K., & Turner, R. (2009). A Model of Project Complexity: Distinguishing dimensions of complexity from severity. In *Proceedings of the 9th International Research Network of Project Management Conference* (pp. 5–18). Berlin.

Zou, W, P. X., Zhang, G., & Wang, J. (2007). Understanding the key risks in construction projects in China. *International Journal of Project Management*, *25*(6), 601–614. https://doi.org/doi:10.1016/j.ijproman.2007.03.001

Publication From The Research

❖ **International Journals**

1. Sruthilaya Dara, Aneetha Vilventhan, and Ramachandra Gopal P. (2023), "Analysis of project complexity factors and their interdependencies in metro rail projects", *Built Environment Project and Asset Management*, 6 December 2023. https://doi.org/10.1108/BEPAM-09-2023-0159

2. Sruthilaya Dara, Aneetha Vilventhan, and Ramachandra Gopal P. (2023), "Development of a project complexity measurement model for metro rail projects", *Engineering, Construction and Architectural Management*, 19 December 2023. https://doi.org/10.1108/ECAM-08-2023-0845

3. Analyzing the Impact of Project Complexity on the Performance Parameters of Metrorail Project Using Machine Learning Models. (Under review).

4. Integrated ISM-ANP Method for project complexity Analysis: A Case Study of Metro Rail Projects (under preparation).

❖ **International Conference**

1. Sruthilaya Dara and Aneetha Vilventhan "Complexities of metro rail project –A case study of Hyderabad Metro rail". Presented paper in *12^th^ Construction Industry Development Board Postgraduate Research Conference- East London South Africa,* pp. 392-401, *10*-12^th^ July 2022.

❖ **National Conference**

1. Sruthilaya Dara. Aneetha Vilventhan, and Ramachandra Gopal. P "Mapping the project complexity of metro rail project using DEMATEL technique" *National Conference on Advances in Construction Materials and Management (ACMM), pp. 15-26 16^th^ -17^th^ December 2022 at National Institute of Technology, Warangal* (Received Best Paper Award).

❖ **Book Chapters**

1. Sruthilaya Dara and Aneetha Vilventhan "Complexities in Metrorail Project- A Case Study of Hyderabad Metro Rail" Towards a Sustainable Construction Industry: The Role of Innovation and Digitalisation (Springer), https://doi.org/10.1007/978-3-031-22434-8_39

2. Sruthilaya Dara. Aneetha Vilventhan, and Ramachandra Gopal. P "Mapping the Project Complexity of the Metro Rail Project Using DEMATEL Technique. In: Vilventhan, A., Singh, S.B., Delhi, V.S.K. (eds) Advances in Construction Materials and Management. ACMM 2022. Lecture Notes in Civil Engineering, vol 346. Springer, Singapore. https://doi.org/10.1007/978-981-99-2552-0_2

Appendix-I

Best and Worst Method Sample Questionnaire

Name: xxx

Designation and Name of the Organization: Project Manager at Larsen and Toubro Limited

Number of Construction Projects Handled and Overall Experience: 13 Projects and 27 Years

Email: xxx

Contact Number: xxx

Best and Worst Method Questionnaire										
Likert Scale: 1- Low; 2- Low to Moderate; 3- Moderate; 4-Moderate to Strong; 5- Strong; 6-Strong to Very Strong, 7- Very Strong; 8- Very Strong to Extreme; 9- Extreme										
Impact of Technological Complexity										
Project Complexity	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Project Complexity Factors**
Technological Complexity								✔		Diverse Technology **(DT)**
Technological Complexity				✔						Uncertainties in Scope **(US)**
Technological Complexity					✔					Change in Design/Construction **(CD/C)**
Technological Complexity			✔							Interrelationship among the technological process **(ITP)**
Impact of Organizational Complexity										
Project Complexity	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Project Complexity Factors**
Organizational Complexity		✔								Compatibility of system with Indian standards **(CSIS)**
Organizational Complexity								✔		Cumbersome Administrative process **(CAP)**
Impact of Contractual Complexity										
Project Complexity	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Project Complexity Factors**
Contractual Complexity						✔				Exchange of information **(EOI)**
Contractual Complexity						✔				Breach of contract **(BOC)**
Contractual Complexity								✔		Internal/external Politics **(IP/EP)**
Impact of Environmental Complexity										
Project Complexity	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Project Complexity Factors**
Environmental Complexity									✔	Change in regulation policy **(CRP)**
Environmental Complexity	✔									Issues in land acquisition **(ILA)**
Environmental Complexity			✔							Delay in Relocation of utilities **(DRU)**
Pairwise Comparison of Location Complexity with Subfactors										
Project Complexity	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Project Complexity Factors**
Location Complexity			✔							Uncertain geotechnical and physical conditions **(UGPC)**
Location Complexity					✔					Project location **(PL)**
Location Complexity				✔						Design changes to suit to non-divertible utilities **(DSNU)**
Location Complexity			✔							Interference with existing structures **(IES)**

Appendix-II

Questionnaire Matrix for Collection of Data for Research on Complexities in Metro Rail Projects

Name: xxxx

Name of the Organization and Designation: Larsen and Toubro Limited, and TFL Head, Experience: 31 Years

Please indicate the numerical number relevant in the matrix table given below: 0- No Influence; 1- Low Influence; 2- Medium Influence; 3- High Influence; 4- Very High Influence.

Complexity Factor	DT	US	RCT	CD/C	ITP	CRP	ILA	DRU	CSIS	CAP	UGPC	PL	DSNU	IES	EOI	IP/EP	BOC
Diverse Technology **(DT)**		2	3	1	3	0	0	1	3	1	4	2	4	2	1	1	0
Uncertainties in Scope **(US)**	2		1	3	2	1	3	1	2	1	3	4	2	1	1	2	1
Risk of complex technologies **(RCT)**	3	1		2	3	1	1	1	3	0	2	2	2	1	0	0	2
Change in Design/Construction **(CD/C)**	1	3	2		2	1	1	1	2	1	0	3	1	0	2	1	0
Interrelationship among the technological process **(ITP)**	3	2	3	2		2	0	3	1	4	2	0	2	4	3	3	1
Change in regulation policy **(CRP**	0	1	1	1	2		2	0	0	3	1	4	1	2	2	4	2
Issues in land acquisition **(ILA)**	0	3	1	1	0	2		2	0	4	1	4	1	2	2	1	0
Delay in Relocation of utilities **(DRU)**	1	1	1	1	3	0	2		1	2	0	2	3	2	2	3	1
Compatibility of system with Indian standards **(CSIS)**	3	2	3	2	1	0	0	1		2	1	0	1	1	3	2	0
Cumbersome administrative process **(CAP)**	1	1	0	1	4	3	4	2	2		0	2	0	3	2	4	1
Uncertain geotechnical and physical conditions **(UGPC)**	4	3	2	0	2	1	1	0	1	0		3	1	3	1	1	1
Project location **(PL)**	2	4	2	3	0	4	4	2	0	2	3		2	3	2	4	1
Design changes to suit non-divertible utilities **(DSNU)**	4	2	2	1	2	1	1	3	1	0	1	2		1	1	0	0
Interference with existing structures **(IES)**	2	1	1	0	4	2	2	2	1	3	3	3	1		2	1	1
Exchange of information **(EOI)**	1	1	0	2	3	2	2	2	3	2	1	2	1	2		2	1
Internal/external Politics **(IP/EP)**	1	2	0	1	3	4	1	3	2	4	1	4	0	1	2		1
Breach of contract **(BOC)**	0	1	2	0	1	2	0	1	0	1	1	1	0	1	1	1	

Appendix -III

Project performance Parameters

Dear sir/madam

This email request is regarding collecting the data for the impact of project performanceparameters in metro rail projects". I intend to use the data collected to assist in creating project research on the occurrence of complexities in metro rail projects. I am attaching a google form questionnaire. We assure you that all protocols will be followed, and privacy regulations adhere to.

Best regards
Sruthilaya Dara
Research Scholar-NITW

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* Required

1. Email *

2. Name of the Respondent *

3. Organization *

4. Type of metro -Underground/elevated/Both *

5. How does Project Parameters impact the overall performance of project on scale 1-5 *

Mark only one oval per row.

	Very Low-1	Low-2	Moderate-3	High-4	Very High-5
Time					
Cost					
Quality					
Scope					
Reliability					
Sustainability					

Appendix-IV

PPP Sample Collection

Name: xxx

Name of the Organization: Larsen and Toubro Limited

Designation: TFL Head

Overall Experience: 31 Years

Number of Construction Projects Handled: 11

Email: xxx

Contact Number: xxx

Please rank the impact of project complexity on the performance of the metro rail projects on a scale of 1-5

Likert Scale: 1- Very Low; 2- Low; 3- Moderate; 4- High; 5- Very High

Type of complexity	Complexity Factors	Very High	High	Moderate	Low	Very low
Technological Complexity	Diverse Technology **(DT)**			✔		
	Uncertainties in Scope **(US)**				✔	
	Change in Design/Construction **(CD/C)**				✔	
	Interrelationship among the technological process **(ITP)**			✔		
	Effect of dynamic complexity **(EDC)** (Change due to external /internal influence)		✔			
Organizational Complexity	Compatibility of system with Indian standards **(CSIS)**		✔			
	Cumbersome Administrative process **(CAP)**			✔		
Contractual Complexity	Exchange of information **(EOI)**				✔	
	Breach of contract **(BOC)**				✔	
	Internal/external Politics **(IP/EP)**			✔		
Environmental Complexity	Change in regulation policy **(CRP**					✔
	Issues in land acquisition **(ILA)**		✔			
	Delay in Relocation of utilities **(DRU)**				✔	
Location Complexity	Uncertain geotechnical and physical conditions **(UGPC)**		✔			
	Project location **(PL)**				✔	
	Design changes to suit to non-divertible utilities **(DSNU)**				✔	
	Interference with existing structures **(IES)**		✔			

Please rank the impact of project complexity on the performance of the metro rail projects on a scale of 1-5

Likert Scale: 1- Very low; 2- Low; 3- Moderate; 4- High; 5- Very high.

Type of Complexity	**Complexity Factors**	**Time**	**Cost**	**Quality**	**Scope**	**Sustainability**	**Reliability**
Technological Complexity	Diverse Technology **(DT)**	4	3	4	2	3	4
	Uncertainties in Scope **(US)**	3	3	2	5	4	3
	Change in Design / Construction **(CD/C)**	1	1	2	1	1	1
	Interrelationship among the technological process **(ITP)**	3	2	4	2	3	3
Organizational Complexity	Compatibility of system with Indian standards **(CSIS)**	2	1	3	2	4	4
	Cumbersome Administrative process **(CAP)**	3	2	4	4	1	1
Contractual Complexity	Exchange of information **(EOI)**	4	4	4	4	2	5
	Breach of contract **(BOC)**	5	5	4	3	3	4
	Internal/external Politics **(IP/EP)**	4	2	1	3	2	4
Environmental Complexity	Change in regulation policy **(CRP**	5	4	3	4	4	5
	Issues in land acquisition **(ILA)**	3	4	2	4	5	4
	Delay in Relocation of utilities **(DRU)**	4	4	5	4	5	3
Location Complexity	Uncertain geotechnical and physical conditions **(UGPC)**	4	4	3	4	1	3
	Project location **(PL)**	4	4	2	4	4	4
	Design changes to suit to non-divertible utilities **(DSNU)**	4	2	3	3	4	4
	Interference with existing structures **(IES)**	2	3	4	4	4	5

Appendix-V

Semi Structured Interview Questions

1. What are the different forms of contracts used in the project?
2. What are the changes made in contract terms and reasons behind them during the project?
3. How many work packages are there in the project?
4. What is the experience of the company?
5. What are the local laws that caused the delay to the project?
6. What are the various disputes during the project at pre-construction, construction, and post construction?
7. What were the dispute resolution mechanisms used to resolve disputes?
8. What are the reasons behind contract terminations, if any?
9. What is the effect of misinterpretation of clauses in the project and specific to your project?
10. Did they pay any liquidated damages for delays?
11. Are there any claims in the projects? If yes, what are they?
12. How did the procurement process affect the project? What are the processes followed at the project?
13. What are the new technologies used in this project during the design phase, construction phase in fact throughout the project life cycle?
14. What are the new materials used?
15. What are the design problems associated with new products?
16. What are the resources used in this project?
17. What is the status of resource availability?
18. What type of skilled resources are required?
19. How does experience with technology impact a project?
20. What are the channels of communication?
21. How is ICT implemented on the site?
22. How is trust ensured among stakeholders?
23. How did the level of influence of stakeholders impact the decisions?
24. How do you manage the difference of opinions and perspectives among stakeholders?
25. How does the experience of the person involved in the project affect the project?
26. What is the impact of politics on the project? (both adversial and beneficial aspects)
27. How is the public agenda managed in this project?
28. How many suppliers for materials?
29. How is the inventory managed?
30. How many global contractors are there in the project?
31. Were there any accidents in the project?
32. What are the project safety measures followed?
33. What is the employee turnover rate? Does working environment influence it?
34. How does industry regulations impact the project in Indian scenario?

35. How do internal politics impact the project?
36. What are the different languages used on the site?
37. How did cultural differences among people impact productivity at this site?
38. What is the organizational structure in a company, and does it impact the project?
39. How well did the employees aware of the clarity in goals and scope?
40. What are the outcomes of goals?
41. What are the different project management methods and tools applied?
42. What are the effects of interdependences of different departments / teams' coordination (in case of exchange of information, scope, and objective of work) on the project's performance?
43. How did leadership capabilities impact the project?
44. What is the land acquisition act in which land was acquired?
45. How much percentage of the land was acquired before the contract was given? And after the contract was awarded?
46. What were the relocation issues occurred at site?
47. How well the design of the project is connected to the existing infrastructure?
48. What are the geological/hydrological conditions that hindered the project?
49. What is the impact of site compensation on schedule?
50. How remote is the site?
51. What are the clearances required for the project?
52. Do you have the utility records of the site?
53. What are the quality standards followed in the construction?
54. How frequent were quality audits?
55. What are the quality assurances given? Does it affect the project schedule?
56. Were there any quality deviations? What were the quality measures taken to bring the desired quality?
57. What is the vision of higher-level management for quality?