A FRAMEWORK FOR ASSESSING AND INTEGRATING DATA, INFORMATION, AND KNOWLEDGE IN HIGHWAY INFRASTRUCTURE LIFE-CYCLE MANAGEMENT: A DATA-DRIVEN DECISION-MAKING APPROACH

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by

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Dedicated to

Parents, brother, and family

CERTIFICATE

This is to certify that the thesis entitled **"A framework for Assessing and Integrating Data, Information, and Knowledge in Highway Life-cycle Infrastructure Management: A Data-driven Decision-making approach"**, submitted by **Mr. Chenchumurali Krishna** (Entry No. 2019CEZ8622) to the Department of Civil Engineering, Indian Institute of Technology Delhi for the fulfilment of the requirements of the award of the degree of **Doctor of Philosophy** is a bonafide record of the research work carried out by him. He has worked under our supervision and guidance and has fulfilled the requirements for the submission of this thesis, which, to our knowledge, has reached the requisite standard. The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma.

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or exchanging thoughtful gifts during special occasions, these moments created a strong bond and made the research environment feel like home. Your support, friendship, and joy made each day brighter and this journey far more meaningful.

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ABSTRACT

The rapid digital transformation within the infrastructure sector has led to the generation of large volumes of data across the life cycle of highway projects, particularly in India. Advanced tools such as Geographic Information Systems (GIS), Building Information Modeling (BIM), sensor networks, and the National Highways Authority of India's (NHAI) Data Lake initiative have significantly expanded data collection capacities. Examples include traffic volume counts, pavement condition surveys, environmental clearances, and project cost estimates. Yet, key omissions such as real-time sensor feeds, standardized documentation, and predictive maintenance data limit the usability of this otherwise vast dataset. Much of this data remains poorly structured, inaccessible, or detached from real-time decision-making, resulting in missed opportunities for performance improvement and project efficiency.

This research addresses this challenge by examining how data quality dimensions, stakeholder perspectives, and knowledge management barriers influence the usability of infrastructure data, and by developing an integrated framework to strengthen data-to-decision pathways. Stakeholders within NHAI were mapped and engaged through structured surveys and interviews, with the semiotic framework guiding the analysis of syntactic, semantic, empiric, and pragmatic dimensions. Structural Equation Modeling confirmed that data structure and accessibility exert the strongest influence on usability, while semantic richness alone does not guarantee effective usage. To address knowledge integration, 35 knowledge management barriers were identified and validated, then analyzed through Social Network Analysis to reveal interdependencies and systemic effects.

Based on the initial analysis of data usage assessment and knowledge management barriers, a novel Data-Information-Knowledge-Decision (DIKD) integration framework was developed. The framework visualizes how data transitions through layers of interpretation and context to inform decisions. It identifies “active,” “inactive,” and “missing” data pathways, providing a structured method to diagnose weaknesses in data use. A Composite Integration Score (CIS) was introduced to quantify integration effectiveness, allowing organizations to evaluate their performance on a standardized scale. When applied to actual NHAI project datasets, the framework revealed moderate integration levels, 62.16% in the pre-construction phase and 69.34% post-construction on a 0-100 scale, where 100 represents complete integration. These scores indicate that while digital tools are in place, substantial gaps remain in data transformation and knowledge application.

Gap analysis using developed framework further revealed systemic inefficiencies in data-to-decision pathways. The framework's application provided actionable diagnostics, pinpointing where and why data fails to support timely decisions. It emphasizes the need for coordinated governance, cross-functional communication, and role-based data responsibility to ensure that data collection efforts translate into organizational intelligence.

This research makes significant contributions to both theory and practice by introducing an adaptable and empirically validated framework that integrates data science principles into infrastructure decision-making. The DIKD framework addresses critical disconnections between data generation and decision-making by aligning stakeholder needs, data quality expectations, and organizational workflows. It enables infrastructure agencies to benchmark their data integration maturity, identify systemic inefficiencies, and pursue targeted improvements. While grounded in the Indian highway context, the framework is designed to be transferable across infrastructure systems globally, promoting transparency, efficiency, and long-term sustainability through a holistic, stakeholder-sensitive approach.

Keywords: Infrastructure data integration, Decision-making frameworks, Knowledge management barriers, Social network analysis, Data quality, Semiotic framework.

सार

बुनियादी ढाँचा क्षेत्र में तेज़ी से हो रहे डिजिटल परिवर्तन के कारण, विशेष रूप से भारत में, राजमार्ग परियोजनाओं के जीवन-चक्र के दौरान बड़ी मात्रा में डेटा का सृजन हुआ है। भौगोलिक सूचना प्रणाली (जीआईएस), भवन सूचना मॉडलिंग (बीआईएम), सेंसर नेटवर्क और भारतीय राष्ट्रीय राजमार्ग प्राधिकरण (एनएचएआई) की डेटा लेक पहल जैसे उन्नत उपकरणों ने डेटा संग्रह क्षमताओं का उल्लेखनीय विस्तार किया है। उदाहरणों में यातायात की मात्रा की गणना, फुटपाथ की स्थिति का सर्वेक्षण, पर्यावरणीय मंज़ूरी और परियोजना लागत अनुमान शामिल हैं। फिर भी, वास्तविक समय सेंसर फ़ीड, मानकीकृत दस्तावेज़ीकरण और पूर्वानुमानित रखरखाव डेटा जैसी प्रमुख कमियाँ इस विशाल डेटासेट की उपयोगिता को सीमित कर देती हैं। इस डेटा का अधिकांश भाग खराब तरीके से संरचित, दुर्गम, या वास्तविक समय निर्णय लेने की प्रक्रिया से अलग रहता है, जिसके परिणामस्वरूप प्रदर्शन सुधार और परियोजना दक्षता के अवसर चूक जाते हैं।

यह शोध इस चुनौती का समाधान इस बात की जाँच करके करता है कि डेटा गुणवत्ता के आयाम, हितधारक दृष्टिकोण और ज्ञान प्रबंधन बाधाएँ बुनियादी ढाँचे के डेटा की उपयोगिता को कैसे प्रभावित करती हैं, और डेटा-से-निर्णय पथों को मज़बूत करने के लिए एक एकीकृत ढाँचा विकसित करके। एनएचएआई के हितधारकों का मानचित्रण किया गया और संरचित सर्वेक्षणों और साक्षात्कारों के माध्यम से उनसे संपर्क किया गया, जिसमें वाक्यात्मक, अर्थगत, अनुभवजन्य और व्यावहारिक आयामों के विश्लेषण का मार्गदर्शन सांकेतिक ढाँचे द्वारा किया गया। संरचनात्मक समीकरण मॉडलिंग ने पुष्टि की कि डेटा संरचना और सुगम्यता प्रयोज्यता पर सबसे अधिक प्रभाव डालती है, जबकि केवल अर्थगत समृद्धि ही प्रभावी उपयोग की गारंटी नहीं देती। ज्ञान एकीकरण को संबोधित करने के लिए, 35 ज्ञान प्रबंधन बाधाओं की पहचान की गई

और उनका सत्यापन किया गया, फिर सामाजिक नेटवर्क विश्लेषण के माध्यम से उनका विश्लेषण किया गया ताकि परस्पर निर्भरता और प्रणालीगत प्रभावों का पता लगाया जा सके।

डेटा उपयोग मूल्यांकन और ज्ञान प्रबंधन बाधाओं के प्रारंभिक विश्लेषणों के आधार पर, एक नया डेटा-सूचना-ज्ञान-निर्णय (DIKD) एकीकरण ढाँचा विकसित किया गया। यह ढाँचा यह दर्शाता है कि डेटा किस प्रकार व्याख्या और संदर्भ की परतों से होकर निर्णयों को प्रभावित करता है। यह "सक्रिय", "निष्क्रिय" और "अनुपलब्ध" डेटा मार्गों की पहचान करता है, और डेटा उपयोग में कमज़ोरियों के निदान हेतु एक संरचित विधि प्रदान करता है। एकीकरण प्रभावशीलता को मापने के लिए एक समग्र एकीकरण स्कोर (CIS) की शुरुआत की गई, जिससे संगठन एक मानकीकृत पैमाने पर अपने प्रदर्शन का मूल्यांकन कर सकें। वास्तविक NHAI परियोजना डेटासेट पर लागू करने पर, इस ढाँचे ने मध्यम एकीकरण स्तर प्रदर्शित किए, निर्माण-पूर्व चरण में 62.16% और निर्माण-पश्चात 0-100 के पैमाने पर 69.34%, जहाँ 100 पूर्ण एकीकरण को दर्शाता है। ये स्कोर दर्शाते हैं कि डिजिटल उपकरण तो मौजूद हैं, लेकिन डेटा रूपांतरण और ज्ञान अनुप्रयोग में अभी भी पर्याप्त कमियाँ हैं।

विकसित ढाँचे का उपयोग करते हुए अंतराल विश्लेषण ने डेटा-से-निर्णय मार्गों में प्रणालीगत अक्षमताओं को और उजागर किया। ढाँचे के अनुप्रयोग ने कार्रवाई योग्य निदान प्रदान किए, यह इंगित करते हुए कि डेटा कहाँ और क्यों समय पर निर्णय लेने में विफल रहता है। यह समन्वित शासन, अंतर-कार्यात्मक संचार और भूमिका-आधारित डेटा उत्तरदायित्व की आवश्यकता पर बल देता है ताकि यह सुनिश्चित किया जा सके कि डेटा संग्रह प्रयास संगठनात्मक बुद्धिमत्ता में परिवर्तित हों।

यह शोध एक अनुकूलनीय और अनुभवजन्य रूप से मान्य ढाँचे को प्रस्तुत करके सिद्धांत और व्यवहार दोनों में महत्वपूर्ण योगदान देता है जो डेटा विज्ञान के सिद्धांतों को

अवसंरचना संबंधी निर्णय लेने में एकीकृत करता है। DIKD ढाँचा हितधारकों की आवश्यकताओं, डेटा गुणवत्ता अपेक्षाओं और संगठनात्मक कार्यप्रवाहों को संरेखित करके डेटा निर्माण और निर्णय लेने के बीच महत्वपूर्ण वियोगों को दूर करता है। यह अवसंरचना एजेंसियों को अपनी डेटा एकीकरण परिपक्वता का आकलन करने, प्रणालीगत अक्षमताओं की पहचान करने और लक्षित सुधारों को आगे बढ़ाने में सक्षम बनाता है। भारतीय राजमार्ग संदर्भ पर आधारित होने के बावजूद, इस ढाँचे को वैश्विक अवसंरचना प्रणालियों में हस्तांतरणीय बनाने के लिए डिज़ाइन किया गया है, जो एक समग्र, हितधारक-संवेदनशील दृष्टिकोण के माध्यम से पारदर्शिता, दक्षता और दीर्घकालिक स्थिरता को बढ़ावा देता है।

कीवर्डः बुनियादी ढांचा डेटा एकीकरण, निर्णय-निर्माण रूपरेखाएँ, ज्ञान प्रबंधन में आने वाली बाधाएँ, सामाजिक नेटवर्क विश्लेषण, डेटा की गुणवत्ता, सैमिओटिक (अर्थ-संकेत) ढांचा

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AVE	Average Variance Extracted
AHP	Analytic Hierarchy Process
AIMQ	A Methodology for Information Quality Assessment
AMOS	Analysis of Moment Structures
BIM	Building Information Modeling
BSM	Bosua-Scheepers Model
CAN	Correlation Network Analysis
CB-SEM	Covariance-Based Structural Equation Modeling
CDQ	Comprehensive Methodology for Data Quality Management
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CGM	Chief General Manager
CGS	Critical Gap Score
CIS	Composite Integration Score
COLDQ	Cost-effect of Low Data Quality
DGM	Deputy General Manager
DIK	Data-Information-Knowledge
DIKW	Data-Information-Knowledge-Wisdom
DPR	Detailed Project Report
DQ	Data Quality
DQAF	Data Quality Assessment Framework
EFA	Exploratory Factor Analysis
EIA	Environmental Impact Assessment
FMI	Fails Management Institute

FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GFI	Goodness-of-Fit Index
GIS	Geographic information systems
GPS	Global Positioning System
HDQM	A Data Quality Methodology for Heterogeneous Data
HIQM	Hybrid Information Quality Management
HTMT	Heterotrait-Monotrait Ratio
IEC	International Electrotechnical Commission
IoT	Internet of Things
ISO	International Organization for Standardization
KM	Knowledge Management
KNA	Knowledge Network Analysis
KSEM	Knowledge-Sharing Environment Model
LiDAR	Light Detection and Ranging
MORTH	Ministry of Road Transport and Highways
NHAI	National Highways Authority of India
NSV	Network Survey Vehicle
OODADQ	The Observe-Orient-Decide-Act Methodology
PCA	Principal Component Analysis
PCS	Path Connectivity Score
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
PRL	Project Level
PSL	Project Selection Level
RACI	Responsible, Accountable, Consulted, and Informed
RI	Redundancy Index

RMSEA	Root Mean Square Error of Approximation
SEM	Structural Equation Modeling
SMEs	Small and Medium-sized Enterprises
SNA	Social Network Analysis
SPDQM	Square-Aligned Portal Data Quality Model
SPSE	Semantics, Pragmatics, Syntactic, and Empirics
SPSS	Statistical Package for the Social Sciences
SRMR	Standardized Root Mean Square Residual
SSHC	Social Sustainability Health Check
TAM	Transportation Asset Management
TBDQ	Task-Based Data Quality Method
TDQM	Total Data Quality Management
TIQM	Total Information Quality Management
TLI	Tucker-Lewis Index
UK	United Kingdom
USA	United States America