DEVELOPMENT OF A RESILIENCE MODEL AND TOOL FOR RESILIENCE OPTIMIZATION FOR INTERDEPENDENT CRITICAL INFRASTRUCTURE

Bawantha Sandaruwan Rathnayaka

218043J

Doctor of Philosophy (PhD)

Department of Civil Engineering

Faculty of Engineering

University of Moratuwa

Sri Lanka

March 2025

DEVELOPMENT OF A RESILIENCE MODEL AND TOOL FOR RESILIENCE OPTIMIZATION FOR INTERDEPENDENT CRITICAL INFRASTRUCTURE

Bawantha Sandaruwan Rathnayaka

218043J

Thesis submitted in partial fulfillment of the requirements for the degree

Doctor of Philosophy (PhD)

Department of Civil Engineering

Faculty of Engineering

University of Moratuwa

Sri Lanka

March 2025

DECLARATION

I declare that this is my own work, and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date: 29/09/2025

The above candidate has carried out research for the PhD thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Dr. Varuna Adikariwattage

Signature of the Supervisor: Date: 29/09/2025

DEDICATION

This thesis is dedicated to the resilient and hardworking people of Sri Lanka at every level, from those who clean our streets to the highest-level professionals, whose relentless efforts and sacrifices form the backbone of our society. To the people, whose sweat drives our economy, your contributions are invaluable. Despite the many hardships you face, your unwavering commitment to paying taxes sustains the free education system that has empowered countless individuals, including myself, to pursue our dreams. I am deeply indebted to the system of free education, a beacon of hope and opportunity that reflects the power of collective investment in our nation's future. It stands as a testament to the belief that every child, regardless of their background, deserves the chance to learn, grow, and succeed.

To the dedicated teachers who have guided and nurtured me since grade one, your unwavering dedication, wisdom, and encouragement have been instrumental in shaping my journey. Your impact extends far beyond the classroom, and for this, I am profoundly grateful.

To all the unsung heroes who have supported and inspired me through their hard work and dedication. Your contributions have made this journey possible.

ACKNOWLEDGMENT

I would like to express my deepest gratitude to my supervisory panel: Dr. Varuna Adikariwattage (University of Moratuwa), Dr. Chandana Siriwardana (Massey University), Prof. Dilan Robert (RMIT University), Prof. Sujeeva Setunge (RMIT University) and Prof. Dilanthi Amaratunga (University of Huddersfield) for their invaluable guidance, unwavering support, and patience throughout my PhD journey. Their expertise and insightful feedback have been instrumental in shaping this research. I would also like to sincerely thank Prof. H.R. Pasindu (University of Moratuwa), Prof. Lasantha Meegahapola (RMIT University), and Dr. Erica Kuligowski (RMIT University) for their valuable feedback and support. It has been an immense privilege to work under the mentorship of such esteemed academics, and I am truly grateful for their contributions to my research and professional development.

I sincerely acknowledge the RMIT-UoM PhD Cotutelle Program for support in making this long and rewarding journey possible. A special appreciation goes to the School of Engineering at RMIT University and the University of Moratuwa for their generous financial assistance, which was instrumental in the successful completion of my studies. I am also grateful to all the experts who participated in this study, sharing their invaluable knowledge and perspectives.

My heartfelt appreciation extends to my family—my beloved mother, deceased father, and my wife—whose unwavering love, encouragement, and strength have been my pillars of support. Their sacrifices and belief in me have been a driving force behind my achievements.

To my friends and colleagues, your constant encouragement, thoughtful advice, and companionship have made this journey even more meaningful. Your support, whether in times of challenge or celebration, has been truly invaluable, and I am forever grateful.

Thank you all for being part of this incredible journey.

Bawantha Sandaruwan Rathnayaka

ABSTRACT

Critical Infrastructures (CIs) are highly interdependent systems making them vulnerable to cascading failures during disruptions. The resilience assessment of CIs has become a crucial aspect at present yet challenging due to the interdependencies that drive their systematic behaviour, compounded by their dynamic nature. This thesis aims to bridge this gap by developing a comprehensive resilience assessment model for CIs, which incorporates the complexities of interdependencies through the application of Dynamic Bayesian Networks (DBN) and Machine Learning (ML) techniques. The study begins with a systematic review of CI resilience literature, including definitions, interdependencies, climate change impacts, modelling techniques, and resilience frameworks. The study also identifies eight governance measures to enhance the resilience of CIs. Moreover, Climate Change Adaptation (CCA) measures for enhancing resilience of CIs are prioritised based on different stages of infrastructure cycle, using the Analytical Hierarchical Process (AHP), with an expert survey. Then, a systematic literature review and expert survey were conducted to identify and validate the resilience assessment parameters. Then, a novel methodology to quantify the resilience of the CI system, accounting for both the interdependencies of CIs and the dynamic nature of their capacities, is proposed utilising the DBN. A case study from Sri Lanka demonstrated the DBN model's practical applicability, showing strong agreement with expert assessments. Simulation data generated from the DBN model was used to train and validate six ML algorithms, resulting in a robust resilience prediction tool. SHAP analysis was used to interpret ML outcomes and highlight key drivers of resilience. It further validates the research output identified in the early stages of the present study. The outcomes of this study can be used as a foundation for developing a resilience optimisation tool. It provides actionable insights for policymakers and infrastructure managers, offering a validated, transferable tool to strengthen CI resilience across diverse contexts.

Keywords: Machine Learning; Climate Change Adaptation; Resilience assessment; Critical Infrastructure; Disaster Risk Reduction; Disasters; Climate Change; Dynamic Bayesian Network

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

- CI : Critical Infrastructure
- CCA : Climate Change Adaptation
- DRR : Disaster Risk Reduction
- GHG : Green House Gas
- IPCC : Intergovernmental Panel on Climate Change
- PACC : Paris Agreement on Climate Change
- SFDRR: Sendai Framework for Disaster Risk Reduction
- SDGs : Sustainable Development Goals
- CIN : Consistency Index
- RI : Random Consistency Index
- CR : Consensus Ratio
- CPT : Conditional Probability Tables
- BN : Bayesian Network
- DBN: Dynamic Bayesian Network