MODELING DESIGN INTERDEPENDENCY AND ITERATION FOR MULTIPLE TWO-WAY INFORMATION EXCHANGES IN CONSTRUCTION PROJECTS

PURVA MUJUMDAR

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2017

MODELING DESIGN INTERDEPENDENCY AND ITERATION FOR MULTIPLE TWO-WAY INFORMATION EXCHANGES IN CONSTRUCTION PROJECTS

by

PURVA MUJUMDAR

To be submitted in fulfillment for the award of degree of Doctor of Philosophy

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2017

I dedicate this effort

To My Parents

and

To My Husband

CERTIFICATE

This is to certify that the thesis titled "**Modeling Design Interdependency and Iteration for Multiple Two-way Information Exchanges in Construction Projects**" being submitted by **Ms. Purva Mujumdar** to the Indian Institute of Technology Delhi, (India) for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work carried out by her. She has worked under our guidance and supervision and has fulfilled the requirements for submission of this thesis, which to the best of our knowledge has reached the requisite standard. The results contained in this thesis have not been submitted either in full or in parts to any other University or Institute for the award of any degree or diploma.

Dr. J. Uma Maheswari
Supervisor
Department of Civil Engineering
Indian Institute of Technology Delhi

Dr. Vasant Matsagar
Co-supervisor
Department of Civil Engineering
Indian Institute of Technology Delhi

Date: October 2017

Place: New Delhi, India

ACKNOWLEDGEMENTS

This study could not be embodied without the help, encouragement, cooperation and guidance of a lot of people, mentioned and not mentioned here, and I convey my heartfelt gratitude to all of them.

I express my deepest gratitude to my supervisor **Dr. J. Uma Maheswari** for her stimulating guidance, unwavering support and encouragement. This thesis could not have attained its present form, both in content and presentation, without her active interest, direction and guidance.

I am grateful to my co-supervisor **Dr. Vasant Matsagar** for his timely inputs and meticulous attention which has been a source of great inspiration and motivation throughout the duration of the research. I would also like to take this opportunity to record my sincere indebtedness to all my Research Committee members - **Prof. Mukesh Khare**, **Prof. K.C. Iyer** and **Prof. Ravi Shankar**, for giving valuable suggestions and comments on the work.

I express my gratitude to the Head of Department - **Prof. Manoj Datta** and the former Head - **Prof. A.K. Jain** for all the opportunities provided to me. I acknowledge the efforts of **Prof. B. Bhattacharjee** and all the faculty members of Civil Engineering Department for their contributions.

I express my heartfelt thanks to Mr. S.P. Sreenivas Padala, Mr. Ratnesh Kumar and Colonel Pawan Pandey, my fellow research scholars in the Department for their valuable inputs and continuous support. I pay my sincere thanks to the postgraduate students - Mrs. Soma Bhattacharya and Mr. Prasobh Muraleedharan for providing me with industry case examples to experiment my work. I mention my special remarks of

gratitude to graduate students - Mr. Prashant Kumar and Mr. Rahul Kumar for helping me in developing the prototype software tool.

I gratefully acknowledge the inputs of several experts from highway industry especially Feedback Infrastructures Pvt. Ltd., Gurgaon, Haryana; Mott McDonald Pvt. Ltd., Noida, UP and Ramboll India Pvt. Ltd., Gurgaon, Haryana for providing me with data and information on various highway design case studies for supporting my work. I sincerely thank Mr. Amrit Kumar, Senior Geotechnical Engineer, Mrs. Aruna Tageja, Deputy General Manager, Mr. Ashok Kumar, Bridge design engineer, Mr. Mahender Kumar, Senior pavement engineer, Mr. Tapas Das, Senior hydrology expert, Mrs. Anu Shrivastava, Senior traffic engineer (Feedback Infrastructures Pvt. Ltd.), Mr. Kunal Songra, Structural engineer, and Ms. Deepti Sharma, Draughtsperson (Mott McDonald Pvt. Ltd.) and Mr. Rudrajit Roy, Senior highway engineer, (Ramboll India Pvt. Ltd.) for sharing their valuable time and inputs during data collection for this work. I owe special thanks to my friends Mr. Gaurav Maroo, Senior structural engineer, Samsung Heavy Industries, Noida, UP; and Mrs. Suman Kilania, Senior hydrology engineer, Larsen and Toubro, Faridabad, UP for sharing their technical inputs and suggestions on my work.

I wish to express my gratitude to all the non-teaching staff of the Department of Civil Engineering and the Industrial Research and Development Unit of IIT Delhi for their timely help.

I am very grateful to DST (Department of Science and Technology, Government of India, New Delhi) for providing the financial support to execute the work in this area and also for participating in several international conferences held at India and abroad.

I am indebted to my parents, Diwakar and Rashmi Mujumdar, who were instrumental at every stage and have been a constant source of strength and inspiration in

every aspect of my life. I express my appreciation to my sisters, Priya and Arunima for their continuous support during this work. I am thankful to my parents-in-laws, Dr. Umesh and Sudha Jain, for their care and encouragement. This work would not have been possible without the special support from my husband, Mr. Abhinav Jain. I am thankful for his love, understanding, support and sacrifices. He has been an unending source of strength. Your words of love and affection have renewed my energies to keep me going.

Date: October 2017 *Purva Mujumdar*

ABSTRACT

MODELING DESIGN INTERDEPENDENCY AND ITERATION FOR MULTIPLE TWO-WAY INFORMATION EXCHANGES IN CONSTRUCTION PROJECTS

Planning for any design phase in a construction project involves several entities such as teams, components, activities or parameters along with their corresponding information dependencies. The design process had been generally defined as the continuous exchange of information across numerous designers and stakeholders until the specifications and requirements are met. When these information exchanges occur along the feedback cycles or loops, it is termed as design iteration. In general, the information exchanges traversing within and across several design entities in any direction throughout the design phase are referred in assorted ways such as interdependent, overlaps, two-way information exchanges, bidirectional multiple linkages. In this study, these information exchanges are referred as interdependent. This interdependency and iteration occurring due to the multiple two-way information exchanges are unavoidable in any design phase. It is also a well-known fact that when these interdependencies and iterations are not planned properly, unnecessary rework, repetition, revision or redesign may occur. Hence, the objective of this study is to model these interdependencies and iterations while planning a design phase.

To achieve this objective, an integrated BDM-MDM framework was proposed as a solution to capture and to evaluate the interdependency-iteration. Initially, the interdependent entities are planned to be modeled using the BDM (Beeline Diagramming Method). The BDM is an extension of the PDM (Precedence Diagramming Method) concept and is a potential technique to capture multiple information exchanges that can

traverse in any direction. Subsequently, the MDM (Multiple-Domain Matrix) is utilized to represent the iteration and also to determine the sequence of execution. Here, the MDM is chosen owing to its efficiency to represent information dependencies within and across multiple entities. Then, the appropriate execution sequence is determined using Markov Chain by evaluating the blocks.

The proposed problem-solution concept is applied on a four-lane highway design case through extensive data collected from twelve participating design teams. Approximately eight months of continuous interactions and discussions are done with the twelve teams for collecting the required case data. Further, the proposed concepts are illustrated also with a six-storey structural steel building design case and are finally reviewed with the design experts. This application and illustration revealed that there is huge potential for applying this concept to construction projects. For the construction firms to adopt this practice, implementation of the proposed approach to industry is discussed. A prototype tool in MATLAB (Matrix Laboratory) is developed as the software implementation to automate the calculations.

Keywords: Multiple two-way design information exchanges, Interdependency, Iteration, Beeline Diagramming Method (BDM), Multiple-Domain Matrix (MDM), Markov Chain.

सार

निर्माण प्रोजेक्ट्स में कई दो-तरह की जानकारी एक्सचेंजों के लिए मॉडलिंग डिजाइन अंतरदंड और सूचना

निर्माण परियोजना में किसी भी डिजाइन चरण के लिए योजना में टीमों, घटकों, गतिविधियों या मानदंडों जैसे उनकी संबंधित जानकारी निर्भरता के साथ कई संस्थाएं शामिल हैं। डिज़ाइन प्रक्रिया को आम तौर पर कई डिजाइनरों और हितधारकों में जानकारी के निरंतर आदान-प्रदान के रूप में परिभाषित किया गया था जब तक विनिर्देशों और आवश्यकताओं को पूरा नहीं किया जाता है। जब ये सूचना एक्सचेंज फीडबैक चक्र या लूप के साथ होते हैं, इसे डिजाइन पुनरावृत्ति कहा जाता है सामान्य तौर पर, डिज़ाइन चरण के दौरान किसी भी दिशा में किसी भी दिशा में और कई डिजाइन संस्थाओं के पार आने वाले सूचना एक्सचेंजों को विभिन्न तरह से संदर्भित किया जाता है जैसे कि अन्योन्याश्रित, ओवरलैप, दो-तरफा जानकारी एक्सचेंज, द्विदिश बहु संपर्क। इस अध्ययन में, इन सूचना एक्सचेंजों को परस्पर निर्भर निर्भर कहा जाता है। कई दो-तरफा जानकारी एक्सचेंजों के कारण यह अंतर-निर्भरता और चलना किसी भी डिजाइन चरण में अपरिहार्य है। यह भी एक प्रसिद्ध तथ्य है कि जब ये अंतर-निर्भरता और पुनरावृत्तियों को ठीक से नहीं नियोजित किया जाता है, तो अनावश्यक पुन: कार्य, पुनरावृत्ति, संशोधन या रीडिझाइन हो सकता है। इसलिए, इस अध्ययन का उद्देश्य एक डिजाइन चरण की योजना के दौरान इन परस्पर निर्भरता और पुनरावृत्तियों का आदर्श बनाना है।

इस उद्देश्य को प्राप्त करने के लिए, एक एकीकृत बीडीएम-एमडीएम फ्रेमवर्क को परस्पर निर्भरता-पुनरावृत्ति का आकलन करने और मूल्यांकन करने के लिए एक समाधान के रूप में प्रस्तावित किया गया था। प्रारंभ में, अन्योन्याश्रित संस्थाओं को बीडीएम (बीलाइन डायग्रामिंग पद्धति) का उपयोग करके मॉडलिंग की योजना बनाई गई है। बीडीएम, पीडीएम (प्रीडेंसेंस डायगर्मिंग मेथड) अवधारणा का एक विस्तार है और कई सूचना एक्सचेंजों को पकड़ने के लिए एक संभावित तकनीक है जो कि किसी भी दिशा में फैल सकती है। इसके बाद, एमडीएम (मल्टीपल-डोमेन मैट्रिक्स) का इस्तेमाल चलन का

प्रतिनिधित्व करने के लिए किया जाता है और निष्पादन के क्रम को निर्धारित करने के लिए भी किया जाता है। यहां, एमडीएम को कई संस्थाओं के भीतर और उसके अंदर सूचना निर्भरता का प्रतिनिधित्व करने के लिए चुना गया है। फिर, उचित निष्पादन अनुक्रम ब्लॉक का मूल्यांकन करके मार्कोव चेन का उपयोग करके निर्धारित किया जाता है।

प्रस्तावित समस्या-समाधान की अवधारणा को चार लेन राजमार्ग डिजाइन मामले पर लागू किया जाता है, जिसमें बारह भाग लेने वाली डिज़ाइन टीमों से एकत्रित किए गए व्यापक आंकड़ों के माध्यम से उपयोग किया जाता है। लगभग आठ महीने की निरंतर बातचीत और विचार-विमर्श बारह टीमों के साथ आवश्यक केस डेटा इकट्ठा करने के लिए किया जाता है। इसके अलावा, प्रस्तावित अवधारणाओं को छह मंजिला संरचनात्मक स्टील बिल्डिंग डिज़ाइन केस के साथ भी सचित्र किया गया है और अंत में डिजाइन विशेषज्ञों के साथ समीक्षा की गई है। इस आवेदन और उदाहरण से पता चला कि इस अवधारणा को निर्माण परियोजनाओं के लिए लागू करने के लिए बहुत बड़ी संभावनाएं हैं। निर्माण कंपनियों को इस अभ्यास को अपनाने के लिए, उद्योग के लिए प्रस्तावित दृष्टिकोण के कार्यान्वयन पर चर्चा की जाती है। मैट्रिक्स लैबोरेटरी में एक प्रोटोटाइप टूल को गणनाओं को स्वचालित करने के लिए सॉफ़्टवेयर कार्यान्वयन के रूप में विकसित किया गया है।

कीवर्ड: एकाधिक दो-तरफा डिजाइन सूचना एक्सचेंज, इंटरदॉन्डेंसी, इटरेशन, बीलाइन डायग्रामिंग मेथड (बीडीएम), मल्टीपल-डोमेन मैट्रिक्स (एमडीएम), मार्कोव चेन।

TABLE OF CONTENTS

Description			Page
Certificate			i
Acknowledgement			iii
Abstract			vii
List of Figures			xiii
List of Tables			xvii
Chapter 1	**INTRODUCTION**		
	1.1	General	1
	1.2	Motivation for the Present Study	2
		1.2.1 Literature Review	2
		1.2.2 Pilot Case Studies	5
	1.3	Background	7
	1.4	Research Aim and Methodology	12
	1.5	Organization of the Thesis	13
Chapter 2	**LITERATURE REVIEW**		
	2.1	Introduction	15
	2.2	Interdependency vs. Overlaps	15
	2.3	Planning and Executing Interdependency	18
	2.4	Iteration	19
		2.4.1 Types of Design Iteration	19
		2.4.2 Causes of Iteration	24
		2.4.3 Execution Strategies of Iteration	26
	2.5	Design Planning Techniques	28
		2.5.1 Graph Based Methods	28
		2.5.2 Matrix Based Methods	34
	2.6	Gaps in the Literature	37
Chapter 3	**OBJECTIVES AND RESEARCH METHODOLOGY**		
	3.1	Introduction	41
	3.2	Research Objectives	41
	3.3	Scope	41
	3.4	Problem - Solution Framework	41
	3.5	Research Methodology	44
	3.6	Summary	46

Chapter 4 PROPOSED SOLUTION CONCEPT

4.1 Introduction 47

4.2 Proposed Solution Methodology 47

4.3 Illustration - Hypothetical example 52

4.3.1 Modeling Design Interdependency 52

4.3.2 Modeling Design Iteration 61

4.4 Summary 66

Chapter 5 CASE ILLUSTRATION AND RESULTS

5.1 Introduction 67

5.2 Description of the Case Study 67

5.2.1 Project Overview 67

5.2.2 Project Goals 68

5.2.3 Project Stages 69

5.2.4 Design Teams 70

5.2.5 Design Management Strategy 70

5.2.6 Traditional Design Process and Challenges during Design 71

5.3 Data Collection Methodology 72

5.4 Case Analysis and Results 74

5.4.1 Modeling Design Interdependency 74

5.4.2 Modeling Design Iteration 78

5.5 Impact to Design Process 84

5.6 Implementation of Proposed Approach to Design 87

5.6.1 Industry Implementation 87

5.6.2 Software Implementation 88

5.7 Summary 94

Chapter 6 TESTING AND DISCUSSIONS

6.1 Introduction 97

6.2 Comparison with Existing Methods 97

6.3 Illustration on Building Design 100

6.3.1 Description of the Case 100

6.3.2 Case Analysis and Results 101

6.4 Discussions 107

6.4.1 Significance 107

6.4.2 Limitations 108

Chapter 7 SUMMARY AND CONCLUSIONS

7.1 Summary 113

7.1.1 Problem Concept 113

7.1.2 Integrated Solution Framework 113

7.1.3 Case Illustration 114

7.2 Conclusions 114

7.3 Research Contributions 115

7.4 Scope for Future Research 116

APPENDIX A CASE ILLUSTRATION – HIGHWAY DESIGN 119

APPENDIX B THE MATLAB PROTOTYPE TOOL 129

APPENDIX C INTEGRATED FRAMEWORK FOR AUTOMATING THE STRUCTURAL DESIGN ITERATION 139

APPENDIX D DERIVATION OF EQUATIONS FOR BDM NETWORK ANALYSIS 151

APPENDIX E MDM DEVELOPMENT AND DERIVING RELATIONSHIPS AMONG DSMs and DMMs 155

APPENDIX F DERIVATION FOR MARKOV CHAIN EQUATIONS 163

REFERENCES 168

LIST OF PUBLICATIONS 184

LIST OF FIGURES

Figure No.	Figure Caption	Page
Figure 1.1	Differing stakeholders' influence on beam penetration design	2
Figure 1.2	Differing viewpoints of design teams in offshore facility design	4
Figure 1.3	Causal loop diagram for requirement of design phase planning	6
Figure 1.4	Evolution of a typical design phase	7
Figure 1.5	Structural design process in a typical building	8
Figure 1.6	Work-breakdown structure of design entities in highway design	9
Figure 1.7	Types of information dependencies in a highway design phase	10
Figure 1.8	Types of overlaps in a highway design phase	11
Figure 1.9	Overall research methodology	13
Figure 2.1	Divisive overlapping	17
Figure 2.2	Planning interdependency	19
Figure 2.3	Framework for design iteration	20
Figure 2.4	Information and communication iteration in highway design	22
Figure 2.5	Influence diagram of design iteration	26
Figure 2.6	Iteration execution strategies	27
Figure 2.7	Digraph representation for a typical construction phase	29
Figure 2.8	DFD representation for a typical drainage design	30
Figure 2.9	IDEF0 representation for a typical building design	31
Figure 2.10	Petri net representation for excavation work	32
Figure 2.11	Signal flow graph representation for a die design	33
Figure 2.12	Applied signposting model	33
Figure 2.13	Beeline diagramming method for hypothetical example	34
Figure 2.14	Design structure matrix for hypothetical example	35
Figure 2.15	Multiple-domain matrix for an interceptor sewer design	36
Figure 3.1	Interdependency-Iteration problem framework	42
Figure 3.2	Integrated BDM-MDM solution framework	44
Figure 3.3	Research methodology	45
Figure 4.1	Flowchart for modeling interdependency on a BDM network	48
Figure 4.2	Flowchart for modeling design entities on MDM	49
Figure 4.3	DSM partitioning algorithm	51
Figure 4.4	Flowchart for modeling and estimating iteration	53

Figure No.	Figure Caption	Page
Figure 4.5	Flowchart for determining team duration	54
Figure 4.6	BDM network representation - Hypothetical example	55
Figure 4.7	BDM network analysis - Hypothetical example	57
Figure 4.8	Generation of skeleton MDM	62
Figure 4.9	Capturing BDM N-N linkages in MDM skeleton framework	62
Figure 4.10	Populating parameter DSM – Hypothetical example	63
Figure 4.11	Populating parameter-team DMM – Hypothetical example	63
Figure 4.12	Populating team-parameter DMM – Hypothetical example	63
Figure 4.13	Population of team DSM – Hypothetical example	63
Figure 4.14	Highlighting iteration blocks in parameter DSM	64
Figure 4.15	Rework probability values for the iteration block in parameter DSM	65
Figure 5.1	Key plan of the project stretch	68
Figure 5.2	Challenges during highway design phase	72
Figure 5.3(a)	Data collection methods for the case study	73
Figure 5.3(b)	Methodology for data collection	73
Figure 5.4	Information exchanges in highway design phase	75
Figure 5.5	BDM network representation of highway design phase	76
Figure 5.6	BDM network analysis of highway design phase	77
Figure 5.7	Critical path for highway design phase	78
Figure 5.8	MDM generation and population for highway design phase	79
Figure 5.9	Iteration blocks and design sequence for highway design phase	80
Figure 5.10	Rework probability values for the blocks in highway design phase	81
Figure 5.11	Markov Chain for iteration block 1	81
Figure 5.12	Final design duration for case 1	81
Figure 5.13	Final design duration for case 2	82
Figure 5.14	Final MDM for highway design phase	84
Figure 5.15	Sensitivity analysis with rework probability for parameter HD3	85
Figure 5.16	Sensitivity analysis with rework probability for parameter SD3	86
Figure 5.17	Sensitivity analysis with rework probability for parameter HY2 for loop HY2-HY3	86
Figure 5.18	Sensitivity analysis with rework probability for parameter HY2 for loop HY2-SD1	87

Figure No.	Figure Caption	Page
Figure 5.19	Practical implementation framework of proposed approach to design projects	89
Figure 5.20	Mapping of data collection methods with data required in design projects	90
Figure 5.21	Flowchart for prototype tool development	91
Figure 5.22	Text input for BDM network analysis	92
Figure 5.23	Output highlighting critical segment of design teams for BDM analysis	92
Figure 5.24	Excel input for block formation in MDM	93
Figure 5.25	Output highlighting populated MDM	93
Figure 5.26	Output highlighting blocks and the team duration	94
Figure 5.27	Data analysis	95
Figure 6.1	Proposed BDM network analysis on construction phase	98
Figure 6.2	Existing BDM network analysis on highway design phase	99
Figure 6.3	Six-storey structural steel office building design	101
Figure 6.4	Work-breakdown structure for building design	102
Figure 6.5	BDM network representation for building design	103
Figure 6.6	BDM network analysis for building design	104
Figure 6.7	Critical path and critical activities for building design	104
Figure 6.8	MDM generation and population for building design	105
Figure 6.9	Iteration block in activity DSM for building design	105
Figure 6.10	Rework probability values for the block in building design	106
Figure 6.11	Final MDM for building design	106
Figure A.1	BDM representation of complete highway design	120
Figure A.2	BDM network analysis for complete highway design	121
Figure A.3	Critical path and critical parameters for complete highway design	122
Figure A.4	Capturing of iterations in MDM for complete highway design	123
Figure A.5	Iteration blocks for complete highway design	124
Figure A.6	Parameter details for complete highway design	125
Figure A.7	Duration of iteration block 1 for complete highway design	126
Figure A.8	Duration of iteration block 2 for complete highway design	127
Figure A.9	Duration of iteration block 3 for complete highway design	128
Figure A.10	Duration of iteration block 4 for complete highway design	128
Figure B.1	MATLAB code for BDM network analysis	130

Figure No.	Figure Caption	Page
Figure B.2	Text input for BDM network analysis	131
Figure B.3	Enter input file name for BDM network analysis	131
Figure B.4	Output results highlighting critical segment of highway design teams for BDM analysis	131
Figure B.5	Output results - BDM network computations for highway design	132
Figure B.6	MATLAB code for block formation	133
Figure B.7	Excel input for modeling iteration in MDM	134
Figure B.8	Enter input file name for MDM population	134
Figure B.9	Processing input file for MDM population	134
Figure B.10	Output results - Populated MDM for highway design	135
Figure B.11	Processing input file for block formation	135
Figure B.12	Output results – Iteration blocks for highway design	136
Figure B.13	Processing estimation of iteration block for all design sequences for highway design	136
Figure B.14	Output results - Block duration for all design sequences for highway design	137
Figure B.15	Output results – Total duration for block 1 for highway design	138
Figure B.16	Output results – Total duration for block 2 for highway design	138
Figure C.1	Structural design flow	142
Figure C.2	Structural design iterations using DSM	144
Figure C.3	Proposed integration framework	144
Figure C.4	Solution methodology	146
Figure C.5	General layout of the six-storey building	147
Figure C.6	Automation of iterations using OpenSTAAD	148
Figure C.7	Design results after iterations	150
Figure E.1	Methodology for MDM Generation	156
Figure E.2	Entity mapping of MDM in design phase	156
Figure E.3	Generic arrangement of DMMs and DSMs in a typical MDM	157
Figure E.4	Methodology for MDM Population	157
Figure E.5	MDM for interceptor sewer	159
Figure E.6	DSMs and DMMs depicted on MDM for interceptor sewer	160
Figure E.7	DSMs obtained after matrix multiplication of DMMs	161
Figure E.8	MDM for Manhole	162
Figure E.9	DSMs after matrix multiplication in MDM for Manhole	162

LIST OF TABLES

Table No.	Table Caption	Page
Table 2.1	Design relationships vs. Overlaps	16
Table 2.2	Divisive overlap strategy	17
Table 2.3	Causes of design iteration	25
Table 2.4	List of design entities modeled in MDM	36
Table 4.1	EET calculation for the hypothetical network	58
Table 4.2	LET calculation for the hypothetical network	59
Table 4.3	Float calculation for the hypothetical network	60
Table 5.1	List of teams and parameters for the highway design	76
Table 5.2	Total design duration for case 1	82
Table 5.3	Total design duration for case 2	83
Table 6.1	Details of building design case	101
Table 6.2	List of design entities in building design case	103
Table C.1	List of activities for the structural design flow	143
Table E.1	List of entities for the interceptor sewer design	158