3-2-2021

A BIM-based Approach for Predictive Safety Planning in the Construction Industry

Mohammadsaeid Parsamehr

University of Windsor

Recommended Citation

Parsamehr, Mohammadsaeid, "A BIM-based Approach for Predictive Safety Planning in the Construction Industry" (2021). *Electronic Theses and Dissertations*. 8529.
https://scholar.uwindsor.ca/etd/8529

A BIM-based Approach for Predictive Safety Planning in the Construction Industry

By

Mohammadsaeid Parsamehr

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2020

A BIM-based Approach for Predictive Safety Planning in the Construction Industry

by

Mohammadsaeid Parsamehr

APPROVED BY:

M. Belalia
Department of Mathematics and Statistics

S. Das
Department of Civil and Environmental Engineering

R. Ruparathna, Advisor
Department of Civil and Environmental Engineering

December 17, 2020

DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates materials that are a result of joint research, as follows:

Chapters 1, 2, 3, and 4 of this thesis were completed under the supervision of Dr. Rajeev Ruparathna. In all cases, the key ideas, primary contributions, designs, data analysis, interpretation, and writing were performed by the author, and the contribution of co-authors was primarily through the provision of feedback on the refinement of ideas and editing of the manuscript.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis.

I certify that this thesis, and the research to which it refers, is the product of my own work.

II. Previous Publication

This thesis includes 4 original papers that have been previously published/submitted for publication in peer-reviewed journals, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Chapter [2]	A Systematic Review of BIM-based Approaches Related to Predictive Decision-making in Construction Projects Management.	Completed
Chapter [3]	Building Information Modeling (BIM) Based Safety Hazard Prediction. CSCE Annual General Conference (2020)	Published
Chapter [3]	BIM-based Approach for Predictive Safety Planning in the Construction Industry.	Completed
Chapter [4]	Building Information Modeling (BIM)-based Model Checking to Ensure Occupant Safety in Buildings.	Completed

I certify that I have obtained a written permission from the copyright owner(s) to include the above-published material(s) in my thesis. I certify that the above material describes work completed during my registration as a graduate student at the University of Windsor.

III. General

I declare that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published. Otherwise, they are fully acknowledged following the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office and that this thesis has not been submitted for a higher degree to any other University or Institution.

ABSTRACT

The number of safety incidents in the construction industry is higher than that in most of the other industries. These safety incidents can be attributed to a lack of information and training. The new line of thinking in management has been moving toward predictive decision-making methods with the aid of artificial intelligence (AI). In this regard, the construction industry has been lagging on embracing modern management concepts. Hence, it is vital to re-engineer construction management to be on par with industries such as manufacturing. Building Information Modelling (BIM) can be recognized as the most promising technology that is introduced to the construction sector in the recent past. The information contained in a BIM model can be manipulated to aid construction safety management. This research presents BIM-based methods for predictive safety planning in the construction industry. At first, a comprehensive review of construction management challenges was conducted. This review revealed that although there are some studies regarding BIM-based predictive decision-making, still some knowledge gaps can be mentioned in the safety management of construction workers and building residents. To address the mentioned challenges, at first, this study integrates BIM with fuzzy logic to improve predictive safety planning to reduce the safety incidents in the construction projects. A Fuzzy Inference System (FIS) was developed based on the causality of safety incidents. The FIS extracts construction project data from BIM models while automatically assessing the risk of each potential hazard and also the total risk of a project. The proposed method enables construction managers to prevent construction incidents and enhance the health and safety of construction workers. Furthermore, this study develops a methodological framework for rule checking and the safety-focused ruleset for BIM-enabled building construction projects in Ontario, Canada. Identified safety standards were defined in Solibri Model checker software as a ruleset. The outcomes of this section will ensure the occupant’s safety through a proper design. Moreover, the findings of this will support promoting BIM in the Canadian construction industry.

DEDICATION

To My Family

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to Dr. Rajeev Ruparathna for his unfailing support throughout my Master's Degree at the University of Windsor. His immense support, wisdom, and advice have guided me to successfully finish my studies. I am forever grateful for the inspiration, motivation, and energy he showed, which influenced me in many ways to pursue my master's studies and beyond.

I would like to thank my committee members, Dr. Sreekanta Das and Dr. Mohamed Belalia. The advice and encouragement I received from them have helped me to improve the quality of this thesis.

I would like to thank the faculty of the School of Civil Engineering and the administrative staff of the University of Windsor for their support. I especially thank the support of Dr. Paul Henshaw and Ms. Suneeta Singh.

The input from many external institutes and individuals was crucial for the successful completion of this study. I would like to acknowledge the CSA group for the financial support for this research. I thank Dr. Jennifer Teague, Director, Standards Research, CSA group, ON. Her assistance helped significantly in the smooth progress of my research.

Furthermore, I express my sincere thanks to Mr. Davide Petretta, President, Petretta Construction Inc. for sharing the safety report, building drawings, and specifications of one of the Petretta Company's projects.

I am grateful to my parents for the support and faith they have given me. Their support and guidance have made me into the person I am.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background and Problem Statement

The construction industry is one of the most dangerous industries. According to the latest report of Occupational Safety and Health Administration (OSHA) published for occupations in the U.S., 40% of workplace accidents and 20.7% (or 971 out of 5,147) of workers who were killed on the job in 2017 were in the construction industry [1]. According to the previous safety-related studies, major construction accident causes are harsh site conditions, human behavior, unsafe work methods, and unsafe equipment [2].

Safety management can be effectively performed by determining the hazards. Hazard identification can commence from preconstruction and span throughout the operational stage [3]. Challenges for hazard identification include inappropriate data sharing among project participants, decision making based on uncertain information, non-standard procedure, and undisciplined tasks [4][5]. Identifying the cause-effect relationship for safety incidents will provide a plausible basis for safety management [4]. Historical data-based accident analysis presents useful but general information regarding the safety assessment of the project. Due to the uniqueness of each project, the type of information is not adequate to predict the date and location of the occurred accidents. Therefore, to provide an easier understanding of construction sequence and predict places and activities with a high level of risk, a proactive preventive decision-making method is required. This method must be capable of evaluating the data for detecting unsafe conditions and acts [6].

Building Information Modeling (BIM) is the most convenient solution that can mobilize the construction sector to keep on par with comparable industries. BIM has been creating a paradigm shift in the construction sector. BIM digitally represents the physical and functional characteristics of a building, systems, and components that aid the life cycle management of construction projects [7][8][9]. Moreover, BIM provides a multidisciplinary environment that brings all project participants together [10][11][12]. BIM model is an information repository that can support construction managers in their decision making.

The use of predictive and smart techniques is considered as the contemporary utopia in decision making. Predictive decision-making methods support narrowing the gap between the known and unknown. Incorporating predictive techniques can enhance construction management decision making. Until the emergence of BIM, there has not been a reliable basis to support predictive decision making in construction. BIM's ability to store physical and functional data along with cost, schedule, sustainability, and facilities management allows extracting project-specific data for further analysis and prediction [13][14][15]-[17]. Recently, there has been a growing interest in Architecture, Engineering, and Construction (AEC) industry in using BIM for safety management [14][15]. In this regard, the dispersed research on numerous capabilities of BIM needs to be merged to identify trends in research particularly in the lens of construction management.

Previous studies on BIM-based safety management have focused on (i) safety planning and scheduling, (ii) hazard detection, and (iii) collaboration and communication enhancement. BIM supports enhanced communication and collaboration that enables constructors to share their knowledge with designers to propose safety improvements throughout the project life cycle [18][19]. Golparvar-Fard et al. reported that the integration of BIM and D4AR presents a better visualization of construction operations and their sequences to provide an easy-to-understand and detailed model for project participants for improving remote monitoring [20]. Le proposed the integration of BIM with mobile web map service and GIS to enable useful and essential data exchange in real-time for Risk

Management of Adjacent Buildings [21]. Identifying the causality of project hazards supports enhancing safety [22]. Detecting project hazards with BIM has been another research interest in academia. Several studies have used BIM as the data domain to perform safety checks. Qi et al. and Zhang et al. proposed a BIM-based method to check fall hazards [4][23]. This approach allows construction managers to take preventive measures during the preconstruction stage [23]. Chavada et al. presented the integration of BIM with the Critical Path Method (CPM) to enable safety managers to accurately manage workspaces on construction sites for preventing works incidents [24]. The third major area of research has been safety management through safety-focused planning and scheduling. Project safety can be enhanced through the scheduling and planning performed by simulation [25]. Moon et al. integrated BIM with a genetic algorithm to develop an active simulation for minimizing the simultaneous interference level of the schedule-workspace [26]. This approach aids managers to solve schedule-workspace interference and prevent safety hazards. Zhang and Hu proposed a BIM-based framework to analyze conflicts and structural safety problems before starting the project to prevent safety incidents occurring during the construction phase [27].

A comprehensive literature review of the existing BIM-based research in safety management revealed two critical knowledge gaps: 1) overlooking the uncertainty of BIM-based safety assessment methods and 2) a lack of Canadian BIM-based rulesets for building resident safety. These two gaps are briefly discussed in the following.

1) Overlooking the uncertainty of BIM-based safety assessment methods

Hazard identification and risk assessment are key steps in safety management [28]. An expert system can assess construction safety risks. However, expert systems are generally associated with their inherent uncertainties [29]. Based on previous studies in construction management, fuzzy logic has been used to address uncertainties. Researchers have used fuzzy logic to manage cost, schedule, and safety in construction projects [29]-[33]. On the other hand, a BIM model-based expert system can predict the construction safety risks more accurately. BIM-based expert systems have been researched in the past for construction safety risk assessment. For example, Zhang et al. [34] proposed a BIM-based Risk Identification Expert System (B-RIES) to solve challenges in traditional safety risk identification and assessment in tunnel construction. However, a BIM-based FIS has not been used for construction project risk assessment.

2) A lack of Canadian BIM-based rulesets for building resident safety

Building codes assist the construction sector to reduce hazards and ensure the safety of construction workers and future occupants [35][36]. Engineers are required to adhere to the above codes and standards during the detailed design. BIM-based model checking evaluates a building design based on a set of rules [35]. Most of the BIM-based previous studies have performed model checking using rules based on the Occupational Safety and Health Administration (OSHA), National Building Code of Canada (NBCC), etc. Standard rulesets available in model checking applications include some sections such as general space check, the intersection between architectural components and MEP models, and architectural models. However, no approach has dealt with BIM-based safety-related Canadian building codes or the Canadian Standards Association (CSA).

1.2 Objectives

The overall objective of this research project is to develop a BIM-based approach for predictive safety planning in the construction industry. During this research, BIM-based methods are presented to enhance the safety of construction workers and building residents. The following are specific sub-objectives of this work:

1. Determine the causality of construction safety hazards.

2. Develop a Fuzzy Inference System (FIS) to predict the safety risk of a construction project.
3. Develop a BIM-based safety risk assessment method by combining BIM and FIS.
4. Develop a safety ruleset to ensure the safety of building users.
5. Develop a BIM-based strategy map to enhance construction safety.

1.3 Research Methodology

The mentioned objectives are achieved using a specific methodology. Four interrelated phases form the methodology for this project. These phases are outlined in the diagram in Figure 1-1.

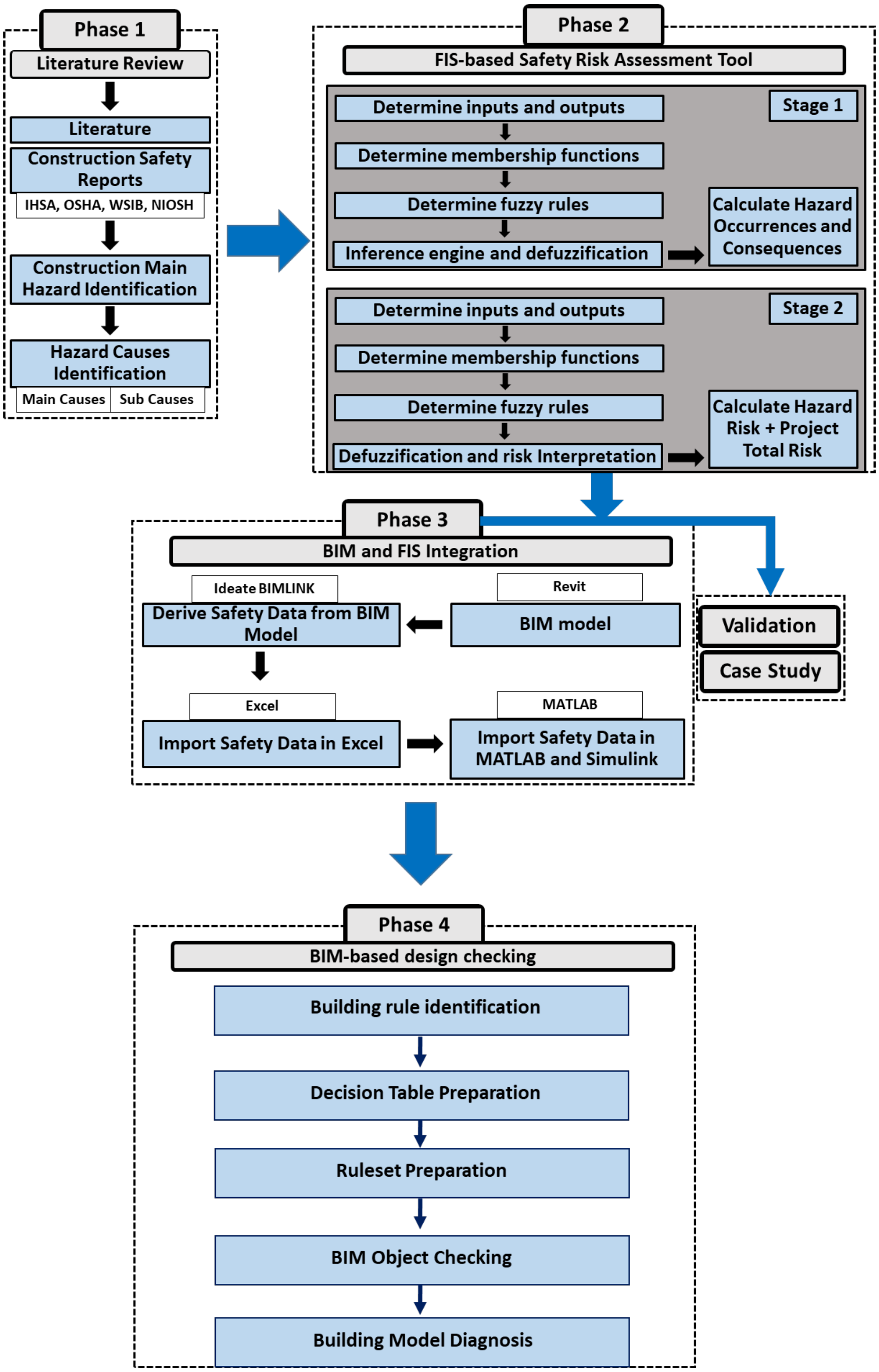


Figure 1-1: Overview of the Research Methodology

1.3.1 Phase 1: A literature review to determine the causality of construction safety hazards

In the first phase, major construction hazards and their causes were identified. Publications by reputed institutions such as National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), Worker Safety Insurance Board (WSIB), and Infrastructure Health & Safety Association (IHSA) were reviewed. According to the above sources, six major hazards in the construction industry are fall hazards, struck by objects hazards, construction machinery hazards, electrical hazards, suffocation hazards, and fire hazards. Literature was used to identify the main causes of construction hazards. Moreover, the sub-causes of construction hazards were identified from the literature. In this way, a total of 104 sub-causes were detected.

1.3.2 Phase 2: FIS-based Safety Risk Assessment Tool

MATLAB fuzzy logic toolbox was used for computations in this research. It provides graphical user interfaces, MATLAB functions, and Simulink blocks for designing and simulating Fuzzy Logic systems. To build the mentioned risk model in MATLAB, 14 FISs and 4859 FIS rules were defined for six construction hazards, namely, fall hazard, struck by object hazard, construction machinery hazard, electrical hazard, suffocation hazard, and fire hazard. The process of modeling the risk equation in MATLAB for assessing the safety risk of construction projects was divided into two stages.

Stage 1: Hazard Analysis: In Stage 1, the occurrence and consequence of each hazard were calculated. To calculate these two parameters, one FIS was defined for each hazard. Therefore, 12 FISs were prepared in Stage 1. Hazard analysis includes 4 steps, namely determining inputs and outputs, determining membership functions, determining fuzzy rules and inference engine, and defuzzification.

Stage 2: Risk aggregation: In Stage 2, the occurrence and consequence of each hazard are used as the inputs to calculate the safety risk of each hazard. FIS 13 is used to calculate the safety risk of each hazard. Moreover, FIS 14 is applied to calculate the total safety risk of a construction project. The steps of Stage 2 are like those of Stage 1. At the end of this stage, the total risk of the project is calculated through the defuzzification process in FIS 14.

The defuzzified value should be interpreted into understandable terms to be useful for construction managers or experts. The five-level safety risk interpretation was defined based on previous construction safety risk analysis [37][38]. The proposed methodology determines the degree of membership of safety risks to each safety risk level. The use of linguistic expressions reflects the vague imprecise fuzzy atmosphere of a construction site.

1.3.3 Phase 3: BIM and FIS integration

Project-specific data are obtained from a BIM model. BIM models contain comprehensive data and information from a construction project. The proposed fuzzy expert system was linked with BIM using the external links. "Ideate BIMLink" software was interlinked with Autodesk Revit as a plug-in to obtain safety risk-related data from the BIM model [39]. Using this software plug-in is necessary since Autodesk Revit is not able to generate the files with .xls format. Moreover, to interlink BIM with FIS, an .xls file format must be generated. MATLAB reads this file format containing safety risk data. The fuzzy-based expert system automatically loads the intended data for each section and starts calculating the safety risk of the construction project.

1.3.4 Phase 4: BIM-based design checking

In this phase, first, a comprehensive review was conducted to determine safety-related regulations, standards, and best practices included in the Ontario Building Code (OBC) and standards published by Canada Standards Association

(CSA). Then, a methodological framework including five steps, namely, building rule identification, decision table preparation, the ruleset preparation, BIM object checking, and building model diagnosis was developed. This framework is useful for rule checking and the safety-focused ruleset for BIM-enabled building construction projects in Ontario, Canada. Identified safety standards were defined in Solibri Model checker software as a ruleset. A case study was conducted to demonstrate how the proposed ruleset is implemented.

1.4 Thesis Organization

This thesis consists of five chapters with the following contents:

Chapter 1 describes the problem statement, research gaps, motivation, objectives, methodology, and the overall methodology framework. Chapter 2 presents a comprehensive literature review on the related topics. Chapters 3 and 4 are focused on the deliverables of this research, the BIM-FIS-based safety risk assessment tool, and the Canadian BIM-based safety ruleset. Finally, Chapter 5 discusses conclusions, contributions, limitations, and future research recommendations. Further details of each process are discussed in the following chapters.

1.5 References

[1] OSHA, “OSHA,” 2019. https://www.osha.gov/data/commonstats.

[2] J. Park, S. M, K. Kim, Y. K. Cho, and A M, “Framework of Automated Construction-Safety Monitoring Using Cloud-Enabled BIM and BLE Mobile Tracking Sensors,” *J. Constr. Eng. Manag.*, vol. 143, no. 2, pp. 1–12, 2017, doi: 10.1061/(ASCE)CO.1943-7862.0001223.

[3] J. Qi, J., Issa, R., Olbina, S., and Hinze, “Use of building information modeling in design to prevent construction worker falls.,” *J. Comput. Civ. Eng., 10.1061/(ASCE)CP.1943-5487.0000365, A4014008.*, 2014.

[4] S. Zhang, J. Teizer, J. Lee, C. M. Eastman, and M. Venugopal, “Building Information Modeling (BIM) and Safety : Automatic Safety Checking of Construction Models and Schedules,” *Autom. Constr.*, vol. 29, pp. 183–195, 2013, doi: 10.1016/j.autcon.2012.05.006.

[5] M. Martinez-rojas, “Building information modeling and safety management : A systematic review,” no. March 2019, 2018, doi: 10.1016/j.ssci.2017.08.015.

[6] S. Han, S. Lee, and F. Peña-Mora, “Comparative study of motion features for similarity-based modeling and classification of unsafe actions in construction,” *J. Comput. Civ. Eng.*, vol. 28, no. 5, pp. 1–11, 2014, doi: 10.1061/(ASCE)CP.1943-5487.0000339.

[7] P. T. Rafael Sacks, Chuck Eastman, Ghang Lee, *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*. .

[8] C. Eastman, “Building product models: Computer environments,” *Support. Des. Constr. CRC Press. Boca Raton, FL*, 1999.

[9] S. Popov, V., Juocevicius, V., Migilinskas, D., Ustinovichius, L., Mikalauskas, “The use of virtual building design and construction model for developing an effective project concept in 5D environment,” *Autom. Constr. Vol.19. pp. 357-367.*, 2010.

[10] V. Benjaoran, “A cost control system development: A collaborative approach for small and medium-sized contractors,” *Int. J. Proj. Manag. 27(3), 270–277.*

[11] C. Vanlande, R., Nicolle, C., and Cruz, “IFC and building lifecycle management,” *Autom. Constr., 18(1), 70–78*, 2008.

[12] S. Fu, C., Aouad, G., Lee A., Wu, “IFC model viewer to support nD model application,” *Autom. Constr. 15, 178-185.*, 2006.

[13] R. Sebastian, “Changing Roles of the Clients Architects and Contractors Trough BIM,” *Eng. Constr. Archit. Manag.*, vol. 18, no. 2, pp. 176–187, 2011.

[14] A. A. Latiffi, J. Brahim, and M. S. Fathi, “The Development of Building Information Modeling (BIM) Definition The Development of Building Information Modeling (BIM) Definition,” *Appl. Mech. Mater.*, no. June, 2014, doi: 10.4028/www.scientific.net/AMM.567.625.

[15] B. Azhar, A., Hein, M., and Sketo, “Building Information Modeling (BIM): Benefits, Risks and Challenges,” *Proc., 44th Assoc. Sch. Constr. Natl. Conf. Auburn, AL*, 2008.

[16] W. Kymmell, “Building Information Modelling : Planning and Managing Construction Project with 4D CAD and simulation,” *United State Am. Mc Graw Hill*, 2008.

[17] B. Hardin, “BIM and Construction Management,” *Indianap. Wiley Publ. IN.*, 2009.

[18] W. Zhou, J. Whyte, and R. Sacks, “Automation in Construction Construction safety and digital design : A review,” *Autom. Constr.*, vol. 22, pp. 102–111, 2012, doi: 10.1016/j.autcon.2011.07.005.

[19] M. D. Martínez-aires, M. López-alonso, and M. Martínez-rojas, “Building information modeling and safety management : A systematic review,” *Saf. Sci.*, vol. 101, no. February 2017, pp. 11–18, 2018, doi: 10.1016/j.ssci.2017.08.015.

[20] M. Golparvar-fard, M. Asce, F. Peña-mora, M. Asce, and S. Savarese,

"Integrated Sequential As-Built and As-Planned Representation with D 4 AR Tools in Support of Decision-Making Tasks in the AEC / FM Industry," vol. 137, no. December, pp. 1099–1116, 2011, doi: 10.1061/(ASCE)CO.1943-7862.0000371.

[21] B.-C. . Le, H.Q., Hsiung, "A novel mobile information system for risk management of adjacent buildings in urban underground construction," *Southeast Asian Geotech. Soc.*, vol. 45, no. 3, pp. 52–63, 2014.

[22] S. Zhang, K. Sulankivi, M. Kiviniemi, I. Romo, C. M. Eastman, and J. Teizer, "BIM-based fall hazard identification and prevention in construction safety planning," *Saf. Sci.*, vol. 72, pp. 31–45, 2015, doi: 10.1016/j.ssci.2014.08.001.

[23] J. Qi *et al.*, "Use of Building Information Modeling in Design to Prevent Construction Worker Falls," *J. Comput. Civ. Eng*, vol. 28, no. 5, pp. 1–10, 2014, doi: 10.1061/(ASCE)CP.1943-5487.0000365.

[24] Rajiv Chavada, "Construction workspace management : the development and application of a novel nD planning approach and tool CONSTRUCTION WORKSPACE MANAGEMENT : THE DEVELOPMENT AND APPLICATION OF A NOVEL nD PLANNING," *J. Inf. Technol. Constr.*, no. August, 2014.

[25] S. Andradóttir, K. J. Healy, D. H. Withers, B. L. Nelson, and M. J. Sims, "Proceedings of the 1997 Winter Simulation Conference," in *simulation conference*, 1997, pp. 67–69.

[26] H. Moon, H. Kim, C. Kim, and L. Kang, "Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces," *Autom. Constr.*, vol. 39, pp. 93–105, 2014, doi: 10.1016/j.autcon.2013.06.001.

[27] J. P. Zhang and Z. Z. Hu, "BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction : 1 . Principles and methodologies," *Autom. Constr.*, vol. 20, pp. 155–166, 2011, doi: 10.1016/j.autcon.2010.09.013.

[28] Y. Jung, S. Kang, Y. S. Kim, and C. Park, "Assessment of safety management information systems for general contractors," *Saf. Sci.*, vol. 46, no. 4, pp. 661–674, 2008, doi: 10.1016/j.ssci.2007.06.009.

[29] M. Amiri, A. Ardeshir, M. Hossein, and F. Zarandi, "Fuzzy probabilistic expert system for occupational hazard assessment in construction," *Saf. Sci.*, vol. 93, pp. 16–28, 2017, doi: 10.1016/j.ssci.2016.11.008.

[30] X. Bai and H. Zhao, "RELIABILITY EVALUATION IN CONSTRUCTION QUALITY," *Civ. Eng. J.*, no. 33, pp. 411–424, 2018, doi: 10.14311/CEJ.2018.03.0033.

[31] N. Ibadov, "Construction project planning under fuzzy time constraint," *Int. J. Environ. Sci. Technol.*, vol. 16, no. 9, pp. 4999–5006, 2019, doi: 10.1007/s13762-018-1695-x.

[32] X. Wang, "Application of fuzzy math in cost estimation of construction project Xinzheng Wang *," *J. Discret. Math. Sci. Cryptogr.*, vol. 20, no. 4, pp. 805–816, 2017.

[33] R. Ruparathna, K. Hewage, and R. Sadiq, "Economic evaluation of building energy retrofits : A fuzzy based approach," *Energy Build.*, vol. 139, pp. 395–406, 2017, doi: 10.1016/j.enbuild.2017.01.031.

[34] L. Zhang, X. Wu, L. Ding, M. J. Skibniewski, and Y. Lu, "Bim-Based Risk Identification System in tunnel construction," *J. Civ. Eng. Manag.*, vol. 22, no. 4, pp. 529–539, 2016, doi: 10.3846/13923730.2015.1023348.

[35] R. K. Dhillon and H. S. Rai, “Automation of Building Code checking with BIM,” *Int. J. Adv. Res. Comput. Eng. Technol.*, vol. 6, no. 10, pp. 1522–1525, 2017.

[36] C. Eastman, J. min Lee, Y. suk Jeong, and J. kook Lee, “Automatic rule-based checking of building designs,” *Autom. Constr.*, vol. 18, no. 8, pp. 1011–1033, 2009, doi: 10.1016/j.autcon.2009.07.002.

[37] H. T. Liu and Y. lin Tsai, “A fuzzy risk assessment approach for occupational hazards in the construction industry,” *Saf. Sci.*, vol. 50, no. 4, pp. 1067–1078, 2012, doi: 10.1016/j.ssci.2011.11.021.

[38] U. M. ngen G.Emre Gurcanli, “An occupational safety risk analysis method at construction sites using fuzzy sets,” *Int. J. Ind. Ergon. 39*, vol. 39, pp. 371–387, 2009, doi: 10.1016/j.ergon.2008.10.006.

[39] K. P. Reddy, “BIM for Building Owners and Developers: Making a Business Case for Using BIM on Projects,” *John Wiley Sons, Inc. United State Am.*, 2012.

CHAPTER 2

A SYSTEMATIC REVIEW OF BIM-BASED APPROACHES RELATED TO PREDICTIVE DECISION-MAKING IN CONSTRUCTION PROJECT MANAGEMENT

2.1 Construction Safety

The construction industry is a key determinant of the socio-economic development of a country [1][2]. The construction sector accounts for 6.7% and 7% of the Gross Domestic Product (GDP) of the United Kingdom and Canada respectively [3][4]. A significant portion of a nation's workforce is employed in the construction sector. Hence, good management of the construction industry has direct implications for the economy. However, the construction industry has been criticized for its lack of emphasis on modern management practices [5]-[8]. Statistics show that construction site fatalities include 20% of all occupational fatalities in the United States [9]. Moreover, 40% of the total accidents in Japan and 25% in the United Kingdom are related to construction accidents such as falls, construction machinery hazards, and electrocution [10]. Construction accidents cost billions of dollars as health costs, lost time, property damage, and permanent disabilities of victims [11]. The ultimate goal of safety management is to achieve zero accidents [11]. Lack of proper coordination of project data [33][34] and lack of integration in the structure of the industry [28][29][32] are the major challenges that prevent the construction site from being safe. To prevent construction incidents, state-of-the-art safety systems need to be developed [17].

2.2 Building Information Modeling (BIM)

Building Information Modeling (BIM) is the closest solution that could mobilize the construction sector to keep on par with comparable industries. BIM has been creating a paradigm shift in the construction sector. BIM digitally represents physical and functional characteristics of a building, systems, and components that aid life cycle management of construction project [18][19][20]. Moreover, BIM provides a multidisciplinary environment that brings all project participants together[21][22][23]. BIM model is an information repository that can support construction managers in their decision making. Recently, BIM has been employed in Architecture, Engineering, and Construction (AEC) industry for improving schedule management, cost management, safety management, and quality management [24][25].

2.3 Construction Management Challenges

Cost, schedule, and quality have been referred to as the construction management triangle. With the increased emphasis on worker safety, a new challenge has been imposed for construction managers. These challenges were used as the framework for conducting this research.

2.3.1 Schedule Management:

Generating a schedule requires broad information while the final schedule does not explain the process and assumptions behind the activity sequences. To generate an effective schedule, all details such as resource and equipment allocation, time-cost trade-offs, constructability issues, and optimum productivity should be addressed [26]. The accuracy of a project schedule may vary based on the experience and knowledge of the construction manager [27]. A project planner should determine the sequence for construction activities to allocate resources properly and use limited site spaces effectively. Currently, most of the decision makings in the construction projects are manual. Due to the huge volume of information that should be handled, this manual method causes a large burden on the project team. Furthermore, real-time data can provide valuable information in this regard. However, the human-based decision-making process cannot appropriately incorporate the type of data due to its limitations regarding performing what-if scenario analysis [28]. For instance, when work crews of different specialties working on concurrent activities share a common workplace, their activities may interfere, leading to time-space conflicts [29]. Moreover, scope changes are common in any construction project. Scope changes should be updated in schedules. Current scheduling tools require complex and time-consuming data entry to reflect the changes incorporated [30]. More importantly, the final schedule should be synchronized with all project participants. Besides, many clients cannot relate affected activities by viewing a CPM schedule due to some difficulties in visualizing the project sequence [30]. In addition, some construction-related activities are subject to significant uncertainty. Diverse possible sources of uncertainty are unavailable resources, adverse weather conditions, strikes, activities that may take some time compared to the originally estimated, imprecise date of arrival of material in comparison with project time plan. It is obvious that human-centered method of planning is error prone and involves uncertainty and variability during the construction phase [7]. Therefore, predictive schedule management is required to prevent the mentioned challenges related to human-centered or traditional method of planning and scheduling.

2.3.2 Cost Management:

Accurate cost estimation at early project stages prevents cost overruns. Cost estimators need to consider historical cost data and market trends to estimate costs with higher accuracy [31]. Limited information availability and uncertainty are the main challenges for the above quest that create major impacts on the final project outcome [32]-[34][35][36]. Other hurdles for cost management include poor site management, waiting for information, changes in scope, aggressive competition, and low speed of decision making [37]-[39][40]. Another challenge for estimators is understanding how building design influences construction costs. Traditional estimating software help estimators to make a relationship between a component in a product model and a cost item in a cost-estimating database. However, these relationships do not represent the estimator's rationale for relating the design and cost information. Therefore, automated support is necessary to store and use the estimator's rationale [41]. As a result, throughout the lifecycle of a project, a key parameter for the success of the project is decision-making related to cost control. The parameter requires historical data access to enable the project manager to input project cost and duration properly for decision making in different stages of projects. Thus, a predictive decision-making method is needed to extract useful information from the huge volume of historical cost data stored in a database and totally improve the cost estimation quality [7].

2.3.3 Safety Management:

Safety incidents adversely impact project efficiency and economy [42]. Safety management can be effectively performed through the determination of hazards. Hazard identification can commence from preconstruction and span throughout the operational stage [43]. Challenges for hazard identification include inappropriate data sharing among project participants, decision making based on uncertain information, non-standard procedure, and undisciplined tasks [42][44]. Identifying the cause-effect relationship for safety incidents will provide a plausible basis for safety management [42]. Historical-data-based accidents analysis presents useful but general information regarding the safety assessment of the project. Due to the uniqueness of each project, the type of information is not adequate to predict the date and location of accidents occurrence. Therefore, to provide an easier understanding of construction sequence and predict places and activities with a high level of risk, a proactive preventive decision-making method is required. This method must be capable of evaluating the data for detecting unsafe conditions and acts [45].

2.3.4 Quality Management:

Construction quality management includes control measures to avoid defects, errors, rework, and failure [46]. Quality issues in construction projects result in cost overrun, time overrun, and non-conformance to requirements [47]. Construction quality issues may arise due to multiple reasons such as documentation errors [48], poor managerial practices [49], construction error, change, and omission [50]. Quality management is a data-intensive process. Traditional methods are implemented by on-site inspection and control and managers use manual recording by paper-based documents, leading to inefficient management. Thus, the same as the previous sections of construction management, a predictive decision-making method is necessary to avoid defects in construction projects.

The traditional view on construction management ignores causality due to a lack of data. Figure 2-1 summarizes the above-mentioned construction management challenges.

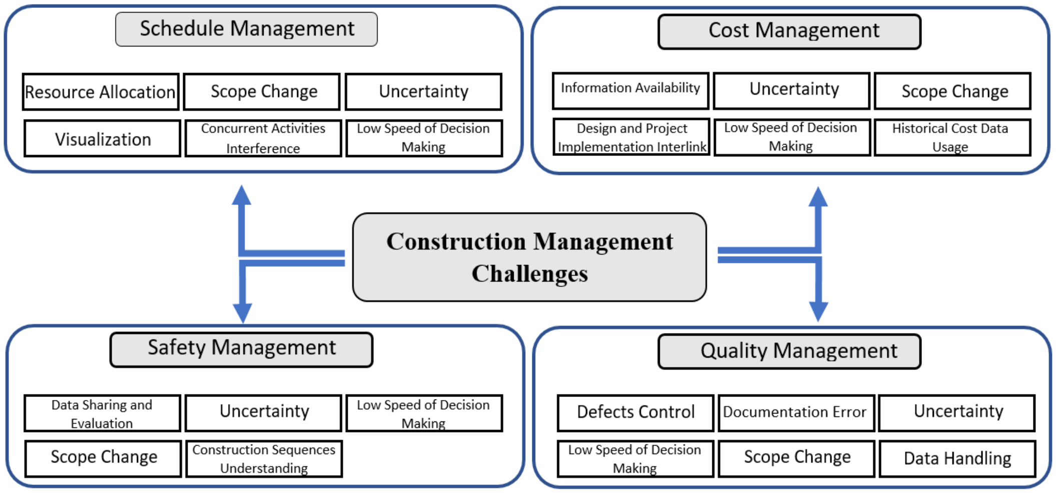


Figure 2-1: Construction Management Challenges

2.3.5 Predictive Decision-making:

Industries and organizations around the world are currently moving toward proactive decision-making methods to enhance the economy and productivity of organizational operations [51]. Predictive decision making includes complex functions and heavily depends on the reliability of data [52]. This approach has emerged from data science where it identifies patterns in big data to make forecasts. Moreover, the consequences of decisions must be also analyzed to optimize the solution [53].

Predictive decision-making is a key factor to achieve success in construction projects that require handling large amounts of data, conflicting aspects, and clashes [54]. This mechanism aids managers to characterize complex scenarios in all four sections of construction project management before starting the project [55]. For example, predictive decision making will support on-time project completion within the planned budget [56]. Applying the predictive decision models increase the accuracy of estimates at the pre-project planning. This accuracy, in turn, allows completing construction projects within the estimated budget [57]. There are some decision-making support methods in the construction industry. The first one is the Multi-Criteria Decision-Making (MCDM) method [55], which provides separating numerous criteria, regardless of the character of the data [54]. This method, also, considers qualitative data in the decision-making process and transforms them into linguistic terms. The most common MCDM methods are AHP, Elektra, Promethee, Copras-G, and fuzzy sets [55]. The second method is the decision-making trees. This non-parametric method summarizes all events that may occur as a result of making particular decision aid managers deal with decision-making problems with multiple branching variants [58]. The last method is Case-based Reasoning (CBR), which is an artificial intelligence-related approach comprising a knowledge base containing information from previous real-life cases to provide the skills to cope with new situations [59]. One of the common CBR methods is Monte Carlo simulation [60].

2.4 BIM for Predictive Decision Making in Construction Management

Being a repository of project life cycle data, BIM helps predictive decision-making [2][4]. In the following, various methods used for BIM-based construction management decision-making are discussed.

2.4.1 Schedule Management:

BIM-based schedule management had a rising trend in recent years [61]-[67]. In the domain of schedule management, previous researchers have focused on five areas, namely, schedule overlap and delay minimizing, automated scheduling, error and incompleteness detection, clash detection, and lean construction.

Schedule overlap is inherently risky because it increases uncertainties and leads to more changes during a construction project and rework [68]. Overlapping tasks can exist in both highly-detailed project schedules and high-level summary schedules. Moon et al. presented an active construction schedule management system by integrating BIM, fuzzy-based risk analysis algorithm, and genetic algorithms [69]. This method found the optimal schedule with a minimum overlapping level for project managers. Management of a construction project in the design and execution phase heavily depends on easier access to data [14][13]. BIM and GIS integration eliminates data redundancy, enables seamless data transfer between design and construction, and achieves optimum schedule for a construction project [70]. Bansal and Pal (2009) made an early attempt on 4D visualization of construction sequence by linking GIS and project schedule with a 3D model of the project [71][72]. This process allowed a less experienced project participant to understand what should be built when it is scheduled and where it is installed. Therefore, this process provides the shortest schedule of operating this project to the construction project manager. Irizarry and Karan integrated BIM and GIS to determine the optimal locations of tower cranes. The outcome of this research solved the problem of identifying optimal locations for a minimal number of tower cranes that could eliminate potential conflicts in schedule [73]. Chen and Nguyen integrated BIM and WMS for construction material selection [74]. This approach provided multiple data related to material, such as locations, availability, costs, and transportation methods that help the project team estimate the final cost and delivery time of the material. Integration of semantic web with BIM and GIS can assist the construction manager in the enhancement of access to data, eliminating the paper documentation, recording data in a multimedia format, removing the misunderstanding in the documents, and collaboration improvement among the project participants [13]. Multiple projects have attempted to improve the interoperability between BIM and GIS. Karan and Irizarry proposed a method to enhance the interoperability of BIM, GIS, and semantic web to manage in the preconstruction stage. This approach allows BIM users to easily use the building and geospatial data from web-based data providers. In another project, Karan et al. developed semantic web technology to enhance semantic interoperability between BIM and GIS using EXPRESS schema [87]. Kang and Hong proposed a method to enhance the integration of BIM, GIS, and FM systems [77].

Automated scheduling is a key domain in BIM-based project management research that reduces the time required to create the project schedule. Estimation of activity duration is a challenge in the preconstruction stage. Accurate activity duration directly correlated with project management experience. Mikulakova et al. proposed a knowledge-based system for automated schedule generation. This method combined BIM, and construction processes with past data from successfully executed similar projects in determining the project duration [78]. Developing such knowledge-based systems for predicting work task durations has been a growing domain of research over the recent past [79]. Wang and Rezazadeh proposed a BIM-based framework for generating the project schedules of concrete-framed buildings. This method is based on using prior knowledge to develop rules by considering building objects and their attributes to generate a list of work packages, along with their duration, and sequences [80]. Cheng and Chang presented an optimization model for BIM-based dynamic task scheduling for construction site material site layout [81]. This method addressed challenges in determining resource demand.

Detection of errors and clashes is vital for schedule management. A missing relationship between two or more activities or an incorrect scheduled sequence among activities may lead to major disruption and delay at the construction site [72]. Pre-defining construction sequencing rules, generating task lists, and evaluating their duration improves the accuracy of the schedule [82]. Park et al. proposed a method for automated registration of daily photos to 4D BIM. This method enabled the identification of BIM objects associated with corresponding photos to grasp the contents and context [83]. A clash can be geometric, schedule-based, or changes/updates not made to drawings [73]. Li et al. applied BIM and Radio Frequency Identification Device (RFID) to enhance coordination between project stakeholders. This method first identifies and analyzes the critical schedule risk factors and, followed by developing an RFID-enabled BIM platform that integrates different involved stakeholders and information flow to handle the critical schedule factor. This research attempted at ensuring timely project delivery in prefabricated housing construction by addressing schedule risks [84]. Wang et al. developed a method to assess the precast concrete bridge deck panels automatically. BIM has been used for maintenance projects in recent years. Chen and Tang proposed a workflow design integrating BIM and digital programming to address schedule and cost uncertainties during the maintenance stage. This method can prevent the delays in building maintenance [85]. Biagini et al. used laser scanning and BIM for construction management historical building restoration projects by reconstructing a digital model of the building [86].

BIM is of good assistance in implementing modern management techniques such as lean construction to reduce time wastes during construction projects [25][26]. Same researchers used lean construction and BIM for the optimization of material procurement. Sheikhkhoshkar et al. proposed automated and cost-effective planning to resolve the problem of traditional methods of designing construction joints [87]. Kim et al. developed a BIM-based framework for estimating demolition wastes in the design phase [88]. This method estimates the C&D waste generation and waste management costs. Furthermore, it provides data for recycling practices, environmental impact assessment, and disaster preparedness. Table 2-1 provides an overview of published literature on BIM-based schedule management

Table 2-1: BIM-based articles related to schedule management

Studies	**BIM-based Approaches**					**Techniques and Purposes**	**Country**	**Year**
	Schedule overlap and Delay minimization	Automated Scheduling	Error and incompleteness detection	Clash detection	Lean Construction			
[69]	✓		✓			The integration of BIM, Fuzzy theory, and Genetic Algorithm (GA) to enhance the operational performance of a project	Korea	2015
[66]	✓	✓				The integration of BIM, Industry Foundation Classes (IFC) file, and GA to provide an optimal schedule	China	2016
[63]		✓	✓			The integration of BIM, simulation, optimization, and ontology to facilitate the automatic generation of optimized activity level construction schedule for under resource constraints building projects	Canada	2015
[64]	✓	✓				The integration of BIM, simulation, optimization, and ontology to manage construction schedules by conducting a dynamic visualization of the construction procedure given the optimized schedules	Korea	2012
[72]	✓		✓			The integration of BIM, and GIS to manage each stage of projects, which in turn causes an impeccable schedule	India	2009
[75],	✓	✓				The integration of BIM, GIS, and Semantic Web (SW) technology to process the	USA	2015

[76]						transferred data between construction project participants		
[73]		✓		✓		The integration of BIM and GIS to identify feasible locations of tower cranes	USA	2012
[77]	✓	✓				The integration of BIM and GIS to improve facilities management	Korea	2015
[89]	✓					The integration of BIM with RFID to enable managers to track and match both the dynamic site needs and supply status of materials	China	2020
[74]	✓	✓				The integration of BIM and Web Map Service (WMS) to present a source selection of sustainable construction materials as a decision support tool	Taiwan	2019
[90]		✓				The integration of BIM, LBS, WBS, and OPS to apply construction schedule in the context of small and medium-sized enterprises (SMEs)	Italia	2018
[78]		✓		✓		The integration of BIM and Case-based Reasoning (CBR) to solve difficulties in the construction process and determine the planning subject	Germany	2010
[91]		✓				The integration of BIM with RFID to improve prefabricated construction scheduling	Singapore	2020
[80]		✓				The integration of BIM, Rule-based Reasoning (RBR), and CBR reasoning to generate automated schedules for concrete-framed buildings	Canada	2019
[92]		✓		✓		The integration of BIM and Application Programming Interface (API) to quantify the ripple effect of owner-requested design changes	Canada	2017
[83]		✓				The integration of BIM and Content-Based Image Retrieval (CBIR) to automatically register daily photos and determine BIM objects	USA	2018
[93]	✓				✓	The integration of BIM and LPS to handle the complexity involved in construction projects	Brazil	2019

[94]					✓	The integration of BIM and LPS to enhance productivity and decrease construction waste	Germany	2019
[95]				✓		A BIM-based study to digitalize geotechnical works and reduce reworks	Russia	2020
[88]		✓			✓	The integration of BIM and direct as well as an indirect method of construction waste quantification to reach efficient and streamlined planning and management	Korea	2017
[87]		✓		✓	✓	The integration of BIM, Optimization, and Ontology to introduce an automated solution for concrete joint positioning	Iran	2019
[81]		✓			✓	The integration of BIM, Optimization, and Ontology to investigate the optimization of material layout from the perspective of dynamic task scheduling	Taiwan	2018
[84]		✓				The integration of BIM and RFID to address delay problems in prefabrication housing construction	Hong Kong	2017
[96]		✓		✓		The integration of BIM and Laser Scanner Data to automatically estimate the dimensions of precast concrete bridge deck panels	Singapore	2018
[85]		✓				The integration of BIM and API to propose an innovative management workflow design to implement an efficient schedule of building fabric maintenance	China	2019
[86]	✓	✓				The integration of BIM and Laser Scanner Data to develop an innovative approach regarding restoration of historical building management	Italy	2016
[97]	✓					The integration of BIM with Takt Time and Discrete Event Simulation (DES) to achieve optimal planning	Iran	2020

2.4.2 Cost Management:

BIM-based cost management research entails four key research areas, namely automated cost estimation and prediction, cost optimization, clash detection, and economic evaluation. Automated cost estimation has been the most popular area of research in BIM-based cost management. Zhiliang et al. proposed a BIM IFC-based approach to develop an information requirement model for estimating construction cost. The extended IFC standards presented in this study provide division-item property sets, cost-items, and mathematical relationships. The results of this study demonstrate the capability of this approach to develop automated BIM-based application software for construction cost estimating[98]. Lee et al. proposed an automated work item searching system based on the integration of BIM with the ontological inference process. The proposed approach, aids cost estimators to use BIM data more easily and find work items with greater ease. Moreover, it eliminates the need for the intervention of cost estimator’s subjectivity [99]. Xu et al. proposed a framework by integrating BIM with semantic web ontology and forward chain algorithm to establish new means of taking data from a BIM model. Next, they used such data for creating the essential items to perform the quantity take-off. The proposed framework aids researcher to develop a BIM-based automated cost estimation system [100]. Cheung et al. proposed a BIM-based cost estimation module to assess different aspects of building design in early design stages. The multi-level cost estimation tool presented by this study enables users to automatically obtain measurements from 30 models and evaluate the functionality, economics, and performance of buildings [101]. Lawrence et al. integrated BIM with query language to propose a generic approach for creating and maintaining a cost estimate. The outcome of this approach is to add flexibility to cost estimation and enables the estimator to encode a broad variety of relationships between the design and estimate [102]. Niknam and Karshenas used the integration of BIM and Semantic Web Service technologies, as well as ontology inference process to improve the level of cost estimation quality by reducing the human involvement in repetitive cost estimating activities [103].

The second research approach discussed in the articles is cost optimization. The cost optimization is a process to ensure the compliance of the cost of the building with the estimated cost limits [104]. This process includes collecting and measuring the cost record of a project and the work progress. The main aim of cost optimization of a construction project is to maximize the profit in the design stages [104][105]. Faghihi et al. proposed graphical relationships between pre-defined objectives of cost optimization based on the integration of BIM with Pareto Front analysis. This study presented managerial tools to help project managers to optimize project cost and schedule [106]. Eleftheriadis et al. employed the integration of BIM with GA and Finite Element Modeling (FEM) to propose an optimization approach for the cost and embodied carbon optimization of reinforced concrete structures. This approach enables managers to make proper early design decisions [107]. He et al. developed a five-dimensional construction cost optimization model using the integration of BIM with GA. The results of this study demonstrate the efficiency and capability of this model to deal with the complicated problem of period and cost [108].

As the author reviewed clash detection in schedule management, in the following, this approach is discussed from the views of BIM experts in construction cost management. Clash detection is an accepted BIM-based approach among all sizes of architectural, engineering, and construction companies [109]. This approach provides cost savings and efficiencies; therefore, 3D modeling with clash detection is of great importance to building designers [109]. Liu and Hu proposed a 5D BIM-based cost estimation method that can be used in the electric power construction industry. The result of this study indicates the capability of 5D BIM in collision detection, work reduction, and rapid cost estimation [110]. Shan et al. developed a BIM-based approach to reinforce the impact of whole process cost management

(WPCM) in Dangerous Chemical construction projects. The outcomes of this research are pipeline collision reduction, rework reduction, and project cost decrease [111].

The fourth approach in BIM-based cost management is the economic evaluation, which is a process of identification, assessment, and valuation of the inputs and outcomes of two alternative activities [112]. The main objective of this approach is to determine the best course of action, based on the evidence available. There are some types of this evaluation such as cost-benefit analysis and cost-effectiveness analysis [112]. Cha and Lee proposed a framework based on the integration of BIM with time/cost analysis to identify work items and recognize the relationships among activities. The advantage of the proposed framework is to reduce human error and increase work efficiency [113]. Wang et al. proposed a method by utilizing BIM and cost-based progress curve to identify established construction progress curves. This method defines search criteria (e.g. cost item and object) to identify takeoff objects to derive quantities of cost items related to each activity. This study shows that this method can prevent errors in the manual typing of cost-item names [114]. Sun et al. proposed a project cost and schedule risk early warning model based on the integration of BIM and Earned Value Analysis (EVA) to address the problems of traditional methods which rely on the experience of project participants in construction management [115]. Lu et al. presented a cost-benefit analysis of BIM in building projects utilizing the time-effort distribution curve. The results of the case study in this research shows a 6.92% cost saving after implementing BIM [116].

Reviewing the 1974-2019 articles regarding BIM-based cost management revealed that having access to historical data to conduct a more precise cost estimation has received more attention in the literature. Moreover, reviewed studies show that time is a key issue to examine the success of project control. Hence, reliable cost and time estimation of a construction project are indispensable inputs for decision making in the diverse stages of projects. Furthermore, based on the approach categorization provided in this study, automation cost estimation and prediction have the largest number of articles in the cost management section. It means that construction experts are eager to apply automated cost estimation models to reduce rework and cost of projects. Table 2-2 provides an overview of published literature on BIM-based cost management.

Table 2-2: BIM-based articles related to cost management

Study	BIM-based Approaches				Techniques and Purposes	Country	Year
	Automatic Cost Estimation and Prediction	Cost Optimization	Clash Detection	Economic Evaluation			
[98],[117]	✓				The integration of IFC standard with BIM to provide a sound foundation for developing the construction cost estimator software	China	2010, 2013
[118]	✓				Using BIM-Assisted Detailed Estimating (BADE) tools to present a quantified evaluation method	USA	2010
[101]	✓				The integration of New Rule Measurement (NRM) with BIM to evaluate the economics and performance of the buildings, as well as their functionality in the design stage	England	2012
[115]				✓	The integration of BIM and earned value analysis (EVA) to develop a cost and schedule risk early warning model	China	2015
[114]	✓			✓	The integration of BIM with cost-based progress curve (called S-curve) to combine schedule and cost management for data acquisition	Taiwan	2016

					and storage		
[119]	✓			✓	The integration of BIM with random forest and simple linear regression to predict BIM labor cost	Taiwan	2020
[120]	✓			✓	The integration of BIM with Life Cycle Costing (LCC) to improve the economic dimension of the sustainability concept	Belgium	2020
[121]		✓			The integration of BIM with Management Information Systems (MIS) to optimize cost trade-off and energy consumption of smart building’s equipment	Iran	2020
[110]	✓		✓		Applying a 5D model to use in the electric power construction industry to manage and reduce project costs	China	2016
[111]			✓		Increasing the impact of cost management in the dangerous chemical construction project by a BIM model	China	2018
[35]	✓			✓	The integration of BIM with Query languages to increase the impact of cost management in the dangerous chemical construction project	USA	2014
[122]	✓				The integration of BIM with LCC to predict the cost of the project in the early design phase	Korea	2020
[123]				✓	The integration of BIM with the spreadsheet to recognize barriers that prevent utilizing the life cycle costing process and improve the efficiency of construction projects	Ireland	2017
[124]				✓	The integration of BIM with neural network analysis to provide Multi-label and multi-class classifications for cost prediction of projects	England	2020

[116]				✓	The integration of BIM with Cost-benefit analysis (CBA) to measure BIM benefits for cost estimating	Hong Kong	2014
[113]		✓			The integration of BIM with time/cost analysis to remodel an aged-housing project	Korea	2015
[99]	✓	✓			The integration of BIM with ontology and semantic technology to help engineers to find work items easily	Korea	2013
[103]	✓				The integration of BIM with ontology and semantic technology to enable combining, accessing, and sharing information over the internet in a machine-processable format	USA	2015
[100]	✓				The integration of BIM with ontology and semantic technology to obtain data from the BIM linked to a project and utilize it to make the essential items for a bill of quantity is established	England	2016
[106]		✓			The integration of BIM with optimization and Pareto Front analysis as well as GA to develop graphical relationships between pre-defined objectives of schedule optimizations which in turn leads to cost and schedule optimization	USA	2016
[109]			✓	✓	The integration of BIM with a cost-benefit analysis to evaluate the clash detection ability of BIM for cost savings	Germany	2020
[107]	✓	✓			The integration of BIM with optimization and GA and finite element modeling (FEM) to aid managers in early design decisions	England	2018
[125]		✓		✓	The integration of BIM with optimization to enhance the feasibility of	Italy	2019

					evaluating the economic performance and economic losses of a building exposed to seismic risk and deal with a huge amount of data		
[108]		✓		✓	The integration of BIM with GA and optimization and Pareto Front analysis to deal with the complicated problem of period and cost	China	2019
[126]				✓	The integration of BIM with an energy analysis to prove straw bale houses as healthier and more cost-effective than concrete/brick homes usually built-in Balkan region	Bosnia and Herzegovina	2017

2.4.3 Safety Management:

Previous research on BIM-based safety management has focused on (i) safety planning and scheduling, (ii) hazard detection, and (iii) collaboration and communication enhancement.

BIM supports enhance communication and collaboration, enabling constructors to share their knowledge with designers to propose safety improvements throughout the project life cycle [127][128]. Succar and Kassem proposed macro-BIM adoption models to systematically evaluate BIM adoption across markets. These models are a type of BIM model consisting of higher-level building elements that can be used for macro-level analysis including visualization, spatial validation, cost modeling. The models assist BIM managers in analyzing, developing, and improving BIM diffusion policies during a construction project [129]. Dossick et al. investigated the role of BIM in coordination and collaboration enhancement in a construction project and tried to address the organizational divisions [130]. They concluded that an inspirational leader is necessary to navigate a complex project hierarchy which requires a huge volume of data and make information exchange between project participants possible. Ganah and John for improving health and safety for onsite construction suggested integrating Toolbox Talk with the BIM environment because labors can visually realize H&S issues as work progresses during the toolbox talk onsite [131]. Lin et al. developed a BIM-based Intelligent Productivity and Safety System (IPASS) to aid project stakeholders to collaboratively assess the safety performance before the project start [132]. Golparvar-Fard et al. proposed the integration of BIM and D4AR to present a better visualization of construction operations and their sequences. According to their results, this model can provide an easy-to-understand and detailed model for project participants for improving remote monitoring [133]. Le proposed the integration of BIM with mobile web map service and GIS to enable useful and essential data exchange in real-time for risk Management of Adjacent Buildings [134]. Nawari proposed the integration of BIM with the Information Delivery Manual (IDM) to resolve the difficulties related to advancing the national BIM standard to facilitate more reliable data exchange between project participants, enhance information quality, and improve safety-based decision making more effectively [135]. Niu et al. presented a BIM-based framework for augmenting construction resources with technologies conferring autonomy, awareness, and the ability to interact with their vicinity to be smart construction objects (SCOs). The proposed method enables managers to improve safety-based predictive decision-making [136]. Park and Kim proposed the integration of BIM with Augmented Reality (AR), location tracking, and game engine to improve the real-time collaboration between manager and workers. This method enables project safety managers to have a safer monitoring of workers during the construction phase of projects [137]. Ciribini et al. proposed an interoperable IFC-based procedure to improve the collaboration code checking during the design phase[138].

Identification of causality of project hazards supports enhancing safety [139]. Detecting project hazards with BIM has been another research interest in academia. Several researchers have used BIM as the data domain to perform safety checks. Qi et al. and Zhang et al. proposed BIM-based methods to check fall hazards [42][140]. This approach allows construction managers to take preventive measures during the preconstruction stage [140]. Chavada et al. presented the integration of BIM with the Critical Path Method (CPM) to enable safety managers to accurately manage workspaces on construction sites for preventing works incidents [141]. BIM has been integrated with other technologies such as real-time locating systems, wireless sensing, and real-time audio warning for safety-focused applications. Wang et al. used BIM with range point cloud data to detect fall hazards in geotechnical projects [142]. Protective measures for falls were proposed upon identifying the fall hazards. Akula et al. presented a method based on the integration of BIM with 3D imaging technologies to identify safety hazards related to placing embeds into existing reinforced concrete structures [143]. Ding et al. used BIM and semantic web technology to model construction risk knowledge. This framework was able to produce a risk map and recommend a risk prevention plan [144]. Golovina et al. investigated hazard causes related to construction equipment and proposed a GPS, and BIM-based method for recording, detecting, and analyzing interactive hazardous near-miss situations between workers-on-foot and heavy construction equipment [145]. Hu et al. presented a BIM-based framework to detect construction collision for site entities [146]. This algorithm used boundary representation (B-rep) to detect collisions [146]. Hu et al. developed a 4D BIM model that provides complete information on dynamic connections between scaffold systems and the construction process [147]. This model was used to analyze the safety of scaffolding [147]. Kim et al. prepared a query set for a BIM model that automatically identify similar accident using a project management information system (PMIS)[148]. Kim et al. integrated BIM with automated data collection and a real-time locating system to reduce the time laborers are exposed to a hazard [149]. Proactive Behavior-Based Safety (PBBS), which is the combination of traditional BBS management with the Proactive Construction Management System (PCMS), enables managers to identify potential causes of unsafe behaviors and automatically monitoring location-based behaviors. Li et al. used PBBS for a BIM model to automatically monitor location-based behaviors, search the main causes of unsafe behaviors, and enhance the productivity of safety of the construction project [150]. Luo et al. developed a BIM-based method for code compliance checking for high-risk deep foundation construction projects [151]. Malekitabar et al. presented a review to aid managers to detect more than 40% of potential fatalities in construction projects by providing five sets of safety risk drivers as construction incident sub-causes. These safety risk sub-causes can be derived from a BIM model [152]. Riaz et al. linked BIM and wireless sensors to monitor workers working in confined spaces [153]. Zhang et al. integrated BIM and GPS to identify and visualize potentially congested workspaces to prevent suffocation hazards for workers [154].

Several researchers have used BIM and Unmanned Aerial Vehicle (UAV) to track workers in construction sites. Teizer et al. used BIM with unmanned aerial vehicles and laser scanning to automatically track construction workers to identify potential hazards for workers and prevent related hazards [155]. Liu et al. employed BIM and UAV technology to enhance the level of safety inspection during the construction phase and prevent safety incidents in the construction site [156]. Cheung et al. developed a system to monitor safety status via a spatial colored interface and automatically remove any hazardous gas from the construction site based on the integration of BIM with a wireless sensor network [157]. This system uses wireless sensor nodes placed on underground construction sites to collect hazardous gas levels. Moreover, the integrated BIM model will alert the region whenever it requires. Mihic et al. linked BIM with a construction hazards database for early hazard detection [158].

The third major area of research has been safety management through safety-focused planning and scheduling. Project safety can be enhanced through the simulation-based scheduling and planning performed [159]. Moon et al. integrated BIM with a genetic algorithm to develop an active simulation for minimizing the simultaneous interference level of the schedule-workspace [160]. This approach aids managers to solve schedule-workspace interference and prevent safety hazards. Zhang and Hu proposed a BIM-based framework to analyze conflicts and structural safety problems before starting the project to prevent safety incidents occurring during the construction phase [161]. Bansal and Pal linked information from the GIS database with respective activities in a schedule developed in 4D BIM to enable safety managers to detect incompleteness and logical errors in a project schedule [162]. Zheng et al. proposed an ontology-based semantic BIM modeling to enable effective inquiry of safety knowledge. This system provides automated safety planning for the analysis of construction site hazards to prevent worker safety incidents [163]. To address the safety challenges associated with limited workspace for piping and steel trades crews, Bannier et al. proposed a BIM-based approach to enhance workplace efficiency [164]. Choi et al. proposed a BIM-based framework to handle space planning in preconstruction management. This research provided a decision support tool to resolve safety issues related to workers in construction sites [165]. Kim and Teizer proposed a BIM-based approach to design and plan scaffolding systems automatically to prevent safety issues for construction workers who work on scaffolds [166]. Marzouk and Abubakr proposed a framework based on the integration of BIM with genetic algorithm and Analytical hierarchy process (AHP) to select the most appropriate tower crane types and locations at construction sites. This method prevents clashes in the operation of the tower crane group to assure safety in projects [167]. Moon et al. developed a BIM-based methodology to identify schedule and workspace conflict. This method increases the level of safety for construction workers [168]. Kim et al. presented a BIM-based decision support system to provides safety plans for scaffolding. This system allows users to develop a plan with a minimized safety hazard [169]. Park et al. used BIM with Bluetooth Low-Energy (BLE)-based location detection for identifying unsafe conditions and analyze labor routes considering potential safety hazards. This integrated system enables safety managers to monitor construction workers and prevent safety incidents [170]. Mirhadi et al. developed a tool that enables designers to optimize the building layout that supports occupant safety during evacuation [171]. Similarly, Marzouk and Daour proposed using BIM to simulate evaluation routes for laborers during an emergency [172].

Based on the mentioned information regarding three BIM-based approaches, it can be concluded that although most studies have focused on the improvement of health and safety of construction workers, there are few studies to deal with building resident safety. Some research presented preventive methods in the planning stage while some others have developed a system for monitoring workers during the construction phase.

Table 2-3 summarizes the published literature on BIM-based strategies used for safety management in construction projects. According to Table 2-3, most studies have tried to develop BIM-based approaches to identify and detect construction hazards.

Table 2-3: BIM-based articles related to safety management

Study	BIM-based Approaches			Techniques and Purposes	Country	Year
	Collaboration and Communication Enhancement	Hazard Detection	Safety Planning and Scheduling			
[129]	✓			Some macro-adoption models such as matrices and a chart are introduced to systematically evaluate BIM adoption across markets and inform the structured progress of country-specific BIM adoption policies.	Australia	2015
[173]	✓			The integration of BIM with ontology to introduce a framework to investigate the delivery foundation for industry stakeholders	Australia	2009
[138]	✓		✓	The integration of BIM and IFC to support the management of pre-construction and construction stages, operating advanced model and code checking, and analysis of the construction stage	Italy	2016
[130]	✓			The use and influence of BIM for mechanical, electrical, plumbing, and fire life safety (MEP) coordination	USA	2010

[174]	✓			Measurement of BIM impacts on stakeholder collaboration during the lifecycle of construction projects to help the fragmentation reduction in the construction industry	England	2013
[175]	✓	✓		The integration of BIM with AR for the maintenance of fire safety equipment	Taiwan	2020
[131]	✓			The integration of BIM with Health and Safety (H&S) to reduce on-site accidents probability	England	2015
[133]	✓	✓	✓	The integration of BIM with D4AR to monitor safety and improve collaboration and coordination	USA	2011
[134]	✓	✓	✓	The integration of BIM with mobile web map service and GIS to enable useful and essential data exchange in real-time	Vietnam	2014
[176]			✓	The integration of BIM with Virtual Reality (VR) to improve workspace planning	Italy	2020
[135]	✓			The integration of BIM with IDM to facilitate more reliable information exchange between project participants	USA	2012
[177]		✓		The integration of BIM with Indoor positioning system-inertial measurement unit (IPS-IMU) to develop an automated real-time warning system	USA	2020
[136]	✓	✓		The introduction on the integration of BIM with Smart Construction Objects (SCOs) to enable a safer, greener, more productive, and efficient construction system	Hong Kong	2016
[137]	✓	✓		The integration of BIM with Augmented Reality (AR), location tracking, and game engine to improve the real-time collaboration between manager and workers, hazard detection, and increase the risk recognition capacity of workers	Korea	2013

[178]		✓		The integration of BIM with finite element analysis to improve scaffolding safety	China	2020
[179]	✓	✓		Use of open-BIM to automatically check construction safety	Korea	2015
[180]	✓			The integration of BIM with IPD to prevent accidents and enhance collaboration	China	2011
[181]			✓	BIM-based research to manage workers' workspace conflicts	Vietnam	2020
[156]	✓	✓		The integration of BIM with augmented Unmanned aerial vehicles (UAV) to enhance safety inspection efficiency as well as enable managers to make timely and comprehensive safety decisions	China	2019
[132]	✓	✓		The use of BIM to develop a framework for enhancing productivity and safety monitoring systems	Singapore	2017
[182]	✓		✓	The use of BIM to apply an off-site manufacturing strategy for accelerating project delivery and improving the level of safety	England	2018
[140]		✓		The use of BIM for PtD enhancement by automatically fall hazards checking in building information models then provides design alternative to users	USA	2014
[42]	✓	✓	✓	An automated model to identify hazards and corrections during the design phase with the use of BIM and simulation for PtD improvement	USA	2012
[139]		✓		A BIM-based approach to investigate the fall hazards and eliminate them in the early stages of construction projects	USA	2015
[183]	✓	✓	✓	To check the safety hazard in models in the planning process, the applied rule-based checking algorithms are designed to be add-ons to existing BIM software	Germany	2013
[141]		✓	✓	The integration of BIM with Critical Path Method (CPM) to manage the Activity Execution Workspace (AEW) and provide real-time management	England	2014

[142]		✓	✓	The integration of BIM with a range point cloud data to detect fall and cave-in hazards linked to excavation pits and models, among other temporary geotechnical excavation objects that are essential fall protection equipment	Germany	2015
[143]		✓		The integration of BIM with 3D imaging technology to investigate real-time monitoring approaches for hazardous engineering processes	USA	2013
[184]		✓	✓	The integration of BIM with GIS to develop a safe execution sequence	India	2011
[144]		✓		The integration of BIM with ontology and semantic web technology to provide a framework for the management of risk knowledge in the BIM environment	China	2016
[185]		✓		The integration of BIM with a real-time audio warning to help in the recording of data and the ability to make relatively objective observations from them	Australia	2014
[145]		✓		The integration of BIM with GPS to introduce a method for recording, detecting, and analyzing interactive hazardous near-miss situations between workers-on-foot and heavy construction equipment	Germany	2016
[186]	✓	✓	✓	a BIM-based framework to automatically generate a resistance model, structural geometry, and loading conditions	China	2008
[146]		✓		The integration of BIM with a developed algorithm using boundary representation (B-rep) method to detect construction collision for site entities to enhance safety management	China	2010
[147]		✓		The use of BIM to present a scaffold safety analysis method during construction	China	2010

[148]		✓		The integration of BIM with a project management information system (PMIS) to compose a query set for automatically search for and provide similar accident cases	Korea	2015
[149]		✓		The integration of BIM with Automated data collection (ADC) and Real-time locating system (RTLS) to reduce the time laborers are exposed to a hazard	Korea	2016
[187]	✓	✓		The use of BIM for scaffolds to combine temporary structures into an approach of checking the safety	Korea	2016
[150]		✓		The integration of BIM with Proactive Behavior-Based Safety (PBBS) that uses simulation and real-time location system to improve safety management	Hong Kong	2015
[151]		✓		The use of BIM to present code compliance checking for deep foundation construction	China	2015
[152]		✓		A BIM-based study to help managers to detect more than 40% of potential fatalities in construction projects by providing five sets of safety risk drivers	Iran	2016
[153]		✓		The integration of BIM with Wireless Sensor Technology (WST) to decrease Health and Safety (H&S) hazards	Pakistan	2014
[155]	✓	✓	✓	The integration of BIM with unmanned aerial vehicles and laser scanning to sense and track construction assets and workforce automatically to improve safety	Germany	2015
[188]		✓	✓	The use of BIM within facilities management to improve safety management related to space planning and energy analysis	China	2013
[161]		✓	✓	The integration of BIM with construction simulation and to analyze safety and conflict during construction	China	2011

[163]		✓	✓	The integration of BIM with ontology to provide automated safety planning for analyzing job hazards	USA	2015
[154]		✓	✓	The integration of BIM with GPS to resource location tracking and analyze workspace requirements in construction projects	USA	2015
[164]			✓	The integration of BIM with the knowledge of work envelope requirements to enhance the efficiency of workspace management	USA	2016
[162]			✓	The integration of BIM with GIS to improve construction safety by extracting information from the database and linking with respective activities in a schedule developed in GIS	India	2011
[189]	✓		✓	The use of BIM to develop a model in a Product, Organization, and Process (POP) data definition structure	China	2014
[165]			✓	The use of BIM to enhance work-space problem detection and status representation	Korea	2014
[190]			✓	The introduction of two BIM-based tools to support risk management activities in a construction project	Netherland	2012
[166]			✓	The use of BIM to design and plan scaffolding systems automatically	USA	2014
[167]			✓	The integration of BIM with GA to ensure the tower crane group safety operation	Egypt	2016
[168]			✓	The integration of BIM with a developed algorithm to detect schedule and workspace conflict	Korea	2014
[160]			✓	The integration of BIM and GA to develop an active simulation system for	Korea	2014

				minimizing the simultaneous interference level of the schedule-workspace		
[157]		✓		The integration of BIM with Wireless Sensor Network (WSN) to monitor safety status via a spatial-colored interface and automatically remove any hazardous gas	Taiwan	2018
[158]		✓		The integration of BIM with specially developed construction hazards database to decrease the number of accidents and injuries by an automated hazard detection	Croatia	2018
[191]		✓		The integration of BIM with evacuation/rescue route optimization with Bluetooth-based technology for preventing building fire and disaster relief	Taiwan	2017
[192]		✓	✓	The use of BIM to improve health and safety on-site management	England	2017
[193]		✓	✓	The use of BIM to provide a framework to make safe scaffolding plans without excessive manual effort	USA	2018
[169]		✓	✓	The use of BIM to develop a scaffolding plan that considers workflow, cost, and duration and, at the same time, minimizes safety hazards	USA	2018
[170]		✓	✓	The integration of BIM with Bluetooth Low-Energy (BLE)-based location detection technology and a cloud-based communication platform to improve monitoring system of safety	USA	2017
[194]			✓	The integration of BIM with UAV to provide an automated acquisition processing of as-built	Germany	2019
[171]		✓	✓	The integration of BIM with IFC-centric performance-based evaluation and fire dynamics simulation to improve construction safety	Canada	2019

[172]		✓	✓	The integration of BIM with computer simulation to present a method for planning labor evacuation for construction sites	Egypt	2018

2.4.4 Quality Management:

Defects or failures are momentous concerns for construction project managers [47]. Quality management controls the comparison of the obtained results with desired results to prevent harmful consequences [189]. Since quality management on site is implemented by the visual senses of site managers, inspections are often omitted. Therefore, rework will appear, leading to construction project quality reduction and harmful impact on projects cost and schedule [195]. Thus, the first BIM-based research has been studied on defect management to find solutions for these management problems. To reach the goal, some technologies were integrated with BIM such as AR, image-matching. Park et al. proposed a framework based on the integration of BIM with AR and an ontology-based data collection template to decrease the defect that occurs during the construction process [195]. Kwon et al. presented a method based on the integration of BIM with image-matching and AR to identify omissions and errors at real job sites for reinforced concrete to enhance defect management [196]. Lin et al. presented a framework based on the integration of BIM and web-based technology to enable on-site managers to track and manage defects. The results of this study show the capability of this system to provide effective visual defect management [197]. Lin et al. proposed an approach based on the integration of BIM with Trapezoid Structural Transfer Layer (TSTL) to detect collisions for optimizing the construction process and enhancing project quality control [198]. They proposed an approach based on the integration of BIM with web-based systems to facilitate easy interface updating and transfer in the BIM environment. This method aids users to handle defects in the pre-construction phase [199]. Hamledari et al. developed a BIM-based technique to automatically transfer site data (based on the site observation for inspected building elements) to the BIM model. This system, which supports reality-capture techniques, facilitates the process of defect detection [200]. Elbeltagi and Dawood employed the integration of BIM with GIS to reduce potential defects of repetitive actions during the decision-making process [201].

The second area is about improving collaboration and communication among project participants. The construction projects have become more complicated and the information amount increased dramatically. Hence, to enhance data exchange in both pre-construction and construction phases, a variety of investigations based on the integration of BIM with some techniques have been proposed. Kubicki et al. used the integration of BIM with SmartWhiteBoard systems to make synchronous interactive devices for enhancing coordination between project participants [202]. Chen and Lu developed a BIM-based method for improving information quantity, quality, and accessibility [203]. The results show that this method facilitates the data exchange between project participants. Lin and Yang developed a BIM-based collaboration management method to reduce the time required for the model checking process [204]. Ma et al. used the integration of BIM with indoor positioning technology to resolve the omission of check items and facilitate the process of entering inspection results from paper-based records into computers. The results of this study show the improvement of collaboration among the construction stakeholders. [205]. Oh et al. presented a BIM-based integrated system to improve the collaborative design. This method addresses the challenges related to using different BIM-based software among collaboration during the design phase. Therefore, it can resolve a variety of problems such as including loss of data and difficulty in communication [206]. Koseoglu proposed a framework based on the integration of BIM with lean construction principles to focus on digital transformations performed on the construction site for enlightening project participants regarding BIM application capabilities [207]. Larsen developed a BIM-based framework to address the challenges in traditional report progress. This framework consists of three steps for minimizing manual reporting and improving communication during the reporting process [208]. Park et al. proposed a method based on the integration of BIM with web-based systems to enable real-time information sharing of daily 4D BIM. This method improves the collaborations and communications among project participants regarding daily construction operations, aiding project managers to make appropriate decisions [209].

The third approach to quality management studies is related to progress monitoring. The success of progress monitoring in a construction project depends on detailed and efficient tracking, analysis, and visualization of the actual status of buildings under construction [210]. In this area, the integration of BIM with GIS and laser scanning and some other techniques have been applied to present automated progress monitoring systems. Wang et al. used the integration of BIM and Laser Scanner Data to automatically estimate the dimensions of precast concrete bridge deck panels for improving quality inspection of panels [96]. Costin et al. used the integration of BIM with RFID to generate real-time data to produce leading indicators for building protocol control this system enables managers to monitor worker performance [211]. Bosché presented a method based on integrating BIM with laser scanning to automatically recognize 3D CAD model objects and calculate as-built dimensions. The results of this study show that this system improves the level of quality inspection during the construction phase [212]. Choi et al., regarding the challenges related to improper work-space planning such as poor quality and loss of productivity, proposed a framework that uses the integration of BIM with path analysis to enhance monitoring workspaces [213]. Bosche et al. used the integration of BIM with laser scanning to present automated objects recognition. The results of implementing this method show its potential to control as-built dimension calculation [214]. To monitor the supply chain status and present warning signals to assure the delivery of materials, Irizarry developed an approach based on the integration of BIM with GIS to monitor [215]. Bosché et al. quality presented a system by integrating BIM with laser scanning to develop structural works tracking, in particular for MEP work control [216]. Dimitrov and Golparvar proposed a vision-based material recognition method based on the integration of BIM with point cloud data. This method can generate a BIM model from unordered site image collections. This capability improves the automated monitoring of construction progress [217]. Shahi et al. used the integration of BIM with imaging and UltraWideBand (UWB) to track the progress of construction activities[218]. Han et al. developed an appearance-based recognition method using the integration of BIM with 3D point cloud models. This method suggests the actual state of construction progress for BIM elements. The results of implementing this system demonstrate its capability to monitor construction progress deviations at the operational level [219]. Deng et al. proposed a method based on the integration of BIM with the computer vision method to automatically calculate the number of tiles. This method facilitates the progress monitoring of this activity during the construction phase [220]. Braun and Borrman developed a method based on the integration of BIM with inverse photogrammetry technique to automatically labeling construction images. This system enhances the image-based object detection, which is the basis of construction progress monitoring [221]. Asadi et al. proposed a BIM-based method to facilitate as-built and as-planned data comparison. This system automatically registers real-time images to a BIM model. Therefore, it aids managers in indoor monitoring of construction [222].

Table 2-4 shows all research related to quality management. According to this table, most studies have focused on the improvement of progress monitoring methods.

Table 2-4: BIM-based articles related to quality management

Study	**BIM-based Approach**			**Techniques**	**Country**	**Year**
	Defect Management Enhancement	Collaboration and Communication Improvement	Automated Progress Monitoring			
[195]	✓			The integration of BIM with AR and Ontology-Based Data Collection (OBDC) template to present construction defect management framework	Korea	2013
[196]	✓			The integration of BIM with image-matching and AR to develop a system to improve reinforced concrete defect management	Korea	2014
[189]	✓			The use of BIM to develop a model in a product, organization, and process (POP) data definition structure	China	2016
[223]	✓			The use of BIM to design prefabricated and assembled concrete structures for improving construction quality management	China	2017
[202]		✓		The integration of BIM with Smart Whiteboard (SWB) systems to make synchronous interactive devices for enhancing coordination between participants	Luxembourg	2019
[203]	✓	✓		To make the mechanism linking Bridge BIM and Building (BBB) and	China	2019

				Information Management (IM) for improving the information quantity, quality, and accessibility		
[204]		✓		The use of BIM Collaboration Management (CM) method to decrease the required time for model checking and enhance work quality	Taiwan	2018
[224]			✓	The integration of BIM with computer vision to develop an automated progress monitoring of tiles	China	2020
[225]			✓	The integration of BIM and Laser Scanner Data (LSD) to automatically estimate the dimensions of precast concrete bridge deck panels for improving quality inspection of panels	Singapore	2018
[226]		✓		The integration of BIM with Data Envelopment Analysis (DEA) to enhance the performance of construction by optimum resource allocation	China	2018
[205]		✓	✓	The integration of BIM with indoor positioning technology to make effective and collaborative quality management	China	2018
[198]	✓			The integration of BIM with Trapezoid Structural Transfer Layer (TSTL) to optimize construction procedure and enhance quality control of projects	China	2017
[227]			✓	The integration of BIM with Wireless Sensor Network (WSN) to develop a monitoring system for parking garages	Taiwan	2020
[197]	✓		✓	The integration of BIM with web-based technology to manage the status and results of the corrective works performed effectively	Taiwan	2016
[211]			✓	The integration of BIM with RFID to track workers' location	USA	2015
[213]			✓	The integration of BIM with path analysis to enhance the work-space	Korea	2014

				planning process		
[228]	✓	✓		The integration of BIM with IFC to enhance the productivity of the construction domain and improve text information management	China	2013
[229]	✓		✓	The integration of BIM with image processing, machine learning, and VR to improve the quality of progress monitoring in construction projects	England	2020
[199]		✓	✓	The integration of BIM with information systems to improve Interface Management (IM) for rework minimization	Taiwan	2015
[206]		✓		An integrated BIM-based system to make a collaborative design for improving the quality and productivity of construction projects	Korea	2015
[230]	✓			The integration of BIM with performance simulation analysis to make up traditional design methods defects and make their design more intuitive	China	2018
[200]	✓		✓	The integration of BIM with IFC to make inspected building elements auto-updateable on-site observations for enabling potential diagnostics and tractability	USA	2018
[231]	✓		✓	The integration of BIM with the point cloud process to extract building geometrics for demystifying and accelerating the as-is building model	USA	2015
[207]		✓		The use of BIM integrated with lean construction principles in mobile devices to enlighten construction participants concerning site BIM application capabilities	Turkey	2018
[214]			✓	The integration of BIM with laser scanning to present automated object recognition to improve the quality of project monitoring	Canada	2009

[232]			✓	The integration of BIM with 3D laser scanning for improving on-site data acquisition to reach enhanced progress monitoring	China	2020
[212]			✓	The integration of BIM with laser scanning to automatically recognize 3D CAD model objects as well as calculate as-built dimensions for improving quality control	Switzerland	2010
[201]	✓		✓	The integration of BIM with GIS to help decision making regarding repetitive construction projects	Egypt	2011
[233]			✓	The integration of BIM with laser scanning to develop an automated progress tracking	Canada	2012
[215]			✓	The integration of BIM with GIS to monitor the supply chain status and present warning signals to assure the delivery of materials	USA	2013
[216]			✓	The integration of BIM with laser scanning to develop structural works tracking, in particular, MEP works	Canada	2014
[217]			✓	The integration of BIM with support vector machines to classify materials from single images taken under an unknown viewpoint	USA	2014
[218]			✓	The integration of BIM with imaging and Ultra-Wide Band (UWB) to tracking the progress of construction activity	Canada	2015
[210]		✓	✓	The integration of BIM with IFC to recognize physical progress based on two emerging information sources	USA	2015
[219]	✓		✓	The integration of BIM with 3D Point Cloud Models(3PCM) to monitor project progress deviations during construction based on a new	USA	2015

				appearance-based material categorization approach		
[220]	✓		✓	The integration of BIM with computer vision to automatically monitor the progress of tiles	China	2019
[221]			✓	The integration of BIM with inverse photogrammetry to label construction site images automatically	Germany	2019
[208]		✓	✓	The use of BIM to present a process with three steps for minimizing manual reporting and improving its quality	Norway	2018
[222]		✓	✓	The integration of BIM with augmented monocular simultaneous localization and mapping to register video sequence to an as-planned model in real-time	USA	2019
[234]		✓	✓	The integration of BIM with computer vision to enhance the automated monitoring of indoor progress	Germany	2018
[209]		✓	✓	The integration of BIM with web-based methods to make real-time information sharing of daily 4D BIM through enhancing collaboration and communications among project participants	USA	2017
[235]			✓	The use of the Scan-vs-BIM method to measure the point cloud quality for monitoring the construction procedure	Slovenia	2017

2.5 Summary

Contemporary construction management requires large volumes of data for efficient project delivery. Yet access to key construction management data is still a major challenge primarily due to implementation issues. The new line of thinking in management has been moving towards predictive decision making methods with the aid of artificial intelligence. The construction industry has been lagging behind on embracing modern management concepts. Hence, it is vital to re-engineer construction management to be in par with industries such as manufacturing. The advent of Building Information Modeling (BIM) has been creating a paradigm shift in construction management. BIM is an information repository that could support implementation of state-of-the-art management techniques in the construction sector. This research presents a critical review of BIM-based construction management decision making methods. This review focused on the four key challenges of construction management (i.e. schedule, cost, safety and quality management). This study revealed that although there are some studies regarding BIM-based predictive decision-making, still some knowledge gaps can be mentioned in each section of construction management which will be reviewed in this study. A roadmap was proposed to support implementation of BIM-based construction management decision making.

2.6 Reference

[1] I. O. Oladinrin, T. O., Ogunsemi, D. R. and Aje, "Role of Construction Sector in Economic Growth," *Empir. Evid. from Niger. African J. Online, Vol. 7, No 1.*, 2012.

[2] J. Wells, "The Role of Construction in Economic Growth and Development," *Habitat Int. Vol. 9, No. 1, pp. 55-70.*, 1985.

[3] L. O. of N. S. (ONS)., "ONS Annual Business Survey (ABS)," 2011.

[4] DBIS, “UK Construction: An economic analysis of the sector,” *London Dep. Business, Innov. Ski.*, 2013.

[5] P. T. I. Lam, F. W. H. Wong, and K. T. C. Tse, “Effectiveness of ICT for Construction Information Exchange among Multidisciplinary Project Teams,” *J. Comput. Civ. Eng.,* vol. 24, no. August, pp. 365–376, 2010, doi: 10.1061/(ASCE)CP.1943-5487.0000038.

[6] J. M. Sardroud, “Perceptions of automated data collection technology use in the construction industry,” *” J. Civ. Eng. Manag.*, vol. 21, no. 1, pp. 54–66, 2015.

[7] M. Martínez-rojas, N. Marín, and M. A. Vila, “The Role of Information Technologies to Address Data Handling in Construction Project Management,” vol. 30, no. 4, pp. 1–20, 2016, doi: 10.1061/(ASCE)CP.1943-5487.0000538.

[8] R. Ahuja, V., Yang, J., and Shankar, ““Benchmarking framework to measure extent of ict adoption for building project management,” *J. Constr. Eng. Manag.*, pp. 538–545, doi: , 10.1061/(ASCE)CO.1943-7862.0000155.

[9] OSHA, “OSHA,” 2019. https://www.osha.gov/data/commonstats.

[10] M. O. Sanni-Anibire, A. S. Mahmoud, M. A. Hassanain, and B. A. Salami, “A risk assessment approach for enhancing construction safety performance,” *Saf. Sci.*, vol. 121, no. August 2019, pp. 15–29, 2020, doi: 10.1016/j.ssci.2019.08.044.

[11] H. T. Liu and Y. lin Tsai, “A fuzzy risk assessment approach for occupational hazards in the construction industry,” *Saf. Sci.*, vol. 50, no. 4, pp. 1067–1078, 2012, doi: 10.1016/j.ssci.2011.11.021.

[12] N. Forcada, M. Casals, X. Roca, and M. Gangolells, “Adoption of web databases for document management in SMEs of the construction sector in Spain,” vol. 16, pp. 411–424, 2007, doi: 10.1016/j.autcon.2006.07.011.

[13] A. P. Chassiakos and S. P. Sakellaropoulos, “Advances in Engineering Software A web-based system for managing construction information,” vol. 39, pp. 865–876, 2008, doi: 10.1016/j.advengsoft.2008.05.006.

[14] Y. Lu, Y., Li, Y., Skibniewski, M., Wu, Z., Wang, R., and Le, “Information and communication technology applications in architecture, engineering, and construction organizations: A 15-year review,” *J. Manag. Eng.,* 2014, doi: 10.1061/(ASCE)ME.1943-5479.0000319.

[15] G. Rezgui, Y., Boddy, S., Wetherill, M., and Cooper, “Past, present and future of information and knowledge sharing in the construction industry: Towards semantic service-based e-construction,” *Comput. Aided Des.,* vol. 43, no. 5, pp. 502–515, 2011.

[16] A. Adriaanse, H. Voordijk, and G. Dewulf, “Adoption and Use of Interorganizational ICT in a Construction Project Adoption and Use of Interorganizational ICT,” no. September, 2010, doi: 10.1061/(ASCE)CO.1943-7862.0000201.

[17] E. . Wilson, J.M., Koehn, E.E., J.M., Koehn, “SAFETY MANAGEMENT: PROBLEMS ENCOUNTERED AND RECOMMENDED SOLUTIONS,” *J. Constr. Eng. Manag.*, vol. 126, no. February, pp. 77–79, 2000.

[18] P. T. Rafael Sacks, Chuck Eastman, Ghang Lee, *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*. .

[19] C. Eastman, “Building product models: Computer environments,” *Support. Des. Constr. CRC Press. Boca Raton, FL*, 1999.

[20] S. Popov, V., Juocevicius, V., Migilinskas, D., Ustinovichius, L., Mikalauskas, “The use of virtual building design and construction model for developing an

effective project concept in 5D environment," *Autom. Constr. Vol.19. pp. 357-367.*, 2010.

[21] V. Benjaoran, "A cost control system development: A collaborative approach for small and medium-sized contractors," *Int. J. Proj. Manag. 27(3), 270–277.*

[22] C. Vanlande, R., Nicolle, C., and Cruz, "IFC and building lifecycle management," *Autom. Constr., 18(1), 70–78*, 2008.

[23] S. Fu, C., Aouad, G., Lee A., Wu, "IFC model viewer to support nD model application," *Autom. Constr. 15, 178-185.*, 2006.

[24] A. A. Latiffi, J. Brahim, and M. S. Fathi, "The Development of Building Information Modeling (BIM) Definition The Development of Building Information Modeling (BIM) Definition," *Appl. Mech. Mater.*, no. June, 2014, doi: 10.4028/www.scientific.net/AMM.567.625.

[25] B. Azhar, A., Hein, M., and Sketo, "Building Information Modeling (BIM): Benefits, Risks and Challenges," *Proc., 44th Assoc. Sch. Constr. Natl. Conf. Auburn, AL*, 2008.

[26] B. Koo and M. Fischer, "FEASIBILITY STUDY OF 4D CAD IN COMMERCIAL CONSTRUCTION.," *J. Constr. Eng. Manag.*, vol. 126, no. 4, p. 251, 2000.

[27] D. Cherneffet et al., 19901 Cherneff, J., Logcher, R., Sriram, "Integrating CAD with Construction Schedule Generation," *J. Comput. Civ. Eng. ASCE,* 1990.

[28] A. H. Behzadan, C. C. Menassa, J. L. Tishman, F. Scholar, and A. R. Pradhan, "Enabling Real Time Simulation of Architecture, Engineering, Construction, and Facility Management (AED/FM) Systems: A Review of Formalism, Model, Architecture, and Data Representation," vol. 20, pp. 1–23, 2015.

[29] M. Akinci, B., Staub, S. and Fischer, "Productivity and Cost Analysis Based on a 4D Model," *IT Support Constr. Process Reengineering*, 1997.

[30] R. Davis, F. ; Devine, M. ; Lutz, "Scheduling activities among conflicting facilities to minimize conflict cost," *Math. Program. 1974, Vol.6(1), pp.224-228*.

[31] J. Chou, "Cost simulation in an item-based project involving construction engineering and management," *JPMA*, vol. 29, no. 6, pp. 706–717, 2011, doi: 10.1016/j.ijproman.2010.07.010.

[32] S. Ji, M. Park, and H. Lee, "Cost estimation model for building projects using case-based reasoning," vol. 581, no. September, pp. 570–581, 2011, doi: 10.1139/L11-016.

[33] S. Ji *et al.*, "Military Facility Cost Estimation System Using Case-Based Reasoning in Korea," vol. 25, no. June, pp. 218–231, 2011, doi: 10.1061/(ASCE)CP.1943-5487.0000082.

[34] S. Staub-french, M. Fischer, and J. Kunz, "An Ontology for Relating Features," no. July, 2002.

[35] M. Lawrence, R. Pottinger, S. Staub-french, and M. Prasad, "Creating flexible mappings between Building Information Models and cost information," *Autom. Constr.*, vol. 45, pp. 107–118, 2014, doi: 10.1016/j.autcon.2014.05.006.

[36] D. Baloi and A. D. F. Price, "Modelling global risk factors affecting construction cost performance," *Int. J. Proj. Manag.*, vol. 21, pp. 261–269, 2003, doi: 10.1016/S0263-7863(02)00017-0.

[37] J. S. Shane *et al.*, "Construction Project Cost Escalation Factors," vol. 25, no. October, pp. 221–229, 2009, doi: 10.1061/(ASCE)0742-597X(2009)25.

[38] S. M. Trost, M. Asce, G. D. Oberlender, and F. Asce, "Predicting Accuracy of

Early Cost Estimates Using Factor Analysis and Multivariate Regression," vol. 129, no. 2, pp. 198–204, 2003, doi: 10.1061/(ASCE)0733-9364(2003)129.

[39] K. C. Iyer and K. N. Jha, "PROJECT Factors affecting cost performance : evidence from Indian construction projects," vol. 23, pp. 283–295, 2005, doi: 10.1016/j.ijproman.2004.10.003.

[40] T. P. Williams and J. Gong, "Predicting construction cost overruns using text mining , numerical data and ensemble classi fi ers," *Autom. Constr.*, vol. 43, pp. 23–29, 2014, doi: 10.1016/j.autcon.2014.02.014.

[41] Timberline, "Precision Estimating Extended and CAD Integrator," 2001.

[42] S. Zhang, J. Teizer, J. Lee, C. M. Eastman, and M. Venugopal, "Building Information Modeling (BIM) and Safety : Automatic Safety Checking of Construction Models and Schedules," *Autom. Constr.*, vol. 29, pp. 183–195, 2013, doi: 10.1016/j.autcon.2012.05.006.

[43] J. Qi, J., Issa, R., Olbina, S., and Hinze, "Use of building information modeling in design to prevent construction worker falls.," *J. Comput. Civ. Eng., 10.1061/(ASCE)CP.1943-5487.0000365, A4014008.*, 2014.

[44] M. Martinez-rojas, "Building information modeling and safety management : A systematic review," no. March 2019, 2018, doi: 10.1016/j.ssci.2017.08.015.

[45] S. Han, S. Lee, and F. Peña-Mora, "Comparative study of motion features for similarity-based modeling and classification of unsafe actions in construction," *J. Comput. Civ. Eng.*, vol. 28, no. 5, pp. 1–11, 2014, doi: 10.1061/(ASCE)CP.1943-5487.0000339.

[46] A. Mills, P. E. D. Love, and P. Williams, "Defect Costs in Residential Construction," vol. 135, no. 1, pp. 12–17, 2009.

[47] S. Chin, K. Kim, and Y. Kim, “A process-based quality management information system,” *Autom. Constr.*, vol. 13, pp. 241–259, 2004, doi: 10.1016/j.autcon.2003.08.010.

[48] D. Cusack, “Implementation of ISO 9000 in Construction,” *ISO 9000 Forum Symp,* 1992.

[49] G. Rounce, “Quality , waste and cost considerations in architectural building design management,” vol. 16, no. 2, pp. 123–127, 1998.

[50] Construction Industry Institute (CII), “Benchmarking andMetrics Value of Best Practices Report,” *Univ. Texas Austin, Austin, Tex., 2003, pp. 1–48.*

[51] H. Doloi, “Cost Overruns and Failure in Project Management : Understanding the Roles of Cost Overruns and Failure in Project Management : Understanding the Roles of Key Stakeholders in Construction Projects,” *J. Constr. Eng. Manag.* ·, no. May, 2014, doi: 10.1061/(ASCE)CO.1943-7862.

[52] Y. Wang *et al.*, “Prediction of product design decision Making: An investigation of eye movements and EEG features,” *Adv. Eng. Informatics*, vol. 45, no. March 2018, p. 101095, 2020, doi: 10.1016/j.aei.2020.101095.

[53] A. Mosavi, Y. Bathla, and and A. Varkonyi-Koczy, “Predicting the Future Using Web Knowledge: State of the Art Survey,” *Adv. Intell. Syst. Comput.*, vol. 660, pp. 342–344, 2018.

[54] D. Jato-espino, E. Castillo-lopez, J. Rodriguez-hernandez, and J. C. Canteras-jordana, “A review of application of multi-criteria decision making methods in construction,” *Autom. Constr.*, vol. 45, pp. 151–162, 2014, doi: 10.1016/j.autcon.2014.05.013.

[55] A. Dziadosz and A. Konczak, “Review of Selected Methods of Supporting Decision-making Process in the Construction Industry,” *Archives of Civil*

Engineering, vol. LXII, no. 1, 2016.

[56] D. Mohamed, F. Srour, W. Tabra, and and T. Zayed, “A Prediction Model For Construction Project Time Contingency,” in *ASCE*, 2009.

[57] PASC, “Applying predictive analytics in construction,” 2020.

[58] V. S. D. Joshi, “Application of Decision Tree Technique to Analyze Construction Project Data,” in *International Conference on Information Systems, Technology and Management*, 2010, pp. 304–313.

[59] Y. Zhu, “The construction safety accident emergency decision support system based on ontology and CBR,” *Appl. Mech. Mater. Vols.*, vol. 426, pp. 2149–2153, 2013, doi: 10.4028/www.scientific.net/AMM.423-426.2149.

[60] V. Kumar and N. Viswanadham, “A CBR-based Decision Support System Framework for Construction Supply Chain Risk Management,” in *Proceedings of the 3rd Annual IEEE Conference on Automation Science and Engineering*, 2007, pp. 980–985.

[61] L. Moon, H., Kim, H., Kamat, V., and Kang, “BIM-based construction scheduling method using optimization theory for reducing activity overlaps,” *J. Comput. Civ. Eng., 29(3), 04014048*, 2015.

[62] S. Curry, E., O’Donnell, J., Corry, E., Hasan, S., Keane, M., and O’Riain, “Linking building data in the cloud: Integrating cross-domain building data using linked data,” *Adv. Eng. Inf., 27(2), 206–219.*, 2013.

[63] H. Liu, M. Al-hussein, and M. Lu, “BIM-based integrated approach for detailed construction scheduling under resource constraints,” *Autom. Constr.*, vol. 53, pp. 29–43, 2015, doi: 10.1016/j.autcon.2015.03.008.

[64] S. Song, J. Yang, and N. Kim, “Computers in Industry Development of a BIM-

based structural framework optimization and simulation system for building construction §," *Comput. Ind.*, vol. 63, no. 9, pp. 895–912, 2012, doi: 10.1016/j.compind.2012.08.013.

[65] Z. Wang, "BIM-based draft schedule generation in reinforced concrete-framed buildings," *Constr. Innov.*, vol. 19, no. 2, pp. 280–294, 2019, doi: https://doi.org/10.1108/CI-11-2018-0094.

[66] H. Wang and X. Song, "Research on BIM Construction Schedule Generating Algorithm," *Int. J. Simul. -- Syst. Sci. Technol.* ., vol. 16, no. 1, pp. 1–7, 2016, doi: 10.5013/IJSSST.a.16.1B.10.

[67] C. E. Program, C. E. Program, and C. E. Program, "Project Scheduling Techniques Within a Building Information Modeling (BIM) Environment : A Survey Study," *IEEE Eng. Manag. Rev.*, vol. 47, no. 2, pp. 133–143, 2019, doi: 10.1109/EMR.2019.2916365.

[68] J. Y. R. R.Dehghan, "The Mechanism of Design Activity Overlapping in Construction Projects and the Time-Cost Tradeoff Function," *Procedia Eng.*, vol. Volume 14, pp. 1959–1965, 2011.

[69] H. Moon, H. Kim, V. R. Kamat, and L. Kang, "BIM-Based Construction Scheduling Method Using Optimization Theory for Reducing Activity Overlaps," *J. Comput. Civ. Eng*, vol. 29, no. 3, 2015, doi: 10.1061/(ASCE)CP.1943-5487.0000342.

[70] H. Wang, Y. Pan, and X. Luo, "Integration of BIM and GIS in sustainable built environment: A review and bibliometric analysis," *Autom. Constr.*, vol. 103, no. March, pp. 41–52, 2019, doi: 10.1016/j.autcon.2019.03.005.

[71] V. K. Bansal, M. Pal, and C. A. D. Modeling, "Generating , Evaluating , and Visualizing Construction," *J. Comput. Civ. Eng*, vol. 22, no. August, pp. 233–242,

2008, doi: 10.1061/(ASCE)0887-3801(2008)22.

[72] V. K. Bansal and M. Pal, “Construction schedule review in GIS with a navigable 3D animation of project activities,” *Int. J. Proj. Manag.*, vol. 27, no. 5, pp. 532–542, 2009, doi: 10.1016/j.ijproman.2008.07.004.

[73] J. Irizarry and E. P. Karan, “Optimizing location of tower cranes on construction sites through GIS and BIM integration,” *Electron. J. Inf. Technol. Constr.*, vol. 17, no. March, pp. 361–366, 2012.

[74] P. Chen and T. C. Nguyen, “A BIM-WMS integrated decision support tool for supply chain management in construction,” *Autom. Constr.*, vol. 98, no. November 2018, pp. 289–301, 2019, doi: 10.1016/j.autcon.2018.11.019.

[75] E. P. Karan and J. Irizarry, “Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services,” *Autom. Constr.*, vol. 53, pp. 1–12, 2015, doi: 10.1016/j.autcon.2015.02.012.

[76] E. P. Karan, J. Irizarry, and J. Haymaker, “BIM and GIS Integration and Interoperability Based on Semantic Web Technology,” *J. Comput. Civ. Eng.*, vol. 30, no. 3, pp. 1–11, 2016, doi: 10.1061/(ASCE)CP.1943-5487.0000519.

[77] T. W. Kang and C. H. Hong, “A study on software architecture for effective BIM/GIS-based facility management data integration,” *Autom. Constr.*, vol. 54, pp. 25–38, 2015, doi: 10.1016/j.autcon.2015.03.019.

[78] E. Mikulakova, M. König, E. Tauscher, and K. Beucke, “Knowledge-based schedule generation and evaluation,” *Adv. Eng. Informatics*, vol. 24, no. 4, pp. 389–403, 2010, doi: 10.1016/j.aei.2010.06.010.

[79] E. ELWAKIL and T. Zayed, “Data Management for Construction Processes Using Fuzzy Approach,” *Constr. Res. Congr.*, no. Mathiassen 1993, pp. 778–786, 2012.

[80] E. R. A. Ziwei Wang, “BIM-based draft schedule generation in reinforced concrete-framed buildings,” *Constr. Innov.*, vol. 19, no. 4, 2019.

[81] M. Y. Cheng and N. W. Chang, “Dynamic construction material layout planning optimization model by integrating 4D BIM,” *Eng. Comput.*, vol. 35, no. 2, pp. 703–720, 2019, doi: 10.1007/s00366-018-0628-0.

[82] Z. Wang, “BIM-based Automated Schedule Generation in Reinforced Concrete-framed Buildings by Ziwei Wang Author ’ s Declaration,” 2018.

[83] J. Park, H. Cai, and D. Perissin, “Bringing Information to the Field : Automated Photo Registration and 4D BIM,” *J. Comput. Civ. Eng.*, vol. 32, no. 2, 2018, doi: 10.1061/(ASCE)CP.1943-5487.0000740.

[84] G. Q. Li, Clyde Zhengdao ; Zhong, Ray Y ; Xue, Fan ; Xu, Gangyan ; Chen, Ke ; Huang, George Guoquan ; Shen, “Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction,” *J. Clean. Prod.*, vol. 165, pp. 1048–1062, 2017.

[85] C. Chen and L. Tang, “BIM-based integrated management work fl ow design for schedule and cost planning of building fabric maintenance,” *Autom. Constr.*, vol. 107, no. February, p. 102944, 2019, doi: 10.1016/j.autcon.2019.102944.

[86] C. Biagini, P. Capone, V. Donato, and N. Facchini, “Towards the BIM implementation for historical building restoration sites,” *Autom. Constr.*, 2016, doi: 10.1016/j.autcon.2016.03.003.

[87] M. Sheikhkhoshkar, F. P. Rahimian, M. H. Kaveh, M. R. Hosseini, and D. J. Edwards, “Automated planning of concrete joint layouts with 4D-BIM,” *Autom. Constr.*, vol. 107, no. July, p. 102943, 2019, doi: 10.1016/j.autcon.2019.102943.

[88] Y. Kim, W. Hong, J. Park, and G. Cha, “An estimation framework for building information modeling (BIM) -based demolition waste by type,” 2017, doi:

10.1177/0734242X17736381.

[89] D. M. H. Qian Chen, Bryan T. Adey, Carl Haas, “Using look-ahead plans to improve material flow processes on construction projects when using BIM and RFID technologies,” *Constr. Innov.*, vol. 20, no. 3, pp. 471–508, 2020.

[90] G. Malacarne, “Investigating Benefits and Criticsm of BIM for Construction Scheduling in SMES : An Italian Case Study,” *J. Sus. Dev. Plann.*, vol. 13, no. 1, pp. 139–150, 2018, doi: 10.2495/SDP-V13-N1-139-150.

[91] E. L. S. Abbott and D. K. H. Chua, “The Intelligent use of RFID in Prefabricated , Construction Work Flow and BIM Volumetric,” in *MATEC Web of Conferences*, 2020, vol. 312.

[92] V. Moayeri, O. Moselhi, and Z. Zhu, “BIM-based model for quantifying the design change time ripple effect,” *NRC Res. Press*, vol. 642, no. September 2016, pp. 626–642, 2017, doi: dx.doi.org/10.1139/cjce-2016-0413.

[93] R. Bortolini, C. Torres, and D. D. Viana, “Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling,” *Autom. Constr.*, vol. 98, no. October 2018, pp. 248–264, 2019, doi: 10.1016/j.autcon.2018.11.031.

[94] D. Heigermoser *et al.*, “BIM-based Last Planner System tool for improving construction project management,” *Autom. Constr.*, vol. 104, no. January, pp. 246–254, 2019, doi: 10.1016/j.autcon.2019.03.019.

[95] V. Konyushkov, S. Sotnikov, V. Veretennikov, and I. Ershov, “Application of 4D BIM modelling in planning and construction of zero cycle works,” in *E3S Web of Conferences*, 2020, vol. 164, pp. 1–10.

[96] Q. Wang, H. Sohn, M. Asce, J. C. P. Cheng, and A. M. Asce, “Automatic As-Built BIM Creation of Precast Concrete Bridge Deck Panels Using Laser Scan Data,”

vol. 32, no. 3, pp. 1–17, 2018, doi: 10.1061/(ASCE)CP.1943-5487.0000754.

[97] S. Abbasi, K. Taghizade, E. Noorzai, and M. Asce, “BIM-Based Combination of Takt Time and Discrete Event Simulation for Implementing Just in Time in Construction Scheduling under Constraints,” *J. Constr. Eng. Manag.*, vol. 146, no. 12, 2021, doi: 10.1061/(ASCE)CO.1943-7862.0001940.

[98] M. Zhiliang, W. Zhenhua, S. Wu, and L. Zhe, “Application and extension of the IFC standard in construction cost estimating for tendering in China,” *Autom. Constr.*, vol. 20, no. 2, pp. 196–204, 2011, doi: 10.1016/j.autcon.2010.09.017.

[99] S. Lee, K. Kim, and J. Yu, “BIM and ontology-based approach for building cost estimation,” *Autom. Constr.*, vol. 41, pp. 96–105, 2014, doi: 10.1016/j.autcon.2013.10.020.

[100] S. Xu, K. Liu, L. C. M. Tang, and W. Li, “A framework for integrating syntax , semantics and pragmatics for computer-aided professional practice : With application of costing in construction industry,” *Comput. Ind.*, vol. 83, pp. 28–45, 2016, doi: 10.1016/j.compind.2016.08.004.

[101] F. K. T. Cheung, J. Rihan, J. Tah, D. Duce, and E. Kurul, “Early stage multi-level cost estimation for schematic BIM models,” *Autom. Constr.*, vol. 27, pp. 67–77, 2012, doi: 10.1016/j.autcon.2012.05.008.

[102] M. Lawrence, R. Pottinger, S. Staub-french, and M. Prasad, “Creating fl exible mappings between Building Information Models and cost information,” *Autom. Constr.*, vol. 45, pp. 107–118, 2014, doi: 10.1016/j.autcon.2014.05.006.

[103] M. Niknam and S. Karshenas, “Integrating distributed sources of information for construction cost estimating using Semantic Web and Semantic Web Service technologies,” *Autom. Constr.*, vol. 57, pp. 222–238, 2015, doi: 10.1016/j.autcon.2015.04.003.

[104] A. Rajguru, “Effective Techniques In Cost Optimization Of Construction Projects,” *Int. J. Inf. Futur. Res.*, vol. 3, no. 5, pp. 1646–1658, 2016.

[105] U. M. P. Klanšek, “Cost Optimization of Construction Project,” no. 1973, pp. 976–982, 2004.

[106] V. Faghihi, K. F. Reinschmidt, and J. H. Kang, “Objective-driven and Pareto Front analysis : Optimizing time , cost , and job-site movements,” *Autom. Constr.*, vol. 69, pp. 79–88, 2016, doi: 10.1016/j.autcon.2016.06.003.

[107] S. Eleftheriadis, P. Duffour, P. Greening, J. James, B. Stephenson, and D. Mumovic, “Energy & Buildings Investigating relationships between cost and CO 2 emissions in reinforced concrete structures using a BIM-based design optimisation approach,” *Energy Build.*, vol. 166, pp. 330–346, 2018, doi: 10.1016/j.enbuild.2018.01.059.

[108] D. K. Wei He, Yichao Shi, “Construction of a 5D duration and cost optimisation model based on genetic algorithm and BIM,” *J. Eng. Des. Technol.*, 2019, doi: https://doi.org/10.1108/JEDT-12-2018-0214.

[109] R. Chahrour *et al.*, “Cost-benefit analysis of BIM-enabled design clash detection and resolution,” *Constr. Manag. Econ.*, pp. 1–18, 2020, doi: 10.1080/01446193.2020.1802768.

[110] R. Liu and X. Hu, “Case Study of Construction Cost Estimation in China Electric Power Industry Based on BIM Technology,” *Int. J. Grid Distrib. Comput.*, vol. 9, no. 10, pp. 173–186, 2016.

[111] R. Shan, X. Xiao, J. Luan, Y. Guo, and Q. Kang, “Whole Process Cost Management Control of Dangerous Chemical Product Construction Projects,” *Ital. Assoc. Chem. Eng.*, vol. 71, pp. 1279–1284, 2018, doi: 10.3303/CET1871214.

[112] A. J. Cooke, *The Economic Evaluation of Construction Projects*. Springer London,

1996.

[113] H. S. Cha and D. G. Lee, “A Case Study of Time / Cost Analysis for Aged-Housing Renovation using a Pre-made BIM Database Structure,” *KSCE J. Civ. Eng.*, vol. 19, pp. 841–852, 2015, doi: 10.1007/s12205-013-0617-1.

[114] K. Wang, W. Wang, H. Wang, P. Hsu, W. Wu, and C. Kung, “Applying building information modeling to integrate schedule and cost for establishing construction progress curves,” *Autom. Constr.*, vol. 72, pp. 397–410, 2016, doi: 10.1016/j.autcon.2016.10.005.

[115] C. Sun, Q. Man, and Y. Wang, “Study on BIM-based construction project cost and schedule risk early warning,” *J. Intell. Fuzzy Syst.*, vol. 29, pp. 469–477, 2015, doi: 10.3233/IFS-141178.

[116] W. Lu, A. Fung, Y. Peng, C. Liang, and S. Rowlinson, “Cost-benefit analysis of Building Information Modeling implementation in building projects through demysti fi cation of time-effort distribution curves,” *Build. Environ.*, vol. 82, pp. 317–327, 2014, doi: 10.1016/j.buildenv.2014.08.030.

[117] Z. Ma, Z. Wei, and X. Zhang, “Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model,” *Autom. Constr.*, vol. 30, pp. 126–135, 2013, doi: 10.1016/j.autcon.2012.11.020.

[118] Z. Shen, “Quantitative Evaluation of the BIM-assisted Construction Detailed Cost Estimates,” *J. Inf. Technol. Constr.*, 2010.

[119] C. Huang and S. Hsieh, “Predicting BIM labor cost with random forest and simple linear regression,” *Autom. Constr.*, vol. 118, p. 103280, 2020, doi: 10.1016/j.autcon.2020.103280.

[120] T. Vandenbergh and L. Pyl, “BIM-based life cycle assessment and life cycle costing of an office building in Western Europe,” *Build. Environ.*, vol. 169, 2020,

doi: 10.1016/j.buildenv.2019.106568.

[121] A. Mashayekhi and G. Heravi, “A decision-making framework opted for smart building ’ s equipment based on energy consumption and cost trade-off using BIM and MIS,” *J. Build. Eng.*, vol. 32, p. 101653, 2020, doi: 10.1016/j.jobe.2020.101653.

[122] J. Lee, H. Yang, J. Lim, T. Hong, and J. Kim, “BIM-based preliminary estimation method considering the life cycle cost for decision-making in the early design phase,” *J. Asian Archit. Build. Eng.*, vol. 19, no. 4, pp. 384–399, 2020, doi: 10.1080/13467581.2020.1748635.

[123] D. Kehily and J. Underwood, “EMBEDDING LIFE CYCLE COSTING IN 5D BIM,” *J. Inf. Technol. Constr.*, vol. 22, no. August 2016, 2017.

[124] Y. Hong, A. W. A. Hammad, A. Akbarnezhad, and M. Arashpour, “Automation in Construction A neural network approach to predicting the net costs associated with BIM adoption,” *Autom. Constr.*, vol. 119, p. 103306, 2020, doi: 10.1016/j.autcon.2020.103306.

[125] U. Vitiello, V. Ciotta, A. Salzano, D. Asprone, G. Manfredi, and E. Cosenza, “Automation in Construction BIM-based approach for the cost-optimization of seismic retro fi t strategies on existing buildings,” *Autom. Constr.*, vol. 98, no. November 2018, pp. 90–101, 2019, doi: 10.1016/j.autcon.2018.10.023.

[126] E. Krasny, S. Klari, and A. Korjeni, “Analysis and comparison of environmental impacts and cost of bio- based house versus concrete house,” *J. Clean. Prod.*, vol. 161, pp. 968–976, 2017, doi: 10.1016/j.jclepro.2017.05.103.

[127] W. Zhou, J. Whyte, and R. Sacks, “Automation in Construction Construction safety and digital design : A review,” *Autom. Constr.*, vol. 22, pp. 102–111, 2012, doi: 10.1016/j.autcon.2011.07.005.

[128] M. D. Martínez-aires, M. López-alonso, and M. Martínez-rojas, “Building information modeling and safety management : A systematic review,” *Saf. Sci.*, vol. 101, no. February 2017, pp. 11–18, 2018, doi: 10.1016/j.ssci.2017.08.015.

[129] B. Succar and M. Kassem, “Macro-BIM adoption : Conceptual structures,” *Autom. Constr.*, vol. 57, pp. 64–79, 2015, doi: 10.1016/j.autcon.2015.04.018.

[130] C. S. Dossick, M. Asce, and G. Neff, “Organizational Divisions in BIM-Enabled Commercial Construction,” vol. 136, no. April, pp. 459–467, 2010, doi: 10.1061/(ASCE)CO.1943-7862.0000109.

[131] A. Ganah and G. A. John, “Integrating Building Information Modeling and Health and Safety for Onsite Construction,” *Saf. Health Work*, vol. 6, no. 1, pp. 39–45, 2015, doi: 10.1016/j.shaw.2014.10.002.

[132] E. Teo, A. Lin, G. Ofori, I. Tjandra, and H. Kim, “Framework for productivity and safety enhancement system using BIM in Singapore,” 2017, doi: 10.1108/ECAM-05-2016-0122.

[133] M. Golparvar-fard, M. Asce, F. Peña-mora, M. Asce, and S. Savarese, “Integrated Sequential As-Built and As-Planned Representation with D 4 AR Tools in Support of Decision-Making Tasks in the AEC / FM Industry,” vol. 137, no. December, pp. 1099–1116, 2011, doi: 10.1061/(ASCE)CO.1943-7862.0000371.

[134] B.-C. . Le, H.Q., Hsiung, “A novel mobile information system for risk management of adjacent buildings in urban underground construction,” *Southeast Asian Geotech. Soc.*, vol. 45, no. 3, pp. 52–63, 2014.

[135] N. O. Nawari, “BIM Standard in Off-Site Construction,” *J. Archit. Eng*, vol. 18, no. June, pp. 107–113, 2012, doi: 10.1061/(ASCE)AE.1943-5568.0000056.

[136] Y. Niu, W. Lu, K. Chen, G. G. Huang, and C. Anumba, “Smart Construction Objects,” *J. Comput. Civ. Eng*, vol. 30, no. 2001, 2016, doi:

10.1061/(ASCE)CP.1943-5487.0000550.

[137] C. Park and H. Kim, “A framework for construction safety management and visualization system,” *Autom. Constr.*, vol. 33, pp. 95–103, 2013, doi: 10.1016/j.autcon.2012.09.012.

[138] A. L. C. Ciribini, S. M. Ventura, and M. Paneroni, “Implementation of an interoperable process to optimise design and construction phases of a residential building : A BIM Pilot Project,” *Autom. Constr.*, vol. 71, pp. 62–73, 2016, doi: 10.1016/j.autcon.2016.03.005.

[139] S. Zhang, K. Sulankivi, M. Kiviniemi, I. Romo, C. M. Eastman, and J. Teizer, “BIM-based fall hazard identification and prevention in construction safety planning,” *Saf. Sci.*, vol. 72, pp. 31–45, 2015, doi: 10.1016/j.ssci.2014.08.001.

[140] J. Qi *et al.*, “Use of Building Information Modeling in Design to Prevent Construction Worker Falls,” *J. Comput. Civ. Eng*, vol. 28, no. 5, pp. 1–10, 2014, doi: 10.1061/(ASCE)CP.1943-5487.0000365.

[141] Rajiv Chavada, “Construction workspace management : the development and application of a novel nD planning approach and tool Construction Workspace Management : The Development and Application of a Novel Nd Planning,” *J. Inf. Technol. Constr.*, no. August, 2014.

[142] J. Wang, S. Zhang, and J. Teizer, “Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling,” *Autom. Constr.*, vol. 49, pp. 250–261, 2015, doi: 10.1016/j.autcon.2014.09.002.

[143] M. Akula, R. R. Lipman, M. Franaszek, K. S. Saidi, G. S. Cheok, and V. R. Kamat, “Real-time drill monitoring and control using building information models augmented with 3D imaging data,” *Autom. Constr.*, vol. 36, pp. 1–15, 2013, doi:

10.1016/j.autcon.2013.08.010.

[144] L. Y. Ding, B. T. Zhong, S. Wu, and H. B. Luo, “Construction risk knowledge management in BIM using ontology and semantic web technology,” vol. 87, pp. 202–213, 2016, doi: 10.1016/j.ssci.2016.04.008.

[145] O. Golovina, J. Teizer, and N. Pradhananga, “Heat map generation for predictive safety planning : Preventing struck-by and near miss interactions between workers-on-foot and construction equipment,” *Autom. Constr.*, vol. 71, pp. 99–115, 2016, doi: 10.1016/j.autcon.2016.03.008.

[146] X. Hu, Z., Zhang, J, Zhang, “Construction collision detection for site entities based on 4-D space-time model,” *Gongcheng Lixue/Engineering Mech.*, vol. 50, no. 6, pp. 820–825, 2010.

[147] X. Hu, Z., Zhang, J, Zhang, “4D construction safety information model-based safety analysis approach for scaffold system during construction,” *Gongcheng Lixue/Engineering Mech.*, vol. 27, no. 12, pp. 192–200, 2010.

[148] H. Kim *et al.*, “Information Retrieval Framework for Hazard Identification in Construction,” *J. Comput. Civ. Eng.*, vol. 04014052, no. 10, pp. 1–10, 2015, doi: 10.1061/(ASCE)CP.1943-5487.0000340.

[149] H. Kim, H. Lee, M. Park, B. Chung, and S. Hwang, “Automated hazardous area identification using laborers ’ actual and optimal routes,” *Autom. Constr.*, vol. 65, pp. 21–32, 2016, doi: 10.1016/j.autcon.2016.01.006.

[150] H. Li, M. Lu, S. Hsu, M. Gray, and T. Huang, “Proactive behavior-based safety management for construction safety improvement,” *Saf. Sci.*, vol. 75, pp. 107–117, 2015, doi: 10.1016/j.ssci.2015.01.013.

[151] H. Luo and P. Gong, “A BIM-based Code Compliance Checking Process of Deep Foundation Construction Plans,” pp. 549–576, 2015, doi: 10.1007/s10846-014-

0120-z.

[152] H. Malekitabar, A. Ardeshir, M. Hassan, and R. Stouffs, “Construction safety risk drivers : A BIM approach,” *Saf. Sci.*, vol. 82, pp. 445–455, 2016, doi: 10.1016/j.ssci.2015.11.002.

[153] Z. Riaz, M. Arslan, A. K. Kiani, and S. Azhar, “CoSMoS : A BIM and wireless sensor based integrated solution for worker safety in con fi ned spaces,” *Autom. Constr.*, vol. 45, pp. 96–106, 2014, doi: 10.1016/j.autcon.2014.05.010.

[154] S. Zhang, J. Teizer, N. Pradhananga, and C. M. Eastman, “Workforce location tracking to model , visualize and analyze workspace requirements in building information models for construction safety planning,” *Autom. Constr.*, vol. 60, pp. 74–86, 2015, doi: 10.1016/j.autcon.2015.09.009.

[155] J. Teizer, “Advanced Engineering Informatics Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites,” *Adv. Eng. Informatics*, vol. 29, no. 2, pp. 225–238, 2015, doi: 10.1016/j.aei.2015.03.006.

[156] D. Liu, J. Chen, D. Hu, and Z. Zhang, “Dynamic BIM-augmented UAV safety inspection for water diversion project,” *Comput. Ind.*, vol. 108, pp. 163–177, 2019, doi: 10.1016/j.compind.2019.03.004.

[157] W. Cheung, T. Lin, and Y. Lin, “A Real-Time Construction Safety Monitoring System Network and Building Information Modeling Technologies,” *MDPI*, 2018, doi: 10.3390/s18020436.

[158] M. Mihić, A. Cerić, and I. Završki, “Developing Construction Hazard Database for Automated Hazard Identification Process,” *Teh. Vjesn.*, pp. 1761–1769, 2018.

[159] S. Andradóttir, K. J. Healy, D. H. Withers, B. L. Nelson, and M. J. Sims, “Proceedings of the 1997 Winter Simulation Conference,” in *simulation*

conference, 1997, pp. 67–69.

[160] H. Moon, H. Kim, C. Kim, and L. Kang, “Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces,” *Autom. Constr.*, vol. 39, pp. 93–105, 2014, doi: 10.1016/j.autcon.2013.06.001.

[161] J. P. Zhang and Z. Z. Hu, “BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction : 1 . Principles and methodologies,” *Autom. Constr.*, vol. 20, pp. 155–166, 2011, doi: 10.1016/j.autcon.2010.09.013.

[162] V. K. Bansal and M. Pal, “Construction Projects Scheduling Using GIS Tools CONSTRUCTION PROJECTS SCHEDULING USING GIS,” *Int. J. Constr. Manag.*, vol. 3599, no. 2011, 2014, doi: 10.1080/15623599.2011.10773158.

[163] S. Zhang, F. Boukamp, and J. Teizer, “Ontology-based semantic modeling of construction safety knowledge : Towards automated safety planning for job hazard analysis (JHA),” *Autom. Constr.*, vol. 52, pp. 29–41, 2015, doi: 10.1016/j.autcon.2015.02.005.

[164] P. J. Bannier and P. M. Goodrum, “Modeling of work envelope requirements in the piping and steel trades and the influence of global anthropomorphic characteristics,” *J. Inf. Technol. Constr.*, 2016.

[165] B. Choi *et al.*, “Framework for Work-Space Planning Using Four-Dimensional BIM in Construction Projects,” *J. Constr. Eng. Manag.*, vol. 140, no. 9, pp. 1–13, 2014, doi: 10.1061/(ASCE)CO.1943-7862.0000885.

[166] K. Kim and J. Teizer, “Advanced Engineering Informatics Automatic design and planning of scaffolding systems using building information modeling,” *Adv. Eng. Informatics*, vol. 28, no. 1, pp. 66–80, 2014, doi: 10.1016/j.aei.2013.12.002.

[167] M. Marzouk and A. Abubakr, “support for tower crane selection with building information models and genetic algorithms,” *Autom. Constr.*, vol. 61, pp. 1–15, 2016, doi: 10.1016/j.autcon.2015.09.008.

[168] H. Moon, N. Dawood, and L. Kang, “Development of workspace conflict visualization system using 4D object of work schedule,” *Adv. Eng. Informatics*, vol. 28, no. 1, pp. 50–65, 2014, doi: 10.1016/j.aei.2013.12.001.

[169] K. Kim, Y. Cho, A M, and K. Kim, “BIM-Driven Automated Decision Support System for Safety Planning of Temporary Structures,” *J. Constr. Eng. Manag.*, vol. 144, no. 8, pp. 1–11, 2018, doi: 10.1061/(ASCE)CO.1943-7862.0001519.

[170] J. Park, S. M, K. Kim, Y. K. Cho, and A M, “Framework of Automated Construction-Safety Monitoring Using Cloud-Enabled BIM and BLE Mobile Tracking Sensors,” *J. Constr. Eng. Manag.*, vol. 143, no. 2, pp. 1–12, 2017, doi: 10.1061/(ASCE)CO.1943-7862.0001223.

[171] F. Mirahadi, B. Mccabe, and A. Shahi, “IFC-centric performance-based evaluation of building evacuations using fire dynamics simulation and agent-based modeling,” *Autom. Constr.*, vol. 101, pp. 1–16, 2019, doi: 10.1016/j.autcon.2019.01.007.

[172] M. Marzouk and I. Al, “Planning labor evacuation for construction sites using BIM and agent-based simulation,” *Saf. Sci.*, vol. 109, pp. 174–185, 2018, doi: 10.1016/j.ssci.2018.04.023.

[173] B. Succar, “Building information modelling framework : A research and delivery foundation for industry stakeholders,” *Autom. Constr.*, vol. 18, no. 3, pp. 357–375, 2009, doi: 10.1016/j.autcon.2008.10.003.

[174] R. Eadie, M. Browne, H. Odeyinka, C. Mckeown, and S. Mcniff, “BIM implementation throughout the UK construction project lifecycle : An analysis,”

Autom. Constr., vol. 36, pp. 145–151, 2013, doi: 10.1016/j.autcon.2013.09.001.

[175] Y. Chen, Y. Lai, and Y. Lin, "BIM-based augmented reality inspection and maintenance of fi re safety equipment," *Autom. Constr.*, vol. 110, p. 103041, 2020, doi: 10.1016/j.autcon.2019.103041.

[176] V. Getuli, P. Capone, A. Bruttini, and S. Isaac, "BIM-based immersive Virtual Reality for construction workspace planning : A safety-oriented approach," *Autom. Constr.*, vol. 114, 2020, doi: 10.1016/j.autcon.2020.103160.

[177] D. Liu *et al.*, "Scenarios for Integrating IPS – IMU System with BIM Technology in Construction Safety Control," *Pr. Period. Struct. Des. Constr*, vol. 25, pp. 1–7, 2020, doi: 10.1061/(ASCE)SC.1943-5576.0000465.

[178] Q. Du, Changqing; Bing, Bo; Mao, Xintong; Liu, Wei; Liu, Yinying; Xu, "Research on Automatic Monitoring and Early Warning System Based on BIM Smart Infrastructure Risk," in *6th InternationalConference on Environmental Science and Civil Engineering*, 2020.

[179] S. Park and I. Kim, "BIM-BASED QUALITY CONTROL FOR SAFETY ISSUES IN THE DESIGN AND CONSTRUCTION PHASES," *Int. J. Archit. Res.*, vol. 9, no. 3, pp. 111–129, 2015.

[180] C. (jump link) Xu, Y., Wang, Y., Yao, "Study on the construction project IPD collaborative management based on Building Information Model," *China Civ. Eng. J.*, vol. 44, no. 12, pp. 138–143, 2011.

[181] N. Nhi and T. Tran, "4D BIM Workspace Conflict Detection for Occupational Management A Case Study for Basement Construction Using Bottom Up Method," in *ICEBT*, 2020, pp. 72–77.

[182] M. Tresidder, "Briefing : Design for manufacture and off-site construction at Woolston Wastewater Treatment Works (UK)," vol. 171, pp. 137–140, 2018.

[183] J. Melzner, S. Zhang, J. Teizer, and H. Bargstädt, “A case study on automated safety compliance checking to assist fall protection design and planning in building information models A case study on automated safety compliance checking to assist fall protection design and planning in building information mo,” *Constr. Manag. Econ. ISSN*, vol. 6193, no. May, 2013, doi: 10.1080/01446193.2013.780662.

[184] V. K. Bansal, “Application of geographic information systems in construction safety planning,” *Int. J. Proj. Manag.*, vol. 29, no. 1, pp. 66–77, 2011, doi: 10.1016/j.ijproman.2010.01.007.

[185] P. Forsythe, “Proactive construction safety systems and the human factor,” vol. 167, 2014.

[186] H. U. Zhenzhong, Z. Jianping, and D. Z. G兰, “Construction Process Simulation and Safety Analysis Based on Building Information Model and 4D Technology *,” vol. 13, no. October, pp. 266–272, 2008.

[187] K. Kim, Y. Cho, and S. Zhang, “Integrating work sequences and temporary structures into safety planning : Automated scaffolding-related safety hazard identi fi cation and prevention in BIM,” *Autom. Constr.*, vol. 70, pp. 128–142, 2016, doi: 10.1016/j.autcon.2016.06.012.

[188] Y. Wang, X. Wang, J. Wang, P. Yung, and G. Jun, “Engagement of Facilities Management in Design Stage through BIM : Framework and a Case Study,” *Adv. Civ. Eng.*, vol. 2013, no. 30836, 2013.

[189] L. Chen and H. Luo, “A BIM-based construction quality management model and its applications,” *Autom. Constr.*, vol. 46, pp. 64–73, 2014, doi: 10.1016/j.autcon.2014.05.009.

[190] T. Hartmann, H. Van Meerveld, N. Vossebeld, and A. Adriaanse, “Aligning

building information model tools and construction management methods," *Autom. Constr.*, vol. 22, pp. 605–613, 2012, doi: 10.1016/j.autcon.2011.12.011.

[191] M. Cheng, K. Chiu, Y. Hsieh, I. Yang, J. Chou, and Y. Wu, "BIM integrated smart monitoring technique for building fire prevention and disaster relief," *Autom. Constr.*, vol. 84, no. June, pp. 14–30, 2017, doi: 10.1016/j.autcon.2017.08.027.

[192] A. A. Ganah and G. A. John, "BIM and project planning integration for on-site safety induction," *J. Eng. Des. Technol.*, vol. 15, no. 3, pp. 341–354, 2017, doi: 10.1108/JEDT-02-2016-0012.

[193] K. Kim, A. M, Y. K. Cho, A. M, and K. Kim, "BIM-Based Decision-Making Framework for Scaffolding Planning," *J. Manag. Eng*, vol. 34, no. 6, 2019, doi: 10.1061/(ASCE)ME.1943-5479.0000656.

[194] H. Freimuth and M. König, "A Framework for Automated Acquisition and," *MDPI*, pp. 1–23, 2019, doi: 10.3390/s19204513.

[195] C. Park, D. Lee, O. Kwon, and X. Wang, "A framework for proactive construction defect management using BIM , augmented reality and ontology-based data collection template," *Autom. Constr.*, vol. 33, pp. 61–71, 2013, doi: 10.1016/j.autcon.2012.09.010.

[196] O. Kwon, C. Park, and C. Lim, "A defect management system for reinforced concrete work utilizing BIM , image-matching and augmented reality," *Autom. Constr.*, vol. 46, pp. 74–81, 2014, doi: 10.1016/j.autcon.2014.05.005.

[197] Y. Lin, J. Chang, and Y. Su, "DEVELOPING CONSTRUCTION DEFECT MANAGEMENT SYSTEM USING BIM TECHNOLOGY IN QUALITY INSPECTION," *J. Civ. Eng. Manag.*, vol. 22, no. 7, pp. 903–914, 2016, doi: 10.3846/13923730.2014.928362.

[198] L. Lin, M. Huang, J. Li, X. Song, and Y. Sun, "The Application and Exploration of

the TSTL in Construction Management Based on BIM," *J. Appl. Sci. Eng.*, vol. 20, no. 3, pp. 309–317, 2017, doi: 10.6180/jase.2017.20.3.05.

[199] Y. Lin, "Use of BIM approach to enhance constrUction interface management : A Case Study," *J. Civ. Eng. Manag.*, vol. 21, no. 2, pp. 201–217, 2015, doi: 10.3846/13923730.2013.802730.

[200] H. Hamledari, S. M, E. R. Azar, A. M, B. Mccabe, and A M, "IFC-Based Development of As-Built and As-Is BIMs Using Construction and Facility Inspection Data : Site-to-BIM Data Transfer Automation," *J. Comput. Civ. Eng*, vol. 32, no. 2, pp. 1–15, 2018, doi: 10.1061/(ASCE)CP.1943-5487.0000727.

[201] E. Elbeltagi and M. Dawood, "Integrated visualized time control system for repetitive construction projects," *Autom. Constr.*, vol. 20, no. 7, pp. 940–953, 2011, doi: 10.1016/j.autcon.2011.03.012.

[202] S. Kubicki, A. Guerriero, L. Schwartz, E. Daher, and B. Idris, "Assessment of synchronous interactive devices for BIM project coordination : Prospective ergonomics approach," *Autom. Constr.*, vol. 101, no. February, pp. 160–178, 2019, doi: 10.1016/j.autcon.2018.12.009.

[203] K. Chen and W. Lu, "Bridging BIM and building (BBB) for information management in construction implementation," *Eng. Constr. Archit. Manag.*, vol. 26, no. 7, pp. 1518–1532, 2019, doi: 10.1108/ECAM-05-2018-0206.

[204] Y. Lin and H. Yang, "A Framework for Collaboration Management of BIM Model Creation in Architectural Projects," *J. Asian Archit. Build. Eng.*, pp. 39–46, 2018.

[205] Z. Ma, S. Cai, N. Mao, Q. Yang, J. Feng, and P. Wang, "Construction quality management based on a collaborative system using BIM and indoor positioning," *Autom. Constr.*, vol. 92, no. March, pp. 35–45, 2018, doi: 10.1016/j.autcon.2018.03.027.

[206] M. Oh, J. Lee, S. Wan, and Y. Jeong, “Integrated system for BIM-based collaborative design,” *Autom. Constr.*, vol. 58, pp. 196–206, 2015, doi: 10.1016/j.autcon.2015.07.015.

[207] O. Koseoglu, “Mobile BIM implementation and lean interaction on construction site A case study of a complex airport project,” *Eng. Constr. Archit. Manag.*, vol. 25, no. 10, pp. 1298–1321, 2018, doi: 10.1108/ECAM-08-2017-0188.

[208] Ø. Mejlænder-larsen, “A three-step process for reporting progress in detail engineering using BIM , based on experiences from oil and gas projects,” *Eng. Constr. Archit. Manag.*, vol. 26, no. 4, pp. 648–667, 2018, doi: 10.1108/ECAM-12-2017-0273.

[209] J. Park, S. M, H. Cai, M, P. S. Dunston, and A M, “Database-Supported and Web-Based Visualization for Daily 4D BIM,” *J. Constr. Eng. Manag.*, vol. 143, no. 10, pp. 1–12, 2017, doi: 10.1061/(ASCE)CO.1943-7862.0001392.

[210] M. Golparvar-fard, A. M. Asce, and F. Pe, “Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models,” *J. Comput. Civ. Eng*, vol. 29, no. 1, pp. 1–19, 2015, doi: 10.1061/(ASCE)CP.1943-5487.0000205.

[211] A. M. Costin, J. Teizer, B. Schoner, and T. Thingmagic, “RFID and BIM-enabled Worker Location Tracking to Support Real-time Building Protocol Control and Data Visulaization,” - *J. Inf. Technol. Constr.*, vol. 20, pp. 495–517, 2015.

[212] F. Bosché, “Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction,” *Adv. Eng. Informatics*, vol. 24, no. 1, pp. 107–118, 2010, doi: 10.1016/j.aei.2009.08.006.

[213] B. Choi *et al.*, “Framework for Work-Space Planning Using Four-Dimensional

BIM in Construction Projects," *J. Constr. Eng. Manag.*, vol. 140, no. 9, pp. 1–13, 2014, doi: 10.1061/(ASCE)CO.1943-7862.0000885.

[214] F. Bosche, M, C. T. Haas, M, B. Akinci, and M, "Automated Recognition of 3D CAD Objects in Site Laser Scans for Project 3D Status Visualization and Performance Control," *J. Comput. Civ. Eng*, vol. 23, no. December, pp. 311–318, 2009, doi: 10.1061/(ASCE)0887-3801(2009)23.

[215] J. Irizarry, E. P. Karan, and F. Jalaei, "Integrating BIM and GIS to improve the visual monitoring of construction supply chain management," *Autom. Constr.*, vol. 31, pp. 241–254, 2013, doi: 10.1016/j.autcon.2012.12.005.

[216] F. Bosché *et al.*, "Tracking the Built Status of MEP Works : Assessing the Value of a Scan-vs . -BIM System," *J. Comput. Civ. Eng*, vol. 28, no. 2011, pp. 1–13, 2014, doi: 10.1061/(ASCE)CP.1943-5487.0000343.

[217] A. Dimitrov and M. Golparvar-fard, "Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections," *Adv. Eng. Informatics*, vol. 28, no. 1, pp. 37–49, 2014, doi: 10.1016/j.aei.2013.11.002.

[218] A. Shahi, M. Safa, C. T. Haas, F, J. S. West, and M, "Data Fusion Process Management for Automated Construction Progress Estimation," *J. Comput. Civ. Eng*, vol. 29, no. 6, pp. 1–9, 2015, doi: 10.1061/(ASCE)CP.1943-5487.0000436.

[219] K. K. Han and M. Golparvar-fard, "Appearance-based material classi fi cation for monitoring of operation-level construction progress using 4D BIM and site photologs," *Autom. Constr.*, vol. 53, pp. 44–57, 2015, doi: 10.1016/j.autcon.2015.02.007.

[220] H. Deng, H. Hong, D. Luo, Y. Deng, A. M. Asce, and C. Su, "Automatic Indoor Construction Process Monitoring for Tiles Based on BIM and Computer Vision,"

J. Constr. Eng. Manag., vol. 146, no. 1, pp. 1–12, 2019, doi: 10.1061/(ASCE)CO.1943-7862.0001744.

[221] A. Braun and A. Borrmann, “Combining inverse photogrammetry and BIM for automated labeling of construction site images for machine learning,” *Autom. Constr.*, vol. 106, 2019, doi: 10.1016/j.autcon.2019.102879.

[222] K. Asadi *et al.*, “Real-Time Image Localization and Registration with BIM Using Perspective Alignment for Indoor Monitoring of Construction,” *J. Comput. Civ. Eng*, vol. 33, no. 5, pp. 1–15, 2019, doi: 10.1061/(ASCE)CP.1943-5487.0000847.

[223] Y. Yan, “Research and application of BIM technology in the design of prefabricated and assembled concrete structures,” 2017.

[224] H. Deng, H. Hong, D. Luo, Y. Deng, A. M. Asce, and C. Su, “Automatic Indoor Construction Process Monitoring for Tiles Based on BIM and Computer Vision,” *J. Constr. Eng. Manag.*, vol. 146, no. 1, pp. 1–12, 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001744.

[225] Q. Wang, H. Sohn, M. Asce, J. C. P. Cheng, and A. M. Asce, “Automatic As-Built BIM Creation of Precast Concrete Bridge Deck Panels Using Laser Scan Data,” *J. Comput. Civ. Eng*, vol. 32, no. 3, pp. 1–17, 2018, doi: 10.1061/(ASCE)CP.1943-5487.0000754.

[226] W. Wu, C. Ren, Y. Wang, T. Liu, and L. Li, “DEA-Based Performance Evaluation System for Construction Enterprises Based on BIM Technology,” *J. Comput. Civ. Eng*, vol. 32, no. 2, pp. 1–10, 2018, doi: 10.1061/(ASCE)CP.1943-5487.0000722.

[227] Y. Lin, W. Cheung, and D. Ph, “Developing WSN / BIM-Based Environmental Monitoring Management System for Parking Garages in Smart Cities,” *J. Manag. Eng*, vol. 36, no. 3, pp. 1–17, 2020, doi: 10.1061/(ASCE)ME.1943-5479.0000760.

[228] S. Jiang, H. Zhang, and J. Zhang, “Research on BIM-based Construction Domain

Text Information Management," *J. NETWORKS*, vol. 8, no. 6, pp. 1455–1465, 2013, doi: 10.4304/jnw.8.6.1455-1464.

[229] F. Pour, S. Seyedzadeh, S. Oliver, and S. Rodriguez, "On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning," *Autom. Constr.*, vol. 110, no. August 2019, p. 103012, 2020, doi: 10.1016/j.autcon.2019.103012.

[230] A. Lisha, Y. Deng, and M. Ren, "Structural reconstruction design and performance simulation analysis of old buildings based on BIM," *Int. J. Low-Carbon Technol.*, vol. 13, pp. 255–259, 2018, doi: 10.1093/ijlct/cty024.

[231] C. Wang, Y. K. Cho, and C. Kim, "Automatic BIM component extraction from point clouds of existing buildings for sustainability applications," *Autom. Constr.*, vol. 56, pp. 1–13, 2015, doi: 10.1016/j.autcon.2015.04.001.

[232] S. M. A. Haoxiong, "Three-dimensional Laser Combined with BIM Technology for Building Modeling , Information Data Acquisition," *Nonlinear Opt. Quantum Opt.*, vol. 52, pp. 191–203, 2020.

[233] Y. Turkan, F. Bosche, C. T. Haas, and R. Haas, "Automated progress tracking using 4D schedule and 3D sensing technologies," *Autom. Constr.*, vol. 22, pp. 414–421, 2012, doi: 10.1016/j.autcon.2011.10.003.

[234] C. Kropp, C. Koch, and M. König, "Interior construction state recognition with 4D BIM registered image sequences," *Autom. Constr.*, vol. 86, pp. 11–32, 2018, doi: 10.1016/j.autcon.2017.10.027.

[235] D. Rebolj, Z. Pu, Č. Nenad, M. Bizjak, and D. Mongus, "Point cloud quality requirements for Scan-vs-BIM based automated construction progress monitoring," *Autom. Constr.*, vol. 84, pp. 323–334, 2017, doi: 10.1016/j.autcon.2017.09.021.

CHAPTER 3

BIM-BASED APPROACH FOR PREDICTIVE SAFETY PLANNING IN THE CONSTRUCTION INDUSTRY

3.1 Introduction

The construction industry is highly related to people. Currently, 1.4 million Canadians are employed in the construction sector [1] and 70% of the 368,000 construction industry firms employ less than five people [1]. Hence, the construction industry is a major employer for small and medium companies. Construction is a hazardous profession, however [2]. workers are exposed to safety hazards when they are climbing high off the ground, digging for foundations, handling large pieces of material, operating large machinery, and working with hazardous substances [3]. Recent trends show that construction-related critical injuries in Canada have risen by 7% from 2015 to 2017 [4]. Additionally, extraordinary events such as pandemic can adversely impact construction worker safety. There is an industry-wide responsibility to safeguard its workers. Yet, the construction industry has been known for its reluctance to embrace advanced technologies to enhance its processes. Therefore, it is vital to adopt cutting edge technologies to manage construction worker health and safety proactively.

Over the years, the construction industry has become accustomed to a standard set of safety guidelines [5]. Many researchers have highlighted that it is vital to use information technology for construction safety [6][7]. Despite being a popular topic in construction management literature, predictive safety assessment has been overlooked by previous researchers [5]. This research has the potential to shift construction safety management from a prescriptive approach to a predictive procedure. A successful system would ensure that construction managers receive the information that they need to plan for and evaluate hazards at the design stage. Moreover, it can guarantee to implement some procedures to reduce safety hazards on a timely basis. There are new challenges for construction safety regarding the increasing project complexities and changing nature of construction methods.

There is an industry-wide responsibility to safeguard its workers. Hence, it is vital to adopt cutting edge technologies to proactively manage construction project safety risks [8][9]. With increasingly complex construction projects, adopting non-conventional safety management procedures can significantly improve safety within the construction site [10]. The construction industry has been going through a paradigm shift with the advent of building information modeling (BIM) that enables the digital representation of physical and functional characteristics of a facility [11]. BIM integrated construction-related safety data can be used to develop a data-driven incident predictive method that supports construction project planning and management [3][12][13].

BIM can be recognized as the most promising technology introduced to the construction sector in the recent past. Also, BIM facilitates collaboration and communication among project participants through a digital representation of the construction procedure [14]. This modeling transforms conventional 3D models into n-dimensional models that contain an extensive range of information for the life cycle management of a facility [15]. Hazard identification and risk assessment are key steps in safety management [16]. The information contained in a BIM model can be manipulated to aid the above. So, a BIM model-based expert system can predict the construction safety risks more accurately.

Expert systems are generally associated with their inherent uncertainties [17]. Uncertainties in safety risk assessment can be categorized into two categories. The first group includes statistical uncertainty, which is related to environmental, natural, or time changes randomness (e.g. spatial heterogeneity). The second group includes non-statistical uncertainty, which is due to the relative information or dispersion of data (e.g. expert opinions or sparse data sets) [18]. Fuzzy logic can be used to address the uncertainties of the project data [19]. Based on previous studies in construction management, fuzzy logic has been used to address uncertainties. Researchers have used fuzzy logic to manage cost, schedule, and safety in construction projects [17][20]-[23].

A Fuzzy Inference System (FIS) maps a given input to an output using fuzzy logic [24]. A FIS can account for data uncertainties and provide a comprehensive safety risk assessment [25]. BIM-based expert systems have been researched in the past for construction safety risk assessment. For example, Zhang et al. [26] proposed a BIM-based Risk Identification Expert System (B-RIES) to solve challenges in traditional safety risk identification and assessment in tunnel construction. This method integrates BIM and knowledge-based management for risk identification. Jin et al. developed a 4D BIM-based tool to assess construction safety risk during the early phases of multistory building projects. This tool presents a proactive measure in the design phase to reduce site hazards [27]. Kim et al. proposed a BIM-based automated construction site risk assessment methodology to identify construction site hazards and evaluate them by a risk rating system [28]. However, a BIM-based FIS has not been used for the safety risk assessment of construction projects.

The objective of this chapter is to propose a FIS for construction safety risk prediction during the preconstruction stage. The FIS is integrated with BIM to automatically extract construction project data. The proposed FIS was validated using a building construction case study. The outcome of this research will reinforce safety risk management practices in construction projects that will lead to reduced safety incidents.

3.2 Background

In construction projects, safety risk can be defined as the occurrence of an incident multiplied by consequences [29]. The safety risks in construction projects can be the result of the following [30]:

i) Technical factors that are associated with inappropriate project design, poor workmanship, and substandard site condition

ii) Natural factors that are associated with bad weather conditions and heavy precipitation

iii) Social factors such as lack of collaboration and communication

The risk assessment will inform construction managers to make mediatory measures before they occur. However, this process is hindered by data uncertainty. Previous researchers have used Monte Carlo simulation and fuzzy set theory to address uncertainties [31]. With the increasing complexity in construction projects, advanced risk assessment methods are required [32]. Serpella et al. identified the lack of knowledge as the main challenge for safety risk management in the construction industry [33]. BIM can improve the quality of safety data exchange and be a repository of historical safety data [27]. Table 3-1 shows the numerous theories and tools proposed by previous researchers for safety risk management.

According to Table 3-1, AHP and FST have been frequently used in risk analysis. As can be seen from Table 3-1, no previous study has integrated BIM and fuzzy logic to address prevailing challenges such as data uncertainties and data exchange. This study addresses this knowledge gap by proposing BIM-based FIS to improve the level of predictive decision-making for assessing the safety risk in the construction project.

Table 3-1: Main tools and theories of previous research to risk assessment

Study	Main Tools or Theories																													
	FST	RR	TA	BS	MCS	ID	WBS	AHP	FT	S	O	WS	RS	3DV	REA	AV	WIP	IMU	GSM	CPD	DF	FRA	EAA	VR	SOS	BIM	BBN	ACA	UAV	AR
[32]	✓																													
[34]		✓	✓																											
[35]	✓																													
[36]				✓																										
[37]	✓				✓	✓																								
[38]							✓	✓																						
[39]								✓																						
[40]	✓																													
[41]	✓							✓																						
[42]	✓								✓																					
[43]	✓							✓																						
[44]	✓							✓																						
[45]			✓																											
[46]						✓				✓																				
[47]								✓			✓																			
[48]								✓				✓	✓																	
[49]														✓	✓															
[50]								✓								✓														
[51]								✓									✓													
[52]																		✓	✓											
[53]																				✓	✓									
[54]								✓														✓								
[55]		✓															✓		✓											
[56]		✓										✓											✓							
[57]	✓							✓																						
[58]		✓																						✓						
[59]						✓																			✓					
[60]																										✓	✓	✓		
[61]								✓																					✓	
[62]	✓																										✓			
[27]																										✓				
[63]						✓																				✓				
[64]			✓																							✓				✓
[28]								✓																		✓				

Note: Fuzzy set theory (FST); risk registering (RR); theoretical argument (TA); breakdown structure (BS); Monte Carlo simulation (MCS); influence diagraming (ID); web-based system (WBS); analytical hierarchy process (AHP); fault tree (FT); simulation (S); optimization (O); wearable sensors (WS); remote sensing (RS); three-dimensional (3D) visualization (3DV); rapid entire body assessment (REA); augmented virtuality (AV); wearable insole pressure system (WIP); inertial measurement units (IMU); gait stability metrics (GSM); canonical polyadic decomposition (CPD); data fusion (DF); functional resonance analysis method (FRA); electrodermal activity Analysis (EAA); virtual reality (VR); smartphone orientation sensor (SOS); building modeling information (BIM); bayesian belief network (BBN); ant colony algorithm (ACA); unmanned aerial vehicle (UAV); augmented reality (AR)

3.2.1 Fuzzy Set Theory

Zadeh presented the fuzzy set theory to address the challenges with imprecise and incomplete data [65]. This theory is a breakthrough in representing vague information. Fuzzy set theory aids the researcher to deal with non-statistical uncertainties [23].

A fuzzy set $\tilde{A}$ in the universe of X can be defined by a membership $\mu_{\tilde{A}}$(x) that is associated with each element x in X [65]. The fuzzy set definition is as follows:

$$\tilde{A}= \{x, \mu_A(x)\}, \quad x \in X$$

Equation 3-1

where $\mu_{\tilde{A}}$(x) is the membership function, its range being the subset of nonnegative real numbers between 0 and 1. The number 0 denotes the complete non-membership and 1 shows the complete membership. The distinction of fuzzy set theory with the classical set theory is that if μ_A(x) takes a value between 0 and 1. Also, x belongs partially to the fuzzy set $\tilde{A}$, meaning that the appropriateness of x is true with the membership degree given by μ_A(x) [66][65].

One of the special classes of fuzzy quantities is fuzzy numbers. A fuzzy number is a fuzzy set in which conditions of normality can be satisfied.

$$\text{Sup } \tilde{A}[x]_{x \in X}=1$$

Equation 3-2

And of convexity

$$\tilde{A}[\lambda x_1 + (1- \lambda)\, x_2] \geq \min[A(x_1), A(x_1)]$$

Equation 3-3

For $\lambda \in [0,1]$ and all $x_1, x_2 \in X$.

Fuzzy Numbers Classes

There are different classes of fuzzy numbers; however, trapezoidal and triangular fuzzy numbers are most common in scientific societies. Equation (4) and Figure 3-1 present the triangular fuzzy number membership functions [66][65]:

$$\mu_A(\mathrm{x}) = \begin{cases} 0 & x < a, \\ \frac{x-a}{b-a} & a \leq x \leq b, \\ \frac{c-x}{c-b} & b \leq x \leq c, \\ 0 & x > c, \end{cases}$$

Equation 3-4

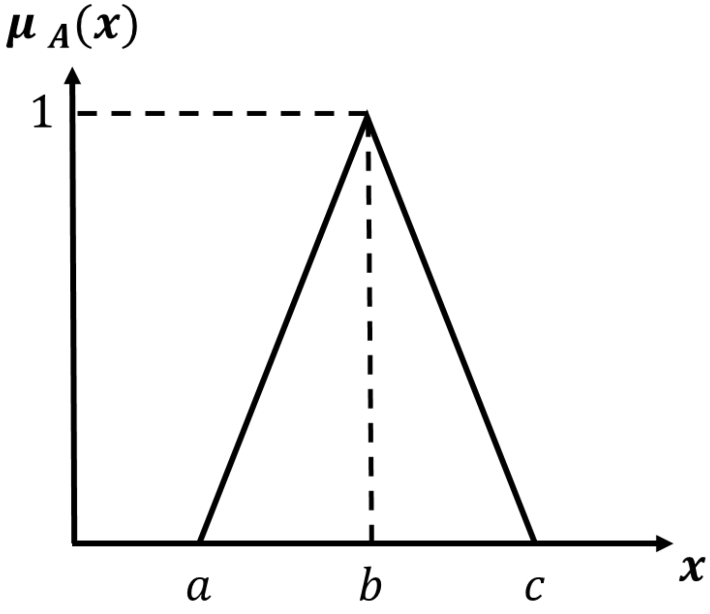


Figure 3-1: Triangular fuzzy number membership function

where “a”, “b”, and “c” denote the x coordinates of the three vertices of μ_A(x) in a fuzzy set A. The lower boundary is “a” and the upper boundary is “c” so that the membership degree in these two coordinates is 0. The center is “b”, for which the membership degree in this coordinate is 1.

Fuzzy logic can be used to incorporate uncertainties associated with linguistic values. Therefore, it can handle types of information that are used for real-world applications.

3.2.2 Fuzzy Inference System

FIS uses fuzzy set theory to map inputs to outputs. FIS can incorporate membership functions, logical operations, and If-Then rules. Figure 3-2 shows the structure of a FIS that includes, a fuzzifier, a rule base, and a defuzzifier. The fuzzifier converts information into fuzzy quantities while the defuzzifier converts fuzzy numbers to crisp numbers [67]. The core of this system is the knowledge base that enables the system for approximate reasoning.

One of the most important steps in FIS is determining the fuzzy rules. They are usually expressed as “If-Then” rules and thus are formulated in linguistic terms than in numerical terms, making the formulation process more convenient. Fuzzy conditional statements easily can implement linguistic terms. Two parts can be mentioned for If-Then rules: the antecedent and the consequent. The first one is compared to the inputs and the latter one is the result. All the rules contain some truth in their premises. The rules will contribute to the fuzzy conclusion set. Each rule is triggered to a degree that is a function of the degree to which its antecedent matches the input. An interpolation between possible input states is necessary when there is imprecise matching. As a result, it leads to minimizing the number of rules required to define input-output relations. Although If-Then fuzzy rules can represent human expertise, these rules can address real challenges.

“If-Then” rule collections define relationships between variables in the fuzzy system based on expert opinions, which are usually expressed in natural language. If α and β are linguistic values respectively defined by fuzzy sets on the universal sets X and Y, the

"If-Then" rule has the following form: "If x is α, then y is β", where the first part is antecedent and the second part is conclusion [68].

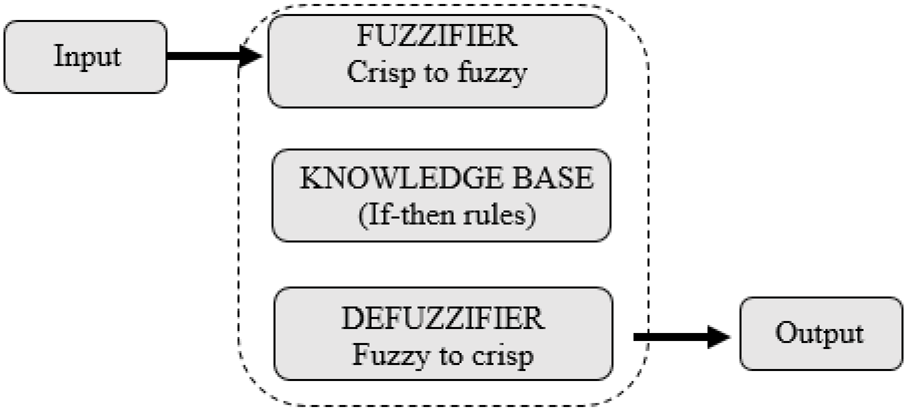


Figure 3-2: Basics of the FIS structure

There are two main types of Fuzzy Inference Systems (FIS), namely the Mamdani type and the Takagi, Sugeno, and Kang (TSK) type. TSK type is computationally efficient, well-suited to mathematical analysis and linear techniques, and guarantees output surface continuity. Mamdani type, on the other hand, is intuitive and contains a more interpretable rule base. This method is well-suited to applications based on human input. Among techniques in applied fuzzy logic, Mamdani inference is one of the most popular techniques. Mamdani inference has been employed in different fields such as management and finance [69][70], risk assessment [71][72], and economics [73][74].

Mamdani FIS was originally used for control systems that employ rules defined by experienced operators. Mamdani systems make rule bases easier to understand [75]. The output of each rule is a fuzzy set derived from the output membership function of the FIS. Mamdani FIS consists of the following steps [75]:

Step1. Applying Fuzzy Operator

After the fuzzification of inputs, the degree of satisfaction of each antecedent for each rule is determined. Since the result of applying fuzzy rules should be a number between 0 and 1, the fuzzy operator is applied when the antecedent of a rule includes more than one part. Membership values from fuzzified input variables are inputs of the fuzzy operator. Consequently, the output is always a single truth value. There are two fuzzy operators: AND operator and OR operator. Some methods can be applied for AND operators such as the t-normˆ (minimum) and production. The first one is usually adopted for the logic connective "And". The t-normˆ equation is expressed as follows:

$$\mu_A(\mathrm{x}) \text{ AND } \mu_B(\mathrm{x}) = \mathrm{MIN}\{\mu_A(\mathrm{x}), \mu_B(\mathrm{x})\}$$

Equation 3-5

Among the OR operator methods such as s-norm, V (maximum), and probabilistic method, the maximum method is usually preferred. The equation of this method is as follows [76]:

$$\mu_A(\mathrm{x}) \text{ OR } \mu_B(\mathrm{x}) = \mathrm{MAX}\{\mu_A(\mathrm{x}), \mu_B(\mathrm{x})\}$$

Equation 3-6

Step 2. Applying Implication Method

The implication method can be initialized by assigning weights to each rule. Membership functions weight linguistic characteristics properly and represent a fuzzy set as the result of implication. The consequent is reshaped using a function associated with the antecedent (a single number). A single number is the input of the implication process and the process for each rule will be implemented. The fuzzy number resulting from the logic operations can have an implication relation R to the consequent and $\tilde{B}$ through the inference machine. The minimum is the most common implication method, which expressed by Equation 3-7 [77]:

$$\mu_R(\mathrm{x}, \mathrm{y}) = \mathrm{MIN}\{\mu_A(x), \mu_B(x)\}$$

Equation 3-7

There are two alternative operators including multiplication by Larsen and Max-Min by Zadeh, represented by Equations 3-8 and 3-9, respectively [77][78]:

$$\mu_R(\mathrm{x, y}) = \{\mu_A(x) * \ \mu_B(x)\}$$

Equation 3-8

$$\mu_R(\mathrm{x, y}) = \mathrm{MAX}\{1 - \mu_A(x), \quad \mathrm{MIN}\{\mu_A(x)\ , \mu_B(x)\ \}\}$$

Equation 3-9

It is of note that the composition of the implication relation and fuzzy singleton can explain the output fuzzy number of each rule. Max-prod, Max-Min, and Max-Media are commonly used among composition operators. Equations 10 to 12 represent these three operators, respectively [78]:

$$\mathrm{S.R(x, z)} = \mathrm{MAX}\ \{(\mu_S(x,y) * \mu_R(y,z)\}$$

Equation 3-10

$$\mathrm{S{\circ}R(x, y)} = \mathrm{MAX}\{\mathrm{MIN}(\mu_S(x,y), \mu_R(y,z)\}$$

Equation 3-11

$$\mathrm{S{\oplus}R(x, y)} = \mathrm{MAX}\{1/2(\mu_R(x,y) + \ \mu_R(x,y)\}$$

Equation 3-12

Step 3. Aggregation of All Outputs

Considering that evaluation of all rules in a FIS is the base of decision-making, the rule outputs should be combined accordingly. To combine fuzzy sets into a single fuzzy set, the aggregation process is required. The process only happens once for each output variable before the final defuzzification stage [65]. It is worth mentioning that the input of the process includes the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable. Diverse operators such as Min, Max, arithmetic, and geometric or harmonic means can be used for the aggregation process [78]. Equation 3-13 indicates the Max operator, which is recommended when compensation between variables is desirable [77][78].

$$\text{AG(.)= MAX}(\mu_{R_1}(\text{x}), \mu_{R_2}(\text{x}), \ldots, \mu_{R_n}(\text{x}))$$

Equation 3-13

Step 4. Defuzzification

This process uses the aggregate output fuzzy set as its input. The output of defuzzification is a single crisp number. However, since the aggregate of a fuzzy set encompasses a range of output values, it must be defuzzified to obtain a single output value from the set. Among defuzzification methods such as centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum, the centroid that returns the center of the area under the curve is the most popular method. The following equation represents the centroid method:

$$\text{Center of area } Z_{COA} = \frac{\int_Z \mu_A(Z)Z\,dz}{\int_Z \mu_A(Z)\,dz}$$

Equation 3-14

where Z is the discrete points number of the fuzzy set and $\mu_A(Z)$ is the aggregated output MF[79].

The inference process of a Mamdani system is described in the fuzzy inference process and summarized in the following equations:

Considering A, $\acute{A}$(a proposition close to A), B and $\acute{B}$(a proposition close to B) as fuzzy sets in X, Y, and Z and A→B as a fuzzy relation in X×Y, the fuzzy set B can be inferred based on the “x is A” proposition. So, “if x is A then y is B” can be defined as follows:

$$\mu_{\acute{B}}\ (y) = \max\{\min[\mu_{\acute{A}}\ (x),\ \mu_R\ (x, y)]\} = \vee_x\ [\mu_{\acute{A}}\ (x) \wedge \mu_R\ (x, y)]$$

Equation 3-15

Equivalently:

$$\acute{B} = \acute{A} \circ R = \acute{A} \circ A \rightarrow B$$

Equation 3-16

Equation 3-15 can be extended to be generalized for a fuzzy inference system with more than one rule and antecedent. Considering the following propositions, we have:

Fact: x is $\acute{A}$ and y is $\acute{B}$

Rule 1: if x is A_1 and y is B_1 then z is C_1

Rule 2: if x is A_2 and y is B_2 ,then z is C_2

Result: z is $\acute{C}$

And $R_1 = A_1 \times B_1 \rightarrow C_1$ and $R_2 = A_2 \times B_2 \rightarrow C_2$,

$$\acute{C} = (\acute{A} \times \acute{B}) \circ (R_1 \cup R_2) = [\ (\acute{A} \times \acute{B}) \circ R_1\ ] \cup [\ (\acute{A} \times \acute{B}) \circ R_2\ ] = \acute{C}_1 \cup \acute{C}_2$$

Equation 3-17

where $\acute{C}_1$ and $\acute{C}_2$ are the inferred fuzzy sets from rules 1 and 2. Figure 3-3 illustrates the fuzzy inference process explained above [80]. Here, $\acute{C}$ (which is a fuzzy set) is the output of the fuzzy inference system and defuzzification methods can be applied on it to calculate the crisp output value [80].

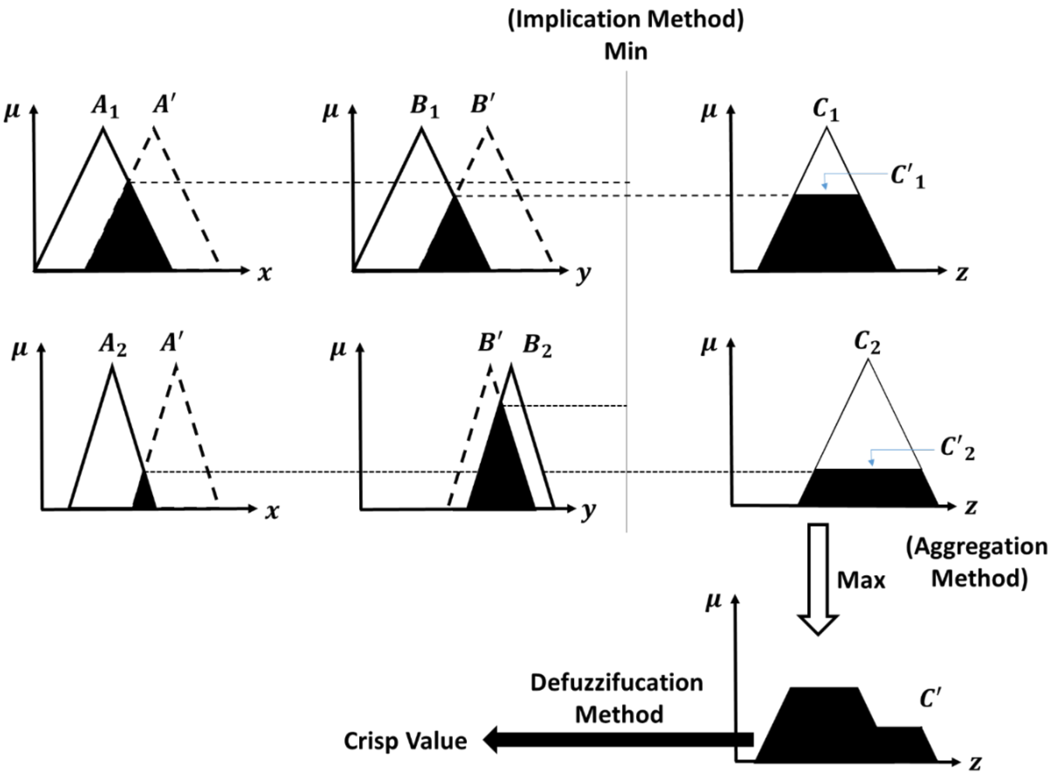


Figure 3-3: Fuzzy inference for a system with some rules and antecedents

3.3 Methodology

Figure 3-4 presents the methodology used in this research. This research was conducted in three interlinked phases.

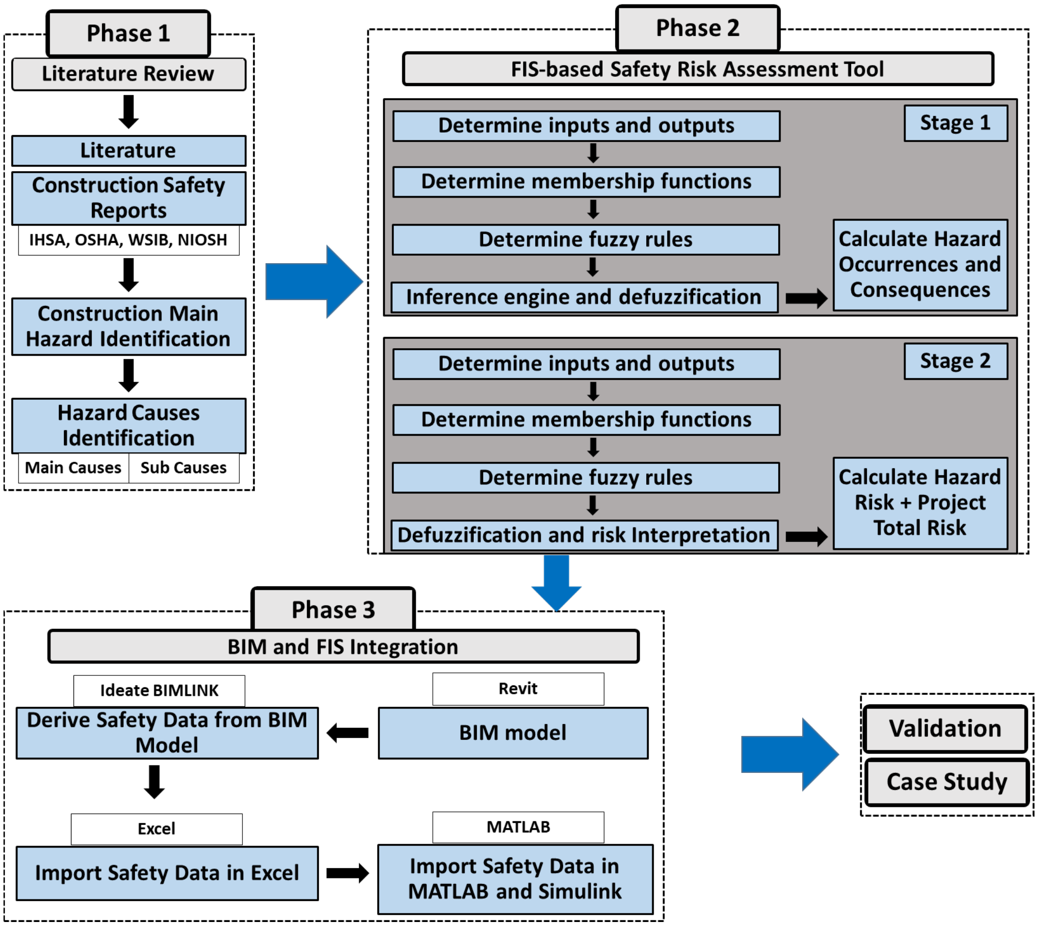


Figure 3-4: The BIM-based method for safety risk prediction

3.3.1 Phase 1: Identification of Cause-effect for Safety Incidents

In Phase 1, major construction hazards and their causes were identified. Publications by reputed institutions such as National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), Worker Safety Insurance Board (WSIB), and Infrastructure Health & Safety Association (IHSA) were reviewed as well. According to the above sources, six major safety hazards in the construction sites are fall, struck by objects, construction machinery hazards, electrocution hazards, suffocation, and fire hazards. Literature was used to identify the causes of construction hazards. Table 3-2 lists the main safety hazards in construction projects and their main causes.

Table 3-2: Construction safety hazards and their main causes

Construction Safety Hazards					
Fall	**Struck by Objects**	**Construction Machinery**	**Electrical**	**Suffocation**	**Fire**
Slips	Inappropriate Protective Means	Striking Labors and Material	Improper Grounding	Narrow Entrance Size	Electrical Supplies and Equipment Hazards
Trips	Inappropriate Protective Structures	Equipment collapse or buckling	Exposed Electrical parts	Unsafe operation	Evacuation Hazards
Harsh Weather Condition	Unsafe scaffolding	Equipment Overturn	Inadequate Insulation	Rare Oxygen Level	Inefficient Fire Extinguishing Systems
Unprotected Edges	Improper Housekeeping	Driver Hazards	Overload Circuits	Lack of Exit Means	Open and Waste Fire Hazards
Unsafe Travel Restraint System	Tools and Equipment	Lack of training	Weather Condition	External Excessive pressure on the soil near the excavation	Inappropriate Fire Protection Systems
Unsafe Safety Net	Unsecured Safety Net		Overhead Power Lines	Lack of training	Flammable and Combustible Building Materials
Unsafe Fall Arrest Systems and Fall Restricting System	Unsafe Temporary Elevator		External Causes		Lack of training
Lack of training	Unsafe Hoisting and Rigging		Lack of training		
Floor holes and wall openings	Struck by Construction Machinery				
Unsafely positioned ladders	Lack of Training				
Unsafe scaffolding					

Sub-causes about the main causes of construction hazards (Table 3-2), which are 104 in total, were identified from the literature. Similar Tables (appendices A-E) were developed for other safety hazards.

Table. 3-3: Main causes and sub-causes for fall hazard

Fall Hazards		
No.	**Main Causes**	**Sub-causes**
1	Slips	Low roughness of floor materials
		Unsuitable floor coverings
		Uneven or damaged floor surfaces
		Contaminated floor surfaces, for example, liquid or grease
		Precipitation and freezing
2	Trips	Poor lighting
		Trailing cables
		Additional material of construction, for example, extra rebars of concrete reinforcing operation
		Deposit materials
3	Harsh Weather Condition	Changing the location of labors because of the heavy wind
		Heat exhaustion
4	Unprotected Edges	Lack of guardrail installation
		Improper height of toe boards
5	Unsafe Travel Restraint System	Unsafe roof anchor (fixed support system)
		Damaged rope
6	Unsecured Safety Net	Gaps in the safety net
		Inferior quality of the net
7	Unsafe Fall Arrest Systems and Fall Restricting System	Full-body harness vest inferior quality
		Damaged lanyard and lifeline
		Unsafe connections
8	Lack of Training	
9	Floor holes and wall openings	Lack of opening and hole covering
		Inadequate warning signs
10	Ladder Incidents	Unsecure footing of the ladder at the base
		Defective ladders
		Slippery step or rungs
		Workers fault while climbing up or down
		Improper position of workers on ladders
		Ladders toppling because of high winds
		Improper position of ladders near electrical lines
		Lack of using stabilizers when needed

11	Unsecure scaffolding	Planks sliding off or breaking
		Erecting and dismantling scaffolds
		Climbing up and down scaffolds
		Improper loading or overloading
		Lack of guardrails
		Platforms not fully planked
		Lack of installation of required components, e.g. baste plates
		Moving rolling scaffolds near overhead electrical wires
		Moving rolling scaffolds with workers on the platform.

Table 3-4 lists of factors that affect the severity of safety incidents identified from published literature.

Table. 3-4: Construction accidents consequence severity factors

	Related parameters to the severity of hazard consequences					
No.	**Fall**	**Struck by Objects or Machinery**	**Machinery**	**Electrical**	**Suffocation**	**Fire**
1	Height of Fall	Height of falling	Speed of Machine	Electric Current Path	Soil Debris Volume	Fire Location
2	Age of Worker	Age of Workers	Driver fall Height	Electric Current Voltage	Debris Material Type	Type of in-fire Object
3	Ground or Floor Surface Material Type	Collision Intensity	Fall Location of Machine	Electric Current Type and Frequency	Cave-in Duration	Amount of Fire
4	Material Type on the ground	Object Type	Age of Worker	Duration of Electric Shock	Age of Worker	Age of Worker
5		Object Mass				

3.3.2 Phase 2: Fuzzy expert system for safety risk prediction

Safety hazards identified in Phase 1 are associated with stochastic data. Fuzzy logic can easily model stochastic data and address uncertainties. Therefore, fuzzy logic is used in this study to assess the safety risk of a construction project.

Safety risk in a construction site (R) is defined as:

$$R = O \otimes C$$

Equation 3-18

where O is the fuzzy occurrence of a safety risk and C is the fuzzy consequence of the occurrence [81].

To further explain this study FIS and to clarify each step of the methodology followed in this study, the process can be defined as follows:

If there are "n" inputs in a FIS, they can be expressed as $x_1 , x_2 , \dots , x_i , \dots , x_n$ and fuzzy sets for inputs are $A_{1l_1} , A_{1l_2} , \dots , A_{il_j} ,\dots, A_{nl_n}$, where i shows the corresponding input and l_j shows the corresponding membership function of input i. Moreover, since in this study, FISs are multiple input single-output (MISO) systems, outputs can be shown as $B_{l_1}, B_{l_2}, \dots , B_{l_i}, \dots , B_{l_n}$. Therefore, the rule(s) of a FIS can be shown as follows:

If x_1 is A_{1l_1} and x_2 is A_{2l_2} and … x_n is A_{nl_n} , then y is B_{ly}.

In this study, the MIN operator was chosen as the fuzzy operator for applying to the antecedent part of fuzzy rules. $\mu_{A_i l_j}(x_i)$ and $\mu_{B_{ly}}(y)$ are the degree of truth of inputs and the output, respectively. Also, the Mamdani minimum was selected as the implication method for fuzzy rules. Therefore, the fuzzy set result is expressed as:

$$I_k = \wedge(\alpha_k , \mu_{B_{ly_k}}(y))$$

Equation 3-19

where $$\alpha_k = \bigwedge_{i=1}^{n} \bigwedge_{j=1}^{m} \mu_{A_i l_j}(x_i) = \bigwedge(\mu_{A_1 l_1}(x_1), \dots, \mu_{A_n l_m}(x_n))$$

Equation 3-20

where n shows the number of inputs and m shows the number of membership functions of each input.

In the following, because of selecting the MAX method for the aggregation of fuzzy set results of all rules, the aggregated fuzzy set can be defined as:

$$\acute{A} = \bigvee_{k=1}^{q} I_k$$

Equation 3-21

where q shows the fuzzy rule numbers in a FIS.

To generate the crisp output value of this FIS, defuzzification methods use $\acute{A}$ parameter. MATLAB fuzzy logic toolbox was used for computations in this research. This software provides graphical user interfaces, functions, and Simulink blocks for designing and simulating Fuzzy Logic systems. To model the mentioned risk equation in MATLAB, 14 FISs and 4859 FIS rules were defined for six construction hazards, namely fall hazard, struck by object hazard, construction machinery hazard, electrical hazard, suffocation hazard, and fire hazard. The process of modeling the risk equation in MATLAB for assessing the safety risk of construction projects is divided into two stages.

Figure 3-5 illustrates the methodological framework of the fuzzy expert system. The two stages in the fuzzy expert system are hazard analysis and risk aggregation. In Stage 1, there are 12 FIS to calculate the occurrence and consequence of hazards. For example, FIS 1 calculates the occurrence of fall hazards and FIS 2 calculates the consequence of fall hazards in a construction project. Stage 2 consists of two FIS to assesses the safety risk of each hazard and also the total risk of a construction project.

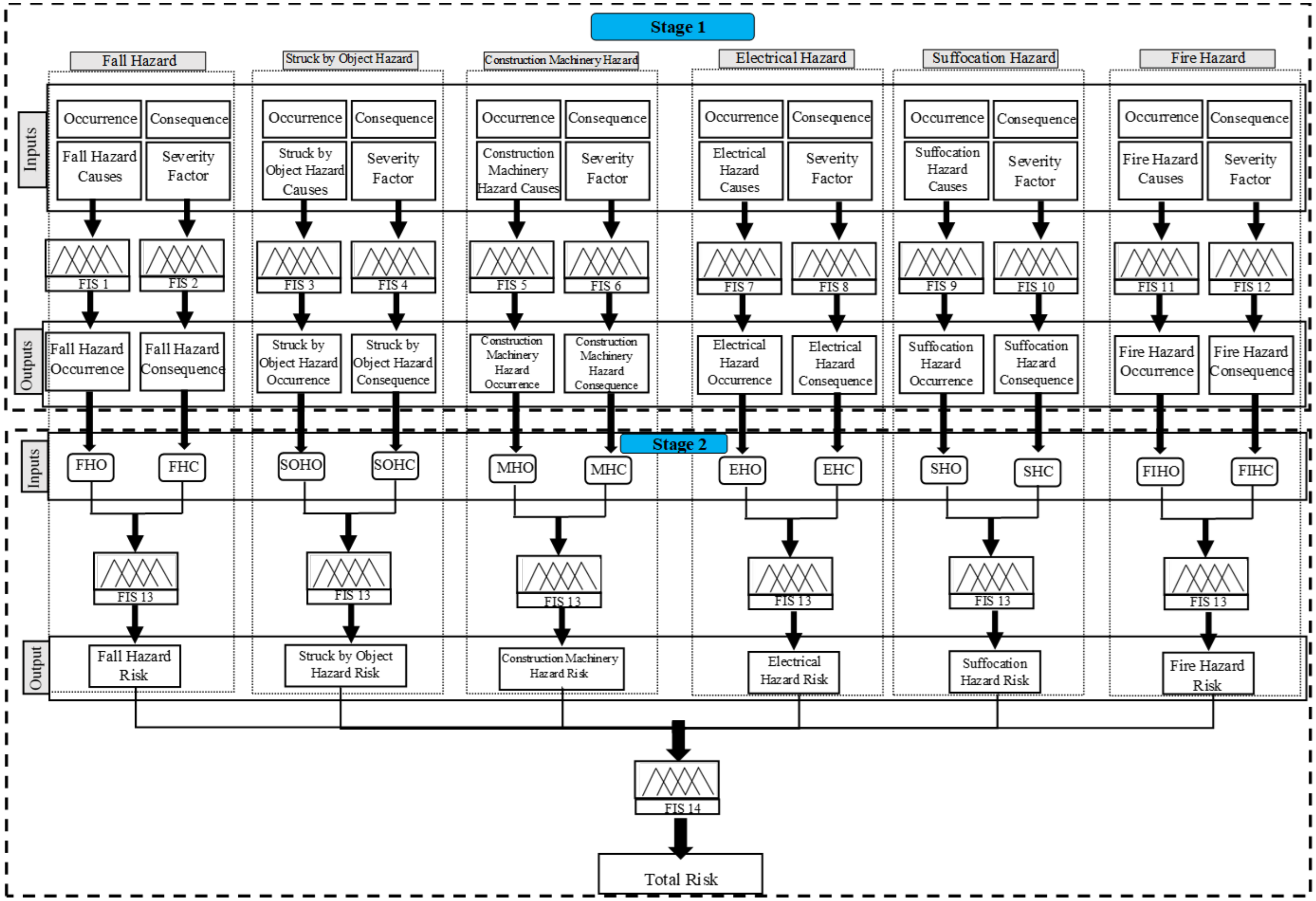


Figure 3-5: Safety risk assessment framework

Stage 1: Hazard analysis

In Stage 1, the occurrence and consequence of each hazard were calculated. To calculate these two parameters, one FIS was defined for each hazard. There are 12 FISs in Stage 1 (FISs 1-12).

To link the safety risk to the construction hazard causes, the following equations were used:

Calculation of the occurrence of an accident:

The occurrence of a hazard is calculated using FISs 1, 3, 5, 7, 9, and 11, and Equation 3-22:

$$O_{\beta} = \frac{\int_Z \mu_{\acute{A}_{\beta}}(Z) Z \, dz}{\int_Z \mu_{\acute{A}_{\beta}}(Z) \, dz}$$

Equation 3-22

where $A'_{\beta} = \bigvee_{k=1}^{q}(\bigwedge_{k=1}^{q}(\alpha_{k_{\beta}}, \mu_{B_{ly_{k_{\beta}}}}(y)))$ and β shows the FIS number, which can be one of 1, 3, 5, 7, 9, and 11.

where $\alpha_{k_{\beta}} = \bigwedge_{i=1}^{n} \bigwedge_{j=1}^{m} \mu_{A_{il_j}}(x_i) = \bigwedge(\mu_{A_1 l_1}(x_1), \ldots, \mu_{A_n l_m}(x_n))$

For example, the occurrence of the fall hazard, FIS 1 with 5 inputs, and 243 rules is shown in Equation 3-23:

$$O_{fall\ hazard} = \frac{\int_Z \mu_{\acute{A}_{fall\ hazard}}(Z) Z \, dz}{\int_Z \mu_{\acute{A}_{fall\ hazard}}(Z) \, dz}$$

Equation 3-23

$$A'_{fall\ hazard} = \bigvee_{k=1}^{243}(\bigwedge_{k=1}^{243}(\alpha_{k_{fall\ hazard}}, \mu_{B_{ly_{k_{fall\ hazard}}}}(y))$$

$$\text{where } \alpha_{k_{fall\,hazard}} = \wedge_{i=1}^{5} \wedge_{j=1}^{3} \mu_{A_i l_j}(x_i) = \wedge(\underbrace{\mu_{A_1 l_1}}_{\substack{\text{The area of unprotected} \\ \text{floor openings occurrence} \\ \text{(Membership function: Low)}}}(x_1), \dots, \underbrace{\mu_{A_5 l_3}}_{\substack{\text{The height of unprotected scaffolds occurrence} \\ \text{(Membership function: High)}}}(x_5))$$

Calculation of the consequence of an accident:

The consequence of a hazard event is determined using FISs 2, 4, 6, 8, 10, and 12, and Equation 3-24:

$$C_{\gamma} = \frac{\int_Z \mu_{\acute{B}_{\gamma}}(Z) Z \, dz}{\int_Z \mu_{\acute{B}_{\gamma}}(Z) \, dz}$$

Equation 3-24

where B'_{γ} is a fuzzy set and the result of the aggregation of all fuzzy rules in the mentioned FISs.

Hazard analysis includes 4 steps, namely determining inputs and outputs, determining membership functions, determining fuzzy rules, inference engine, and defuzzification. Details of each step are presented below.

i) Determining inputs and outputs

To model the FIS in MATLAB, it is necessary to define inputs and outputs. Table 3-5 shows the numbers of inputs and outputs of 12 FISs in Stage 1. In this research, the multiple inputs and single-output (MISO) FIS type were used for this purpose. Overall, there are 37 inputs, which are presented in Table 3-5.

Table 3-5: Inputs and outputs of FIS

Stage 1(FIS 1-12)												
	Occurrence						Consequence					
	FH	SOH	MH	EH	SH	FIH	FH	SOH	MH	EH	SH	FIH
Input	5	4	4	4	4	4	2	2	2	2	2	2
Output	1	1	1	1	1	1	1	1	1	1	1	1
Sum = 37												

Inputs of this system were selected based on the hazard sub-causes identified in Phase 1 of this study. Sub-causes were identified based on previous research and BIM capability. Table 3-6 shows the inputs and outputs of one example in Stage 1.

Table 3-6: Inputs and outputs of FIS

Stage 1 (FISs 1-12)			
Example: Fall hazard			
Occurrence		Consequence	
Input	Output	Input	Output
The area of unprotected floor openings (AFO)	Fall hazard Occurrence	Age of worker	Fall hazard consequence severity
The area of unprotected wall openings (AWO)		Height of fall	
Floor material roughness (FMR)			
The height of unprotected floors (edges) (HF)			
The height of unprotected scaffolds (HS)			

i) Determining membership functions

Triangular and trapezoidal fuzzy membership functions have been commonly used in previous research [82]. In the present study, both triangular and trapezoidal fuzzy membership functions were used. Membership function linguistic variables for both occurrence and consequence sections were selected based on previous studies such as Amiri et al. [17]. Linguistic terms of all inputs for calculating the occurrence of hazards are described as “low,” “medium”, and “high”. However, the range of membership for inputs was determined based on the literature. Moreover, the linguistic terms of inputs for calculating the consequence of hazards are not similar. Outputs of FISs 1-12 were provided as the input for FIS 13. Table 3-7 represents the membership function of the outputs of Stage 1. To provide the categorization in Table 3-7, some previous studies such as those of Gurcanli & Mungen, Liu, and Tsai were used [82][83].

Table 3-7: Membership function of outputs of Stage 1

Occurrence				
Rare	Unlikely	Possible	Likely	Almost Certain
(0, 0, 20)	(10, 30, 50)	(30, 50 ,70)	(50, 70, 90)	(80, 100, 100)
Consequence				
Insignificant	Minor	Moderate	Major	Catastrophic
(0, 0, 20)	(10, 30, 50)	(30, 50 ,70)	(50, 70, 90)	(80, 100, 100)

i) Determining fuzzy rules

Fuzzy rules were defined based on previous studies [84][83][81][17]. The number of fuzzy rules can be determined according to the number of fuzzy set membership functions and the number of inputs of FISs. For instance, Table 3-8 shows examples of fuzzy rules used in FIS 1. As shown in Table 3-8, if the floor material roughness (FMR) is “Low”, the area of unprotected floor openings (AFO) is “Low”, the area of unprotected wall openings (AWO) is “Low”, the height of unprotected floors (HF) is “Low”, and the height of unprotected scaffolds (HS) is “High”, then fall hazard occurrence is “Likely”. Appendix F lists complete fuzzy rules of fall hazard.

Table 3-8.: Inference rules of FIS 1

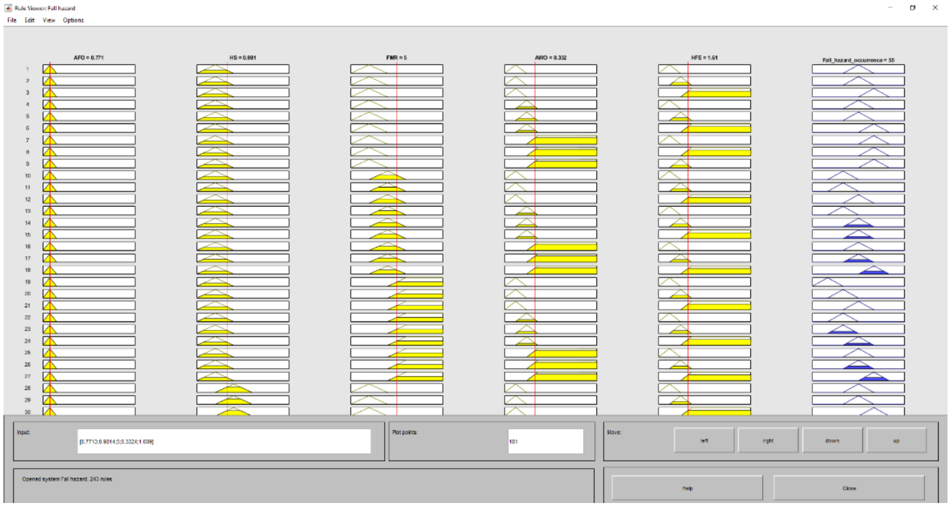
Rules	**IF**					**Then**
	FMR	**AFO**	**AWO**	**HF**	**HS**	**Fall hazard Occurrence**
1	Low	Low	Low	Low	Low	Possible
2	Low	Low	Low	Low	Medium	Possible
3	Low	Low	Low	Low	High	Likely
4	Low	Low	Low	Medium	Low	Possible
5	Low	Low	Low	Medium	Medium	Likely
. . .						
163	High	Low	Low	Low	Low	Rare
164	High	Low	Low	Low	Medium	Unlikely
165	High	Low	Low	Low	High	Possible
166	High	Low	Low	Medium	Low	Unlikely
. . .	. . .	. . .	. . .	. . .	. . .	. . .
243	High	High	High	High	High	Almost Certain
Note: the floor material roughness (FMR); the area of unprotected floor openings (AFO); the area of unprotected wall openings (AWO); the height of unprotected floors (HF); the height of unprotected scaffolds (HS)						

Table 3-9: Rule number of FISs

Stage 1						
Hazards	**Occurrence**			**Consequence**		
	FIS 1			**FIS 2**		
	Input	Output	Rules	Input	Output	Rules
Fall hazard	5	1	243	2	1	15
	FIS 3			**FIS 4**		
Struck by objects hazard	4	1	81	2	1	15
	FIS 5			**FIS 6**		
Construction machinery hazard	4	1	81	2	1	15
	FIS 7			**FIS 8**		
Electrical hazard	4	1	81	2	1	15
	FIS 9			**FIS 10**		
Suffocation hazard	4	1	81	2	1	15
	FIS 11			**FIS 12**		
Fire hazard	4	1	81	2	1	15
	Sum =		648	Sum =		90
Sum = 738 rules						

i) Inference engine and Defuzzification

The center of area method (COA) is used as the defuzzification method. Figure 3-6 presents the structure of fall hazard occurrence. Every row in this figure shows a rule and each column shows a sub-cause of a fall hazard. Therefore, there are five input variables and one output. Inputs are extracted from a BIM model. This process is further explained in Phase 3.



Input: [0.7713;0.9814;5;0.3324;1.609]

Plot points: 101

Opened system Fall hazard, 243 rules

Figure 3-6: Rule viewer of fall hazard occurrence

Stage 2: Risk aggregation

In Stage 2, the occurrence and consequence of each hazard are used as the inputs to calculate the safety risk of each hazard. FIS 13 is used to calculate the safety risk of each hazard. Moreover, FIS 14 is applied to calculate the total safety risk of a construction project.

The safety risk (R) of each hazard can be defined as follows:

$$R_\lambda = \frac{\int_Z \mu_{\acute{C}_\lambda}(Z) Z \, dz}{\int_Z \mu_{\acute{C}_\lambda}(Z) \, dz}$$

Equation 3-25

where $C'_\lambda = \bigvee_{k=1}^{q}(\bigwedge_{k=1}^{q}(\alpha'_{k_\lambda}, \mu_{\beta'_{ly_{k_\lambda}}}(y)))$ and λ shows the hazard name.

where $\alpha'_{k_\lambda} = \bigwedge_{i=1}^{n} \bigwedge_{j=1}^{m} \mu_{A_i l_j}(x_i) = \bigwedge(\mu_{A_1 l_1}(x_1), \dots, \mu_{A_n l_m}(x_n))$

For example, the risk of the fall hazard is expressed by Equation 3-26:

$$R_{fall\ hazard} = \frac{\int_Z \mu_{\acute{C}_{fall\ hazard}}(Z) Z \, dz}{\int_Z \mu_{\acute{C}_{fall\ hazard}}(Z) \, dz}$$

Equation 3-26

$$C'_{\lambda}= \bigvee_{k=1}^{25}(\bigwedge_{k=1}^{25}(\alpha'_{k_{fall\ hazard}}, \mu_{\beta'_{ly_{k_{fall\ hazard}}}}(y))$$

where $\alpha_{k_{fall\ hazard}} = \bigwedge_{i=1}^{2}\bigwedge_{j=1}^{5}\mu_{A_il_j}(x_i) = \bigwedge(\underbrace{\mu_{A_1l_1}}_{\substack{\text{The occurrence of fall hazard}\\\text{(Membership function: Rare)}}}(x_1), \dots, \underbrace{\mu_{A_2l_5}}_{\substack{\text{The consequence of fall hazard}\\\text{(Membership function: Almost certain)}}}(x_5))$

The total risk of a project (R_t) can be defined as follows:

$$R_t = \frac{\int_Z \mu_t(Z)Z\,dz}{\int_Z \mu_t(Z)\,dz}$$

Equation 3-27

$$t= \bigvee_{k=1}^{4096}(\bigwedge_{k=1}^{4096}(\alpha''_k, \mu_{\beta''_{ly_k}}(y)))$$

where $\alpha''_k = \bigwedge_{i=1}^{6}\bigwedge_{j=1}^{5}\mu_{A_il_j}(x_i) = \bigwedge(\underbrace{\mu_{A_1l_1}}_{\substack{\text{The safety risk of fall hazard}\\\text{(Membership function: Very Low)}}}(x_1), \dots, \underbrace{\mu_{A_6l_5}}_{\substack{\text{The safety risk of fire hazard}\\\text{(Membership function: Extreme)}}}(x_5))$

The steps of Stage 2 are explained below.

i) Determining inputs and outputs

The occurrence and consequence of each hazard are the inputs of FIS 13. Moreover, the risk of each construction hazard is the output of this FIS. FIS 14 determines the total project risk based on the six construction hazard risks (i.e., fall hazard and struck by object hazard). It is of note that the type of FISs in Stage 2 is MISO.

ii) Determining membership functions

The input membership functions of FIS 13 in Stage 2 are like the membership functions in Stage 1. The membership functions of the output of FIS 13, inputs, and outputs of FIS 14 are determined based on previous fuzzy-based studies in the construction industry [84][83][81][17]. These functions are presented in Table 3-10.

Table 3-10: Membership function of outputs of FIS 13 and the input and output of FIS 14

Linguistic Term	**Fuzzy Number**
Very Low	(0, 0, 10, 20)
Low	(10, 20, 30, 40)
Medium	(30, 40, 60, 70)
High	(60, 70, 80, 90)
Extreme	(80, 90, 100, 100)

i) Determining fuzzy rules

In this stage, fuzzy rules for FIS 13 and 14 were defined to calculate the total risk of a construction project. Table 3-11 shows the rule base of FIS 13.

Table 3-11: Inference rules of FIS 13

Rules	IF		Then
	Hazard Occurrence	Hazard Consequence	Hazard Risk
1	Rare	Insignificant	Very Low
2	Unlikely	Insignificant	Low
3	Possible	Insignificant	Low
4	Likely	Insignificant	Medium
5	Almost Certain	Insignificant	Medium
6	Rare	Minor	Low
7	Unlikely	Minor	Low
8	Possible	Minor	Medium
9	Likely	Minor	Medium
10	Almost Certain	Minor	High
11	Rare	Moderate	Medium
12	Unlikely	Moderate	Medium
13	Possible	Moderate	High
14	Likely	Moderate	High
15	Almost Certain	Moderate	High
16	Rare	Major	Medium
17	Unlikely	Major	Medium
18	Possible	Major	High
19	Likely	Major	Extreme
20	Almost Certain	Major	Extreme
21	Rare	Catastrophic	High
22	Unlikely	Catastrophic	High
23	Possible	Catastrophic	Extreme
24	Likely	Catastrophic	Extreme
25	Almost Certain	Catastrophic	Extreme

i) Inference engine, defuzzification, and result interpretation

The inference engines of FIS 13 and 14 in Stage 2 use the following operators: “min” method for implication, “max” method for aggregation, and “centroid” for defuzzification.

The defuzzified value should be interpreted into understandable terms to be useful for construction managers or experts. The five-level safety risk interpretation was defined based on previous construction safety risk analysis [84][83]. The proposed methodology determines the degree of membership of safety risks to each safety risk level. The use of linguistic expressions reflects the vague, imprecise, and fuzzy atmosphere of a construction site. Table 3-12 shows the interpretation of each safety risk level.

Table 3-12: The interpretation of each safety risk level

Risk Level	Fuzzy Numbers	Interpretation
Very Low	(0, 0, 10, 20)	Risk is very low and hazardous conditions are eliminated or mitigated. No prevention and improvement measures are required.
Low	(10, 20, 30, 40)	Risk is low and acceptable. Almost all the measures are taken. No improvement measures are required.
Medium	(30, 40, 60, 70)	Risk is moderate and some sort of safety measures exist. However, general prevention and improvement measures are required.
High	(60, 70, 80, 90)	Risk is high and accident risk remains. Hazard prevention measures are required immediately to reduce the risk.
Extreme	(80, 90, 100, 100)	Risk is extreme and no measures are taken. Construction must be terminated until the risk is reduced.

3.3.3 Phase 3: BIM integration

Project-specific data are obtained from a BIM model. BIM models contain comprehensive data and information from a construction project. The proposed fuzzy expert system was linked with BIM using the external links. “Ideate BIMLink” software was interlinked with Autodesk Revit as a plug-in to obtain safety risk-related data from the BIM model [85]. Using this software plug-in is necessary since Autodesk Revit is not able to generate the .xls file format. Moreover, to interlink BIM with FIS, this file format must be generated. MATLAB reads the .xls file format containing safety risk data. The fuzzy-based expert system automatically loads the intended data for each section and starts calculating the safety risk of the construction project.

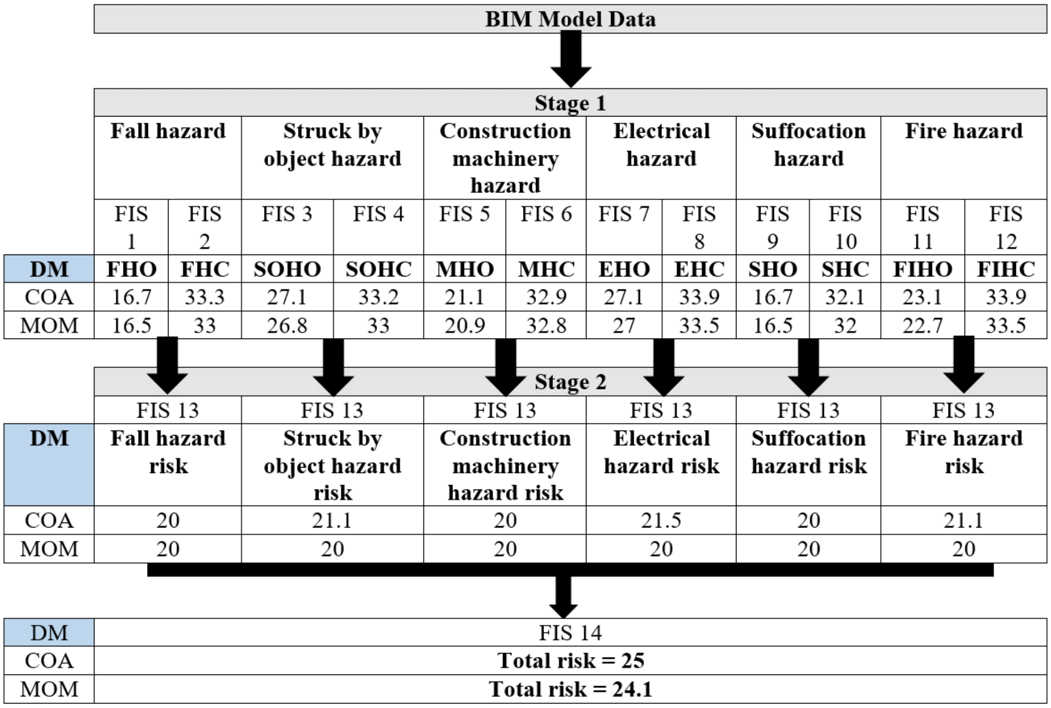
3.4 Case Study and Findings

The proposed framework for assessing construction project safety risk was validated through a case study. Since FIS rules have been derived based on North American standards, a case study located in the city of Windsor in Canada was selected in this research. This building with 1830 m^2 the gross floor area was constructed in early 2020. It is noteworthy that no hazardous substances have been used in this project. Furthermore, as per the safety incident report sent by the project contractor, this project had no safety incidents.

These data were used to demonstrate and validate the proposed fuzzy expert system. First, a BIM model of the building was prepared in Autodesk Revit using building drawings (Figure 3-7). Then, the mentioned BIM and FIS integration process was performed to derive BIM data and determine the project risk level.

Figure 3-7: The Case study building 3D BIM model

Figure 3-8 shows the safety risk assessment procedure. The interpretation of calculated safety risks is provided in Table 3-13. This table shows the safety risk of all hazards as well as the total risk of the project. The table utilizes the information of Table 3-12 to interpret calculated safety risks. Figure 3-9 depicts the total risk in the risk membership function.



BIM Model Data

Stage 1

	Fall hazard		**Struck by object hazard**		**Construction machinery hazard**		**Electrical hazard**		**Suffocation hazard**		**Fire hazard**	
	FIS 1	FIS 2	FIS 3	FIS 4	FIS 5	FIS 6	FIS 7	FIS 8	FIS 9	FIS 10	FIS 11	FIS 12
DM	**FHO**	**FHC**	**SOHO**	**SOHC**	**MHO**	**MHC**	**EHO**	**EHC**	**SHO**	**SHC**	**FIHO**	**FIHC**
COA	16.7	33.3	27.1	33.2	21.1	32.9	27.1	33.9	16.7	32.1	23.1	33.9
MOM	16.5	33	26.8	33	20.9	32.8	27	33.5	16.5	32	22.7	33.5

Stage 2

	FIS 13	FIS 13	FIS 13	FIS 13	FIS 13	FIS 13
DM	**Fall hazard risk**	**Struck by object hazard risk**	**Construction machinery hazard risk**	**Electrical hazard risk**	**Suffocation hazard risk**	**Fire hazard risk**
COA	20	21.1	20	21.5	20	21.1
MOM	20	20	20	20	20	20

DM	FIS 14
COA	**Total risk = 25**
MOM	**Total risk = 24.1**

Figure 3-8: Case study risk assessment result

Table 3-13: The interpretation of calculated safety risks of the project

Safety Risk	**Calculated Value by defuzzification**	**Corresponding safety risk level**
Fall hazard	20	Low (degree of membership = 1)
Struck by object hazard	21.1	Low (degree of membership = 1)
Construction machinery hazard	20	Low (degree of membership = 1)
Electrical hazard	21.5	Low (degree of membership = 1)
Suffocation hazard	20	Low (degree of membership = 1)
Fire hazard	21.1	Low (degree of membership = 1)
Total risk	**25**	**Low (degree of membership = 1)**

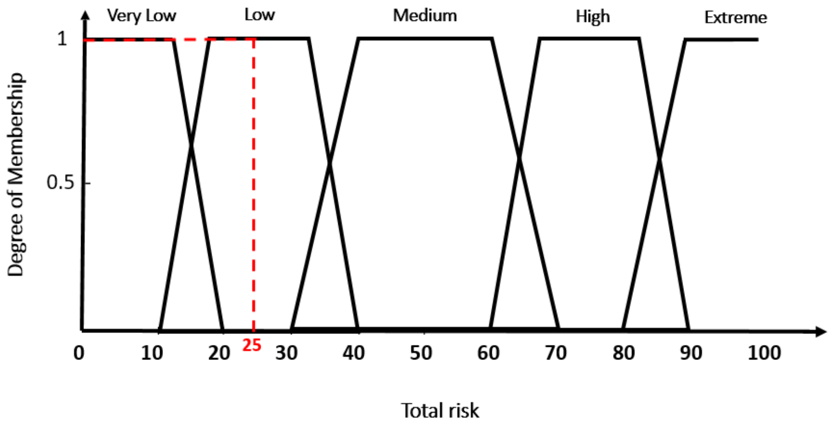


Figure 3-9: Procedure of determining linguistic risk expression of the total risk

The centroid of Area (COA) and Middle of Maximum (MOM) was used to defuzzify the outputs of FISs. According to the results of two defuzzification methods in 14 FISs, the COA method has a higher value in all FISs. Therefore, it is more critical to use the COA method for safety risk analysis. As mentioned in the previous section, outputs of Stage 1 will be used as inputs in Stage 2. Outputs of FIS 13 indicate that all hazard risks are in the "Low" range of safety risk. The total risk of this project is 25, which shows a low-risk project based on the classification provided in Table 3-12. Thus, this case study validates the proposed framework of this research since no safety incidents have been reported in this project.

Based on the information in Figure 3-8, the proposed method determines the safety risk of each hazard. This will help construction managers to be aware of high-risk safety hazards in a project. Therefore, they can implement appropriate measures to prevent accidents for workers.

3.5 Summary

This study integrates BIM with fuzzy logic to improve predictive safety planning to reduce safety incidents in construction projects. A Fuzzy Inference System (FIS) was developed based on the causality of safety incidents. The FIS extracts construction project data from BIM models while automatically assessing the risk of each potential hazard and the total risk of a project. The proposed method was validated by a case study. This method can predict the safety risk of a project and identify the potential hazards before the start of construction. Furthermore, this system calculates and provides the occurrence, consequence, and risk of each hazard, which is helpful to identify the reason for high risk in projects. The proposed method enables construction managers to prevent construction incidents and enhance the health and safety of construction workers.

3.6 Reference

[1] Buildforce, “Quick Facts,” 2018. .

[2] Parachute, “The Cost of Injury in Canada,” Toronto, ON, 2015.

[3] Z. Ismail, S. Doostdar, and Z. Harun, “Factors influencing the implementation of a safety management system for construction sites,” *Saf. Sci.*, vol. 50, no. 3, pp. 418–423, 2012, doi: 10.1016/j.ssci.2011.10.001.

[4] Association of Workers’ Compensation Boards of Canada, *National Work Injury, Disease and Fatality Statistics*. The Association of Workers’ Compensation Boards of Canada, 2018.

[5] Z. Zhou, Y. Miang, and Q. Li, “Overview and analysis of safety management studies in the construction industry,” *Saf. Sci.*, vol. 72, pp. 337–350, 2015, doi: 10.1016/j.ssci.2014.10.006.

[6] F. Alberto, S. Sánchez, G. Isabel, C. Peláez, and J. C. Alís, “Occupational safety and health in construction : a review of applications and trends,” *Ind. Health*, pp. 210–218, 2017.

[7] S. Azhar, “Role of Visualization Technologies in Safety Planning and Management at Construction Jobsites,” *Procedia Eng.*, vol. 171, pp. 215–226, 2017, doi: 10.1016/j.proeng.2017.01.329.

[8] D. Schwartz, “Workplace safety by the numbers,” 2014. http://www.cbc.ca/news/canada/workplace-safety-by-the-numbers-1.2622466.

[9] and D. A. S. Diethelm, E. Pellicer, L. Fernando, “Strategies for improving safety

performance in construction firms," *Accid. Anal. Prev*, vol. 94, pp. 107–118, 2016.

[10] and Y. K. A. Mohammadi, M. Tavakolan, "Factors in fluencing safety performance on construction projects : A review," *Saf. Sci*, vol. 109, pp. 382–397, 2016.

[11] A. P. and K. N. Hewage, "Building Information Modeling (BIM) partnering framework for public construction projects," *Autom. Constr*, vol. 31, pp. 204–214, 2013.

[12] S. Azhar, "Role of Visualization Technologies in Safety Planning and Management at Construction Jobsites," *Procedia Eng*, vol. 171, pp. 215–226, 2017.

[13] and J. C. A. F. Alberto, S. Sánchez, G. Isabel, C. Peláez, "Occupational safety and health in construction : a review of applications and trends," *Ind. Heal.*, pp. 210–218, 2017.

[14] K. Eastman, C., Teicholz, P., Sacks, R., Liston, *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors. Wiley*. 2011.

[15] W. Shou, J. Wang, X. Wang, and H. Y. Chong, "A Comparative Review of Building Information Modelling Implementation in Building and Infrastructure Industries," *Arch. Comput. Methods Eng.*, vol. 22, no. 2, pp. 291–308, 2015, doi: 10.1007/s11831-014-9125-9.

[16] Y. Jung, S. Kang, Y. S. Kim, and C. Park, "Assessment of safety management information systems for general contractors," *Saf. Sci.*, vol. 46, no. 4, pp. 661–674, 2008, doi: 10.1016/j.ssci.2007.06.009.

[17] M. Amiri, A. Ardeshir, M. Hossein, and F. Zarandi, "Fuzzy probabilistic expert system for occupational hazard assessment in construction," *Saf. Sci.*, vol. 93, pp. 16–28, 2017, doi: 10.1016/j.ssci.2016.11.008.

[18] I. Karimi and E. Hüllermeier, "Risk assessment system of natural hazards: A new

approach based on fuzzy probability," *Fuzzy Sets Syst.*, vol. 158, no. 9, pp. 987–999, 2007, doi: 10.1016/j.fss.2006.12.013.

[19] N. Rivera, S.S., McLeod, J.E., "Recommendations generated about a discontinuous distillation plant of biofuel," in *Proceedings of the World Congress on Engineering, vol. 1. WCE London, UK*, 2009, [Online]. Available: https://www.researchgate.net/%0Apublication/44260068_Recommendations_Generated_about_a_Discontinuous_%0ADistillation_Plant_of_Biofuel.

[20] X. Bai and H. Zhao, "RELIABILITY EVALUATION IN CONSTRUCTION QUALITY," *Civ. Eng. J.*, no. 33, pp. 411–424, 2018, doi: 10.14311/CEJ.2018.03.0033.

[21] N. Ibadov, "Construction project planning under fuzzy time constraint," *Int. J. Environ. Sci. Technol.*, vol. 16, no. 9, pp. 4999–5006, 2019, doi: 10.1007/s13762-018-1695-x.

[22] X. Wang, "Application of fuzzy math in cost estimation of construction project Xinzheng Wang *," *J. Discret. Math. Sci. Cryptogr.*, vol. 20, no. 4, pp. 805–816, 2017.

[23] R. Ruparathna, K. Hewage, and R. Sadiq, "Economic evaluation of building energy retrofits : A fuzzy based approach," *Energy Build.*, vol. 139, pp. 395–406, 2017, doi: 10.1016/j.enbuild.2017.01.031.

[24] C.-C. Lee, "Fuzzy logic in control systems: fuzzy logic controller-parts 1 and 2," *IEEE Trans. Syst.*, vol. 20, no. 404–435, 1990.

[25] K. H. Chang, C. H. Cheng, and Y. C. Chang, "Reprioritization of failures in a silane supply system using an intuitionistic fuzzy set ranking technique," *Soft Comput.*, vol. 14, no. 3, pp. 285–298, 2010, doi: 10.1007/s00500-009-0403-7.

[26] L. Zhang, X. Wu, L. Ding, M. J. Skibniewski, and Y. Lu, "Bim-Based Risk Identification System in tunnel construction," *J. Civ. Eng. Manag.*, vol. 22, no. 4, pp. 529–539, 2016, doi: 10.3846/13923730.2015.1023348.

[27] Z. Jin, J. Gambatese, and D. Liu, “Using 4D BIM to assess construction risks during the design phase,” *Eng. Constr. Archit. Manag.*, vol. 26, no. 11, pp. 2637–2654, 2019, doi: 10.1108/ECAM-09-2018-0379.

[28] I. Kim, Y. Lee, and J. Choi, “BIM-based Hazard Recognition and Evaluation Methodology for Automating Construction Site Risk Assessment,” *Appl. Sci.*, vol. 10, 2020.

[29] A. D. F. Baloi, D., Price, “Modelling global risk factors affecting construction cost performance,” *Int. J. Proj. Manag.*, vol. 21, 261–26, 2003.

[30] Z. Zaini, A., Endut, I., and Shehu, “A preliminary study of the subcontractor’s risk identification for the construction projects,” *Business, Eng. Ind. Appl. (ISBEIA), Rahimi Baharom, Bandung,* pp. 878–883.

[31] H. S. Kang, L. S., Kim, S.-K., Moon, H. S., and Kim, “Development of a 4D object-based system for visualizing the risk information of construction projects,” *Autom. Constr.,* vol. 31, no. 1, pp. 186–203, 2013.

[32] J. H. M. Tah and V. Carr, “A proposal for construction project risk assessment using fuzzy logic,” *Constr. Manag. Econ.*, vol. 18, pp. 491–500, 2000.

[33] L. Serpella, A. F., Ferrada, X., Howard, R., and Rubio, “Risk management in construction projects: A knowledge-based approach,” *Procedia Soc. Behav. Sci.,* vol. 119, no. 1, pp. 653–662, 2014.

[34] F. Ackermann, C. Eden, T. Williams, and S. Howick, “Systemic risk assessment : a case study,” pp. 39–51, 2007, doi: 10.1057/palgrave.jors.2602105.

[35] D. Baloi and A. D. F. Price, “Modelling global risk factors affecting construction cost performance,” *Int. J. Proj. Manag.*, vol. 21, pp. 261–269, 2003, doi: 10.1016/S0263-7863(02)00017-0.

[36] F. C. and M. M. Enrico Cagno, “A Multi-Dimensional Analysis of Major Risks in Complex Projects,” *Risk Manag.*, vol. 9, pp. 1–18, 2007, doi: 10.1057/palgrave.rm.8250014.

[37] J. E. Diekmann, “Risk analysis : lessons from artificial intelligence,” vol. 10, no. 2, 1992.

[38] S. H. Han, D. Y. Kim, H. Kim, and W. Jang, “A web-based integrated system for international project risk management,” *Autom. Constr.*, vol. 17, pp. 342–356, 2008, doi: 10.1016/j.autcon.2007.05.012.

[39] A. S. Makarand Hastak, “ICRAM-1 : Model for International Construction RIsk Assessment,” *J. Manag. Eng.*, vol. 16, no. February, pp. 59–69, 2000.

[40] B. Lazzerini and L. Mkrtchyan, “Analyzing Risk Impact Factors Using Extended Fuzzy Cognitive Maps,” *IEEE Syst. J.*, vol. 5, no. 2, pp. 288–297, 2011.

[41] A. Nieto-morote and F. Ruz-vila, “A fuzzy approach to construction project risk assessment,” *Int. J. Proj. Manag.*, vol. 29, no. 2, pp. 220–231, 2011, doi: 10.1016/j.ijproman.2010.02.002.

[42] A. V Thomas, S. N. Kalidindi, and L. S. Ganesh, “Modelling and assessment of critical risks in BOT road projects,” *Constr. Manag. Econ.*, vol. 24, pp. 407–424, 2006, doi: 10.1080/01446190500435275.

[43] J. Zeng, M. An, and N. J. Smith, “PROJECT Application of a fuzzy based decision making methodology to construction project risk assessment,” vol. 25, pp. 589–600, 2007, doi: 10.1016/j.ijproman.2007.02.006.

[44] G. Zhang and P. X. W. Zou, “Fuzzy Analytical Hierarchy Process Risk Assessment Approach for Joint Venture Construction Projects in China,” *J. Constr. Eng. Manag.*, vol. 133, no. October, pp. 771–779, 2007, doi: 10.1061/(ASCE)0733-9364(2007)133.

[45] R. Ben-David, “An integrated approach for risk response development in project planning,” *J. Oper. Res. Soc.*, vol. 52, pp. 14–25, 2001.

[46] D. F. Cioffi and H. Khamooshi, “A practical method of determining project risk contingency budgets,” *J. Oper. Res. Soc.*, vol. 60, pp. 565–572, 2009, doi: 10.1057/palgrave.jors.2602586.

[47] M. Gangolells, M. Casals, N. Forcada, A. Fuertes, and X. Roca, “Model for Enhancing Integrated Identification , Assessment , and Operational Control of On-Site Environmental Impacts and Health and Safety Risks in Construction Firms,” *J. Constr. Eng. Manag.*, vol. 5, no. February, pp. 138–147, 2013, doi: 10.1061/(ASCE)CO.1943-7862.0000579.

[48] D. Wang, S. M. Asce, F. Dai, M. Asce, and X. Ning, “Risk Assessment of Work-Related Musculoskeletal Disorders in Construction : State-of-the-Art Review,” vol. 141, no. 6, pp. 1–15, 2015, doi: 10.1061/(ASCE)CO.1943-7862.0000979.

[49] X. Li *et al.*, “3D Visualization-Based Ergonomic Risk Assessment and Work Modification Framework and Its Validation for a Lifting Task,” *J. Constr. Eng. Manag.*, vol. 144, no. 1, pp. 1–13, 2018, doi: 10.1061/(ASCE)CO.1943-7862.0001412.

[50] S. Bhandari, M. R. Hallowell, L. Van Boven, K. M. Welker, M. Golparvar-fard, and J. Gruber, “Using Augmented Virtuality to Examine How Emotions Influence Construction-Hazard Identification , Risk Assessment , and Safety Decisions,” *J. Constr. Eng. Manag.*, vol. 146, no. 2, pp. 1–12, 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001755.

[51] M. F. Antwi-afari *et al.*, “Construction Activity Recognition and Ergonomic Risk Assessment Using a Wearable Insole Pressure System,” *J. Constr. Eng. Manag.*, vol. 146, no. 7, 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001849.

[52] H. Jebelli, S. M. Asce, C. R. Ahn, A. M. Asce, and T. L. Stentz, “Comprehensive Fall-Risk Assessment of Construction Workers Using Inertial Measurement Units : Validation of the Gait-Stability Metric to Assess the Fall Risk of Iron Workers,” *J. Constr. Eng. Manag.*, vol. 30, no. 3, pp. 1–11, 2016, doi: 10.1061/(ASCE)CP.1943-5487.0000511.

[53] A. Dutta *et al.*, “Fusing imperfect experimental data for risk assessment of musculoskeletal disorders in construction using canonical polyadic decomposition,” *Autom. Constr.*, vol. 119, no. February, 2020, doi:

10.1016/j.autcon.2020.103322.

[54] L. Villarinho, R. Assed, N. Haddad, P. Victor, and R. De Carvalho, “Assessing risk in sustainable construction using the Functional Resonance Analysis Method (FRAM),” *Cogn. Technol. Work*, pp. 559–573, 2015, doi: 10.1007/s10111-015-0337-z.

[55] M. F. Antwi-afari and H. Li, “Fall risk assessment of construction workers based on biomechanical gait stability parameters using wearable insole pressure system,” *Adv. Eng. Informatics*, vol. 38, no. June, pp. 683–694, 2018, doi: 10.1016/j.aei.2018.10.002.

[56] B. Choi, H. Jebelli, and S. Lee, “Feasibility analysis of electrodermal activity (EDA) acquired from wearable sensors to assess construction workers ’ perceived risk,” *Saf. Sci.*, vol. 115, no. June 2018, pp. 110–120, 2019, doi: 10.1016/j.ssci.2019.01.022.

[57] S. R. Mohandes and X. Zhang, “Towards the development of a comprehensive hybrid fuzzy-based occupational risk assessment model for construction workers,” *Saf. Sci.*, vol. 115, no. June 2018, pp. 294–309, 2019, doi: 10.1016/j.ssci.2019.02.018.

[58] X. Chen, C. Guo, J. Song, X. Wang, and J. Cheng, “Occupational health risk assessment based on actual dust exposure in a tunnel construction adopting roadheader in Chongqing , China,” *Build. Environ.*, vol. 165, no. May, p. 106415, 2019, doi: 10.1016/j.buildenv.2019.106415.

[59] M. Zhang, Z. Bai, and X. Zhao, “Real-time Risk Assessment for Construction Workers ’ Trunk Posture Using Mobile Sensor,” in *International Conference on Robotics and Automation Sciences*, 2017, pp. 153–157.

[60] C. Q. Ting-Kwei Wang, “Integration of BIM, Bayesian Belief Network, and Ant Colony Algorithm for Assessing Fall Risk and Route Planning,” *ASCE Constr. Res. Congr.*, pp. 207–220, 2018.

[61] H. I. M. I. F. A. S. Y. Z. X. Z. M. T. and M. Hatami, “Qualitative Assessment of Indirect Risks Associated with Unmanned Aerial Vehicle Flights over Construction Job Sites,” *Comput. Civ. Eng.*, pp. 83–89, 2019.

[62] J. Chen and J. Ji, “Fire risk assessment in cotton storage based on fuzzy comprehensive evaluation and Bayesian network,” *Fire Mater.*, pp. 1–10, 2020, doi: 10.1002/fam.2832.

[63] K. Chien, Z. Wu, and S. Huang, “Identifying and assessing critical risk factors for BIM projects : Empirical study,” *Autom. Constr.*, vol. 45, pp. 1–15, 2014, doi: 10.1016/j.autcon.2014.04.012.

[64] T. Wang and Y. Piao, “Development of BIM-AR-Based Facility Risk Assessment and Maintenance System,” *J. Perform. Constr. Facil.*, vol. 2, no. 6, 2019, doi: 10.1061/(ASCE)CF.1943-5509.0001339.

[65] L. . Zadeh, “Fuzzy sets. Inform. Control 8,” vol. 338–353, 1965.

[66] H.-J. Zimmermann, *Fuzzy Set Theory and Its Applications: a Survey.* 1991.

[67] J. Czogala, E. and Leski, “Fuzzy and Neuro-Fuzzy Intelligent Systems,” *PhysicaVerlag.*, 2000.

[68] G. Demicco, R. and Klir, “Fuzzy Logic in Geology,” *Acad. Press. Sci. (USA).*, 2004.

[69] M. BOJADZIEV, G., & Bojadziev, “Fuzzy Logic for Business, Finance, and Management (2nd ed.),” *Adv. Fuzzy Syst. - Appl. Theory*, vol. 23, no. River Edge, NJ, USA: World Scientific, 2007.

[70] T. KOROL, “Fuzzy Logic in Financial Management. In E. Dadios (Ed.),” *Fuzzy Log. - Emerg. Technol. Appl.*, pp. 259–286. InTech, 2012, doi: doi:10.5772/35574.

[71] N. NAIT-SAID, R., Zidani, F., & Ouzraoui, “Fuzzy Risk Graph Model for Determining Safety Integrity Level,” *Int. J. Qual. Stat. Reliab.*, 2008.

[72] D. DARBRA, R. M., Eljarrat, E., & Barceló, “How to measure uncertainties in

environmental risk assessment," *TrAC - Trends Anal. Chem.*, vol. 27, no. 4, pp. 377–385, 2008.

[73] B. WEST, J. E., & Linster, "The Evolution of Fuzzy Rules as Strategies in Two-Player Games," *South. Econ. J.*, vol. 69(3), 705, 2003.

[74] G. STOJIC, "Using fuzzy logic for evaluating the level of countries' (regions') economic development," *Panoeconomicus*, vol. 59(3), 293, 2012, doi: doi:10.2298/PAN1203293S.

[75] E. H. and S. A. Mamdani, "An experiment in linguistic synthesis with a fuzzy logic controller," *Int. J. Man. Mach. Stud.*, vol. 1, pp. 1–13, 1975.

[76] A. V. S. Kumar, *Fuzzy Expert Systems for Disease Diagnosis*. IGI Global, 2014.

[77] C. . Altrock, "Fuzzy Logic and Neuro fuzzy-Applications in Business and Finance.," *Prentice Hall, New Jersey*, 1995.

[78] S. Orji, I.J., Wei, "An innovative integration of fuzzy-logic and systems dynamics in sustainable supplier selection: a case on manufacturing industry.," *Comput. Ind. Eng*, vol. 88, no. 1–12, 2015.

[79] "MathWorks." https://www.mathworks.com/help/fuzzy/types-of-fuzzy-inference-systems.html.

[80] T. J. Ross, *Fuzzy Logic with Engineering Applications*. 1995.

[81] S. M. Miri Lavasani, Z. Yang, J. Finlay, and J. Wang, "Fuzzy risk assessment of oil and gas offshore wells," *Process Saf. Environ. Prot.*, vol. 89, no. 5, pp. 277–294, 2011, doi: 10.1016/j.psep.2011.06.006.

[82] H. Liu and Y. Tsai, "A fuzzy risk assessment approach for occupational hazards in the construction industry," *Saf. Sci.*, vol. 50, no. 4, pp. 1067–1078, 2012, doi: 10.1016/j.ssci.2011.11.021.

[83] U. M. ngen G.Emre Gurcanli, "An occupational safety risk analysis method at construction sites using fuzzy sets," *Int. J. Ind. Ergon. 39*, vol. 39, pp. 371–387,

2009, doi: 10.1016/j.ergon.2008.10.006.

[84] H. T. Liu and Y. lin Tsai, “A fuzzy risk assessment approach for occupational hazards in the construction industry,” *Saf. Sci.*, vol. 50, no. 4, pp. 1067–1078, 2012, doi: 10.1016/j.ssci.2011.11.021.

[85] K. P. Reddy, “BIM for Building Owners and Developers: Making a Business Case for Using BIM on Projects,” *John Wiley Sons, Inc. United State Am.*, 2012.

CHAPTER 4

BUILDING INFORMATION MODELING (BIM)-BASED MODEL CHECKING TO ENSURE BUILDING USER SAFETY

4.1 Introduction

Building codes, construction and infrastructure standards, and best practice guidelines assist the construction sector to reduce hazards, ensure the safety of construction workers and future occupants, protect the environment and reduce costs [1][2]. Engineers are required to adhere to the above codes, standards, and guidelines during the detailed design. Noncompliance with building codes makes building designs unsuitable for construction. Error with building drawings is a common occurrence in construction projects [3]. Statistics show that approximately 30% of construction costs are rework [4][5]. This issue stems from traditional design approaches that have been embedded in the construction sector. For instance, design engineers have been using 2D drawings to communicate with contractors. The use of 2D drawings makes design engineers adopt manual code compliance checking despite the complexity of the constructed asset [6][7]. Even though the construction industry has acknowledged 2D drawings as an error prone and time-consuming process, reluctance to move from the traditional practices have been a road block.

Building Information Modeling (BIM)-based rule checking can enhance the accuracy of compliance checking [8]. The advent of Building Information Modelling (BIM) has been assisting the construction sector in advancing the design and construction of buildings [9]. BIM enables creating a virtual model of the building that contains its physical and functional data [10]. Numerous studies have demonstrated the benefits of BIM in building design. For example, the 3D model provides better visualization for the building designer [11]. Moreover, BIM aids in the measurement and quantification of model parameters [12]. BIM can be used to exchange information and enhance collaboration between project parties smoothing the construction process [13]. BIM-based rule checking could identify errors with building models that could consequently reduce the need for corrections and rework [6].

BIM-based model checking is defined as a system that considers the configuration of objects and their relationships to assess a building design without any modifications [2]. BIM-based model checking evaluates a building design based on a set of rules [1]. The result of the process can be “pass”, “fail”, “warning”, or “unknown” [2]. BIM-based model checking is a four-step process, namely rule interpretation, building model preparation, rule execution, and rule reporting [7]. Applications and add-ons in the BIM suite such as Solibri Model Checker are used in this process. BIM-based rule checking has been frequently researched by academia in the recent past. For example, Eastman et al. (2009) and Lee (2010) applied a logical approach to check the occupant circulation rules [2][14]. Ding et al. (2004), Dimyadi et al. (2013), and Ding et al. (2006) used an object-based approach for rule interpretation to check disabled access to buildings [15]-[17]. Bouzidi et al. (2012) applied an ontology-based approach for providing technical guides of tile roofs based on relevant codes [18]. Nguyen and Kim (2012), employed an Autodesk Revit model checker to check fire safety requirements [19]. Chahrour et al. studied BIM-based rule checking for clash detection in a USD 75 Million project. This study revealed that rework can be reduced by USD 15.2 Million through rule checking [20]. Most of the previous studies have performed model checking by using rules based on the Occupational Safety and Health Administration (OSHA), the National Building Code of Canada (NBCC), etc. Standard rulesets available in model checking applications include some sections such as general space check, the intersection between architectural components and MEP models, and architectural models. However, no approach has dealt with BIM-based safety-related Canadian building codes or the Canadian Standards Association (CSA) standards.

This study presents a BIM-based safety ruleset to check a BIM-model for building code compliance and to prevent safety hazards for building users. Ontario building code and CSA standards were reviewed to obtain safety-related guidelines. Accordingly, a ruleset was developed for use in building model checking. Regardless of the different approach of this study, in terms of safety rule checking concept, this research is more comprehensive than recent similar research works in Canada [21] or other countries [22][23] that have focused on the fire egress codes. The outcomes of this research can aid building designers in model checking and ensuring the safety of building users.

4.2 Background

BIM-based rule checking involves rule interpretation, model preparation, rule execution, and rule reporting. These steps are explained in detail below.

4.2.1 Rule interpretation

Building codes and standards are typically in written texts, tables, and possibly equations. These rules should be translated into a machine-processable format to be used in a model checker [2]. This is performed in two ways. In the first method, rules are translated into computer codes by a programmer [21]. In the second method, rules are formally translated through the logic of human language [24]. Therefore, construction industry experts without any programming background can execute the second method of rule interpretation through the software or plug-in applications [25].

(i) Programming-based rule interpretation

There are different techniques in interpreting the rules for rule checking development such as ontological approach, logical approach, and object-based approach [7]. Each method is explained below:

Object-based approach: Object-based approach is a technique for organizing knowledge by defining attributes, procedures, rules, and machine learning [26]. Building rules are represented in a three-stage approach. In the first stage, building codes are classified. In the second stage, all relevant building objects and rules are identified. In the third stage, all data and values are stored and maintained in a tabular form as a knowledge base to establish a knowledge base [27]. CoreNet e-PlanCheck is an example of an object-based rule checking system that is officially implemented in Singapore [28].

One advantage of this approach is that standard scope can be covered by contextual concept lattice classes; therefore, rules can be encapsulated within the classes [29]. However, the model developer is entirely responsible to build the concept lattice. Creating and maintaining a complex concept lattice is a time-consuming and error-prone task [30].

Logic-based approach: The first-order predicate logic as the most common language is applied to interpret the natural language. The reason this method is common is that rules are defined by humans and interpreting rules can be done by translating the logic in human language statements [31]. In this approach, explicit and implicit logical conditions such as ‘and’, ‘or’, and ‘If-Then’ are combined and applied to validate and check a building element [32]. To interpret rules into basic logic, a conceptual graph can be employed by rule experts without programming knowledge [33]. There are four stages for translating rules into the conceptual graph.

I. Identification of the main concept of rules

II. Identification of independent sub-rules of each rule

III. Identification of constraints and restrictions identification

IV. Identification of connections of all elements to develop the proper conceptual graph.

Then, to support the process of compliance code checking in the BIM environment, BIM Rule Language (BIMRL) is developed through Structured Query Language (SQL) [33]. BMRL defines a simplified schema that uses the relational database to facilitate access to the building data. This approach is useful for unidirectional data processing where IFC models are loaded into the simplified schema [34].

The advantage of this approach is that predicate calculus constructions provide a sufficient means for constructing any expression [30]. However, they cannot efficiently represent the different evaluation strategies of data items for object classes of different designs. Thus, the final model of predicate logic standard is complicated and arduous to create and maintain [35].

Ontology-based approach: This approach is based on using a graph that displays objects and their logical relations [36]. The ontological approach involves four aspects, as follows:

I. Developing construction regulation database

II. Creating a reasoning model

III. The capitalization of the database

IV. Framework validation by integrating all aspects into a prototype [37].

The advantage of this approach is the effective use of computers in the design process. However, this approach is unable to provide a formal language for describing models [38]. Hence, it difficult to understand how design classifications are achieved. Furthermore, this approach does not explain how evaluation provisions are represented, leading to some problems regarding the understanding of the compliance checking process [30][38].

(ii) BIM application-based rule interpretation

Solibri Model Checker (SMC) is a popular BIM application that is used for checking integrity, quality, and safety BIM models [39]. SMC, which contains built-in geometry-oriented rules, automatically analyzes and checks virtual building models to detect any design deficiencies and missing elements [40]. SMC strictly checks model structure requirements [7]. Furthermore, it provides a user-friendly visualization of the building model and permits a virtual walk-through. This feature has been used for checking safety rules related to fall hazard prevention of construction workers [41]. SMC-based SMART Code system was developed by The International Code Council in North America to check the reliability of rule checking [2]. The advantages of SMC are (i) the ability of reading and correct interpreting IFC files exported from a wide range of BIM authoring tools, (ii) a complete set of spatial operations, and (iii) a high level of maturity (widely used by designers) [42]. On the other hand, SMC has some advantages such as the lack of formal and standard schema for the rule definition and rule templates with hard-coded rules [42].

BIM Assure gives users alike visibility into building data. The features of BIM Assure are cloud-based model viewing (2D/3D), IFC file format supporting, element classification, data viewing, and editing and rule analysis [42]. The advantages of BIM Assure are ease of defining rules, low requirements for programming constructs, minimum domain knowledge required, and proper performance indication [43]. On the other hand, the disadvantages of this tool are having no standard schema for the rule definition, low support for complex rules, no integrated geometry engine, and low interface to other languages and systems [42][43].

There are plugins for BIM applications such as the Autodesk Revit plug-in that enable rule checking. Nguyen and Kim (2011) used this possibility to check openings in firewalls, fire resistance ratings, and horizontal continuity of the firewalls based on the International Building Code (IBC) in the United States [19]. Although the Revit Model Review requires a low level of logic or programming constructs, it has some disadvantages such as no integrated geometry engine, no standard schema for the rule definition, low support for complex rules, and low interface to other languages or rule checking systems [42].

Table 4-1 shows the BIM-based approaches and techniques for developing automated compliance checking. As shown in this table, different rule interpretation techniques have been used. However, no previous research has interpreted BIM-based safety rules according to Canadian building codes and CSA standards.

Table 4-1: Approaches and techniques for a rule interpretation

Study	**Country**	**Rule Checking**	**Approach and Techniques**				
			BIM Application-based		**Programming-based**		
			SMC	**Plug-in**	**OBB**	**LB**	**ONB**
[27]	Singapore	Technical Requirements for Household and Storey Shelters			✓		
[2]	Norway	Building accessibility rules	✓				
[14]	The U.S.	Circulation rule checking				✓	
[33]	U.S. & Singapore	Fire safety & accessibility rules				✓	
[18]	France	Technical guides of tile roofs					✓
[15]-[17]	Australia	Disabled access code			✓		
[19]	The U.S.	Fire safety requirements		✓			
[28]	Singapore	Building service rules			✓		

[32]	Korea	Building permit requirements				✓	
[23]	Turkey	Fire safety requirements			✓		
[14][44]	U.S.	Occupant circulation rules	✓				
[45]	The U.S.	Environmental requirements					✓
[46]	The U.K.	Fire safety requirements			✓		
[41]	The U.S.	Fall hazard protection rules	✓		✓	✓	
[23]	Canada	exterior walls Hygrothermal performance				✓	
[9]	Portugal	Water system regulations				✓	
[47]	Australia	Fire safety requirements					✓
[2]	The U.S.	Energy conservation codes	✓				
[48][49]	Norway, U.S.	Accessibility, building habitable spaces					✓
[50]	China	Construction quality inspection					✓
[51]	The U.K.	Sustainability requirements				✓	✓
[52]	Germany	Secure Data-Flow Compliance Checks		✓		✓	
[21]	Canada	Fire safety in timber buildings		✓	✓		
[53]	Brazil	Fire Fighting in a BIM environment		✓			
[54]	China	Green construction requirements		✓		✓	
[55]	Korea	Fire safety requirements			✓	✓	
[56]	Hong Kong	Building Envelope Energy Efficiency				✓	

*Note: Object-based (OBB); Logic-based (LB); Ontology-based (ONB)

4.2.2 Model Preparation

In this stage, model developers must properly encode modeling requirements in IFC to appropriately translate for model checking. To prepare the building model for the rule checking process, the following steps should be undertaken: (i) model view creation to derive the required data for a specific type of rule checking and to extract subsets of an overall building model, (ii) extracting implicit properties using enhanced objects to derive new information and compute complex properties, (iii) obtaining the new model to make an evaluation of certain implicit relations and properties easier, (iv) performance-based analysis to check rule adequacy, and (v) checking layout rule parameters to check the building model layout types [57].

4.2.3 Rule Execution

Rule execution brings the BIM model and the corresponding rules together [2]. BIM model should be validated before performing the rule check to ensure properties, names, and objects are available [25]. Moreover, in the rule execution stage, a management system is required to coordinate the application of rule modules and their results. This system checks the completeness of the rule checking and model version consistency [41].

4.2.4 Rule Reporting

Rule reporting validates whether design conditions are satisfactory according to the ruleset. Rule checking report also provides a graphical report that shows each element of the BIM model a reference to the source rule [3].

4.3 Methodology

Figure 4-1 illustrates the methodological framework of this research. The four-step process proposed by Eastman et al. (2009) for BIM-based rule checking was considered in this research. This research was performed in 5 inter-related steps. In the following, each step is explained in detail.

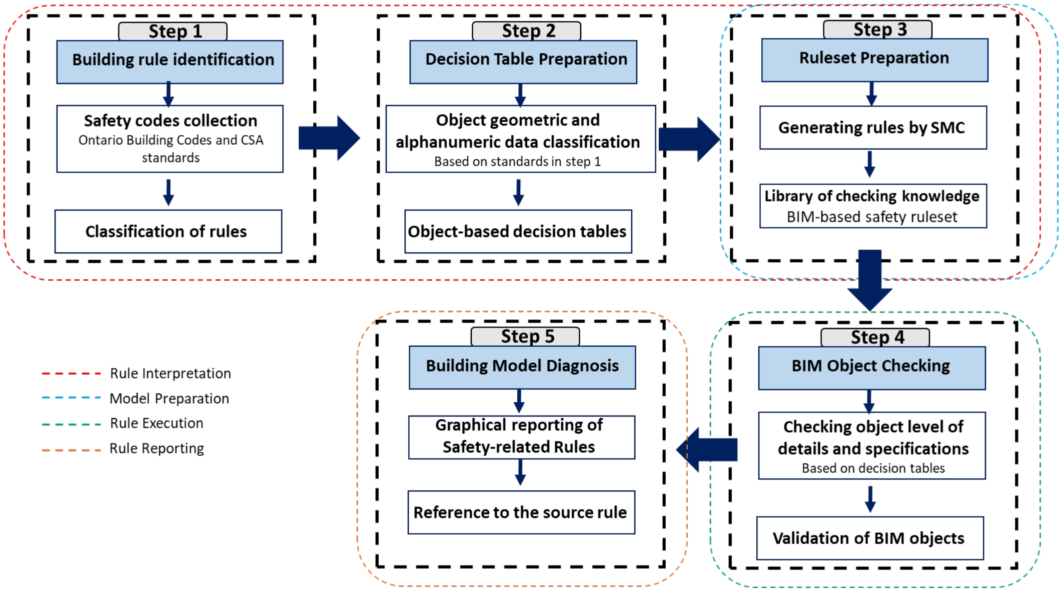


Figure 4-1: Research methodological framework

4.3.1 Step 1. Building Rule Identification

Ontario building code and CSA Standards were reviewed to identify safety-related guidelines. For this purpose, the safety guidelines of Ontario building codes and CSA standards were reviewed. Moreover, safety-based rule checking studies such as [33] and [19] in Table 1 were identified and their approach to finding safety-related rules was considered.

The list of used codes and standards in this study are as follows: Ontario building code and CSA A500-16 (building guards), guidelines in CSA Z1002-12 (occupational health and safety, hazard identification and elimination, and risk assessment and control), CSA Z259.2.4:15 (fall arresters and vertical rigid rails), CSA Z259.13-16 (manufactured horizontal lifeline systems), CSA Z1000:14 (occupational health and safety management), and CSA Z45001:19 (occupational health and safety management system, requirements with guidance for use included safety-related guidelines). For example, based on CSA (A500-16-4.1.9.1) and Ontario building code (9.8.8.3.), “the minimum height of guards within dwelling units shall be not less than 900 mm high”.

The safety-based rules and standards used in this study are classified as follows: (i) egress analysis which deals with issues such as number and location of means of egress,

(ii) stairs and steps to check stairs and step dimensions and configuration, (iii) ramps to check the slope and dimension of ramps, (iv) landings to deals with the location and dimension of landings in a building model, and (v) handrails and guards to check the existence and height (if exists) of building guards.

4.3.2 Step 2. Decision Table Preparation

The object-based decision table was developed to show the geometric information of objects based on the relevant rules from the Ontario building code and CSA standards. Table 4-2 shows the decision table that was used for a rule interpretation.

Table 4-2: A summary of object-based decisions

Rule No	Checking Objects	Checking Points or Condition	Premise	Required data	Reference
Stairs, Step, and Railing					
1	Stairs	Include	True	Stair property	O. Reg. 332/12: BC (9.8)
2	Stairs	Stair width	900 mm < Width	Stair width measured between wall faces or guards	O. Reg. 332/12: BC (9.8.2.1)
3	Stairs	Over-stair heights	1950 mm < Height	The clear height over stairs	O. Reg. 332/12: BC (9.8.2.2)
4	Stairs	Number of step risers	Count > 3	nosing-to-nosing distance	O. Reg. 332/12: BC (9.8.3.2)
5	Stairs	Height of stairs	3.7 m < Height	the vertical height between any landings	O. Reg. 332/12: BC (9.8.3.3)
6	Stairs	Length of step riser	125mm < length < 200mm	nosing-to-nosing distance	O. Reg. 332/12: BC (9.8.4.1) (Private stairs)
7	Stairs	Step Tread Depth	235mm < depth < 355mm	nosing-to-nosing distance	O. Reg. 332/12: BC (9.8.4.1) (Private and rectangular stairs)

8	Stairs	Stair Winders	90° < Winder turn angle	Winders that converge to a center point	O. Reg. 332/12: BC (9.8.4.5)
9	Stairs	Stair Winders	30° < Tread turn angle < 45°	Winders that converge to a center point	O. Reg. 332/12: BC (9.8.4.5)
10	Stairs	Include landing	True	at the top and bottom of each flight of interior and exterior stairs	O. Reg. 332/12: BC (9.8.6.2)
11	Stairs	Width of landing	Width of stair < Width	In straight-run stair which its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
12	Stairs	Length of landing	860 mm < Length	In straight-run stair which its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
13	Stairs	Width of landing	Width of stair < Width	In straight-run exterior stair which its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
14	Stairs	Length of landing	900 mm < Length	In straight-run exterior stair which its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
15	Stairs	Width of landing	Width of stair < Width	30° < landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
16	Stairs	Length of landing	230 mm < Length	30° < landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
17	Stairs	Width of landing	Width of stair < Width	90° < landing turning through	O. Reg. 332/12: BC (9.8.6.3)
18	Stairs	Length of landing	Width of stair < Length	90° < landing turning through	O. Reg. 332/12: BC (9.8.6.3)
19	Stairs	Height over Landings	1950 mm > Height	The clear height over landing	O. Reg. 332/12: BC (9.8.6.4.)

20	Railings (Handrail)	Include	True	One handrail is required for each stair.	CSA (A500-16-4.8.2) O. Reg. 332/12: BC (9.8.7.1)
21	Railings (Handrail)	Continuity of Handrails	True	Where not interrupted by doors	O. Reg. 332/12: BC (9.8.7.2)
22	Railings (Handrail)	Include	False	Where obstruct pedestrian travels	O. Reg. 332/12: BC (9.8.7.3)
23	Railings (Handrail)	Height of Handrails	865 mm < Height < 965 mm	Where guards are not required	CSA (A500-16-4.1.9.1) O. Reg. 332/12: BC (9.8.7.4)
Ramps					
24	Ramps	Ramp width	Width < 860 mm	Pedestrian ramps	O. Reg. 332/12: BC (9.8.5.2)
25	Ramps	Height over Ramps	Height < 1950 mm	The clear height over the ramp	O. Reg. 332/12: BC (9.8.5.3)
26	Ramps	Exterior ramp Slope	Slope < 1 in 10	Ramp slope	O. Reg. 332/12: BC (9.8.5.4)
27	Ramps	Interior ramp Slope	Slope < 1 in 10	Ramp slope	O. Reg. 332/12: BC (9.8.5.4)
28	Ramps	Rise of ramp	Rise between floors or landings < 1500 mm	Where the slope of the ramp is greater than 1 in 12	O. Reg. 332/12: BC (9.8.5.5)
29	Ramps	Include landing	True	at the top and bottom of every ramp with a slope greater than 1 in 50	O. Reg. 332/12: BC (9.8.6.2)
30	Ramps	Include landing	True	where a doorway opens onto a ramp	O. Reg. 332/12: BC (9.8.6.2)
31	Ramps	Width of landing	Width of ramp < Width	In straight-run ramp which its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
32	Ramps	Length of landing	860 mm < Length	In straight-run ramp which its landing turning	O. Reg. 332/12: BC (9.8.6.3)

				through is less than 30	
33	Ramps	Width of landing	Width of ramp < Width	In straight-run exterior ramp which its landing turning through is less than 30	O. Reg. 332/12: BC (9.8.6.3)
34	Ramps	Length of landing	900 mm < Length	In straight-run exterior ramp which its landing turning through less than 30	O. Reg. 332/12: BC (9.8.6.3)
35	Ramps	Width of landing	Width of ramp < Width	30° < landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
36	Ramps	Length of landing	230 mm < Length	30° < landing turning through < 90°	O. Reg. 332/12: BC (9.8.6.3)
37	Ramps	Width of landing	Width of ramp < Width	90° < landing turning through	O. Reg. 332/12: BC (9.8.6.3)
38	Ramps	Length of landing	Width of ramp < Length	90° < landing turning through	O. Reg. 332/12: BC (9.8.6.3)
39	Ramps	Height over Landings	1950 mm > Height	The clear height over landing	O. Reg. 332/12: BC (9.8.6.4)
40	Railings (Handrail)	Include	True	where ramp width < 1100 mm	CSA (A500-16-4.8.2) O. Reg. 332/12: BC (9.8.7.1)
41	Railings (Handrail)	Handrail Number	Count = 2	where ramp width > 1100 mm	CSA (A500-16-4.8.2) O. Reg. 332/12: BC (9.8.7.1)
42	Railings (Handrail)	Continuity of Handrails	True	Where not interrupted by doors	O. Reg. 332/12: BC (9.8.7.2)
43	Railings (Handrail)	Include	False	Where obstruct pedestrian travel	O. Reg. 332/12: BC (9.8.7.3)
Guards					
44	Railings (Guardrail)	Include	True	The surface elevation difference between the	CSA (A500-16-4)

				walking surface and the adjacent surface > 600 mm	O. Reg. 332/12: BC (9.8.8.1)
45	Railings (Guardrail)	Include	True	The elevation difference between the two sides of the door > 600 mm	CSA (A500-16-4) O. Reg. 332/12: BC (9.8.8.1)
46	Railings (Guardrail)	Include	True	interior stair risers > 2	CSA (A500-16-4) O. Reg. 332/12: BC (9.8.8.1)
47	Railings (Guardrail)	Include	True	The elevation difference between the openable window sill and finished floor > 480 mm	CSA (A500-16-4) O. Reg. 332/12: BC (9.8.8.1)
48	Railings (Guardrail)	Include	True	The elevation difference between the two sides of the window < 1800 mm	CSA (A500-16-4) O. Reg. 332/12: BC (9.8.8.1)
49	Railings (Guardrail)	Height of guards	Height > 900 mm	The clear height	CSA (A500-16-4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4)
50	Railings (Guardrail)	Height of guards	Height > 920 mm	For required exit stairs	CSA (A500-16-4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4.)
51	Railings (Guardrail)	Height of guards	Height > 1070 mm	Around landings	CSA (A500-16-4.1.9.1) O. Reg. 332/12: BC (9.8.8.3)

					O. Reg. 332/12: BC (9.8.8.4)
52	Railings (Guardrail)	Height of guards	Height > 1500 mm	Where the elevation difference between exterior stairs and above adjacent level > 10m	CSA (A500-16-4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4)
53	Railings (Guardrail)	Height of guards	Height > 1500 mm	Where the elevation difference between landings and above adjacent level > 10m	CSA (A500-16-4.1.9.1) O. Reg. 332/12: BC (9.8.8.3) O. Reg. 332/12: BC (9.8.8.4)
54	Railings (Guardrail)	Opening in guards	Diameter < 100 mm	Railing (guardrail) opening	CSA (A500-16-4.8.3.1) O. Reg. 332/12: BC (9.8.8.5)
Egress analysis (Means of Egress)					
55	Doors (Exit)	Include	True	if space is set to be a fire exit space, it must have a fire exit door	O. Reg. 332/12: BC (9.9.2.1)
56	Doors (Exit)	Exit width	Width > 900 mm	Emergency exit doors	O. Reg. 332/12: BC (9.9.3.2)
57	Doors (Exit)	Exit width	Width > 800 mm	Where there is only one door leaf or multiple-leaf with one active leaf	O. Reg. 332/12: BC (9.9.6.3)
58	Doors (Exit)	Exit width	Width > 1210 mm	Where multiple-leaf doors are installed with two active leaves	O. Reg. 332/12: BC (9.9.6.3)
59	Corridors	Corridor width	Width > 1100 mm	Corridor used by the public, and exit corridor	O. Reg. 332/12: BC (9.9.3.3)
60	Doors (Exit)	Door Height	Height > 2100 mm	The clear height in exits and access to exits	O. Reg. 332/12: BC (9.9.3.4)

61	Floors	Floor height	Height > 2030 mm	The clear opening height of doorways	O. Reg. 332/12: BC (9.9.6.2)
Ceiling Height					
62	Ceilings	Ceiling height	Height > 2100 mm	Ceilings in passage, hall, or main entrance	O. Reg. 332/12: BC (9.5.3.1)
63	Ceilings	Ceiling height	Height > 2000 mm	The clear height in a storage garage	O. Reg. 332/12: BC (9.5.3.3)
64	Ceilings	Above Ceilings	Height > 400 mm	Clearance above suspended ceilings	O. Reg. 332/12: BC (9.5.3.3)

4.3.3 Step3. Rule set Preparation

BIM library includes information about objects such as geometry and necessary level of detail, geometric relations, name attributes, and domain-specific attributes. Based on the BIM library, the customized parametric rule-set file (BIM-based safety rules) is created using a model checking application (SMC). First, available rule templates in SMC were reviewed to identify the appropriate template related to each rule in the decision table (Table 4-2). Second, based on the rules identified in step 1, safety classes for rule checking were defined in SMC. Eventually, the ruleset classes were customized based on the 64 rules in the decision table.

4.3.4 Step 4. BIM Object Checking

Validation of BIM objects was carried out based on the level of detail and specifications required by decision tables. Object validations before BIM include the correctness of required attribute value, the correctness of embedding an attribute within a BIM object, and the relationships between objects within a building model.

4.3.5 Step 5. Building Model Diagnosis

In this step, the building model is checked and the design errors are determined through a detailed report. A graphical reporting indicates BIM elements that do not comply with standards and building codes after the rule execution. Based on the model checking, the respective element is defined as, accepted, rejected, critical severity (major), moderate severity (normal), and low severity (minor). Table 4-3 presents an instance to determine the difference between severity parameters. Implementation guidelines and best management practices for BIM-based predictive safety management are provided in the comment box in the detailed report.

Table 4-3: Severity parameters

Severity Calculation	Calculation Description	Severity
Stair Max Steps	The difference between the actual number of steps of a stair and the maximum number of steps is greater than 50% of the maximum number of steps.	Critical
	The difference between the actual number of steps of a stair and the maximum number of steps is between 2 steps and 50% of the maximum number of steps.	Moderate
	The difference between the actual number of steps of a stair and the maximum number of steps is 1.	Low

4.4 Case Study: The Method Implementation

To implement the methodology of this study, the Center for Automotive Research and Education (C.A.R.E) building as a part of the University of Windsor located in Windsor (Ontario) is modeled and used as the case study of this research. This 2-story building was founded in 1857 and renovated in 2014. The building is classified as an educational building.

An IFC file was used to transfer building data to the Solibri Model Checker. The exported IFC file format from the Autodesk Revit entails all details with a high level of detail. As presented in Table 4-1, SMC has been used by previous researchers to check safety rules such as building evacuation, fall protection for workers, building safety design, and accessibility. Therefore, due to the specific set of requirements in the decision table (Table 4-2) and regarding the existence of required templates to create the safety ruleset, SMC was utilized to create the ruleset and check the BIM model. The existence of required elements for the safety rule checking process was checked in the IFC file and compared with the Revit model. This measure was performed to verify that the IFC file contains all required elements for the rule checking process.

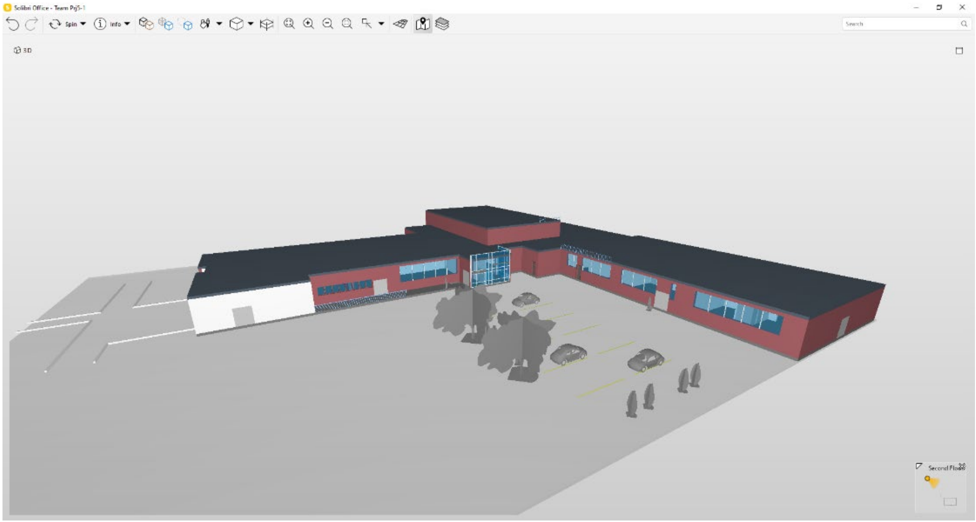


Figure 4-2. The C.A.R.E building used for the case study

The BIM-based safety ruleset file was coded in SMC. This file was imported into the rule checking section of SMC software to execute rules and report the result of code checking.

Table 4-4 provides a summary of the model checking report. This report determines whether each component meets the standard requirements or not. Moreover, it detects clashes between building objects and the number of components that met the standard requirements. The detailed report informs designers of each problematic element and compares the designed value with the standard value of that parameter.

In this case study, there is no "rejected" or "major" error. Therefore, it shows that this case study does not need to be entirely redesigned. However, several "normal" errors indicate the need for a major revision in the parameters of the "means of egress" section.

Table 4-4: The safety code checking report (Summary section)

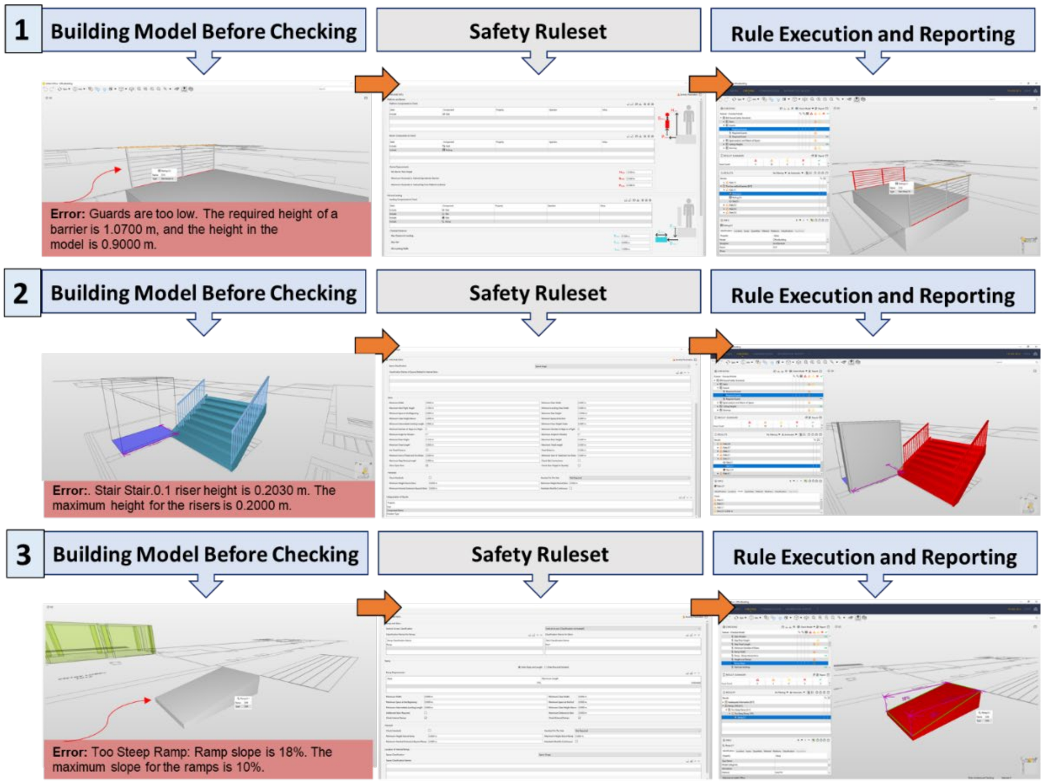
BIM-based Safety Standards	**Accepted**	**Rejected**	**Major**	**Normal**	**Minor**
Stairs				x	x
The model should have stairs					x
The model should have stairs					x
Stair width	OK				

Height over stairs	OK				
Maximum height of stairs	OK				
Stair winders	OK				
Step riser height				x	
Step tread length				x	x
Minimum number of risers	OK				
Ramp width				x	
Ramp-Ramp intersections	OK				
Height over ramps				x	
Ramp slope				x	
Staircase landings					x
Required handrail (ramp)	OK				
Continuity of handrails (ramp)	OK				
Required handrail (stair)	OK				
Continuity of handrails (stair)	OK				
Required handrail (Ramp2)	OK				
Height of handrails (Stair)	OK				
Height of handrails (ramp)	OK				
Guards				x	
Required Guards 1				x	
Required Guards 2				x	
Required Guard 3	OK				
Egress analysis (Means of Egress)				x	
Escape Route Analysis				x	
Escape route analysis from office spaces				x	
If space is set to be a fire exit space, it has to have a fire exit door					x
The model should have exits	OK				
Large spaces must have more than one door				x	
Fire compartment area must be within limits				x	
Firewalls must have the correct wall, door, and window types				x	
Spaces must be included in fire compartments				x	
The model should have stairs				x	
The model should have exits				x	
Spaces must be connected to doors				x	
The model should have spaces	OK				
Ceiling Heights	OK				
Suspended ceiling-suspended ceiling intersections					x
Suspended ceiling intersections					x
Floor heights	OK				

Clearance above suspended ceilings	OK				
Doorway				x	x
Door width					x
Door height	OK				
Clearance in front of doors					x
Spaces must have doors					x

SMC allows users to graphically reference errors in the model. Figure 4-3 indicates three instances of the graphical report and the source of rules in SMC for the case study.

SMC returned the following safety issues with the building design.



Error: Guards are too low. The required height of a barrier is 1.0700 m, and the height in the model is 0.9000 m.

Error:. Stair Stair.0.1 riser height is 0.2030 m. The maximum height for the risers is 0.2000 m.

Error: Too Steep Ramp: Ramp slope is 18%. The maximum slope for the ramps is 10%.

Figure 4-3: The graphical report

4.5 Summary

In this chapter, a methodological framework was developed for rule checking, and the safety-focused ruleset for BIM-enabled building construction projects in Ontario, Canada. A comprehensive review was conducted to determine safety-related regulations, standards, and best practices included in the Ontario Building Code (OBC) and standards published by the Canada Standards Association (CSA). Identified safety standards were defined in Solibri Model checker software as a ruleset. A case study was conducted to demonstrate how the proposed ruleset is implemented. The developed safety ruleset enables design engineers to directly employ it for rule checking in construction projects in Ontario, Canada. Moreover, the proposed framework enables an accurate and fast evaluation of building designs to ensure safety compliance according to building code, standards, and guidelines. The outcomes of this research will guarantee occupant safety through a proper design. Moreover, they can support promoting BIM in the Canadian construction industry.

4.5 Reference

[1] R. K. Dhillon and H. S. Rai, "Automation of Building Code checking with BIM," *Int. J. Adv. Res. Comput. Eng. Technol.*, vol. 6, no. 10, pp. 1522–1525, 2017.

[2] C. Eastman, J. min Lee, Y. suk Jeong, and J. kook Lee, "Automatic rule-based checking of building designs," *Autom. Constr.*, vol. 18, no. 8, pp. 1011–1033, 2009, doi: 10.1016/j.autcon.2009.07.002.

[3] H. Luo and P. Gong, "A BIM-based Code Compliance Checking Process of Deep Foundation Construction Plans," pp. 549–576, 2015, doi: 10.1007/s10846-014-0120-z.

[4] A. Porwal, "Construction waste management at source: A building information modelling based system dynamics approach," University of British Columbia, 2013.

[5] R. Sacks, C. Eastman, G. Lee, and P. Teicholz, *BIM handbook: A guide to building information modeling for owner, managers, designers, engineers, and contractors*, 3rd ed., vol. 73. Hoboken, N.J: Wiley publishing, 2018.

[6] K. Eastman, C., Teicholz, P., Sacks, R., Liston, *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors. Wiley*. 2011.

[7] A. S. Ismail, “A Review on BIM-based automated code compliance checking system,” in *International Conference on Research and Innovation in Information Systems*, 2017.

[8] W. Solihin and C. Eastman, “Automation in Construction Classi fi cation of rules for automated BIM rule checking development,” *Autom. Constr.*, vol. 53, pp. 69–82, 2015, doi: 10.1016/j.autcon.2015.03.003.

[9] A. Martins, J. P., & Monteiro, “A BIM based automated code-checking application for water distribution systems,” *Autom. Constr.*, vol. 29(23), 12, 2013.

[10] R. Miettinen and S. Paavola, “Beyond the BIM utopia: Approaches to the development and implementation of building information modeling,” *Autom. Constr.*, vol. 43, pp. 84–91, 2014, doi: 10.1016/j.autcon.2014.03.009.

[11] Q. Wang, H. Sohn, M. Asce, J. C. P. Cheng, and A. M. Asce, “Automatic As-Built BIM Creation of Precast Concrete Bridge Deck Panels Using Laser Scan Data,” vol. 32, no. 3, pp. 1–17, 2018, doi: 10.1061/(ASCE)CP.1943-5487.0000754.

[12] Z. Shen, “QUANTITATIVE EVALUATION OF THE BIM-ASSISTED CONSTRUCTION DETAILED COST ESTIMATES QUANTITATIVE EVALUATION OF THE BIM-ASSISTED,” *J. Inf. Technol. Constr.*, 2010.

[13] BuildingSMART, “IFC Description,” 2016. http://buildingsmart.org/ifc/.

[14] J. M. Lee, “Automated Checking of Building Requirements on Circulation Over a Range of Design Phases,” Georgia Institute of Technology, 2010.

[15] J. Ding, L., Drogemuller, R., Rosenman, M., Marchant, D., & Gero, “Automating code checking for building designs,” in *Construction Innovation, Clients Driving Innovation International Conference (pp. 1–16). Sydney, Australia.*, 2006.

[16] J. S. Ding, L., Drogemuller, R. , Jupp, J., Rosenman, M. A., & Gero, “Automated Code Checking,” in *In CRC for Construction Innovation, Clients Driving Innovation International Conference*, 2004, pp. 1– 17.

[17] R. Dimyadi, J., & Amor, “Automated Building Code Compliance Checking – Where is it at?,” in *In Proceedings of the 19th World Building Congress: Construction and Society, 5-9 May (pp. 172–185).*, 2013, pp. 172–185.

[18] N. L. Bouzidi, K. R., Fies, B., Faron-Zucker, C., Zarli, A., & Thanh, “Semantic Web Approach to Ease Regulation Compliance Checking in Construction Industry,” *Futur. Internet*, vol. 4(3), 830–, 2012.

[19] J. Nguyen, Tang; Kim, “BUILDING CODE COMPLIANCE CHECKING USING BIM TECHNOLOGY,” in *Proceedings of the Winter Simulation Conference*, 2011.

[20] R. Chahrour *et al.*, “Cost-benefit analysis of BIM-enabled design clash detection and resolution,” *Constr. Manag. Econ.*, pp. 1–18, 2020, doi: 10.1080/01446193.2020.1802768.

[21] P. B. and C. D. Kristina Kincelova, Conrad Boton, “Fire Safety in Tall Timber Building : A BIM-Based Automated Code-Checking Approach,” *Buildings*, 2020.

[22] A. Taciuc, A.; Karlshøj, J.; Dederichs, “Development of Ifc Based Fire Safety Assesment Tools,” in *In Proceedings of the International RILEM Conference Materials, Systems and Structures in Civil Engineering, Lyngby, Denmark, 15–18 August 2016.*

[23] Ö. Balaban and G. Ç. , Elif Sezen Yağmur Kilimci, “Automated Code Compliance Checking Model for Fire Egress Codes,” *Digit. Appl. Constr.*, vol. 2, pp. 1–10, 2012.

[24] S. L. W.J. Rasdorf, “Logic-based approach for modeling organization of design standards,” *J. Comput. Civ. Eng.*, pp. 102–123, 1990.

[25] H. Malekitabar, A. Ardeshir, M. Hassan, and R. Stouffs, “Construction safety risk drivers : A BIM approach,” *Saf. Sci.*, vol. 82, pp. 445–455, 2016, doi: 10.1016/j.ssci.2015.11.002.

[26] J. Martin, J. and Odell, *Object-oriented methods A Foundation*, 2nd ed. Upper Saddle River, N. J.: Prentice Hall, 1998.

[27] X. Yang, Q. Z., & Li, “Representation and Execution of Building Codes for Automated Code Checking,” in *Proceedings of the Ninth International Conference on Computer Aided Architectural Design Futures*, 2001, pp. 315–329.

[28] L. Khemlani, “CORENET e-PlanCheck : Singapore’s automated code checking system,” 2005. http://www.aecbytes.com/buildingthefuture/CORENETePlanCheck.htm.

[29] M. M. . G. J. Hakim, “Issues in modeling and evaluating design standards,” in *Proceedings of the Computer and Building Standards Workshop*, 1992.

[30] M. M. Hakim and J. H. Garrett, “Engineering Computers A Description Logic Approach for Representing Engineering Design Standards,” *Eng. Comput.*, pp. 108–124, 1993.

[31] J. Robbin, *Mathematical Logic: A First Course*. Dover Publicaitons, 2006.

[32] I. Lee, H., Lee, J.-K., Park, S., & Kim, “Translating building legislation into a computer-executable format for evaluating building permit requirements,” *Autom. Constr.*, pp. 49–61, 2016.

[33] W. Solihin, “A simplified BIM data representation using a relational database schema for an efficient rule checking system and its associated rule checking language,” Georgia Institute of Technology, 2016.

[34] J. Dimyadi, C. Eastman, and R. Amor, “Integrating the BIM Rule Language into Compliant Design Audit Processes Integrating the BIM Rule Language into Compliant Design Audit Processes,” no. November, 2016.

[35] H. Jain, D.; Law, K.H; Krawinkler, “On processing standards with predicate calculus,” in *Proceedings of the Sixth Conference on Computing in Civil Engineering, ASCE, Atlanta, Georgia*, 1989.

[36] D. M. Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J. and J. R., Van De Walle, R., & Van Campenhout, “A semantic rule checking environment for building performance checking,” *Autom. Constr.*, pp. 506–518, 2011.

[37] A. Yurchyshyna, A., Faron-Zucker, C., Thanh, N. Le, & Zarli, "Towards an Ontology-based Approach for Formalisation of Expert Knowledge in Conformity Checking Model in Construction," in *In Proceedings of the 7th European Conference on Product and Process Modelling (ECPPM) (pp. 447–456). France.*, 2011.

[38] J. R. Cornick, S.M.; Leishman, D.A.; Thomas, "Integrating building codes into design systems," in *First International Symposium on Building Systems Automation - Integration, Madison, Wisconsin*, 1991.

[39] SMC, "Solibri Inc. (2020)." https://www.solibri.com/products/solibri-model-checker/.

[40] C. Preidel and A. Borrmann, "Automated Code Compliance Checking Based on a Visual Language and Building Information Modeling," 2009.

[41] S. Zhang, J. Teizer, J. Lee, C. M. Eastman, and M. Venugopal, "Building Information Modeling (BIM) and Safety : Automatic Safety Checking of Construction Models and Schedules," *Autom. Constr.*, vol. 29, pp. 183–195, 2013, doi: 10.1016/j.autcon.2012.05.006.

[42] I. Mutis and T. Hartmann, *Advances in Informatics and Computing in Civil and Construction Engineering*. 2018.

[43] C. Koch, J. Beetz, T. Foundations, and I. Practice, *Building Information Modeling*. 2019.

[44] GSA, "GSA Building Information Modeling Guide Series 02 - Spatial Program Validation," *National 3D-4D-BIM Program. Washington, U.S.*, 2019. .

[45] T. H. B. K. L. N. Rezgui, "Towards automated compliance checking in the construction industry.," in *International Conference on Database and Expert Systems Applications*, 2013, pp. 366–380.

[46] D. Malsane, S., Matthews, J., Lockley, S., Love, P. E. D., & Greenwood, "Development of an object model for automated compliance checking," *Autom. Constr.*, vol. 49, 51–58., 2015.

[47] H. Shih, S.-Y., Sher, W., & Giggins, “Assessment of the building code of Australia to inform the development of BIM-enabled code checking system,” in *Proceedings of the 19th World Building Congress: Construction and Society*, 2013, pp. 1–12.

[48] N. Hjelseth, E., & Nisbet, “Capturing Normative Constraints by Use of the Semantic Mark-up RASE Methodology,” in *In Proceedings of the 28th International Conference of CIB*, 2011, pp. 1–10.

[49] N. Hjelseth, E., & Nisbet, “Exploring semantic based model checking,” in *In Proceedings of CIB W78 27th International Conference*, 2010, p. Vol. 27, pp. 1–11.

[50] H. M. Zhong, B. T., Ding, L. Y., Luo, H. B., Zhou, Y., Hu, Y. Z., & Hu, “Ontology-based semantic modeling of regulation constraint for automated construction quality compliance checking,” *Autom. Constr.*, vol. 28, 58–70, 2012.

[51] T. Kasim, “BIM-Based Smart Compliance Checking to Enhance Environmental Sustainability,” Cardiff University, 2015.

[52] S. Peldszus, K. Tuma, D. Strüber, J. Jürjens, and R. Scandariato, “Secure Data-Flow Compliance Checks between Models and Code based on Automated Mappings,” in *ACM/IEEE 22nd International Conference on Model Driven Engineering Languages and Systems*, 2019.

[53] M. F. Porto, R. Maria, and A. B. Porto, “Automatic Code Checking Applied to Fire Fighting and Panic Projects in a BIM environment - BIMSCIP,” *Syst. Cybern. INFORMATICS*, vol. 15, no. 3, pp. 86–90, 2017.

[54] S. Jiang and and Z. Wu, “A BIM-Based Code Checking Approach for Green Construction,” in *ICCREM*, 2017, pp. 156–163.

[55] H. Kim, J. Lee, J. Shin, and J. Choi, “Visual language approach to representing KBimCode-based Korea building code sentences for automated rule checking,” *J. Comput. Des. Eng.*, vol. 6, no. 2, pp. 143–148, 2019, doi: 10.1016/j.jcde.2018.08.002.

[56] H. Zhou, “VPL-Based Code Translation for Automated Compliance Checking of Building Envelope Energy Efficiency,” *Constr. Res. Congr.*, pp. 1–12, 2018.

[57] K. L. C. Han, J. Kunz, “Client/server framework for on-line building code check- ing,” *J. Comput. Civ. Eng.*, pp. 181–194, 1998.

CHAPTER 5

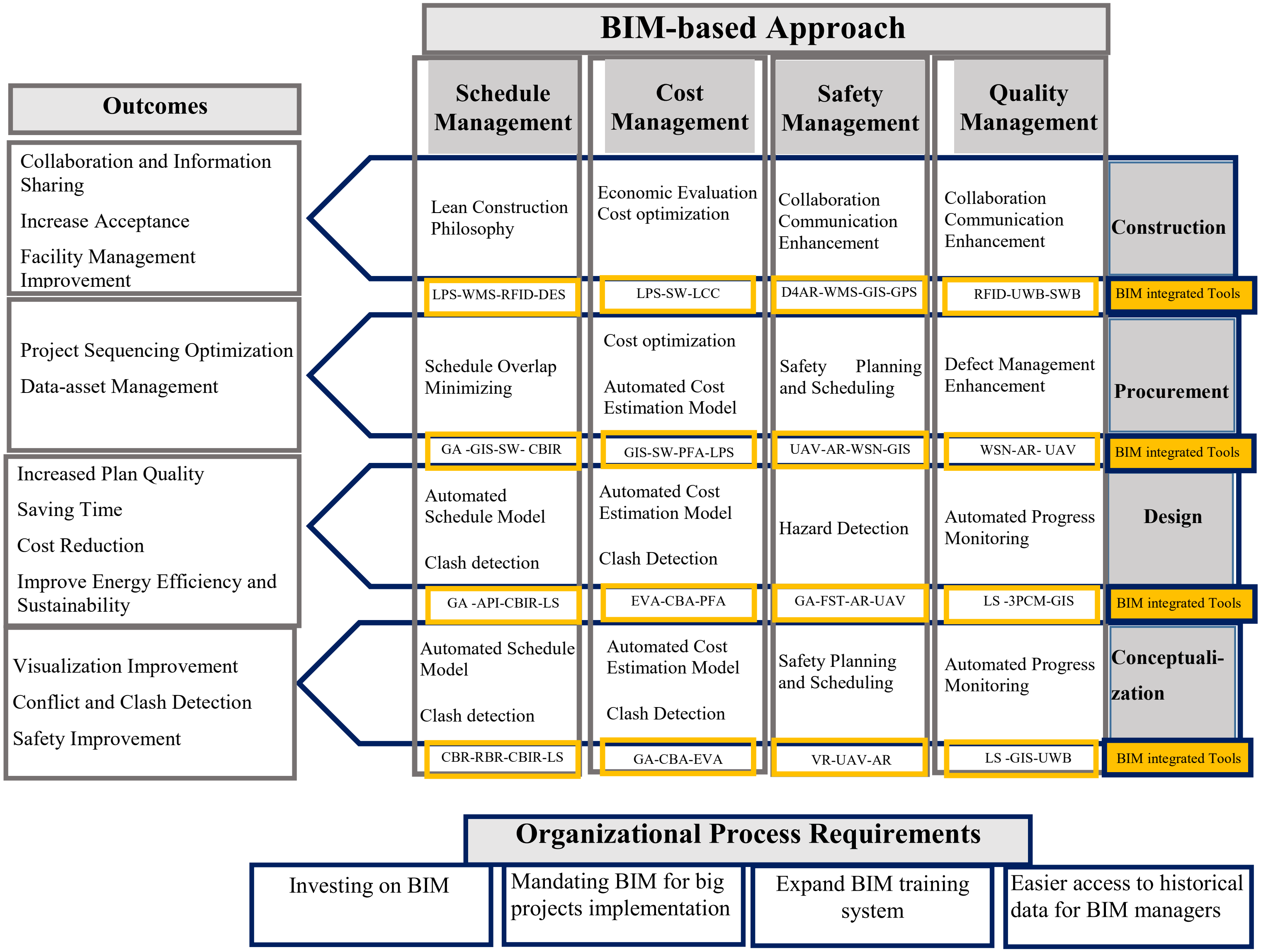
CONCLUSION, CONTRIBUTION, AND LIMITATIONS

In this chapter, the thesis conclusions and contributions of this study are presented, the strengths and limitations of this study are illustrated, and recommendations are provided for potential future research directions.

5.1 Summary and Contributions

Contemporary construction management requires large volumes of data for efficient project delivery. Yet, access to key construction management data is still a major challenge primarily due to implementation issues. The new line of thinking in management has been moving toward predictive decision-making methods with the aid of artificial intelligence. However, the construction industry has been lagging on embracing modern management concepts. Hence, it is vital to re-engineer construction management to be on par with industries such as manufacturing. The advent of Building Information Modeling (BIM) has led to creating a paradigm shift in construction management. BIM is an information repository that could support the implementation of state-of-the-art management techniques in the construction sector. This research presented BIM-based methods for improving predictive safety planning in the construction industry. The conclusions of this study are as follows:

A strategy map was presented to support decision making in construction projects based on the comprehensive literature review provided in chapter 2. The proposed roadmap indicates BIM-based techniques in each section of construction management to support predictive decision making. Moreover, the roadmap determines the outcome of the BIM integrated methods to improve the decision-making in key stages of the project life cycle, meaning conceptual development, design, procurement, and construction. Moreover, the list of an organizational process that supports the implementation of BIM in a construction project was presented, which will eventually support predictive decision making. The proposed strategy map demonstrates that investing in BIM aids construction managers to appropriately manage their projects and prevent cost overrun, time overrun, and safety incidents. Figure 5-1 illustrates the outcomes and benefits of identified BIM-based methods for improving decision making in each stage of a project.



Outcomes	BIM-based Approach				
	Schedule Management	Cost Management	Safety Management	Quality Management	
Collaboration and Information Sharing Increase Acceptance Facility Management Improvement	Lean Construction Philosophy	Economic Evaluation Cost optimization	Collaboration Communication Enhancement	Collaboration Communication Enhancement	**Construction**
	LPS-WMS-RFID-DES	LPS-SW-LCC	D4AR-WMS-GIS-GPS	RFID-UWB-SWB	BIM integrated Tools
Project Sequencing Optimization Data-asset Management	Schedule Overlap Minimizing	Cost optimization Automated Cost Estimation Model	Safety Planning and Scheduling	Defect Management Enhancement	**Procurement**
	GA -GIS-SW- CBIR	GIS-SW-PFA-LPS	UAV-AR-WSN-GIS	WSN-AR- UAV	BIM integrated Tools
Increased Plan Quality Saving Time Cost Reduction Improve Energy Efficiency and Sustainability	Automated Schedule Model Clash detection	Automated Cost Estimation Model Clash Detection	Hazard Detection	Automated Progress Monitoring	**Design**
	GA -API-CBIR-LS	EVA-CBA-PFA	GA-FST-AR-UAV	LS -3PCM-GIS	BIM integrated Tools
Visualization Improvement Conflict and Clash Detection Safety Improvement	Automated Schedule Model Clash detection	Automated Cost Estimation Model Clash Detection	Safety Planning and Scheduling	Automated Progress Monitoring	**Conceptuali-zation**
	CBR-RBR-CBIR-LS	GA-CBA-EVA	VR-UAV-AR	LS -GIS-UWB	BIM integrated Tools

Organizational Process Requirements

- Investing on BIM
- Mandating BIM for big projects implementation
- Expand BIM training system
- Easier access to historical data for BIM managers

Figure 5-1: Roadmap of predictive decision-making improvement

* Note: Radio frequency identification device (RFID); Ultrawideband (UWB); Smart whiteboard (SWB); Global positioning system (GPS); Geographic information system (GIS); Web map service (WMS); Four-dimensional augmented reality (D4AR); Life cycle costing (LCC); Semantic Web technology (SW); Discrete event simulation (DES); Unmanned aerial vehicle (UAV); Augmented reality (AR); Wireless sensor network (WSN); Pareto front analysis (PFA); Content-based image retrieval (CBIR); Genetic algorithm (GA); 3D point cloud models (3PCM); Laser scanning (LS); Fuzzy set theory (FST); Cost benefit analysis (CBA); Earned value analysis (EVA); Application programming interface (API); Virtual reality (VR); Case-based reasoning (CBR); Rule-based reasoning (RBR).

Chapter 3 proposed a BIM-fuzzy framework for the safety risk assessment of construction projects. This method can predict the safety risk of a project and identify the potential hazards before the start of construction. Owing to the capability of this system to interlink the FIS risk assessment system with BIM, the required information for calculating the safety risk is driven automatically from a BIM model. This feature eliminates human errors and reduces the time of risk assessment. Furthermore, this system calculates and provides the occurrence, consequence, and risk of each hazard; which is helpful to identify the reason for high risk in projects. The mentioned features of the proposed approach aid managers to easily conduct a risk assessment for each stage of projects and prevent safety incidents in construction sites. Thus, the level of health and safety for workers in construction projects can be enhanced.

In Chapter 4, a BIM-based rule checking approach is presented to reduce the safety risk for building residents. This study developed a safety-based model checking ruleset for the architecture, engineering, and construction (AEC) industry. This approach enables an accurate and fast evaluation of building designs to ensure safety compliance according to building code, standards, and guidelines. Moreover, a methodological framework was developed to check the compliance with guidelines for safety. Although this study provides a decision table and rule checking process based on the Ontario building code, the methodological framework can be customized to suit other provinces and countries. The proposed framework can identify safety errors in a building design. The generated report of this method informs designers whether the building design requires redesign or major revision or minor revision. Moreover, regarding the object-based classification of the ruleset, the graphical and detailed reports indicate the specific model elements with errors. Identifying design errors enables the project manager to develop a precise quantity take-off and schedule and more importantly ensures the safety of the building.

5.2 Contributions

This research is expected to deliver two unique contributions that would assist in improving the safety of construction workers and building residents.

A BIM-based FIS for safety risk assessment of building designs: This research integrated BIM with fuzzy logic to address the data uncertainty challenge in predictive safety planning of construction projects. The proposed method addresses the deficiencies of current non-BIM-based approaches related to extracting accurate building data for predicting the safety risk of a project. Moreover, this system enables construction managers to assess the safety risk of a project using a BIM model.

A Canadian BIM-based ruleset for building resident safety: This study proposed a safety-based ruleset for buildings in Canada. There are numerous rule checking systems available in the literature which have conducted rule checking process based on OSHA, NBCC, etc. Moreover, standard rulesets available in model checking applications include some sections such as structural components. However, no approach has dealt with BIM-based safety-related Canadian building codes or the Canadian Standards Association (CSA) and standards. Therefore, this study addressed the gap in safety rule checking systems and enhanced the safety of building residents. This rule set can be used to assess buildings constructed in Ontario.

5.3 Limitations of the Study

Limitations of this research are discussed below.

1) The BIM-FIS system:

Unidentified hazard causes: The FISs inputs were defined based on construction hazard causes. A comprehensive review was performed to identify all construction hazard main causes and sub-causes. However, due to the complexity of construction projects and also a large number of project safety reports, some construction hazard sub-causes may be added to the provided list in this study. Besides, based on the construction hazard causes list provided in Chapter 3 of this study, some hazard causes cannot be modeled in a BIM model to be employed for the safety risk assessment.

Regional limitation: Rules could differ according to regional and national construction industry guidelines. Therefore, fuzzy expert system inputs would differ in every region or nation. This research developed these rules based on literature applicable to North America. Hence, this system is limited to use in North American countries.

Limitation in incorporating the location-based parameters of projects: This risk evaluation provides a snapshot view of the construction project risk. So, it is vital to incorporate the location's specific dynamic nature of the construction site into the risk evaluation. The proposed method is unable to affect the location and the environment-based parameters. For example, precipitation can increase the occurrence of slip (which is one of the main causes of fall hazard) for construction workers.

2) BIM-based safety rule checking system:

Hard-coded rule checking system: This study applied Solibri Model Checker, which uses hard-coded rules. Hence, the individual steps of the checking process are not visible and there are limited ways for the users to alter them. Therefore, the user cannot add a new rule which is not available in the SMC templates.

Regional limitation: The proposed ruleset was developed based on Ontario building codes and CSA standards. Therefore, since building codes and standards are different in each region, this ruleset directly can be used to check buildings in Ontario, Canada.

Data collection and availability: This research uses data from a wide variety of sources to help create the safety ruleset for the rule checking framework. Many building codes and standards were found throughout the literature reviews which were selectively chosen to be incorporated in this framework. Some standards may not be considered in the provided decision table due to the extensive and exhaustive list of building codes and standards.

5.4 Future Research

The extensions that may be made to the scope of this research are discussed below.

1) **The BIM-FIS system:**

A system to identify hazardous zones: this method could be extended to develop a system to determine hazardous zones in construction sites in each stage of the project. The proposed safety risk assessment method of this study can be used by this system to determine different zones of a construction site in a BIM model. This approach will provide comprehensive data for predictive safety management.

The use of Artificial Intelligence (AI): AI can automatically identify and address safety issues. This can be done by integrating the proposed method with a database of previous safety incidents and migratory measures.

Application Programming Interface (API): API can be used link the FIS with a BIM-model. This will eliminate the use of external applications such as MATLAB and IdeateBIMlink. This BIM tool will assist wider implementation of the proposed method.

2) **BIM-based safety rule checking system:**

AI-based model checking interface: Model checkers cannot make modifications to a design. Artificial Intelligence (AI) can be used to modify the models based on identified safety errors. Hence, future research should be directed toward developing an AI-based model checking interface for BIM applications.

Rule sets for mechanical and electrical systems of a building model: This study focused on the architectural aspect of a building. Future studies can develop ruleset and automated safety rule checking systems applicable in structural, plumbing, or mechanical sections.

APPENDICES

APPENDIX A: MAIN CAUSES AND SUB-CAUSES OF STRUCK BY OBJECT HAZARDS

Struck by Object Hazards		
No.	**Main Causes**	**Sub Causes**
1	Inappropriate Protective Structures	Lack of guardrail installation
		Lack of guardrail toe board installation
		Short toe boards
		Unsecured gaps between the toe boards and the work surface
		Unsecured gaps between adjoining toe boards
		Lack of mid-rails and the top rail in guardrails
2	Inappropriate Protective Means	Lack of using tool lanyards and tethers
3	Floor holes and wall openings	Lack of open grating cover
		Lack of opening and hole covering
		Inadequate warning signs
4	Unsafe scaffolding	Planks sliding off or breaking
		Erecting and dismantling scaffolds
		Climbing up and down scaffolds
		Improper loading or overloading
		Lack of guardrails
		Platforms not fully planked
		Lack of installation of required components, e.g. baste plates
		Moving rolling scaffolds near overhead electrical wires
		Moving rolling scaffolds with workers on the platform.
5	Improper Housekeeping	Unsecured material
		Storing material and equipment less than standard distance from edges
		Lack of cleaning debris
		Improper stacking of material
6	Tools and Equipment	Unsecured hand tools in work belts
		Incorrect size of carts for carrying material
		Unstable carts
		Carts without sides
		Unsecured extended material over the sides of carts
7	Unsecured Safety Net	Gaps in the safety net
		Inferior quality of the net
8	Unsafe Temporary Elevator	Damaged elevator cable
		Unsafe connections
9	Lack of Training	

10	Unsafe Hoisting and Rigging	Lack of exclusion zone existence
		Lack of barricades
		Lack of warning signs
		Working under the path of the overhead load
		Unsecured loads
		Bad condition of slings and other hardware
		Lack of using tag lines to control loads
		Lack of using proper lifting containers
11	Struck by Construction Machinery	Driver lack of attention to construction site and blind spots
		Lack of proper communication between driver and labors working around(spotters)
		Lack of using barricade to protect workers
		Driver lack of attention to warning signs
		Uncovered moving parts of vehicles
		Unflagged underground utilities or electrical lines
		Unsafe distance of workers from vehicles
		Poor lighting
		Improper available width of pathways and turning points
		Potholes, bearing pressures and deficiencies in pathways
		Lack of emergency stop systems existence
		Weather condition

APPENDIX B: MAIN CAUSES AND SUB-CAUSES OF CONSTRUCTION MACHINERY HAZARDS

Construction Machinery Hazards		
No.	Main Causes	Sub Causes
1	Equipment collapse or buckling	Equipment load limit lack of inspection
		Lack of collision avoidance systems
		Lack of checking periodic safety of equipment
		Improper vehicle assembly
2	Equipment Overturn	Lack of proper communication between driver and labors working around(spotters)
		Driver lack of attention to warning signs
		Poor lighting
		Improper slope of the construction vehicles' parking area
		Improper available width of pathways and turning points
		Lack of emergency stop systems
3	Driver Hazards	Unfastened seatbelt
		Driver lack of attention to mounting and dismounting regulations
		Lack of emergency stop systems existence
4	Inadequate training of workers	

APPENDIX C: MAIN CAUSES AND SUB-CAUSES OF ELECTRICAL HAZARDS

Electrical Hazards		
No.	**Main Causes**	**Sub Causes**
1	Improper Grounding	Removing the ground pin
2	Exposed Electrical parts	Intact insulation on electrical cords
3	Inadequate Insulation	Repairing extension cords with tape
		Hanging extension cord from sharp objects
4	Overloaded Circuits	Improper circuit breakers
5	Weather Condition	Electrical operating in wet conditions
6	Overhead Power Lines	Storing materials or equipment under overhead power
		Improper physical barriers
7	External Causes	Long metal objects deposit near the power lines
		Lack of attention to possible states of a crane and boom crane
		Unscheduled loading and unloading tasks in the vicinity of power lines
		Unsafe scaffolding near the power lines
		Unsecured distance between the power line and equipment
8	Inadequate training of workers	

APPENDIX D: MAIN CAUSES AND SUB-CAUSES OF SUFFOCATION HAZARDS

Suffocation Hazards		
No.	**Main Causes**	**Sub Causes**
1	Narrow Entrance Size	Unplanned empty spaces
2	Unsafe operation	Unsafe operation without equipment in confined spaces
		Operation without gear and safe equipment in narrow confined spaces
		Lack of purging debris and excavated soils near excavation site
3	Low Oxygen Level	Welding, coating or sandblasting tasks in confined spaces
		Internal combustion machines in confined spaces
		Improper ventilation
4	Lack of Exit Means	Lack of existence of ladder or stairs in hatches
		Poor lighting condition
		Improper anchorage system for exit means
5	External Excessive pressure on the soil near excavation	Lack of existence of safeguards and shoring in trenches
		Inappropriate distance to high traffic roads, buildings, walls and piles
		Low safety factor of soil
6	Inadequate training of workers	

APPENDIX E: MAIN CAUSES AND SUB-CAUSES OF FIRE HAZARDS

Fire Hazards		
No.	**Main Causes**	**Sub Causes**
1	Electrical Supplies and Equipment Hazards	Poor installation and maintenance of electrical systems
		Faulty or damaged equipment
		Unsecure fastened operation at temperatures above 75°C
		Unequipped fragile components such as temporary lights
		Improper usage of Low-voltage equipment
		Long usage of temporary wiring
2	Evacuation Hazards	Insufficient paths of travel to exits
		Improper evacuation signage
		Obstructions in evacuation path
		Blocked building's exits
3	Inefficient Fire Extinguishing Systems	Inaccessible location of extinguishers
		Lack of 3 class of fire extinguishers existence
4	Open and Waste Fire Hazards	Unprohibited burning of waste materials
		Warming device existence inside the construction site
5	Inappropriate Fire Protection Systems	Out of service Fire sprinkler and other suppression systems
		Out of service fire detection and alarm systems
6	Flammable and Combustible Building Materials	Long term this type of material storing
		Unsecure area of storing this type of building materials
7	Inadequate training of workers	

APPENDIX F: FUZZY RULES OF THE FALL HAZARD OCCURRENCE

‘1. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘2. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘3. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘4. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘5. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘6. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘7. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘8. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘9. If (AFO is Low) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘10. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘11. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘12. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘13. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘14. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘15. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘16. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘17. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘18. If (AFO is Low) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘19. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Rare) (1) ‘

‘20. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘21. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘22. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘23. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘24. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘25. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘26. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘27. If (AFO is Low) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘28. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘29. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘30. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘31. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘32. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘33. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘34. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘35. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘36. If (AFO is Low) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘37. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘38. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘39. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘40. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘41. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘42. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘43. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘44. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘45. If (AFO is Low) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘46. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘47. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘48. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘49. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘50. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘51. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘52. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘53. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘54. If (AFO is Low) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘55. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘56. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘57. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘58. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘59. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘60. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘61. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘62. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘63. If (AFO is Low) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘64. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘65. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘66. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘67. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘68. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘69. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘70. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘71. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘72. If (AFO is Low) and (HS is High) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘73. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘74. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘75. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘76. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘77. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘78. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘79. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘80. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘81. If (AFO is Low) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘82. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘83. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘84. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘85. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘86. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘87. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘88. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘89. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘90. If (AFO is Medium) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘91. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘92. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘93. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘94. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘95. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘96. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘97. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘98. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘99. If (AFO is Medium) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘100. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘101. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘102. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘103. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘104. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘105. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘106. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘107. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘108. If (AFO is Medium) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘109. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘110. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘111. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘112. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘113. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘114. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘115. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘116. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘117. If (AFO is Medium) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘118. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘119. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘120. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘121. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘122. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘123. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘124. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘125. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘126. If (AFO is Medium) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1)’

‘127. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Unlikely) (1) ‘

‘128. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘129. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Possible) (1) ‘

‘130. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘131. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘132. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘133. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘134. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘135. If (AFO is Medium) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘136. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘137. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘138. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘139. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘140. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘141. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘142. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘143. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘144. If (AFO is Medium) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘145. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘146. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘147. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘148. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘149. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘150. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘151. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘152. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘153. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘154. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘155. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘156. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘157. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘158. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘159. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘160. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘161. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘162. If (AFO is Medium) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘163. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘164. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘165. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘166. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘167. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘168. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘169. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘170. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘171. If (AFO is High) and (HS is Low) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘172. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘173. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘174. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘175. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘176. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘177. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘178. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘179. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘180. If (AFO is High) and (HS is Low) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘181. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘182. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘183. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘184. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘185. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘186. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘187. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘188. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘189. If (AFO is High) and (HS is Low) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘190. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘191. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘192. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘193. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘194. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘195. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘196. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘197. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘198. If (AFO is High) and (HS is Medium) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘199. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘200. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘201. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘202. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘203. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘204. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1)’

‘205. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘206. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1)’

‘207. If (AFO is High) and (HS is Medium) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘208. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘209. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Possible) (1) ‘

‘210. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘211. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Possible) (1) ‘

‘212. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘213. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘214. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘215. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘216. If (AFO is High) and (HS is Medium) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘217. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘218. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘219. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘220. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘221. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘222. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘223. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘224. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘225. If (AFO is High) and (HS is High) and (FMR is Low) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘226. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘227. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘228. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘229. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘230. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1)’

‘231. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘232. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘233. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘234. If (AFO is High) and (HS is High) and (FMR is Medium) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘235. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘236. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘237. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is Low) and (HFE is High) then (Fall_hazard_occurrence is Likely) (1) ‘

‘238. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘239. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is Medium) then (Fall_hazard_occurrence is Likely) (1) ‘

‘240. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is Medium) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘241. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Low) then (Fall_hazard_occurrence is Likely) (1) ‘

‘242. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is Medium) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

‘243. If (AFO is High) and (HS is High) and (FMR is High) and (AWO is High) and (HFE is High) then (Fall_hazard_occurrence is Almost_Certain) (1) ‘

VITA AUCTORIS

NAME: Mohammadsaeid Parsamehr
PLACE OF BIRTH: Hamedan, Iran

YEAR OF BIRTH: 1994

EDUCATION: Madani High School, Hamedan, Iran, 2013

Bu-ali Sina University, B.Sc., Hamedan, Iran, 2018

University of Windsor, M.A.Sc., Windsor, ON, 2020