9-14-2022

BIM Integrated Bid Proposal Evaluation Tool to Aid Sustainable Procurement of Water supply infrastructure projects

Dilusha Hemaal Kankanamge
University of Windsor

BIM Integrated Bid Proposal Evaluation Tool to Aid Sustainable Procurement of Water supply infrastructure projects

by

Dilusha Hemaal Kankanamge

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

2022

BIM Integrated Bid Proposal Evaluation Tool to Aid Sustainable Procurement of Water supply infrastructure projects

by

Dilusha Hemaal Kankanamge

APPROVED BY:

____

M. Zhang
Odette School of Business

____

R. Carriveau
Department of Civil and Environmental Engineering

____

R. Ruparathna, Advisor
Department of Civil and Environmental Engineering

July 29, 2022

DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

- Chapter 5 of this thesis include the outcome of a publication which has the following other co-author: Dr. Rajeev Ruparathna. In all cases only my primary contribution towards this publication is included in this thesis, and the contribution of co-author Dr. Rajeev Ruparathna was primarily through contributed feedback on refinement of ideas and editing of the manuscript.
- Chapter 2, 3 and 6 incorporates unpublished material co-authored with Dr. Rajeev Ruparathna. In all cases the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by myself. Dr. Rajeev Ruparathna contributed through feedback on 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, with the above qualification, 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 to journals for publication, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Chapter 4	Kankanamge, D. H., & Ruparathna, R. (2022). Adopting Ecolabels in the Construction Industry via Blockchain. *CSCE 2022 Annual Conference* Whistler, British Columbia	2022

Chapter 2	Kankanamge, D. H., & Ruparathna, R. (2022). Life Cycle Thinking for Sustainable Public Procurement in Infrastructure Projects: A State-of-the-Art Review. *Canadian Journal of Civil Engineering*	Under peer review
Chapter 3	Kankanamge, D. H., & Ruparathna, R. (2022). Sustainable bid proposal evaluation for water supply infrastructure projects: An automated BIM-based plugin toolkit. *Journal of Cleaner Production*	Under peer review
Chapter 5	Kankanamge, D. H., & Ruparathna, R. (2022). Investigating the implementation of BIM-based sustainable procurement by using Bayesian Belief Networks (BBN)	Under Preparation

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 or otherwise, are fully acknowledged in accordance with 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

Although water supply infrastructure is a vital component of community infrastructure systems, significant environmental, social, and economic impacts are created throughout its life cycle. Previous researchers have identified sustainable construction procurement as a viable method to enhance the Triple Bottom Line (TBL) performance of construction projects. Adopting sustainable procurement in water supply infrastructure projects has been overlooked primarily due to the lack of quantified environmental and social impact data. Environmental Product Declaration (EPDs), and Social Life Cycle Assessment (S-LCA) have the potential to address the above data challenge. Furthermore, there is a paradigm shift in adopting Building Information Modelling (BIM) in the construction sector, enabling more access to project data. Hence, BIM can be used as a platform to link EPDs, social impact data, and cost data for proposal evaluations. Despite the potential benefits of the above approach, there is an implementation challenge in fidelity of EPD data. A comprehensive review revealed that previous researchers have overlooked TBL-based bid proposal evaluations for water supply infrastructure projects.

The vision of this research is to adopt BIM and sustainable procurement to enhance the delivery of water supply infrastructure projects. This research developed a BIM-based plugin toolkit to conduct an automated TBL-based project proposal evaluation. Furthermore, state-of-the-art implementation support tool for EPDs was developed to support BIM-based sustainable construction procurement. Lastly, a Bayesian Belief Network (BBN) model was developed to evaluate the success of BIM-based construction procurement in the Canadian construction industry. The study revealed that, BIM-based sustainable procurement assists decision-makers in identifying the project proposal with the superior sustainability performance. However, implementation resources and client leadership are required to successfully implement BIM-based procurement in the Canadian construction sector. This research benefits the construction industry and policymakers in enhancing the sustainability of construction procurement. Furthermore, outcomes this research promotes the BIM adaptation in the Canadian construction sector.

To my family

.

ACKNOWLEDGEMENT

I would like to convey my wholehearted gratitude to my supervisor Dr. Rajeev Ruparathna for the immense support throughout my graduate studies. He had faith in me to offer an opportunity to work with him as a graduate student at the University of Windsor. His continuous guidance carried me through all the stages to successfully complete my studies. I am forever in debt for the inspiration, motivation, wisdom, and not to mention the kindness he provided both within my studies and beyond.

I would like to extend my warmest gratitude to my committee members, Dr. Rupp Carriveau and Dr. Minjie Zhang. The advice and encouragement I received from them have helped me to improve the quality of this thesis. Moreover, I would like to acknowledge the Faculty of Engineering and the Department of Civil and Environmental Engineering, and the administrative staff at the University of Windsor for their support.

My sincere gratitude goes to Dr. Jennifer Teague and the entire Canadian Standards Association (CSA Group) for awarding me with the CSA graduate scholarship to fund my thesis.

The support I received from my research team at the Building Information Modelling laboratory has been fantastic. I would like to mention Ms. Zahra Mokhtari, Ms. Pranita Shinde, Mr. John Akana, Mr. Tharindu Dodanwala, Mr. Kartik Patel, and Mr. Saeid Parsamehr for their valued input and especially for making my time at the University of Windsor a memorable one.

Last but not least, I would like to thank my parents, who were the pillars of my success throughout my entire life. I consider myself fortunate to be their son. I would also like to mention my sister, who was always there for me. Without their love and care, none of my achievements would have been possible.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

API	Application programming interface
BBN	Bayesian belief network
BIM	Building information modelling
BOO	Build-own-operate
BOOT	Build-own-operate-transfer
COG	Center of gravity
CPr	Crisp probability
CSV	Comma separate values
DB	Design-build
DBB	Design-bid-build
DBOT	Design-build-operate-transfer
EPD	Environmental product declaration
FBN	Fuzzy Bayesian network
FST	Fuzzy set theory
GHG	Greenhouse gas
GIS	Geographic information system
ICT	Information communication technology
ISO	International standards organization
KPI	Key performance indicators
LCC	Life cycle cost
LCCA	Life cycle cost assessment
LCT	Life cycle thinking
MCDM	Multi criteria decision making
POW	Proof of Work
PPP	Public-private-partnerships
PVC	Poly vinyl chloride
RIW	Relative importance weightages
SHDB	Social hotspots database
S-LCA	Social life cycle assessment
SP	Sustainable procurement
TBL	Triple bottom line
TKY	Turnkey
uEPD	Updated Environmental product declaration

CHAPTER 1
INTRODUCTION

1.1 Background

Sustainable development has been heavily discussed amongst world leaders in recent years. Sustainability has been defined as the ability to "meet the needs of the present generation without compromising the ability of future generations to meet their own needs" (WCED, 1987). In aiding this, the United Nations have set 17 Sustainable development goals to be achieved by 2030 (United Nations, 2015). This research supports four sustainable development goals, innovative infrastructure (goal 9), sustainable public procurement (goal 12), accessibility to clean water (goal 6), and climate action (goal 13).

Potable water has been a basic need throughout the existence of mankind. In 2021 approximately 2.2 billion people around the world did not have access to continuous clean water (World Bank, 2021), and a significant portion of that people live in developing countries. However, even in developed countries like Canada, it was found that about 82,400 people did not have access to clean water in 2017 (Wong, 2017). With the rapid growth of the human population, the need for water supply infrastructure projects keeps accumulating (Roser et al., 2019). According to the World Bank Group (2021) and Asian Development Bank (ADB, 2021), a rapid increase in water supply infrastructure projects is expected to be seen in both developed and developing countries.

Water supply infrastructure projects fabricate numerous negative impacts during their life cycles. ECAM (2021) stated that 5% of the global greenhouse gas (GHG) emissions are emitted by the water supply and sanitation sectors. Additionally, significant environmental impacts, such as excessive resource usage, disturbances to the groundwater systems, and emissions of harmful substances, occurred during the construction of water supply infrastructure systems. While green initiatives have been a popularly adopted strategy for sustainability, social and economic paradigms must also be taken into consideration. Published literature has criticized the construction industry supply chains for unsafe work conditions and the high risk of impacting human and labor rights (Khosravi et al., 2014; Wagner & Berntsen, 2016; Adjei-Bamfo et al., 2019; Heddebaut & di Ciommo, 2018). Moreover, water supply projects are associated with substantial capital construction and maintenance costs, raising the need for considering the full life cycle cost as the basis of the evaluation (Fitch et al., 2018). There is a need to enhance the sustainability performance of water supply infrastructure projects by adopting comprehensive solutions.

Sustainable procurement has been identified as a viable strategy for enhancing the sustainability performance of construction projects (Agarchand & Laishram, 2017). Procurement is a set of activities related to purchasing goods, services, and works which are vital to achieving the project goals (Sears et al., 2008). Since procurement holds the power of purchasing, it has the potential to manipulate the purchase of goods, services, and works with minimum environmental, social, and economic impacts. Bid proposal evaluation is a common process in procurement for various project delivery methods (Pietroforte & Miller, 2002; Ruparathna & Hewage, 2015). Hence, TBL-based bid proposal evaluation allows the buyer to purchase sustainable goods, services and works with a superior sustainability performance.

TBL-based selection criteria are often overlooked due to various challenges. Ruparathna & Hewage (2015b) have identified data and data management challenges as major drawbacks in evaluating the sustainability performance of infrastructure assets. Similarly, evaluating the environmental, social, and economic performance of water supply infrastructure projects has been hindered due to the lack of resources and know-how. With the development of information communication technology (ICT), there are potential computer-based solutions which provide a platform for comprehensive infrastructure project evaluation. Yet the construction sector has been adopting a laid-back approach to adopting ICT solutions. Consequently, the construction sector is ranked in the lowest tier for adapting to ICT (Agarwal et al., 2016).

1.2 Research gap

The premise for this research stems from the knowledge gaps identified below. These challenges are specific to water supply infrastructure projects.

1.2.1 The lack of TBL-based proposal evaluation methods for water supply infrastructure projects

The current bid proposal evaluation, which is based on the lowest cost, has been criticized in the literature (Hall 2010; Hampton 1994). Previous researchers have primarily considered life cycle cost (Gransberg and Molenaar, 2004; Chan et al., 2010) and environmental impacts (Kankananamge and Ruparathna, 2022). However, less emphasis has been provided on incorporating social impacts (Hueskes et al., 2017). A comprehensive TBL-based evaluation requires a combination of TBL of sustainability (Agarchand & Laishram, 2017). Yet, a comprehensive evaluation criterion considering environmental, social, and economic impacts has not been used in the water supply infrastructure project proposal evaluation.

1.2.2 Challenges with data accuracy and transparency in TBL based proposal evaluation

Environmental product declaration (EPD) provides quantified data for environmental performance evaluation (Kankanamge & Ruparathna, 2022). Even though, EPDs are valid for substantial periods, the dynamic nature of the supply chains can hinder the credibility of EPD data (Del-Borghi, 2013). In order to address the above, state-of-the-art methods can be used to enhance the real-time accuracy of EPD data.

1.2.3 Challenges with BIM implementation in infrastructure sector

The implementation of BIM is yet to mature in the construction industry (Smith, 2014). This is due to the lack of comprehensive BIM open-source file formats, resources, expert users, guidelines, and BIM libraries (Criminale & Langar, 2017; Smith, 2014). BIM usage in building project delivery has achieved significant advancements with a considerable amount of implementation resources. However, unavailability of standard file formats for sustainable procurement and water supply infrastructure is a major drawback for BIM implementation.

The above literature gaps have raised the following research questions:

I. How to minimize the TBL-based impacts created by water supply infrastructure projects?
II. How to overcome the data accuracy challenges of sustainable procurement evaluation?
III. How to ensure the successful implementation of a BIM-based sustainable procurement?

1.3 Motivation and expected benefits

The motivation for this research originated from two contemporary trends in the construction sector. The first trend is the negative impacts caused by the construction sector. For example, construction material production accounts for 11% of the total GHG emissions in the world (IEA, 2019), and the construction sector has been identified as a hazardous and unsafe work environment (The world counts, 2022). The second motivation is the increasing number of future water supply infrastructure projects around the world. Canada and the European Union are expected to spend over $180 billion between the years 2016-2028 (Government of Canada, 2021) and €298 Billion within 2021-2027 (European Commission, 2021), respectively. Moreover, developing nations in the Asia Pacific region are expected to invest more than $1.7 trillion in infrastructure development from 2016-to 2030 (ADB, 2021).

The derived outcomes of this thesis will benefit multiple stakeholders. The infrastructure industry can utilize the findings of this research to aid in their project selection decision-making. Furthermore, policymakers will be able to establish sustainability benchmarks utilizing the proposed method. Lastly, researchers can replicate the proposed methods to adapt sustainable procurement of roads, buildings, and other types of infrastructure.

1.4 Research Objectives

This study intends to improve the life cycle TBL performance of water supply infrastructure projects by developing an innovative and comprehensive bid proposal evaluation method to assist with sustainable construction procurement. This research also addresses challenges associated with the accuracy of environmental performance data, and implementation of BIM-based sustainable procurement. The following are the sub-objectives of this research.

I. Develop and demonstrate a BIM-based automated bid proposal evaluation tool to assist in sustainable procurement of water supply infrastructure projects.

II. Develop a framework to overcome the data accuracy of EPDs using blockchain to assist sustainable procurement.

III. Investigate the successful industrial implementation of the BIM-based sustainable procurement by using Bayesian Belief Networks (BBN).

1.5 Thesis Organization

As shown in Figure 1-1, this research is comprised of six chapters. Chapter 1 consists of an overall introduction to the research elaborating on the challenges, research gaps, motivations, objectives, and overall research organization. In Chapter 2, a comprehensive literature review on sustainable procurement of infrastructure was done to gather the required background knowledge. Chapter 3 presents the methodological framework and the demonstration of the developed BIM-based plugin toolkit to aid sustainable procurement of water supply infrastructure (objective 1). Chapter 4 presents a blockchain-based EPDs verification and maintenance method (Objective 2). This method enhances the data accuracy of EPD data that will be used in the proposed proposal evaluation method in Chapter 3. In Chapter 5, the internal and external factors for the successful implementation of BIM-based sustainable procurement were assessed (Objective 3). Lastly, Chapter 6 converses the conclusions of the research, contributions, and future recommendations.

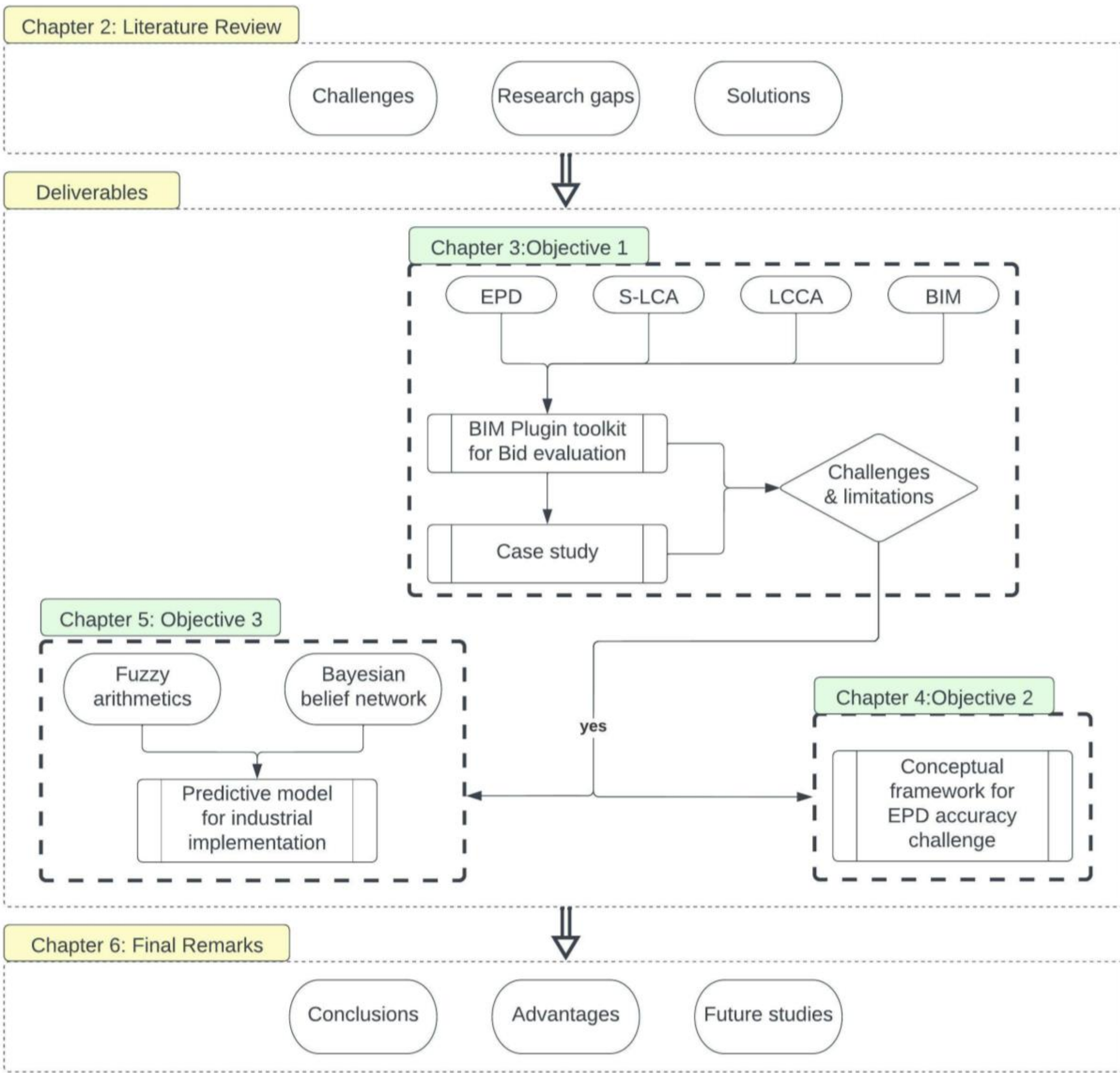

Figure 1-1: Research organization

REFERENCES

ADB. (2021). *Knowledge | Asian Development Bank*. https://www.adb.org/what-we-do/knowledge

Adjei-Bamfo, P., Maloreh-Nyamekye, T., & Ahenkan, A. (2019). The role of e-government in sustainable public procurement in developing countries: A systematic literature review. *Resources, Conservation and Recycling*, *142*, 189–203. https://doi.org/10.1016/j.resconrec.2018.12.001

Agarchand, N., & Laishram, B. (2017). Sustainable infrastructure development challenges through PPP procurement process Indian perspective. *International Journal of Managing Projects in Business*, *10*(3), 642–662. https://doi.org/10.1108/IJMPB-10-2016-0078

Agarwal, R., Chandrasekaran, S., & Sridhar, M. (2016). *Imagining construction's digital future*. https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/imagining-constructions-digital-future2/28

Akintoye, A., Hardcastle, C., Beck, M., Chinyio, E., & Asenova, D. (2010). Achieving best value in private finance initiative project procurement. *Construction Management and Economics*, *21*(5), 461–470. https://doi.org/10.1080/0144619032000087285

BuildingSmart. (2021). *Industry Foundation Classes (IFC)* . https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/

Cetiner, I., & Edis, E. (2014). An environmental and economic sustainability assessment method for the retrofitting of residential buildings. *Energy and Buildings*, *74*, 132–140. https://doi.org/10.1016/J.ENBUILD.2014.01.020

Chan, A. P. C., Lam, P. T. I., Chan, D. W. M., Cheung, E., & Ke, Y. (2010). Critical Success Factors for PPPs in Infrastructure Developments: Chinese Perspective. *Journal of Construction Engineering and Management*, *136*(5), 484–494. https://doi.org/10.1061/(asce)co.1943-7862.0000152

Criminale, A., & Langar, S. (2017). Challenges with BIM Implementation: A Review of Literature . *53rd ASC Annual International Conference Proceedings*. http://www.ascpro.ascweb.org

Del-Borghi, A. (2013). LCA and communication: Environmental Product Declaration. In *International Journal of Life Cycle Assessment* (Vol. 18, Issue 2, pp. 293–295). Springer Verlag. https://doi.org/10.1007/s11367-012-0513-9

Dimitri, N., Piga, G., & Spangnolo, G. (2006). *Handbook of Procurement*. Cambridge University Press. https://faculty.fuqua.duke.edu/~marx/bio/papers/KovacicMarshallMarxRaiffHandbook2006.pdf

Dixon, J. A., & Fallon, L. A. (1989). The concept of sustainability: Origins, extensions, and usefulness for policy. *Society and Natural Resources*, *2*(1), 73–84. https://doi.org/10.1080/08941928909380675

ECAM. (2021). *Assessing the carbon footprint of urban water utilities*. www.wacclim.org

European Commission. 2021. “Global Gateway.” *Press Corner*. Accessed February 25, 2022. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6433.

Fitch, G. J., Odeh, I., Kautz, F., & Ibbs, C. W. (2018). System Dynamics Models for the Valuation of Real Options in P3 Concession Project Agreements. *Journal of Infrastructure Systems*, *24*(1), 04017047. https://doi.org/10.1061/(asce)is.1943-555x.0000409

Government of Canada. 2021. “Infrastructure Canada - Investing in Canada plan.” *Infrastructure Canada Bilateral Agreements*. Accessed November 7, 2021. https://www.infrastructure.gc.ca/pt-sp/index-eng.html.

Gransberg, D. D., & Molenaar, K. R. (2004). Life-Cycle Cost Award Algorithms for Design/Build Highway Pavement Projects. *Journal of Infrastructure Systems*, *10*(4), 167–175. https://doi.org/10.1061/(asce)1076-0342(2004)10:4(167)

Hardie, M., & Saha, S. (2012). Builders' Perceptions of Lowest Cost Procurement and Its Impact on Quality. *Construction Economics and Building*, *9*(1), 1–8. https://doi.org/10.5130/AJCEB.V9I1.3009

Heddebaut, O., & di Ciommo, F. (2018). City-hubs for smarter cities. The case of Lille "EuraFlandres" interchange. *European Transport Research Review*, *10*(1). https://doi.org/10.1007/s12544-017-0283-3

Hueskes, M., K. Verhoest, and T. Block. (2017). "Governing public–private partnerships for sustainability: An analysis of procurement and governance practices of PPP infrastructure projects." *International Journal of Project Management*, 35 (6): 1184–1195. Elsevier Ltd. https://doi.org/10.1016/j.ijproman.2017.02.020

IEA. (2019). *Global Status Report for Buildings and Construction* . https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019

Ismail, S., & Haris, F. A. (2014). Rationales for public private partnership (PPP) implementation in malaysia. *Journal of Financial Management of Property and Construction*, *19*(3), 188–201. https://doi.org/10.1108/JFMPC-04-2014-0006/FULL/XML

ISO. (2006). *ISO 14025: Environmental labels and declarations* . Standards. https://www.iso.org/standard/38131.html

Kankanamge, D. H., & Ruparathna, R. (2022). Adopting Ecolabels in the Construction Industry via Blockchain. *CSCE 2022 Annual Conference Whistler, British Columbia*, 1–15.

Kankanamge, D. H., & Ruparathna, R. (2022). *Life Cycle Thinking for Sustainable Public Procurement in Infrastructure Projects: A State-of-the-Art Review*.

Karel, W., Brauers, M., Zavadskas, K., Peldschus, F., Turskis, Z., & Kazimieras Zavadskas, E. (2010). *Multi-objective decision-making for road design*. https://doi.org/10.3846/1648-4142.2008.23.183-193

Khosravi, Y., Asilian-Mahabadi, H., Hajizadeh, E., Hassanzadeh-Rangi, N., Bastani, H., & Behzadan, A. H. (2014). Factors Influencing Unsafe Behaviors and Accidents on Construction Sites: A Review. *International Journal of Occupational Safety and Ergonomics*, *20*(1), 111–125. https://doi.org/10.1080/10803548.2014.11077023

Laffont, J.-J., & Tirole, J. (1993). *A Theory of Incentives in Procurement and Regulation* . Massachusetts Institute of Technology.

Liang, C., Lu, W., Rowlinson, S., & Zhang, X. (2016). *Development of a Multifunctional BIM Maturity Model*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001186

NewEarth B. (2022). *Social Hotspots Database*. http://www.socialhotspot.org/

Patel, K., & Ruparathna, R. (2021). Life cycle sustainability assessment of road infrastructure: a building information modeling-(BIM) based approach. *Https://Doi.Org/10.1080/15623599.2021.2017113*. https://doi.org/10.1080/15623599.2021.2017113

Pietroforte, R., & Miller, J. B. (2002). Procurement methods for US infrastructure: Historical perspectives and recent trends. *Building Research and Information*, *30*(6), 425–434. https://doi.org/10.1080/09613210210159875

Qiao, Y., & Wang, C. (2011). Issues and Challenges in Implementing China'sGreen Public Procurement Program. *Journal of Environmental Protection*, *02*(08), 1034–1045. https://doi.org/10.4236/jep.2011.28119

Roser, M., Ritchie, H., & Ortiz-Ospina, E. (2019). World Population Growth. In *Molecular Biology and Evolution* (Vol. 17, Issue 1). Society for Molecular Biology and Evolution. https://doi.org/10.1093/OXFORDJOURNALS.MOLBEV.A026233

Ruparathna, R., & Hewage, K. (2015). Sustainable procurement in the canadian construction industry: Challenges and benefits. *Canadian Journal of Civil Engineering*, *42*(6), 417–426. https://doi.org/10.1139/CJCE-2014-0376/ASSET/IMAGES/CJCE-2014-0376TAB10.GIF

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM Handbook: A Guide to Building Information Modelling for Owners, Designers, Engineers, Contractors and Managers* (3rd ed.). John Wiley & sons.

Salehabadi, Z. M., & Ruparathna, R. (2022). User-centric sustainability assessment of single family detached homes (SFDH): A BIM-based methodological framework. *Journal of Building Engineering*, *50*. https://doi.org/10.1016/J.JOBE.2022.104139

Sears, K. S., Sears, G. A., & Clough, R. H. (2008). *Construction Project Management* (5th ed., Vol. 1). John Wiley & Sons, Inc.

Smith, P. (2014). BIM implementation - Global strategies. *Procedia Engineering*, *85*, 482–492. https://doi.org/10.1016/j.proeng.2014.10.575

The world counts. (2022). *Child Labor Facts and Statistics*. From the Sweat of Our Children. https://www.theworldcounts.com/stories/Child-Labor-Facts-and-Statistics

Tien Doan, D., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ur Rehman, A., Tookey, J., & Ghaffarianhoseini, A. (2019). What is BIM? A Need for A Unique BIM Definition. *MATEC Web of Conferences*. https://doi.org/10.1051/matecconf/2019

Tzeng, G.-H., & Huang, J.-J. (2011). Multiple Attribute Decision Making - Methods and Applications. In *Multiple Attribute Decision Making*. Taylor & Francis. https://doi.org/10.1201/b11032-9

United Nations. (2015). *THE 17 GOALS | Sustainable Development*. https://sdgs.un.org/goals

Wagner, I., & Berntsen, L. (2016). Restricted rights: obstacles in enforcing the labour rights of mobile EU workers in the German and Dutch construction sector. *Transfer*, *22*(2), 193–206. https://doi.org/10.1177/1024258916636025

WCED. (1987). Our Common Future . In *Medicine, Conflict and Survival*. Oxford University Press. https://doi.org/10.1080/07488008808408783

Wong, D. (2017). Hundreds of Thousands of Canadians Don't Have Access To Clean Water . *Better Dwelling*. https://betterdwelling.com/hundreds-thousands-canadians-dont-access-clean-water/

World Bank. (2021). *Water Overview*. https://www.worldbank.org/en/topic/water/overview#1

World Bank Group. (2021). *Infrastructure | Data*. Data. https://data.worldbank.org/topic/infrastructure

Zak, J., & Vitasek, S. (2018). Bim superior approach for infrastructure construction in the Czech Republic. *Engineering for Rural Development*, *v 17*, p 578-584. https://doi.org/10.22616/ERDev2018.17.N210

CHAPTER 2

LIFE CYCLE THINKING FOR SUSTAINABLE PUBLIC PROCUREMENT IN INFRASTRUCTURE PROJECTS: A STATE-OF-THE-ART REVIEW

A version of this chapter has been submitted to Canadian Science publishing journal *Canadian Journal of Civil Engineering* titled as "Life Cycle Thinking for Sustainable Public Procurement in Infrastructure Projects: A State-of-the-Art Review" and currently under peer review.

2.1 Introduction

Contemporary census data have projected the urban population to increase up to 10.5 billion by 2050 (European Strategy and Policy Analysis System, 2019). Consequently, the demand for the core civil infrastructure such as water supply, sanitation, and transportation will continue to grow exponentially. Thus, the first world developed countries such as Canada are also expected to spend over $180 billion between the years 2016-2028 (Government of Canada, 2021), and European Union plans to invest around €298 Billion within 2021-2027 (European Commission, 2021). The same, if not more, has been seen in developing nations in Asia and the Pacific region, which are expected to annually invest more than $1.7 trillion from 2016-to 2030 (ADB, 2021) for infrastructure development. The mounting demand for infrastructure projects potentially decreases the likelihood of achieving global sustainability goals (United Nations, 2015) unless major revisions are made to the current practices. This trend can be manipulated by incorporating the triple bottom line (TBL) of sustainability into the procurement of infrastructure projects (Cui et al., 2020; Fitch et al. 2018; Love et al. 2015).

Procurement can be used to enhance the sustainability performance of infrastructure projects (Ruparathna, 2013). Similarly, the procurement process influenced by sustainability can greatly support the sustainable development of a nation (UNEP, 2005). Procurement can also be utilized to promote innovation, performance, and efficiency, which ultimately leads to the sustainability of the project (Eriksson et al., 2019). Said that procurement is typically conducted disregarding environmental and social concerns by pursuing the lowest cost approach (Hardie & Saha, 2012). With the increased emphasis on TBL of sustainability in the past decade, sustainable procurement (SP) has become a popular topic. SP incorporates environmental and social considerations along with traditional areas of focus such as price, quality, and availability into the purchasing decision

(Treasury Board of Canada Secretariat, 2019; Meehan and Bryde, 2011). However, there are several challenges to SP that prevent projects from achieving superior sustainability performance.

Lack of uniformity in green product definition and evaluation criteria, lack of information, insufficient resources for public SP, and relying on a single method-administrative means are negatively affecting SP (Chigudu, 2014; Manu et al., 2018; Qiao and Wang, 2011; Ruparathna and Hewage, 2015b). Hence, adaptation to green products, evaluation criteria, and efficient data management tools can enhance the sustainability performance of infrastructure projects. Even though the data-driven infrastructure sector is known to be complex and high in magnitude (Dodanwala and Santoso, 2021; Dodanwala and Shrestha, 2021; Kankanamge and Santoso, 2021), Building Information Modelling (BIM) has the potential to accommodate sustainability to the infrastructure procurement (Aguiar-Costa and Grilo, 2015). BIM is a computer-based collaborative platform where multiple stakeholders can improve the life cycle management of a project (Tien-Doan et al., 2019). Being an information repository of a construction project, BIM can address the above-identified challenges to aid SP.

Ghadimi et al. (2015) Hong et al. (2012). Ruparathna and Hewage (2015) and Yu et al. (2020) have investigated the research trends of SP in the construction industry in general. They have identified only a handful of studies focus on promoting SP to the construction industry compared to other areas of interest for construction. Agarchand and Laishram (2017) and Regan et al. (2011) have studied the published literature trends in SP of infrastructure projects. However, these studies only investigated the shortcomings of the Public-Private-Partnerships (PPP) respectively, in the Indian and Australian infrastructure sectors. Despite BIM having the potential to enhance the SP of infrastructure projects, research on BIM adaptation has been minimum (Yalcinkaya and Singh, 2015), even though the general research on BIM has shown an increasing trend (Tang et al., 2019; Walker et al., 2012). Therefore, a gap in the literature is observed in SP of infrastructure projects and BIM adaptation for SP.

Driven by the demand for infrastructure and the lack of sustainability practices in infrastructure procurement, contemporary literature review on the subjected domains will advocate sustainability in construction as well as will be beneficial in policy formation. Thus, this study aims to investigate literature content on SP against the key performance indicator (KPIs) of infrastructure projects and identify the potential implementation solutions such as BIM potentials to improve SP. This study delivers the latest research trends in SP and identifies more gaps in the literature for future research. This study will inform public sector institutions to enhance the sustainability of procurement practices and promote BIM adaptation in the heavy construction industry.

2.2 Sustainable infrastructure and procurement

In order to conduct a comprehensive review of SP procurement, it is crucial to identify KPIs of infrastructure delivery. Out of numerous sources, infrastructure rating guides have been identified as credible sources in extracting the KPIs. Compared to building sustainability rating systems, fewer rating systems are available for the infrastructure (FIDIC 2021). Therefore, the Institute for Sustainable Infrastructure (ISI) ENVISION: Sustainable Infrastructure Framework (Institute for Sustainable Infrastructure, 2018), Canada Green Building Council (CGBC) Neighbourhood Development (Canada Green Building Council 2012), Infrastructure Sustainability Council of Australia's (ISCA) IS Rating Scheme (Infrastructure Sustainability Council of Australia, 2020), and BRE Global for sustainable infrastructure`s CEEQUAL Version 6 (BRE Global Limited, 2019) were selected to extract the categories & KPIs. All four selected rating guides were selected based on the exclusiveness of infrastructure and credibility. In fact, these rating systems were accredited by The International Federation of Consulting Engineers (FIDIC) and CGBC.

Table 2-1 compares common KPIs used in the above rating guides. Each rating guide identified above is precisely developed for the infrastructure sector and related to its countries' practices. Each rating criteria has covered all the sections in accordance with the triple bottom line of sustainability. Significant similarities can be observed among the rating guides. All identified categories & KPIs were reviewed to avoid duplication. Overall, 67 KPIs were identified as KPIs that can be characterized into five categories. Each KPI represents a solution to improve the sustainability of infrastructure projects from a Life Cycle Thinking (LCT) point of view.

Table 2-1: KPIs of infrastructure projects

Code	KPI	ISI	CaGBC	ISCA	BRE
QP	QUALITY OF PUBLIC LIFE IMPROVEMENT				
QP_1	Improve Community Quality of Life	y	y	y	y
QP_2	Enhance Public Health & Safety	y	y	y	
QP_3	Improve Construction Safety	y			
QP_4	Minimize Noise & Vibration	y	y		y
QP_5	Minimize Light Pollution	y	y		y
QP_6	Minimize Construction Impacts	y	y		y
QP_7	Improve Community Mobility & Access	y	y		y
QP_8	Encourage Sustainable Transportation	y	y		y
QP_9	Improve Access & Wayfinding	y	y		
QP_10	Advance Equity & Social Justice	y			
QP_11	Preserve Historic & Cultural Resources	y	y	y	y
QP_12	Enhance Views & Local Character	y	y		
QP_13	Enhance Public Space & Amenities	y	y		
QP_14	Regional priority		y		
QP_15	Certified green buildings		Y		
QP_16	Develop Local Skills & Capabilities	y			
LD	LEADERSHIP AND MANAGEMENT				

LD_1	Provide Effective Leadership & Commitment	y			y
LD_2	Foster Collaboration & Teamwork	y			y
LD_3	Provide for Stakeholder Involvement	y		y	y
LD_4	Pursue Byproduct Synergies	y			
LD_5	Establish a Sustainability Management Plan	y			
LD_6	Plan for Sustainable Communities	y			
LD_7	Plan for Long-Term Monitoring & Maintenance	y			y
LD_8	Plan for End of Life	y			
LD_9	Stimulate Economic Prosperity & Development	y			
LD_10	Conduct a Life-Cycle Economic Evaluation	y			y
LD_11	Environmental management plan				y
LD_12	Social management plan			y	
LD_13	Responsible construction management			y	y
LD_14	Innovation		y	y	y
LD_15	Solid waste management infrastructure		y	y	
RA	RESOURCE ALLOCATION				
RA_1	Use Recycled Materials	y	y	y	y
RA_2	Reduce Operational Waste	y		y	y
RA_3	Reduce Construction Waste	y		y	y

RA_4	Balance Earthwork On Site	y		y	
RA_5	Reduce Operational Energy Consumption	y	y	y	y
RA_6	Reduce Construction Energy Consumption	y	y	y	y
RA_7	Use Renewable Energy	y	y	y	
RA_8	Commission & Monitor Energy Systems	y	y		
RA_9	Preserve Water Resources	y	y	y	y
RA_10	Reduce Operational Water Consumption	y	y	y	y
RA_11	Reduce Construction Water Consumption	y	y	y	y
RA_12	Monitor Water Systems	y	y		
EP	ENVIRONMENTAL PRESERVATION				
EP_1	Preserve Sites of High Ecological Value	y	y	y	y
EP_2	Provide Wetland & Surface Water Buffers	y	y		y
EP_3	Preserve Prime Farmland	y	y		y
EP_4	Preserve Undeveloped Land	y		y	y
EP_5	Reclaim Brownfields	y	y		
EP_6	Manage Stormwater/Wastewater	y	y		y
EP_7	Reduce Pesticide & Fertilizer Impacts	y			
EP_8	Protect Surface & Groundwater Quality	y			y
EP_9	Enhance Functional Habitats	y	y		y

EP_10	Enhance Wetland & Surface Water Functions	y	y		y
EP_11	Maintain Floodplain Functions	y	y		
EP_12	Control Invasive Species	y			
EP_13	Protect Soil Health	y			
EP_14	Land use and value				y
CR	CLIMATE AND RESILIENCE				
CR_1	Reduce Net Embodied Carbon	y		y	y
CR_2	Reduce Greenhouse Gas Emissions	y		y	
CR_3	Reduce Air Pollutant Emissions	y		y	
CR_4	Avoid Unsuitable Development	y		y	y
CR_5	Assess Climate Change Vulnerability	y		y	
CR_6	Evaluate Risk and Resilience	y			
CR_7	Establish Resilience Goals and Strategies	y			
CR_8	Maximize Resilience	y			y
CR_9	Improve Infrastructure Integration	y			
CR_10	Heat island reduction		y		

i. Quality of Public Life Improvement (Category QP): 15 KPIs were identified for Quality of Public Life Improvement. This category concerns how to improve public social life through a particular infrastructure project. As an example, whether the project increases job opportunities for the locals and whether local vendors are benefited from the project. This category checks whether the project disturbs the current lifestyle public through noise pollution or destroys any cultural heritages. Overall, this category assesses if the public living standards can be improved.

ii. Leadership and Management (Category LD): This category includes KPIs such as planning for end life, communication, innovation, and efficiency of the project in terms of LCT. The leadership of a project is the stakeholder, which takes all the decisions of a project. Therefore, improving and adhering to the KPIs in the LD category will enhance sustainable decision-making.

iii. Resource Allocation (Category RA): This category focuses on the sustainability of resource utilization. KPIs such as waste reduction, use of recycled material, use of renewable energy, energy efficiency, and preservation of water are included in this category.

iv. Environmental Preservation (Category EP): Environmental Preservation addresses how to understand and minimize negative impacts on the environment while considering ways in which the infrastructure can interact with natural systems in a synergistic, positive way. KPIs considered in the category include how to protect them and preserve waterbodies, reclaim brownfields, control invasive species, balance the eco system, and land use to ensure the selection of lands does not harm any ecosystems.

v. Climate & Resilience (Category CR). The scope of Climate & Resilience is bi-fold and focuses on minimizing emissions that contribute to climate change and ensuring that the infrastructure system is resilient to changing conditions.

Incorporating the KPIs identified in Table 1 into procurement is not as straightforward as it may seem due to multiple processes of multiple procurement strategies available in practice. Therefore, it is important to identify which processes and which strategies the KPIs can be incorporated. Procurement strategies are classified varying on two groups: the type of project delivery and the method of project finance (Miller, 1995). More often, a combination of both types of procurement strategies is practiced tailoring the governmental policies and nature of the project.

Project delivery method: Project delivery methods are often determined by how the procurement is conducted for that project. The entire project procurement can be done as a whole or segmentwise. In segmented procurement, various phases of the project, such as the design phase, construction phase, and operation phase, are procured separately for different contractors (Gordon, 1994; Sweet, 1994). E.g., Design-Build (DB), Design-Bid-Build (DBB), and Turnkey (TKY).

Method of project finance: The method of finance is either direct funding or indirect funding. Indirect funding, the client funds the project, and in indirect funding, a third-party entity will be funding the project with a partnership typically called as Public-Private-Partnerships (PPP). The third-party entity shall take the financial risks for the exchange of future revenues, and in certain scenarios, the third-party entity shall handover the property to the client upon the initial grace period for revenue generation (Pietroforte and Miller, 2002). E.g., Design-Build-Operate-Transfer (DBOT), Build-Own-Operate (BOO), and Build-Own-Operate-Transfer (BOOT)

Ruparathna (2013) has identified requirement definition, bid calling, evaluation, and contract awarding as some of the common processes for any procurement strategy. In the scope of the contemporary and comprehensive literature review, it is crucial to look into the KPI adaptation in the identified procurement strategies and procurement process, as well as in developing a typical, sustainable, BIM-based bidding procedure for various project delivery methods.

2.3 Methodology

The methodology used in this research consists of filtering peer-reviewed journal articles on the subject of SP in infrastructure projects, conducting the bibliometric analysis, and conducting content analysis. The widely accepted methodology of keyword search in the subject-specific database was used for the identification of related literature (Deng and Smyth, 2013; Ruparathna et al., 2015; Xue et al., 2010). The three-phased methodology used in this research is illustrated in Figure 2-1.

Phase 1: Sustainable infrastructure categories & KPIs: Infrastructure rating guides rate an infrastructure project based on its sustainability performance. Due to their wider usage, it is possible to consider these guides as credible resources that represent KPIs of infrastructure. KPIs identified in each rating guide were extracted and pooled together to avoid duplication. Each rating guide has different sections (categories) to determine a specific sustainability attribute, as available in Table 2-1.The final set of KPIs and categories were defined from selected guides in Section 2.1: Sustainable Infrastructure and Procurement.

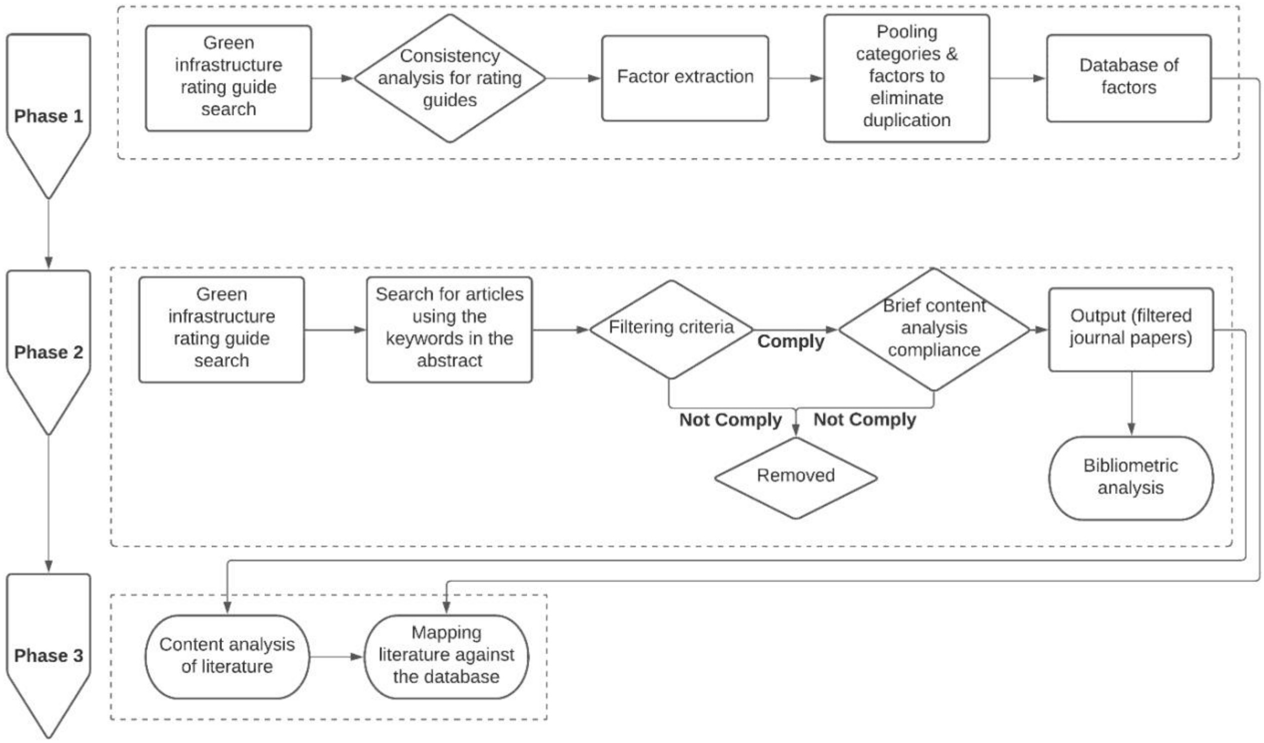

Figure 2-1: Roadmap of the study

Phase 2a: Exploring peer-reviewed journal articles: Compendex Engineering Village search engine for journal articles was used to identify peer-reviewed journal articles on SP via the keywords "Sustainability, Procurement, and Infrastructure." This process allowed to select articles that were solely focused on the SP in infrastructure projects. Journal articles that were published after 2000 were considered for this study to protect the contemporary nature of the study. Identified articles were briefly examined to ensure that the content was related to the scope of this study.

Phase 2b: Trends and Bibliometric Analysis: Once the available peer-reviewed journal articles were identified, a thorough review was conducted to measure the research trends. Research trends of publication years and quality of the articles via the H index were assessed to provide an overview of the status, credibility, and value of the literature in this subject area. Once the filtering criteria were inserted into the Compendex Engineering village search engine, all the complying bibliometric data were filtered and downloaded into a comma separate value (CSV.) file where the analysis was conducted. Using the H-Index of each journal was obtained from a reputed service provider called SCImago. The results were presented in terms of numerical mean and percentages.

Phase 3: Content Analysis: A full-text content analysis of the selected articles was conducted cross-referencing the KPIs determined in Table 2-1. These articles were tabulated with respect to the relevant category and KPI from Table 2-1. Content analysis is conducted for all the Journal Articles that have been filtered. Each article was analyzed according to its scope and findings. Based on the findings of the articles, each article was put into the categories based on what KPI has been discussed. It was determined that even though certain studies passed through the filtering criteria, they did not really emphasize the procurement aspect of sustainable infrastructure.

2.4 State of the current literature on SP of infrastructure

The keywords search in the Engineering Village resulted in 65 peer-reviewed journal articles. However, 6 of those articles were removed from the list due to their noncompliance. The remaining 59 articles were published in 43 different journals and from various regions around the world. Among various bibliometric indicators to measure the quality of the journals, such as cite score, impact factor, and H index, to have a comparison of journals of various ages can be tricky. Impact factor and cite score indicators are based on the number of citations received by a journal for a given time period (Fernandez-Llimos, 2018). Therefore, the cite score and impact factor cannot compare different journals with different ages, and it can only be compared to a given year or years, whereas a certain journal possibly is better than the other in a particular year and otherwise in another given period, it does not provide a full analysis throughout the whole lifespan of the journal. Whereas the H index is the journal's number of articles (h) that have received at least h number of citations over the whole period that the journal has been active (SCImago, 2020). There are 10 journals that have published more than 1 article in the subject field. The H index of all the journals varied from 1 to 258, with the lowest being the Handbook of Environmental Chemistry, Volume 5: Water Pollution and the highest being Renewable and Sustainable Energy Reviews. The average H index of the journals is 69.48, which means each journal has an average of approximately 69 articles with more than 69 citations per article.

Figure 2-2 represents the publication distribution of the selected articles. It can be observed that the highest number of articles on this subject has been published in the year 2019, being 8. However, compared to the 1st decade (between 2000-2010), there are most publications in the second decade; specifically, after 2010, 46 articles have been published, which is around 78% of the total publications done on this subject after 2000. Therefore, the SP in infrastructure projects is becoming a trending topic in the recent past. However, there can be seen a drop in the number of articles published in 2020 and 2021; the main justifiable reason for this dilemma could be the global covid-19 pandemic. Many researchers have focused on investigating the adaptation to the global pandemic in their respective fields (Feng et al., 2020; Bian and Lin, 2020).

Furthermore, a notable fact is that majority of the publications in the last quarter of the selected time span (after 2015) were published in journals which has an H-Index above the 75th percentile of all the H-Index values, which is 106. There are 29 publications between 2015 and 2021, and 11 publications have an H-Index of more than 106, which conveys that these publications are top-notch in quality. Based on the above statistics, it can be deduced that SP has been identified as an important research area, and funding agencies, scientists, researchers, and other parties involved in research and development have focused more on SP of infrastructure than before.

Figure 2-2: Article distribution with year

2.5 Sustainable procurement in infrastructure: a content analysis

There is room for improvements in infrastructure procurement processes. According to Yu et al., the social aspect of sustainability is the least studied area in SP. Previous research and new management thinking have criticized the lowest bid concept in procurement (Hall 2010; Hampton 1994). Therefore, it is important to look for quality-based selection (QBS) criteria that do not solely depend on the price bid (ACEC, 1972). In order to incorporate QBS and sustainability into buildings, Vilas-Boas et al. have conducted a study with green concepts such as energy efficiency and operational costs. Likewise, it is important to investigate what previous researchers have studied and what areas have been paid the least attention to in SP in infrastructure projects.

Table 2-2 categorizes SP literature based on the sustainability categories identified in Section 2. As depicted in Table 2-2, the majority of the articles reviewed have been categorized as LD. Basically, out of 45 journal papers, 26 of them discuss at least 1 KPI in that category. And in terms of LCT, the environmental aspect's representation of categories EP and CR are the least discussed. There are only 15 articles in total in both EP and CR categories that discuss at least one KPI in the respective category.

Table 2-2: Categorization of articles

Category	Articles	Count
QP	(Adjei-Bamfo et al., 2019); (Bouch and Roberts, 2010); (Garvin et al., 2000); (Heddebaut and di-Ciommo, 2018); (Hueskes et al., 2017); (Jefferies and Mcgeorge, 2009); (Kumaraswamy et al., 2015); (Loosemore, 2016); (Montalbán-Domingo et al., 2021); (Oltean-Dumbrava and Miah, 2016); (Oltean-Dumbrava et al., 2012); (Omoregie, 2012); (Pamučar et al., 2021); (Smith et al., 2016)	15
LD	(Alim and Polak, 2016); (Bhaskaran, 2014);(Bjerkan et al., 2019);(Bouch and Roberts, 2010);(Brown et al., 2012);(Chan et al., 2010);(Chan et al., 2005);(Cui et al., 2020); (Fitch et al., 2018);(Goodfellow-Smith et al., 2020); (Gouws, 2015);(Gransberg and Molenaar, 2004); (Hartshorn et al., 2005); (Hartshorn et al., 2005); (Konoza and Sandborn, 2014); (Kumaraswamy et al., 2015); (Lenferink et al., 2013); (Love et al., 2010); (Manu et al., 2019); (Marzouk and Elhesnawi, 2019); (Marzouk and El-Hesnawi, 2018); (Pearson and Pontin, 2013); (Pot, 2021); (Rose et al., 2019); (Sohail and Baldwin, 2004); (Too, 2012)	26
RA	(Arnesano et al., 2012); (Bjerkan et al., 2019); (Bouch and Roberts, 2010); (Clark, 2007); (Garvin et al., 2000); (Gouws, 2015); (Gransberg and Molenaar,	13

	2004); (Hartshorn et al., 2005); (Hueskes et al., 2017); (Kesidou and Sovacool, 2019); (Maybank et al., 2011); (Pamučar et al., 2021); (Smith et al., 2014)	
EP	(Burri et al., 2019); (Cui et al., 2020); (Hartshorn et al., 2005); (Hueskes et al., 2017); (Maybank et al., 2011); (Pamučar et al., 2021); (Smith et al., 2016); (Uttam and le Lann-Roos, 2015)	8
CR	(Arnesano et al., 2012); (Bjerkan et al., 2019); (Cui et al., 2020); (Kesidou and Sovacool, 2019); (Kumaraswamy et al., 2015); (Smith et al., 2016) (Smith et al., 2014)	7

2.5.1 Quality of Public Life Improvement (QP)

The quality of public life improvement (QP) category represents the social aspect of sustainability. The identified KPIs as per Table 2-1 denote the improvements that can be made for the public in terms of mental & physical health, improving local industries and providing employment, preservation of cultural monuments and beliefs, etc. KPIs in the QP category were discussed by only 15 articles which is only 21% of the totally assessed articles. Hueskes et al. (2017) discovered that the social aspect is the least paid attention in infrastructure projects, and therefore, this finding justifies Hueskes et al. (2017). However, Oltean-Dumbrava and Miah (2016) and Oltean-Dumbrava et al. (2012) have studied about QP_4 (Minimize Noise & Vibration) and infused their findings to SP in roads infrastructure to minimize the noise and vibration. Adjei-Bamfo et al. (2019) and Heddebaut and di-Ciommo (2018) have determined that to improve QP-1 (Improve Community Quality of Life), QP_7 (Improve Community Mobility & Access), QP_11 (Preserve Historic & Cultural Resources), and QP_12 (Enhance Views & Local Character) better stakeholder involvement especially the community leaders is necessary. Loosemore (2016) has identified QP_14 (Regional priority), QP_12 (Enhance Views & Local Character), and the lowest bid concept as the barriers to social sustainability in infrastructure.

Scholars have also proposed various approaches to enhance the social sustainability infrastructure procurement, such as Montalbán-Domingo et al. (2021) has established weightages for QP_2, QP_11, and QP_14 to be included in the selection criterion during the procurement process.

Furthermore, Kumaraswamy et al. (2015) have developed a new project delivery method linking PPP with people (as a stakeholder). In this 4P project delivery method, they are improving QP_1, QP_7, QP_9, QP_10-QP_14, and QP_16 KPIs for better social sustainability of the infrastructure project.

2.5.2 Leadership and Management (LD)

The leadership and Management (LD) category represent the stakeholder's involvement throughout the life cycle of a project to enhance effective planning and other decision-making elements to improve the efficiency of time and money. There were 26 journal articles that discuss KPIs in this category which is the highest with 38%.

In order to increase the sustainability of an infrastructure project, it is important to gather all the stakeholder's input, including the private sector and the general public, during the planning stage, which is emphasized by LD_2 (Foster Collaboration & Teamwork), LD_3 (Provide for Stakeholder Involvement), and LD_6 (Plan for Sustainable Communities) (Adjei-Bamfo et al., 2019; Alim and Polak, 2016). According to Bhaskaran (2014), the private sector includes all the micro, small and medium enterprises, and therefore, a much more collaborative project delivery method with more interactions among the stakeholders is recommended. Brown et al. (2012); Chan et al. (2005) have proposed collaborative project delivery methods that include LD_1 (Provide Effective Leadership & Commitment), LD_2 (Foster Collaboration & Teamwork), LD_3 (Provide for Stakeholder Involvement), and LD_14 (Innovation) KPIs. Furthermore, the innovative E-procurement, which is presented by LD_14 (Innovation), has also been studied by Wahid (2013). Kumaraswamy et al. (2015) and Lenferink et al. (2013) have also proposed innovative procurement frameworks with stakeholder involvement and long-term planning, which fall under LD_7 (Plan for Long-Term Monitoring & Maintenance), LD_8 (Plan for End of Life), and LD_14 (Innovation). Lenferink et al. (2013) have linked various stages of infrastructure projects via integrated contract inclusiveness to Design-Build-Finance-Maintain (DBFM) framework for much more sustainable implementation. Gransberg and Molenaar (2004) have investigated about LD_9 (Stimulate Economic Prosperity & Development) and LD_10 (Conduct a Life-Cycle Economic Evaluation) by conducting a life cycle cost analysis and determined that procuring long last material is considered the best bid, and it is far more sustainable than considering the lowest bid. Furthermore, Chan et al. (2010) and Cui et al. (2020) determined that LD_9 (Stimulate Economic

Prosperity & Development), LD_10 (Conduct a Life-Cycle Economic Evaluation), by LD_2 (Foster Collaboration & Teamwork), LD_3 (Provide for Stakeholder Involvement), stable political environment, and judicial government control, and transparency are the KPIs that may determine the success of PPPs. LD_7 (Plan for Long-Term Monitoring & Maintenance) was assessed by, Bjerkan et al. (2019) for the maritime vessel maintenance cost, and Fitch et al. (2018) discussed LD_9 (Stimulate Economic Prosperity & Development) and LD_10 (Conduct a Life-Cycle Economic Evaluation) via a system dynamic model to predict the financial performance of an infrastructure project under various scenarios.

Lastly, certain studies were reviewed and determined that they have investigated the overall leadership and management (LD) category to improve the procurement of infrastructure in a sustainable manner (Marzouk and El-Hesnawi ,2018; Pot, 2021; Rose et al., 2019). LD category is the most investigated category, with around 37% of the articles discussing at least one KPI in the LD category. However, a trend can be seen in most researchers least interested in investigating LD_4 (Pursue Byproduct Synergies), LD_11 (Environmental management plan), LD_12 (Social management plan), and LD_13 (Responsible construction management).

2.5.3 Resource Allocation (RA)

The resource allocation category (RA) provides an overall idea about how the materials and resources are being used in infrastructure projects. 13 articles discussed how it is possible to improve the sustainability of infrastructure via procurement of materials.

According to Arnesano et al. (2012), including RA_7 (Use Renewable Energy) and RA_8 (Commission & Monitor Energy Systems), such as using wave energy and wind energy to the selection criteria shall provide an edge in making the project sustainable. Bjerkan et al. (2019) investigated about RA_5 (Reduce Operational Energy Consumption), RA_6 (Reduce Construction Energy Consumption), and RA_7 (Use Renewable Energy) and mentioned that in the maritime passenger transport sector, the monitoring of energy consumption, using renewable energy sources and reduce operation energy are key components in selecting the best bidders to achieve sustainability. According to Clark (2007) and Kesidou and Sovacool (2019), in developing sustainable communities, centralized energy plants and multiuser involvement will save energy which relates to RA_5 (Reduce Operational Energy Consumption) and RA_8 (Commission &

Monitor Energy Systems). London Olympics in 2012 was one of the major infrastructure projects in the recent past. According to Maybank et al. (2011), the material procured by the management of the London Olympics is recycled material; therefore, it appears that the RA_1 (Use Recycled Materials) has been involved in the procurement of London Olympics.

Furthermore, Gransberg and Molenaar (2004) and Hartshorn et al. (2005) have emphasized the importance of durability in materials for the transportation sector in order to achieve sustainability. KPIs such as RA_1 (Use Recycled Materials), RA_5 (Reduce Operational Energy Consumption), and RA_7 (Use Renewable Energy) has been widely discussed among the scholars in this scope, but RA_2 (Reduce Operational Waste), RA_3 (Reduce Construction Waste), RA_9 (Preserve Water Resources), RA_ 12 (Monitor Water Systems) has not been paid many interests.

2.5.4 Environmental Preservation (EP)

Environmental Preservation (EP) addresses how to minimize negative environmental impacts caused by infrastructure projects. Under this category, only 8 articles were analyzed hence it appears that this category has not been paid much intention in this exclusive subject area.

Burri et al. (2019) have studied about EP_8 (Protect Surface & Groundwater Quality) in procuring sustainable groundwater. They have identified that groundwater quality will be affected by fertilizer and pesticide usage; therefore, in order to protect the groundwater quality, large infrastructure projects must adhere to rectify this issue. EP_5 (Reclaim Brownfields) has been addressed by Burri et al. (2019) and Hartshorn et al. (2005). They have mentioned that due to the large scale of infrastructure projects, the land area it takes is high. Therefore, reclaiming the brownfields should be investigated within the procurement framework. Pamučar et al. (2021) have addressed EP_1 (Preserve Sites of High Ecological Value), EP_3 (Preserve Prime Farmland), EP_4 (Preserve Undeveloped Land), EP_10 (Enhance Wetland & Surface Water Functions), and EP_14 (Land use and value) via a multi-criteria decision-making model to determine the most significant alternative waste disposal facility characteristics. Other than that, in the category of EP, Cui et al. (2020) and Hueskes et al. (2017) have also discussed generally about the importance of environmental preservation in their studies on the scope of procurement in infrastructure projects. Uttam and le Lann Roos (2015) have developed a new procurement procedure that allows the client to engage with the shortlisted bidders to discuss the environmental requirements before awarding the contract. Furthermore, in their model, they have deployed a relative weighting of award criteria, including environmental consideration of long-term and short-term potential environmental threats and how to mitigate them. However, KPIs such as EP_6 (Manage Stormwater/Wastewater), EP_7 (Reduce Pesticide & Fertilizer Impacts), EP_9 (Enhance Functional Habitats) to EP_13 (Protect Soil Health) has not been discussed adequately in this subject area.

2.5.5 Climate and Resilience (CR)

Climate & Resiliency (CR) category represents the emission reduction from infrastructure projects and KPIs that affect robustness and redundancy through resiliency. Due to the rapid climate change phenomena, the scholarly community has shown a great interest in adaptation and resilience. But in the infrastructure sector, this topic has not been discussed. Hence category has been the least discussed category with only 7 articles which is 10% of the totally assessed articles,

Arnesano et al. (2012) have developed a mathematical model for energy planning, which significantly discusses CR_1 (Reduce Net Embodied Carbon) and CR_2 (Reduce Greenhouse Gas Emissions) with regard to carbon reduction and greenhouse emissions reduction. This model will enable efficient decision-making during the procurement of infrastructure projects. Bjerkan et al. (2019) and Smith et al. (2014) also emphasize that machinery and material with less emission shall be given importance in SP of infrastructure projects which address CR_1 (Reduce Net Embodied Carbon), CR_2 (Reduce Greenhouse Gas Emissions), CR_3 (Reduce Air Pollutant Emissions). Incineration plants which procured through PPP shall include a criterion for procurement to make sure the emissions are controlled in a sustainable manner hence the nature of the plant (Cui et al., 2020). As per the assessment, it was able to determine that CR_6 (Evaluate Risk and Resilience) through to CR_10 (Heat Island reduction) have not been discussed in SP of infrastructure. These KPIs represent resiliency; therefore, further research shall be conducted to address the resiliency is SP.

2.6 BIM adaptation for sustainable procurement of infrastructure

EPDs, S-LCA, and LCCA solutions consist of a large amount of data. Thus, conducting a comprehensive evaluation for multiple bid proposals can be time consuming and prone to human errors. Therefore, the need for automation is paramount to conducting a transparent and accurate bid proposal evaluation. BIM is a platform that can manipulate a large amount of construction related data to conduct customized analysis (Tien Doan et al., 2019). BIM is defined as a collaborative platform that enhances the communication process between different stakeholders of a construction project (Alreshidi et al., 2017; Miettinen & Paavola, 2014). Many software providers have developed specific software to aid BIM, however, Autodesk Infraworks is an infrastructure specific BIM software. In fact, it contains the option to script mathematical algorithms to conduct ad hoc evaluation using embedded data in BIM as well as linked with 3rd party databases (Autodesk, 2022). BIM has the potential to aid the sustainability of water supply infrastructure projects as existing BIM initiatives in procurement validate the technology for large scale projects. In the Czech Republic, BIM-based procurement for large-scale infrastructure projects (Over 5.7m Euros) is recommended by the government as way to reach sustainability goals (Zak & Vitasek, 2018). Similarly, the Royal architectural institute of Canada in collaboration with BuildingSmart Canada has begun to develop contracts for BIM applications in industries such as copyrights, model element ownership, and more (RAIC, 2021)

2.6.1 Enhancements for project delivery methods for BIM-based sustainable procurement adaptation

Explicitly in DBB-type project delivery methods, multiple stakeholders are involved due to the segmented nature of procurement. Therefore, incorporating sustainability aspects during the design phase of the project is vital to achieving overall sustainability. Therefore, having BIM as a platform will allow all the stakeholders, not limited to the client and contractor, to provide their input during the design phase. According to Ren et al. (2021) and Sloot et al. (2019), BIM provides the capability to include user-centric parameters such as the identified KPI in the aforementioned sections. Hence, each stakeholder will be able to monitor the sustainability aspects and adapt their efforts accordingly. The collaborative nature of BIM will allow the general public and other not-for-profit organizations to monitor the sustainability of the project during the initial stages and provide inputs for the betterment. In addition, BIM integrated infrastructure procurement expands to actively promote BIM for innovative proposals from the bidders, and the client's role in this is vital (Lindblad and Guerrero, 2020; Lindblad, 2019). However, implementing BIM for infrastructure projects requires additional responsibilities and additional staff, such as an information manager, design coordination manager, and data security manager (Lee et al., 2017).

Thus, the traditional project delivery methods require significant improvements when implementing BIM to achieve sustainability.

There are multiple traditional project delivery methods currently in practice for infrastructure projects. However, BIM integration has not been a feature in any (Asian Development Bank, 2013, 2018; FIDIC, 2011), even though certain tailor-made modifications are done in selected projects to get the BIM benefits (Sloot et al., 2019; Zak and Vitasek, 2018). Gottfried et al. (2015) have proposed an innovative addition, mutual to any project delivery method's bid submission and evaluation framework for public-private partnerships via work technical sheets consisting of a 3-phase submission including a BIM-based submission. Similarly, Mahamadu et al. (2017), Donato et al. (2017), and Ren et al. (2012) have proposed methodologies to conduct bidder evaluations with the aid of BIM that can be used in multiple project delivery methods. Furthermore, certain researchers have emphasized the importance of early involvement of all contractors via BIM, especially in DBB-type project delivery methods (Baldwin et al., 2009; Vernikos et al., 2014). Therefore, it can be concluded that researchers have identified the importance of innovative project delivery methods and proposed improvements to enhance the construction sector. Likewise, integrating sustainability based KPIs into various project delivery methods as well as bidder evaluation criteria via BIM shall navigate the infrastructure sector in a much more sustainable direction.

2.6.2 Challenges in BIM integration for sustainable procurement

Although BIM provides an edge in implementing SP for infrastructure projects, the adaptation is bound to numerous challenges. Researchers have identified a lack of legislation (Bataw et al., 2016), lack of knowledge and resources (Bataw et al., 2016), and interoperability (Hallberg and Tarandi, 2011).

Lack of legislation: Implementation of BIM for infrastructure projects is a new paradigm; therefore, in most countries, legislation for BIM models, such as the ownership of the model, copyrights, data sharing, etc., has not been defined (Bataw et al., 2016). And according to Zak and Vitasek (2018), an extension of time for a given project based on the software and computer delays is not regulated. Furthermore, in multi-stakeholder involvement, the conditions of the involvement of third-party such as the general public, are yet to be stipulated (Vass and Gustavsson, 2017). Due to this lack of legislation, it is horizontal to stakeholder conflicts.

Lack of knowledge and data: BIM implementation for the construction sector itself requires additional knowledge due to its innovativeness. In addition, when implementing BIM-based SP for infrastructure, means of data transferring and tailor-made analysis techniques are required due to the lack of standardization. This conundrum requires firms to provide additional training and resources for their employees to profit from BIM and SP benefits (Bataw et al., 2016). Furthermore, in order to conduct SP based proposal evaluation, a lack of a standard set of indices based on sustainability is also identified as a data challenge (Kankanamge and Ruparathna, 2022)

Interoperability-related issues: BIM integration for sustainability requires multiple multi-stakeholder data sharing. Therefore, interchanging information between various BIM software, commonly known as interoperability, is identified as a crucial process (Marmo et al., 2020). Interoperability is based on standard objects' definitions to be shared between multiple BIM software. Yet, the lack of definitions of object attributes is observed as a major challenge (Marmo et al., 2020). Especially in SP, where the KPIs are not incorporated in the current open-source file formats, which aids interoperability (BuidlingSMART, 2021). Even though ad hoc means are proposed by researchers for selected civil engineering applications to overcome interoperability barriers (Marmo et al., 2020).

2.6.3 Solutions to implement BIM for sustainable procurement

To conduct a comprehensive sustainable evaluation, the requirement of quantified data based on pre-set indices is vital. Emerging green initiatives, such as eco-labels, provide a solution in terms of environmental performance data. Environmental Product Declaration (EPD) is a type III eco-label that contains quantified environmental impact data and has been standardized by the international standards association (ISO, 2006). EPDs consist of pre-defined key performance indicators (KPI) that can be used as parameters to compare the environmental performance of multiple products of a similar domain. Even though for social and economic impacts, standardized KPIs are unavailable in the present, methodologies are in motion to conduct an evaluation. Social life cycle assessment (S-LCA) is a such as methodology to compare products in terms of their social impacts. To assist S-LCA, NewEarth B (2022) has developed a database consisting of social impact risk scores based on the country of manufacture. Using that data, an S-LCA can be conducted for products and determine social impact risk scores based on pre-defined KPIs to conduct an evaluation. Similarly, economic evaluation can be conducted via the data generated by a life cycle cost assessment (LCCA) for each product.

2.7 Discussion

The study analyzed the current research trend of SP in the infrastructure sector via a bibliometric analysis. The journal articles published after the year 2000 were selected from the Compendex Engineering Village databases and filtered through a criterion to select the best-fitting articles. The results of the analysis convey that there has been an increasing trend in the number of publications throughout the years. Furthermore, the H-index of each journal revealed the articles the quality of the research published has increased yearly. Since infrastructure development and partnerships are in the scope of the United Nations in terms of their 2030 sustainable development goals (United Nations, 2015), it is safe to argue that the infrastructure and procurement sector has received better funding in the recent past. Therefore, the number of studies conducted, and the quality of the research work have improved.

The majority of the studies show a trend towards developing the management aspects such as stakeholder involvement, project delivery, and planning of the infrastructure projects. In terms of the social sustainability aspects, a considerable number of studies are conducted on how to include the social parameters such as enhancing public health & safety, preservation of historical & cultural monuments, and regional priority into the selection criteria of procurement. It appears to be that since the world is moving forwards with rapid urbanization, the treasured artifacts need to be preserved to remember their roots. Furthermore, large-scale infrastructure projects may bring change to the surrounding residents' lifestyles. Thus, the locals must benefit from it; therefore, in SP, regional priority shall be considered. Material and the resources used in infrastructure play a huge part in the impacts on the environment. Therefore, most of the researchers have investigated recycled material and renewable energy sources to be utilized in the infrastructure. These aspects are extremely important in compiling SP guidelines. Infrastructure projects pose a significant threat to the environment due to their magnitude. Therefore, the KPIs, such as preservation of natural habitats, reclaiming brownfields, and waste disposal, are a few of the important KPIs of SP that have been discussed in contemporary research. Climate change has been a topic that has been widely discussed over the past decade; greenhouse gasses such as Chlorofluorocarbon emissions during the construction, operations, or maintenance of an infrastructure project shall be minimized. Therefore, procuring high-efficiency machinery and equipment is vital in infrastructure projects.

Furthermore, it was able to determine that there is a knowledge gap in integrating the climate change KPIs not limited to heat island reduction measures, global warming potential, and acidification. Infrastructure resiliency KPIs against flood, tornado, fire, or any other natural disasters, as well as in the environmental sustainability such as preservation of ecological sites, soil health, and land use and value, have not been studied as much as the other aspects of SP. Future possibilities in this subject convey that the utilization of BIM will address most of these gaps in developing SP evaluation frameworks as well as sustainable project delivery methods. Since BIM can include an enormous amount of data, it is possible to manage and mitigate these threats that affect the sustainability of infrastructure projects. Furthermore, it is possible to procure the best proposal in terms of full sustainability and resiliency efficiently and accurately via innovative proposal evaluation methods. Certain researchers indicated that political influences, transparency, and corruption act as barriers to the SP in infrastructure projects (Neupane et al., 2012). Hence, the integration of BIM and e-procurement will provide solutions for these barriers since BIM provides the most transparent form of information about a particular project as well as the easy extraction of the data. However, the study further conveys that there is a gap between integrating SP of infrastructure with BIM in terms of interoperability.

2.8 Summary

SP in infrastructure has been branded as a trending research area among scholars lately. This chapter presents major academic contributions to enhance the SP of infrastructure as well as solutions to implement SP via means of BIM. However, numerous improvements are still required to be satisfied in incorporating sustainability to bid evaluation to overcome interoperability shortcomings, legislations, and standardized guidelines shortcomings, as well as lack of a universally accepted set of indices. With a contemporary comprehensive, state of the art review, the following conclusions were made.

- The research interest in SP in infrastructure among the scholarly community has drastically increased within the last decade, and the quality of the work has exponentially grown within the last 5 years.
- Stakeholder involvement and development of new project delivery methods, inclusive selections criteria, recycled material, and use of renewable energy sources are mainly focused on by the scholars in SP. The same is not observed in emission reduction, preservation of ecological sites, protection of waterbodies, heat island reduction, preservation of cultural heritage, and regional priority KPIs.
- Political forces have an impact on the SP of the infrastructure; therefore, it should be investigated how to include political stability and the interference in infrastructure projects.
- BIM has the potential to integrate sustainability into procurement via an inclusive proposal evaluation method, yet less has been done in this domain.
- Interoperability is identified as a major challenge in implementing BIM. Consequently, a lack of research focusing on open-source file formats to address the interoperability challenge for infrastructure and procurement has been observed.
- The lack of a universal set of indices in assessing environmental, social, and economic performance in infrastructure to conduct procurement evaluations has been identified. And the potential of ecolabels has been acknowledged in addressing the environmental performance evaluation aspect.

Future studies shall be conducted to improve digitalized e-procurement with cutting-edge technologies such as machine learning, cloud-based data sharing, and blockchain. Multi-disciplinary research between civil engineering, computer science, and law is required to enhance the integration of ICT-based solutions for infrastructure procurement and scrutinize the policy and legislation formulation. Lastly, the potential of BIM shall be further investigated for other civil engineering aspects and advocate BIM within both governmental and private organizations.

REFERENCES

ACEC. (1972). *The Brooks Act: federal government selection of architects and engineers*.

ADB. (2021). "Knowledge | Asian Development Bank." Accessed April 16, 2021. https://www.adb.org/what-we-do/knowledge.

Adjei-Bamfo, P., T. Maloreh-Nyamekye, and A. Ahenkan. (2019). "The role of e-government in sustainable public procurement in developing countries: A systematic literature review." *Resources, Conservation and Recycling*, 142: 189–203. Elsevier B.V. https://doi.org/10.1016/j.resconrec.2018.12.001.

Agarchand, N., and B. Laishram. (2017). "Sustainable infrastructure development challenges through PPP procurement process Indian perspective." *International Journal of Managing Projects in Business*, 10 (3): 642–662. https://doi.org/10.1108/IJMPB-10-2016-0078.

Aguiar Costa, A., and A. Grilo. (2015). "BIM-based e-procurement: An innovative approach to construction e-procurement." *Scientific World Journal*, 2015. Hindawi Publishing Corporation. https://doi.org/10.1155/2015/905390.

Alim, S., and J. Polak. (2016). "Public-private partnerships for future urban infrastructure." *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, 169 (4): 150–158. https://doi.org/10.1680/jmapl.16.00001.

Alreshidi, E., Mourshed, M., & Rezgui, Y. (2017). Factors for effective BIM governance. *Journal of Building Engineering, 10,* 89–101. https://doi.org/https://doi.org/10.1016/j.jobe.2017.02.006

Arnesano, M., A. P. Carlucci, and D. Laforgia. (2012). "Extension of portfolio theory application to energy planning problem - The Italian case." *Energy*, 39 (1): 112–124. Elsevier Ltd. https://doi.org/10.1016/j.energy.2011.06.053.

Asian Development Bank. (2013). *Guidelines on the Use of Consultants by Asian Development Bank and Its Borrowers*.

Asian Development Bank. (2018). *ASIAN DEVELOPMENT BANK User's Guide to Procurement of Goods Standard Bidding Document*.

Autodesk. (2022). *InfraWorks 2023* . InfraWorks: Conceptualize Designs in Real-World Context. https://www.autodesk.com/products/infraworks/free-trial

Baldwin, A., H. Li, T. Huang, C. W. Kong, H. L. Guo, N. Chan, and J. Wong. (2009). "Supporting pre-tender construction planning with virtual prototyping." *Engineering, Construction and Architectural Management*, v 16, n 2 (2): p 150-161. https://doi.org/10.1108/09699980910938028.

Bataw, A., R. Kirkham, and E. Lou. (2016). "The Issues and Considerations Associated with BIM Integration." *MATEC Web of Conferences*, v 66. EDP Sciences. https://doi.org/10.1051/matecconf/20166600005.

Bhaskaran, E. (2014). "The Productivity Analysis of Chennai Automotive Industry Cluster." *Journal of The Institution of Engineers (India): Series C*, 95 (3): 239–249. Springer India. https://doi.org/10.1007/s40032-014-0120-6.

Bian, S. X., and E. Lin. (2020). "Competing with a pandemic: Trends in research design in a time of Covid-19." *PLoS ONE*, 15 (9 September). Public Library of Science. https://doi.org/10.1371/JOURNAL.PONE.0238831.

Bjerkan, K. Y., H. Karlsson, R. S. Sondell, S. Damman, and S. Meland. 2019. "Governance in maritime passenger transport: Green public procurement of ferry services." *World Electric Vehicle Journal*, 10 (4). MDPI AG. https://doi.org/10.3390/wevj10040074.

Bouch, C. J., and C. Roberts. (2010). "State of the art for European track maintenance and renewal logistics." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224 (4): 319–326. https://doi.org/10.1243/09544097JRRT315.

BRE Global Limited. (2019). *CEEQUAL Version 6 Technical Manual*.

Brown, K., C. Furneaux, and A. Gudmundsson. (2012). "Infrastructure transitions towards sustainability: A complex adaptive systems perspective." *International Journal of Sustainable*

Development, 15 (1–2): 54–71. Inderscience Publishers. https://doi.org/10.1504/IJSD.2012.044034.

BuidlingSMART. (2021). "Industry Foundation Classes (IFC)" Accessed January 8, 2022. https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/.

Burri, N. M., R. Weatherl, C. Moeck, and M. Schirmer. (2019). "A review of threats to groundwater quality in the anthropocene." *Science of the Total Environment*. Elsevier B.V.

Canada Green Building Council. (2012). *Neighbourhood development*.

Chan, A. P. C., P. T. I. Lam, D. W. M. Chan, E. Cheung, and Y. Ke. (2010). "Critical Success Factors for PPPs in Infrastructure Developments: Chinese Perspective." *Journal of Construction Engineering and Management*, 136 (5): 484–494. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)co.1943-7862.0000152.

Chan, W. T., C. Chen, J. I. Messner, and D. K. Chua. (2005). "Interface Management for China's Build–Operate–Transfer Projects." *Journal of Construction Engineering and Management*, 131 (6): 645–655. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)0733-9364(2005)131:6(645).

Chigudu, D. (2014). "PUBLIC PROCUREMENT IN ZIMBABWE: ISSUES AND CHALLENGES." *Journal of Governance and Regulation*, 3 (4): 21–26.

Clark, W. W. (2007). "Partnerships in creating agile sustainable development communities." *Handbook of Environmental Chemistry, Volume 5: Water Pollution*, 15 (3): 294–302. https://doi.org/10.1016/j.jclepro.2006.02.008.

Cui, C., C. Sun, Y. Liu, X. Jiang, and Q. Chen. (2020). "Determining critical risk factors affecting public-private partnership waste-to-energy incineration projects in China." *Energy Science and Engineering*, 8 (4): 1181–1193. John Wiley and Sons Ltd. https://doi.org/10.1002/ese3.577.

Deng, F., and H. Smyth. (2013). "Contingency-Based Approach to Firm Performance in Construction: Critical Review of Empirical Research." *Journal of Construction Engineering* *and Management*, 139 (10): 04013004. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000738.

Dodanwala, T. C., and D. S. Santoso. (2021). "The mediating role of job stress on the relationship between job satisfaction facets and turnover intention of the construction professionals." *Engineering, Construction and Architectural Management*. Emerald Group Holdings Ltd. https://doi.org/10.1108/ECAM-12-2020-1048. Dodanwala and Santoso, 2021

Dodanwala, T. C., and P. Shrestha. (2021). "Work–family conflict and job satisfaction among construction professionals: the mediating role of emotional exhaustion." *On the Horizon*, 29 (2): 62–75. Emerald Group Holdings Ltd. https://doi.org/10.1108/OTH-11-2020-0042.

Donato, V., C. Biagini, G. Bertini, and F. Marsugli. (2017). "Challenges and opportunities for the implementation of h-bim with regards to historical infrastructures: A case study of the ponte giorgini in castiglione della pescaia (grosseto - Italy)." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, v 42, n 5W1 (5W1): p 253-260. International Society for Photogrammetry and Remote Sensing. https://doi.org/10.5194/isprs-Archives-XLII-5-W1-253-2017.

Eriksson, P. E., L. Volker, A. Kadefors, S. Lingegård, J. Larsson, and L. Rosander. (2019). "Collaborative procurement strategies for infrastructure projects: A multiple-case study." *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, 172 (5): 197–205. https://doi.org/10.1680/jmapl.19.00016.

European Commission. (2021). "Global Gateway." *Press Corner*. Accessed February 25, 2022. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6433.

European Strategy and Policy Analysis System. (2019). *The future of urbanization and Megacities*.

Feng, Y., S. A. Mohamed, T. Le, P. Zhang, W. Shou, W. Bevan, and S. Caldera. (2020). *Sustainable Procurement: Literature Review*. *Western Sydney university research collection*. Sydeny.

Fernandez-Llimos, F. (2018). "Differences and similarities between journal impact factor and citescore." *Pharmacy Practice*. Grupo de Investigacion en Atencion Farmaceutica.

FIDIC. (2011). *FIDIC procurement procedures guide*.

FIDIC. (2021). "Sustainable Infrastructure: rating & certification tools." Accessed February 12, 2021. https://fidic.org/node/5943.

Fitch, G. J., I. Odeh, F. Kautz, and C. W. Ibbs. (2018). "System Dynamics Models for the Valuation of Real Options in P3 Concession Project Agreements." *Journal of Infrastructure Systems*, 24 (1): 04017047. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)is.1943-555x.0000409.

Garvin, M. J., S. C. Wooldridge, J. B. Miller, and T. H. M. J. McGlynn. (2000). "Capital Planning System Applied to Municipal Infrastructure." *Journal of Management in Engineering*, 16 (5): 41–50. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)0742-597x(2000)16:5(41).

Ghadimi, P., A. Hossein Azadnia, C. Heavey, A. Dolgui, and B. Can. (2015). "A review on the buyer-supplier dyad relationships in sustainable procurement context: past, present and future." https://doi.org/10.1080/00207543.2015.1079341.

Goodfellow-Smith, M. E., C. D. F. Rogers, and M. R. Tight. (2020). "Infrastructure value maximisation: finance and insurance appraisal." *Infrastructure Asset Management*, 7 (2): 103–110. Thomas Telford Ltd. https://doi.org/10.1680/jinam.18.00007.

Gordon, C. M. (1994). "Choosing Appropriate Construction Contracting Method." *Journal of Construction Engineering and Management*, 120 (1): 196–210. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)0733-9364(1994)120:1(196).

Gottfried, A., A. C. Devito, B. Daniotti, A. Pavan, and M. A. Chiozzi. (2015). "Methodological framework to improve PPP projects." *ISEC 2015 - 8th International Structural Engineering and Construction Conference: Implementing Innovative Ideas in Structural Engineering and Project Management*, p 1059-1064. ISEC Press. https://doi.org/10.14455/isec.res.2015.8.

Gouws, S. C. (2015). "A review of current tunnelling technology and boring applications in mining and infrastructure development-an EPCM perspective." *Journal of the Southern African Institute of Mining and Metallurgy*. South African Institute of Mining and Metallurgy.

Government of Canada. (2021). “Infrastructure Canada - Investing in Canada plan.” *Infrastructure Canada Bilateral Agreements*. Accessed November 7, 2021. https://www.infrastructure.gc.ca/pt-sp/index-eng.html.

Gransberg, D. D., and K. R. Molenaar. (2004). “Life-Cycle Cost Award Algorithms for Design/Build Highway Pavement Projects.” *Journal of Infrastructure Systems*, 10 (4): 167–175. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)1076-0342(2004)10:4(167).

Hall, J. N. (2010). “Briefing: A practical initiative for the construction industry.” *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 163 (4): 181–183. Thomas Telford Ltd. https://doi.org/10.1680/ensu.2010.163.4.181.

Hallberg, D., and V. Tarandi. (2011). “On the use of open bim and 4d visualisation in a predictive life cycle management system for construction works.” *Journal of Information Technology in Construction (ITcon)*, 16: 445–466.

Hampton, D. (1994). “Procurement Issues.” *Journal of Management in Engineering*, 10 (6): 45–49. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)9742-597x(1994)10:6(45).

Hardie, M., and Saha, S. (2012) “Builders’ Perceptions of Lowest Cost Procurement and Its Impact on Quality.” *Construction Economics and Building*, *9*(1), 1–8. https://doi.org/10.5130/AJCEB.V9I1.3009

Hartshorn, J., M. Maher, J. Crooks, R. Stahl, and Z. Bond. (2005). “Creative destruction: Building toward sustainability.” *Canadian Journal of Civil Engineering*.

Heddebaut, O., and F. di Ciommo. (2018). “City-hubs for smarter cities. The case of Lille ‘EuraFlandres’ interchange.” *European Transport Research Review*, 10 (1). Springer Verlag. https://doi.org/10.1007/s12544-017-0283-3.

Hueskes, M., K. Verhoest, and T. Block. (2017). “Governing public–private partnerships for sustainability: An analysis of procurement and governance practices of PPP infrastructure projects." *International Journal of Project Management*, 35 (6): 1184–1195. Elsevier Ltd. https://doi.org/10.1016/j.ijproman.2017.02.020.

Infrastructure Sustainability Council of Australia. (2020). *IS Rating Scheme*.

Institute for Sustainable Infrastructure. (2018). *ENVISION: Sustainable Infrastructure Framework*. Washington.

Jefferies, M., and W. D. Mcgeorge. (2009). "Using public-private partnerships (PPPs) to procure social infrastructure in Australia." *Engineering, Construction and Architectural Management*.

Kankanamge, D. H., and R. Ruparathna. (2022). "Adopting Ecolabels in the Construction Industry via Blockchain." *CSCE 2022 Annual Conference Whistler, British Columbia*, 1–15.

Kankanamge, D. H., and D. S. Santoso. (2021). "Examining and comparing the facility management services of two universities: Asia and Europe perspectives." *International Journal of Education Economics and Development*, 12 (3): 267. https://doi.org/10.1504/IJEED.2021.10037744.

Kesidou, S., and B. K. Sovacool. (2019). "Supply chain integration for low-carbon buildings: A critical interdisciplinary review." *Renewable and Sustainable Energy Reviews*. Elsevier Ltd.

Konoza, A., and P. Sandborn. (2014). "Evaluating the end of maintenance dates for electronic assemblies composed of obsolete parts." *Journal of Mechanical Design, Transactions of the ASME*, 136 (3). American Society of Mechanical Engineers (ASME). https://doi.org/10.1115/1.4026096.

Kumaraswamy, M., W. Zou, and J. Zhang. (2015). "Reinforcing relationships for resilience – by embedding end-user 'people' in public–private partnerships." *Civil Engineering and Environmental Systems*, 32: 119–129. Taylor and Francis Ltd. https://doi.org/10.1080/10286608.2015.1022727.

Lee, C. Y., H.-Y. Chong, and X. Wang. (2017). "The roles of project stakeholders in EPCM BIM-enabled projects." *International Conference on Research and Innovation in Information Systems, ICRIIS*, v 0. IEEE Computer Society. https://doi.org/10.1109/ICRIIS.2017.8002445.

Lenferink, S., T. Tillema, and J. Arts. (2013). "Towards sustainable infrastructure development through integrated contracts: Experiences with inclusiveness in Dutch infrastructure projects." *International Journal of Project Management*, 31 (4): 615–627. Elsevier Ltd. https://doi.org/10.1016/j.ijproman.2012.09.014.

Lindblad, H. (2019). "Black boxing BIM: the public client's strategy in BIM implementation." *Construction Management and Economics*, v 37, n 1 (1): p 1-12. Routledge. https://doi.org/10.1080/01446193.2018.1472385.

Lindblad, H., and J. R. Guerrero. (2020). "Client's role in promoting BIM implementation and innovation in construction." *Construction Management and Economics*, v 38, n 5 (5): p 468-482. Routledge. https://doi.org/10.1080/01446193.2020.1716989.

Loosemore, M. (2016). "Social procurement in UK construction projects." *International Journal of Project Management*, 34 (2): 133–144. Elsevier Ltd. https://doi.org/10.1016/j.ijproman.2015.10.005.

Love, P. E. D., J. Liu, J. Matthews, C. P. Sing, and J. Smith. (2015). "Future proofing PPPs: Life-cycle performance measurement and Building Information Modelling." *Automation in Construction*, 56: 26–35. Elsevier B.V. https://doi.org/10.1016/j.autcon.2015.04.008.

Love, P. E. D., D. Mistry, and P. R. Davis. (2010). "Price Competitive Alliance Projects: Identification of Success Factors for Public Clients." *Journal of Construction Engineering and Management*, 136 (9): 947–956. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)co.1943-7862.0000208.

Mahamadu, A.-M., L. Mahdjoubi, and C. A. Booth. (2017). "Critical BIM qualification criteria for construction pre-qualification and selection." *Architectural Engineering and Design Management*, v 13, n 5 (5): p 326-343. Taylor and Francis Ltd. https://doi.org/10.1080/17452007.2017.1296812.

Manu, P., A. M. Mahamadu, C. Booth, P. O. Olomolaiye, A. Coker, A. Ibrahim, and J. Lamond. (2019). "Infrastructure procurement capacity gaps in Nigeria public sector institutions."

Engineering, Construction and Architectural Management, 26 (9): 1962–1985. Emerald Group Publishing Ltd. https://doi.org/10.1108/ECAM-11-2017-0240.

Manu, P., A.-M. Mahamadu, C. Booth, P. Olomolaiye, A. Doko Ibrahim, and A. Coker. (2018). "Assessment of procurement capacity challenges inhibiting public infrastructure procurement A Nigerian inquiry." *Built Environment Project and Asset Management*, 8 (4): 386–402. https://doi.org/10.1108/BEPAM-02-2018-0038.

Marmo, R., F. Polverino, M. Nicolella, and A. Tibaut. (2020). "Building performance and maintenance information model based on IFC schema." *Automation in Construction*, 118. Elsevier B.V. https://doi.org/10.1016/J.AUTCON.2020.103275.

Marzouk, M., and M. El-Hesnawi. (2018). "Framework for assessing serviceability and socio-economic risk associated with ppps projects in Libya." *Journal of Civil Engineering and Management*, 24 (7): 556–567. Vilnius Gediminas Technical University. https://doi.org/10.3846/jcem.2018.5623.

Marzouk, M. M., and M. O. Elhesnawi. (2019). "Developing an integrated risk management system for evaluating ppp projects in Libya." *Journal of Engineering and Applied Science*, v 66, n 5: p 635-657.

Maybank, R., J. Roe, I. Guest, B. Laidlaw, and D. Hatton. (2011). "Delivering London 2012: Utilities." *Proceedings of the Institution of Civil Engineers: Civil Engineering*, 164 (6): 17–22. Thomas Telford Services Ltd. https://doi.org/10.1680/cien.2011.164.6.17.

Meehan, J., and D. Bryde. (2011). "Sustainable procurement practice." *Business Strategy and the Environment*, 20 (2): 94–106. https://doi.org/10.1002/bse.678.

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. *Automation in Construction*, *43*, 84–91. https://doi.org/https://doi.org/10.1016/j.autcon.2014.03.009

Miller, J. B. 1995. "Aligning infrastructure development strategy to meet current public needs."

Montalbán-Domingo, L., E. Pellicer, T. García-Segura, and A. Sanz-Benlloch. (2021). "An integrated method for the assessment of social sustainability in public-works procurement." *Environmental Impact Assessment Review*, 89. Elsevier Inc. https://doi.org/10.1016/j.eiar.2021.106581.

Neupane, A., J. Soar, K. Vaidya, and J. Yong. (2012). "Role of public e-procurement technology to reduce corruption in government procurement." Public Procurement Research Center.

Oltean-Dumbrava, C., and A. Miah. (2016). "Assessment and relative sustainability of common types of roadside noise barriers." *Journal of Cleaner Production*, 135: 919–931. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2016.06.107.

Oltean-Dumbrava, C., G. Watts, and A. Miah. (2012). "Procurement of Sustainable Noise-Reducing Devices: State-of-the-Art Review from EU Project QUIESST." *Journal of Management in Engineering*, 28 (3): 324–329. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)me.1943-5479.0000106.

Omoregie, A. (2012). "Culture in sustainable infrastructure: The polycentric cultural framework model." *Proceedings of the Institution of Civil Engineers: Municipal Engineer*, 165 (1): 31–41. https://doi.org/10.1680/muen.2012.165.1.31.

Pamučar, D., A. Puška, Ž. Stević, and G. Ćirović. (2021). "A New Intelligent MCDM Model for HCW Management: The Integrated BWM–MABAC Model Based on D Numbers." *Expert Systems with Applications*, v 175: 114862. Elsevier BV. https://doi.org/10.1016/j.eswa.2021.114862.

Pearson, G., and G. Pontin. (2013). "Briefing: Public-private finance models - Infrastructure procurement." *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, 166 (6): 273–276. https://doi.org/10.1680/mpal.12.00021.

Pietroforte, R., and J. B. Miller. (2002). "Procurement methods for US infrastructure: Historical perspectives and recent trends." *Building Research and Information*, 30 (6): 425–434. https://doi.org/10.1080/09613210210159875.

Pot, W. D. (2021). “The governance challenge of implementing long-term sustainability objectives with present-day investment decisions.” *Journal of Cleaner Production*, 280. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.124475.

Qiao, Y., and C. Wang. (2011). “Issues and Challenges in Implementing China’sGreen Public Procurement Program.” *Journal of Environmental Protection*, 02 (08): 1034–1045. Scientific Research Publishing, Inc,. https://doi.org/10.4236/jep.2011.28119.

RAIC. (2021). *BIM Explained* . http://www.buildingsmart-tech.org/

Regan, M., J. Smith, and P. Love. (2011). “Infrastructure procurement: Learning from private-public partnership experiences ‘down under.’” *Environment and Planning C: Government and Policy*, 29 (2): 363–378. https://doi.org/10.1068/c10122b.

Ren, G., H. Li, S. Liu, J. Goonetillake, A. Khudhair, and S. Arthur. (2021). “Aligning BIM and ontology for information retrieve and reasoning in value for money assessment.” *Automation in Construction*, v 124. Elsevier B.V. https://doi.org/10.1016/j.autcon.2021.103565.

Ren, Y., M. J. Skibniewski, and S. Jiang. (2012). “Building information modeling integrated with electronic commerce material procurement and supplier performance management system.” *Journal of Civil Engineering and Management*, v 18, n 5 (5): p 642-654. https://doi.org/10.3846/13923730.2012.719835.

Rose, T., K. Manley, and K. Widen. (2019). “Do firm-level barriers to construction product innovation adoption vary according to position in the supply chain?” *Construction Innovation*, 19 (2): 212–235. Emerald Group Publishing Ltd. https://doi.org/10.1108/CI-11-2017-0090.

Ruparathna, R., and K. Hewage. (2015a). “Sustainable procurement in the Canadian construction industry: current practices, drivers and opportunities.” *Journal of Cleaner Production*, 109: 305–314. https://doi.org/10.1016/j.jclepro.2015.07.007.

Ruparathna, R., and K. Hewage. (2015b). “Sustainable procurement in the canadian construction industry: Challenges and benefits.” *Canadian Journal of Civil Engineering*, 42 (6): 417–426. Canadian Science Publishing. https://doi.org/10.1139/CJCE-2014-0376/ASSET/IMAGES/CJCE-2014-0376TAB10.GIF.

Ruparathna, R., K. Hewage, and R. Sadiq. (2015). “Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings.” https://doi.org/10.1016/j.rser.2015.09.084.

Ruparathna, R. J. (2013). “Emergy based procurement framework to improve sustainability performance in construction.” Okanagan: University of British Columbia.

Sacks, R., C. Eastman, G. Lee, and P. Teicholz. (2018). *BIM Handbook: A Guide to Building Information Modelling for Owners, Designers, Engineers, Contractors and Managers* . New Jersey: John Wiley & sons.

SCImago. (2020). “Scientific Journal Rankings.” Accessed April 11, 2021. https://www.scimagojr.com/journalrank.php?order=h&ord=desc.

Sloot, R. N. F., A. Heutink, and J. T. Voordijk. (2019). “Assessing usefulness of 4D BIM tools in risk mitigation strategies.” *Automation in Construction*, v 106. Elsevier B.V. https://doi.org/10.1016/j.autcon.2019.102881.

Smith, J., G. Andersson, R. Gourlay, S. Karner, B. E. Mikkelsen, R. Sonnino, and D. Barling. (2016). “Balancing competing policy demands: The case of sustainable public sector food procurement.” *Journal of Cleaner Production*, 112: 249–256. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2015.07.065.

Smith, R., E. Ferrebee, Y. Ouyang, and J. Roesler. (2014). “Optimal Staging Area Locations and Material Recycling Strategies for Sustainable Highway Reconstruction.” *Computer-Aided Civil and Infrastructure Engineering*, 29 (8): 559–571. Blackwell Publishing Inc. https://doi.org/10.1111/mice.12089.

Sohail, M., and A. N. Baldwin. (2004). “Community-partnered contracts in developing countries.” *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*. ICE Publishing.

Sweet, J. (1994). *Legal Aspects of Architecture, Engineering and the Construction Process*. (J. Ed. Sweet and M. M. Schneier, eds.). West Publishing Company, College & School Division.

Tang, S., D. R. Shelden, C. M. Eastman, P. Pishdad-Bozorgi, and X. Gao. (2019). “A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends.” *Automation in Construction*, 101: 127–139. Elsevier B.V. https://doi.org/10.1016/J.AUTCON.2019.01.020.

Tien Doan, D., A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ur Rehman, J. Tookey, and A. Ghaffarianhoseini. (2019). “What is BIM? A Need for A Unique BIM Definition.” *MATEC Web of Conferences*.

Too, E. G. (2012). “A capability model to improve infrastructure asset performance.” *Journal of Construction Engineering and Management*, v 138, n 7.

Treasury Board of Canada Secretariat. (2019). “Green procurement .” Accessed June 14, 2021. https://www.canada.ca/en/treasury-board-secretariat/services/innovation/greening-government/green-procurement.html.

UNEP. (2005). “Sustainable Public Procurement.” *United Nations Environment Programme*. Accessed March 21, 2021. https://www.unep.org/explore-topics/resource-efficiency/what-we-do/sustainable-public-procurement.

United Nations. (2015). “THE 17 GOALS | Sustainable Development.” Accessed June 4, 2021. https://sdgs.un.org/goals.

Uttam, K., and C. le Lann Roos. (2015). “Competitive dialogue procedure for sustainable public procurement.” *Journal of Cleaner Production*, 86: 403–416. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2014.08.031.

Vass, S., and T. K. Gustavsson. (2017). “Challenges when implementing BIM for industry change.” *Construction Management and Economics*, v 35, n 10 (10): p 597-610. Routledge. https://doi.org/10.1080/01446193.2017.1314519.

Vernikos, V. K., C. I. Goodier, T. W. Broyd, P. C. Robery, and A. G. F. Gibb. (2014). “Building information modelling and its effect on off-site construction in UK civil engineering.” *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, v 167, n 3 (3): p 152-159. Thomas Telford Services Ltd. https://doi.org/10.1680/mpal.13.00031.

Vilas-Boas, J., V. Mirnoori, A. Razy, and A. Silva. (2019). "Outlining a New Collaborative Business Model as a Result of the Green Building Information Modelling Impact in the AEC Supply Chain." *IFIP Advances in Information and Communication Technology*, 405–417. Springer New York LLC.

Wahid, F. (2013). "The antecedents and impacts of green eProcurement infrastructure: Evidence from the Indonesian public sector." *International Journal of Internet Protocol Technology*, 7 (4): 210–218. Inderscience Publishers. https://doi.org/10.1504/IJIPT.2013.058648.

Walker, H., J. Miemczyk, T. Johnsen, and R. Spencer. (2012). "Sustainable procurement: Past, present and future." https://doi.org/10.1016/j.pursup.2012.11.003.

Xue, X., Q. Shen, and Z. Ren. (2010). "Critical Review of Collaborative Working in Construction Projects: Business Environment and Human Behaviors." *Journal of Management in Engineering*, 26 (4): 196–208. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000025.

Yalcinkaya, M., and V. Singh. (2015). "Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis." *Automation in Construction*, 59: 68–80. Elsevier. https://doi.org/10.1016/J.AUTCON.2015.07.012.

Yu, A. T. W., S. K. Yevu, and G. Nani. (2020). "Towards an integration framework for promoting electronic procurement and sustainable procurement in the construction industry: A systematic literature review." *Journal of Cleaner Production*. Elsevier Ltd.

Zak, J., and S. Vitasek. (2018). "Bim superior approach for infrastructure construction in the Czech Republic." *Engineering for Rural Development*, v 17: p 578-584. Latvia University of Agriculture. https://doi.org/10.22616/ERDev2018.17.N210.

CHAPTER 3

SUSTAINABLE BID PROPOSAL EVALUATION FOR WATER SUPPLY INFRASTRUCTURE PROJECTS: AN AUTOMATED BIM-BASED PLUGIN TOOLKIT

A version of this chapter has been submitted to Elsevier publishers' *Journal of Cleaner Production* titled as "Sustainable bid proposal evaluation for water supply infrastructure: An automated BIM-based plugin toolkit" and currently under peer review.

3.1 Background

World Bank Group (2021) has estimated approximately a quarter of the world population lack access to clean potable water, especially in low-income developing countries. In response, Asia and Pacific region has allocated an annual expenditure of more than $1.7 trillion from 2016 to 2030 for infrastructure development, including water supply (ADB, 2021). Astonishingly, similar trends can be seen amongst the developed and water-rich countries such as Canada. The Canadian government has invested $1.83 billion in water supply infrastructure from 2016 to 2021 (Government of Canada, 2021). It is essential that in the future, these projects should deliver by minimizing their impact on the triple bottom line (TBL) of sustainability.

Procurement has been defined as purchasing of goods, works, and services via competitive bidding (Laffont & Tirole, 1993). Since procurement exerts a large purchasing power, it has the potential to influence the purchasing of sustainable materials from socially responsible suppliers to aid the overall sustainability of construction projects. United Nations (2015) has emphasized the importance of sustainable public procurement. Yet, sustainable procurement is farfetched in the construction sector due to the traditional lowest bid approach (Hardie & Saha, 2012). A comprehensive bid proposal evaluation criterion based on TBL is a viable substitution for the lowest bid approach to enhance the sustainability of the built environment.

TBL-based proposal evaluation is data intensive, time-consuming, inefficient, and prone to human errors. The lack of quantified data based on a predefined set of indices for environmental and social impacts has been identified as another setback in conducting a sustainable procurement proposal evaluation (Kankanamge & Ruparathna, 2022). Ecolabels and social life cycle assessment (S-LCA) results has the potential to address the data challenges in sustainable procurement. Though the construction sector has been ranked at the lowest tier in adapting to information communication technology (Agarwal et al., 2016), building information modelling (BIM) is a potential computer-based data management solution to address the setbacks of manual TBL-based proposal evaluation. Several studies have utilized BIM as a solution to evaluate the sustainability performance of construction projects (Ren et al., 2021; Sharif & Gentry, 2015).

BIM is a collaborative platform that contains a large amount of physical and functional data of a constructed asset (Sacks et al., 2018). BIM model contains detailed information about building components. Furthermore, BIM has the potential to incorporate ecolabels data and social performance data to aid comprehensive sustainable bidder evaluation (Lee et al., 2006). Several countries have taken initiatives to encourage BIM utilization within the construction sector to assist public procurement. As an example, the Czech Republic requires BIM-based procurement for projects over €5.7m (Zak & Vitasek, 2018). Yet, current BIM-based procurement platforms do not contain TBL evaluation criteria. Moreover, there is a clear knowledge gap on BIM-based sustainable procurement of water supply infrastructure projects.

Consequently, this research was motivated by the aforementioned knowledge gap. This study presents a BIM-based proposal evaluation plugin toolkit for sustainable procurement of water supply infrastructure projects. Three databases consisting of environmental impacts, social impacts, and life cycle cost data were developed to aid the plugin. The proposed BIM plugin was demonstrated by conducting a case study for Southwestern Ontario. As a part of the case study, conventional bid evaluation and the proposed sustainable bid evaluation method were compared. This research advocates BIM adaptation in the construction sector for accurate and efficient decision-making. Furthermore, this study developed the resources to support the transition from the conventional low-cost procurement to sustainable procurement.

3.2 Literature Review

Sustainable procurement is a comprehensive evaluation process considering the TBL of sustainability (Feng et al., 2020). Presently, proposal evaluation in infrastructure sector is cost-oriented and environmental and social paradigms are overlooked (Yu et al., 2020). It is essential to seek for TBL -based selection methods for infrastructure project proposal evaluation (Agarchand & Laishram, 2017). Even though literature has proposed TBL indicators for project proposal evaluation (Laosirihongthong et al., 2019; Meehan & Bryde, 2011), there is no industry wide consensus on the above parameters.

3.2.1 Challenges in sustainable procurement for infrastructure

For a comprehensive sustainable procurement proposal evaluation, quantified environmental, economic, and social data is required (Chigudu, 2014; Gallastegui, 2002). However, in order to maintain the consistency and relevance of proposal evaluation, the data should be based on present indices (Meehan & Bryde, 2011).

Infrastructure sustainability evaluation is a highly data intensive process (Adeli & Jiang, 2009). Furthermore, comprehensive sustainability evaluation is complex, time consuming, and prone to human errors. Adopting cutting edge data management solutions assist in conducting a comprehensive sustainability evaluation.

3.2.2 Ensuring the consistency of TBL evaluation

Based on the published literature, TBL performance can be analyzed using various methods. In order to ensure the consistency of evaluation, the following methods can be used.

Environmental Performance: Researchers have used various Key Performance Indicators (KPIs) to conduct environmental evaluation (Bjerkan et al., 2019; Smith et al., 2014). Yet a standard set of KPIs are required for a consistent project proposal evaluation. Environmental Product Declarations (EPD) consist of a standard set of parameters for indicating the life cycle environmental performance of a product. There are three types of Eco-Labels and type III Eco-Labels are known as Environmental Product Declarations (EPD) (ISO, 2006). EPDs contain quantified life cycle environmental performance data under 6 KPIs. Hence, EPDs provide consistent data for environmental performance evaluation.

Social Performance: Social Hotspots Database (SHDB) contains social impact risk of products which can be used to conduct Social Life Cycle Assessment (S-LCA) (NewEarth B, 2022). Salehabadi & Ruparathna (2022) have used SHDB for evaluating the life cycle social performance of construction products. Despite being a growing field, SHDB provides verified and quantitative data for S-LCA.

Economic Performance: ADB (2021b) has stressed the importance of considering the operational and maintenance costs along with the initial cost. Therefore, in order to conduct a comprehensive economic evaluation, Life Cycle Cost Assessment (LCCA) has been used (Ruparathna et al., 2017). According to Gransberg (2015), LCCA entails two components, cost of ownership considering the initial costs and the second component is denoted by the cost of operations (e.g., energy costs, maintenance costs, and repair, refurbishment, and renovation costs). Therefore, LCCA provides a comprehensive economic evaluation of the infrastructure projects.

Project evaluation by using the above KPIs require state-of-the-art information technology tools. Literature suggests that BIM is a viable platform to conduct complex evaluation due to its core features (Tien Doan et al., 2019). Furthermore, BIM allows users implement algorithms to conduct customized assessments (Eastman et al., 2008). Therefore, BIM provides an efficient and accurate solution to conduct a comprehensive sustainability evaluation by integrating EPD, S-LCA, and LCCA data.

3.2.3 BIM Adaptation for infrastructure sector

An extensive literature review has been conducted to examine the BIM adaptation for TBL evaluation in the infrastructure sector. Table 3-1 summarizes published literature on BIM-based plugin tools for sustainability evaluation.

Table 3-1: BIM integration in infrastructure: Literature summary

Source	**Type of infrastructure**	**Type of analysis**	**Purpose of BIM utilization**
(Patel & Ruparathna, 2021)	Transportation (roads)	Sustainability performance of types of roads	Automation and life cycle impacts consideration
(Salehabadi & Ruparathna, 2022)	Single family detached homes	User centric sustainability performance for green ratings	Automation and user friendliness of evaluation

(Sloot et al., 2019)	Transportation (Canals)	Risk mitigation	4D simulation and collaboration
(Ren et al., 2021)	All infrastructure	Value for money assessment	Data management and automation
(Bracht et al., 2021)	Buildings	Energy simulation	Improve the designs at an early stage
(Mangal et al., 2021)	Steel reinforces structures	Structural integrity	3D spatial data, clash free optimization
(Lin et al., 2018)	Healthcare (Cancer hospital)	Constructability check	Virtual reality and collaboration
(Wang et al., 2014)	Buildings	Safety check for emergency evacuation	Simulations and virtual reality
(Sharif & Gentry, 2015)	Buildings	Generate parametric data of masonry units	Data management and automation
(Rodrigues et al., 2021)	Buildings	Safety check	Automation
(Chen & Nguyen, 2019)	Buildings	Green material selection to assists LEED certification	Link with external databases and automation
(Su et al., 2021)	Buildings	Demolition waste impacts	Data management and automation

Based on the above Table 3-1, BIM has been utilized in various types of infrastructure. However, a common feature is that all the above studies have developed BIM-based tools to conduct sustainability evaluation. Another interesting trend is that majority of the plugins are developed for buildings (Salehabadi & Ruparathna, 2022; Bracht et al., 2021; Chen & Nguyen, 2019; Su et al., 2021). A clear knowledge gap can be seen in using BIM-based tools for evaluating the sustainability performance of other infrastructure classes such as, water supply infrastructure, wastewater infrastructure and irrigation infrastructure. Several researchers have utilized BIM as a data management platform for infrastructure data management (Sharif & Gentry, 2015; Ren et al., 2021; Su et al., 2021). Data in Table 3-1 emphasizes that despite BIM can be used to support sustainable procurement, it is yet to be used in water supply infrastructure.

3.3 Methodology

The methodology consists of data collection, database development, BIM software preparation, tool scripting, and verification via a case study. Figure 3-1 depicts the methodology adopted in this study. Each phase is explained in detail below.

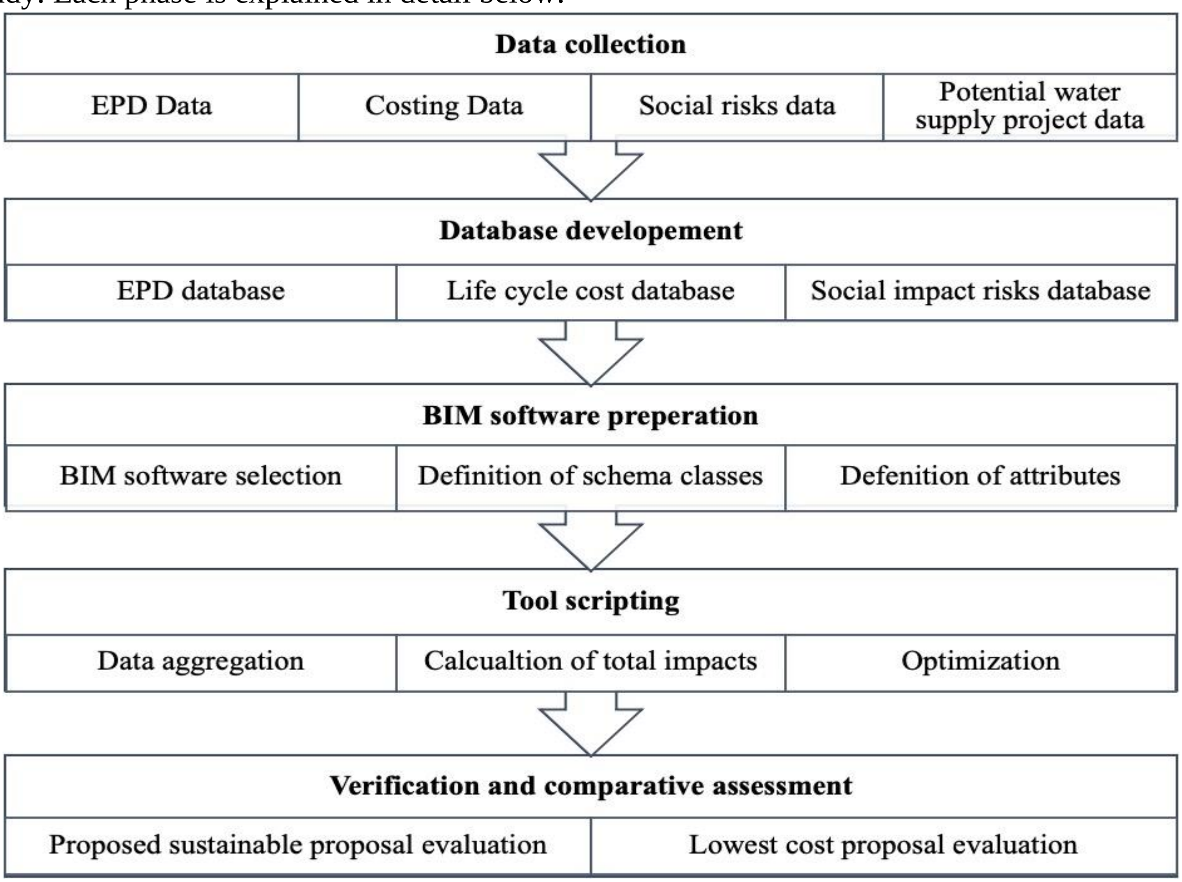

Figure 3-1: Methodology Roadmap

3.3.1 Data Collection

The data collection step consists of various EPDs of PVC pipe manufacturers around the world, standard cost data related to PVC pipes from the 2022 Building Construction Costs Book with RS Means (Gordian, 2022), social impact risk values of various countries for pipes from Social Hotspots Database (NewEarth B, 2022). Gathered EPD, cost, and social data were processed, tabulated, and exported into .CSV format databases to be imported to the BIM plugin. Based on the City of Windsor master plan for 2022, information and data have been gathered to conduct a case study. The data consists of proposed main pipelines in the vicinity, including the pipe lengths and diameters. The collected data were used for the verification of the tool and to assess the effectiveness of the plugin toolkit via scenario analysis.

3.3.2 Database Development

Under this section, three database prototypes are developed in terms of EPD database to gather environmental impacts, cost database to gather life cycle cost components, and social impacts database to gather the social life cycle assessment data.

3.3.2.1 EPD Database

For the purpose of this study, a prototype EPD database was created. Overall, 5 EPDs from 5 different PVC pipe manufacturers were gathered from publicly available data. However, only three have included the environmental KPIs based on ISO 14025, while the other two had followed EN 15804. The developed BIM plugin is exclusive to ISO 14025. Therefore, the KPIs depicted in Table 3-2 have been used for the evaluation.

Table 3-2: Environmental KPIs

KPI	**Unit**
Ozone Depletion (OD)	kg CFC-11 eq
Global Warming Potential (GWP)	kg CO2 eq
Acidification (ACD)	mol H+ eq
Eutrophication (ETP)	PO4 eq

Abiotic depletion potential (ADP)	MJ
Photochemical oxidation potential (POP)	kg C2H4 eq

The prototype database has eight columns starting from the manufacturer name as the identifier. Secondly, the diameter varies from 20-1000mm, and the last six columns contain respective KPI values for each manufacturer's pipe size. Actual EPD data was available for limited functional units. Therefore, this prototype database has interpolated between the diameters to calculate the respective KPI values for multiple diameters.

3.3.2.2 Cost Database

Conducting a Life Cycle Costing Assessment (LCCA) during the procurement evaluation can be denoted as a suitable analysis for achieving economic sustainability in sustainable procurement. (Chiang et al., 2014; S. H. Lee et al., 2015). Based on the nature of the water supply projects' pipe laying segment, the following Equation 3-1 was developed to calculate the LCC of the pipe network for sustainable economic evaluation.

$$LC_C = MT_C + CN_C + RP_C + DP_C \qquad \text{Equation 3-1}$$

LC_C = Life Cycle Cost

RP_C = Repair Cost

MT_C = Material Cost

DP_C = Disposal Cost

CN_C = Construction (labor) Cost

MT_C, CN_C, and RP_C were extracted from Heavy Construction Costs with RSMeans data. And according to Janajreh et al. (2015) and Waste Management (2022), $1,158.5 requires disposing of 1ton of PVC pipes. Therefore, using standard conversions ratios, the disposal cost was calculated for each pipe diameter and has been included in the cost database alongside other KPIs. The entire prototype cost database consists of 4 columns. In contrast, the first is the pipe diameter, and the second is the total material and construction cost, including profit and overhead. The third and fourth columns, respectively, contain the operational and disposal costs in the c$/m functional unit.

3.3.2.3 Social impacts database

Social Hotspots Database is a database that supports SimaPro LCA software to generate the social impact risk values based on the country of manufacture. Using SimaPro, the prototype database was developed for five different countries that manufacture PVC pipes and fittings, including the manufacturing countries of the identified manufacturers with EPDs. The social KPIs were calculated considering the full lifecycle of pipes and fitting. The database consists of KPIs for China, the United States, Mexico, Taiwan, and Canada as manufacturing countries. Accordingly, the database consists of 7 columns with manufacturer name, manufacturing country, and five social KPIs as populated in Table 3-3.

Table 3-3: Social KPIs

KPI	Unit
Labor Rights & Decent Work (LRD)	
Health & Safety (HNS)	
Human Rights (HMR)	Social impact risk score/$
Governance (GVN)	
Community (CMN)	

3.3.3 BIM software preparation

Multiple software providers have developed software to adapt to the BIM environment in the industry. However, Autodesk Infraworks has been identified as BIM software exclusive to infrastructure projects. Infraworks is interoperable with many other pipe networks designing software such as Autodesk Civil 3D and Arc GIS. Furthermore, Infraworks has the potential to access the OpenStreetMaps, Bing Maps, etc., to import true geographical and infrastructure data, as well as Infraworks provides an application programming interface (API) to add customized scripts based on JavaScript computer language to analyze the data based on user preference. Therefore, the proposed automated SP evaluation tool is developed for Infraworks as a plugin. Within the BIM platforms, predefined schemas based on interoperability is limited. Therefore, using Infraworks', *ExtendSchema* function, an extended schema of *Pipelines* was defined as

Pipelines_For_Proc, as shown in Figure 3-2. All the KPIs were defined as extended attributes in the extended schema's inheritance, as shown in Figure 3-3.

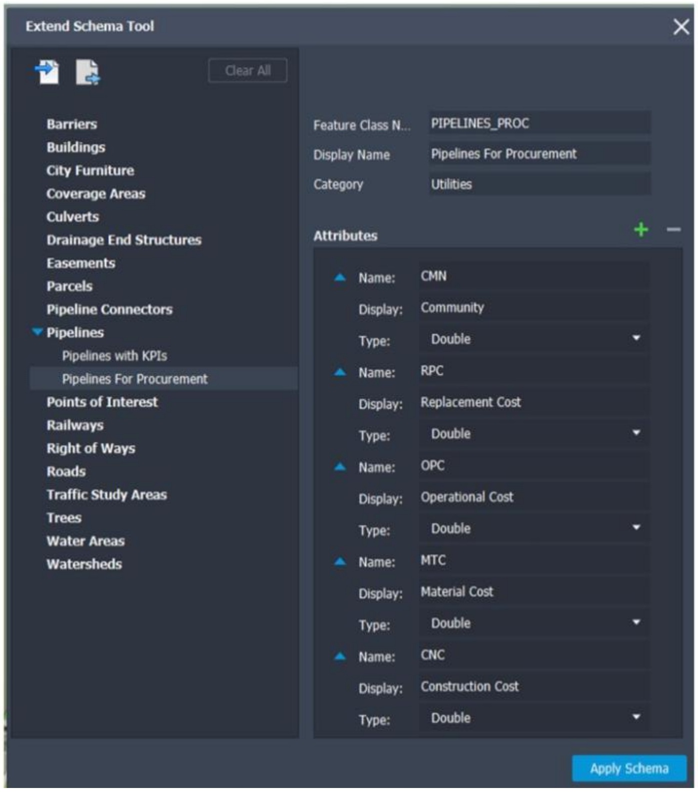

Figure 3-3: Extended attributes

Figure 3-2: Extended Schema

3.3.4 Tool Scripting

Autodesk Infraworks provides a user interface for scripting using JavaScript computer language; hence considering JavaScript reference documentation and Infraworks scripting reference documentation, the comprehensive SP evaluation plugin toolkit was coded. The script contains importing and filtering data from the developed databases, writing the imported data into relevant objects within the Infraworks model, normalization and optimization of imported data for unbiased evaluation, a user interface pop up window to insert evaluator specific data, mathematical algorithm to analyze the data and the final graphical output of the results.

3.3.4.1 Aggregation algorithm development

For the purpose of aggregating a large number of data and optimizing the data accordingly, an algorithm is developed using various commands in JavaScript. Firstly, the algorithm identifies the pipes in the model out of many objects with a filter and tabulates them to a variable matrix as below. The size of the matrix depends on the number of bid proposals.

$$table = filter\ (USER\_PIPELINE\_PROC) \qquad \text{Equation 3-2}$$

In above Equation 3-2, the *table* is the variable name for the matrix, and it contains all the information included in the objects configured under the extended schema *USER_PIPELINE_PROC*. Furthermore, the entire tool is coded within a condition to make sure that the model contains at least two proposals for evaluation. Given that the model contains more than one proposal, using the data in the *table*, each pipe is sorted based on the manufacturer's name and diameter to link with the databases, as shown in Equation 3-3.

$$\begin{aligned} & if\{ \\ & NetworkName = A_i \;\&\; Diameter = B_i \\ & KPI_i = V_i \\ & \} \end{aligned} \qquad \text{Equation 3-3}$$

$NetworkName: Pipe\ network\ name\ in\ the\ BIM\ model$

$Diameter: Pipe\ diamter\ in\ the\ BIM\ model$

$A_i: First\ column\ in\ the\ database\ (manufacturer\ name)$

$B_i: Second\ column\ in\ the\ database\ (pipe\ diamter)$

$KPI_i: Respective\ KPI\ defined\ in\ the\ BIM\ model$

$V_i: Value\ of\ the\ KPI\ in\ the\ database$

$i: Number\ of\ iteration\ between\ of\ the\ total\ number\ of\ pipes\ in\ the\ model$

As shown in Equation 3-3, all the EPD, Social impact risks, and life cycle cost KPIs are accessed and written the respective values to the defined extended attributes using *if conditions, for loops,* and *while loops*. Since the EPD KPIs consist of different functional units per 1-meter length, each KPI was multiplied by the total pipe length of the respective pipe size for each respective bid proposal and normalized to calculate a single environmental performance score as below in

Equation 3-4 and Equation 3-5. Furthermore, the non-beneficial EPD data has been converted into beneficial normalized environmental performance scores via following 2 equations.

$$NKPI_i = \frac{KPI_i}{\sqrt{\sum_{i,=1}^{6} KPI_i}}$$ Equation 3-4

$$S = \frac{E^-}{E^- + E^+}$$ Equation 3-5

$NKPI_i$: Normalized environmental KPI

KPI_i: Environmental KPI

ES: Environmental performance score

E^-, E^+: Negative and positive Euclidean distance

In calculating the LCC for each bid proposal, the summation of each KPI was calculated and multiplied by the total length of respective pipe sizes of the proposal, as shown in equation 1. However, since the SHDB delivers the social impact risk value for the cost unit, the final social performance score was obtained by multiplying the summation of each social KPI by the LCC. A new variable matrix is defined with the environmental performance score, social performance score as well as LCC, as shown in Table 3-4.

Table 3-4: Final performance matrix

	KPIs		
	W_1	**W_2**	**W_3**
	Environmental score	**Bid Price**	**Social score**
Bidder 1	V_{11}	V_{12}	V_{13}
Bidder 2	V_{21}	V_{22}	V_{23}
Bidder n	V_{n1}	V_{n2}	V_{n3}

* Footnote ~ i,j varies from 1 to n; V_{ij}: KPI values; W_i: User input weightage as a Likert scale

Before coding the optimization, a user interface is created to obtain the respective importance of each aspect of the TBL based on a Likert scale as per Table 3-5 depending on evaluator preference.

Table 3-5: Likert scale

Importance	**Score**
Less Important	1
Important	2
More Important	3

1-5 Likert scales have been widely used by various researchers in assessing the importance of the TBL, some particularly in the construction section (Chang et al., 2017; Zhong & Wu, 2015). However, in order to protect the sustainability comprehensiveness, this study uses a central tendency biased 3-point Likert scale disregarding "Not Important" and "Neutral" inputs.

3.3.4.2 Evaluation algorithm development

The TOPSIS MCDM method is used to obtain the final optimized decision-making matrix, which contains a sustainability performance score for each bidder. Importance linguistics were converted into weights as per Equation 3-6 and used for weighted optimization. TOPSIS method ensures that the final sustainability performance matrix is not compromised by the user input weights. The user input weightages have a minimal influence on the result when TOPSIS is utilized (Velasquez & Hester, 2013). TOPSIS algorithm is scripted in JavaScript language as mentioned below from Step 1 to Step 5.

$$W_i = \frac{Score_i}{\sum Scores} \qquad \text{Equation 3-6}$$

W_i: Weightage for each aspect of TBL

Step 1: Normalization

All the values under each KPI (V_{ij}) were normalized (N_{ij}) using the following Equation 3-7.

$$N_{ij} = \frac{V_{ij}}{\sqrt{\sum_{i,j=1}^{n} V_{ij}^2}} \qquad \text{Equation 3-7}$$

Step 2: Weighted normalization

Weighted normalization values are denoted in X_{ij} (i,j vary from 1 to n). W_i is the weightage. Equation 3-8 represents the weighted normalization equation.

$$X_{ij} = N_{ij} \times W_i \qquad \text{Equation 3-8}$$

Step 3: The positive and negative ideal solution

In deciding between ideal positive and negative solutions, Social KPIs and LCC KPIs are considered non-beneficial values; therefore, the positive ideal solution is the minimum weighted normalized value, and the negative ideal solution is the maximum weighted normalized value. Environmental KPIs have been normalized in phase 2, and therefore environmental score is considered a beneficial parameter. Equation 3-9 and Equation 3-10 were used in determining the positive and negative ideal solutions.

$$X_i^+ = Max\ X_{ij}^+ \qquad \text{Equation 3-9}$$

$$X_i^- = Min\ X_{ij}^- \qquad \text{Equation 3-10}$$

Step 4: Positive and negative Euclidean distance

Positive (D_i^+) and negative (D_i^-) Euclidean distances were calculated as shown below in Equation 3-11 and Equation 3-12.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(X_{ij} - X_i^+\right)^2} \qquad \text{Equation 3-11}$$

$$D_i^- = \sqrt{\sum_{i,j=1}^{n} \left(X_{ij} - X_i^-\right)^2}$$ Equation 3-12

Step 5: Performance score

Performance score (S_i) is calculated for all the alternatives as per Equation 3-13, the final weighted normalized decision-making matrix is shown in Table 3-6.

$$S_i = \frac{D_i^-}{D_i^- + D_i^+}$$ Equation 3-13

Table 3-6: Weighted normalized decision-making matrix

	KPIs					
	W_1	**W_2**	**W_3**			
	Environmental score	**Bid Price**	**Social score**	**D_i^-**	**D_i^+**	**S_i**
Bidder 1	X_{11}	X_{12}	X_{13}	D_1^-	D_1^+	S_1
Bidder 2	X_{21}	X_{22}	X_{23}	D_2^-	D_2^+	S_2
Bidder n	X_{n1}	X_{n2}	X_{n3}	D_n^-	D_n^+	S_n
X_i^+	X_1^+	X_2^+	X_3^+			
X_i^-	X_1^-	X_2^-	X_3^-			

* Footnote ~ i,j varies from 1 to n; X_{ij}: Weighted normalized values; D_i: Euclidean Distance; W_i: User input weightage as a percentage; S_i: Performance score

The final output of the result is displayed in the popup window using the *alert* command in JavaScript. The results consist of the names of bidders, total pipe length of each bid proposal, normalized environmental performance score, total potential social risk score, total life cycle cost, bid price, bid price variation to the standard rates, and the optimized sustainability performance score of each proposal as well as the best-suited bidder based on the sustainability performance scores of all the bid proposals.

3.3.5 Verification and comparative analysis

The last phase of the methodology of this study is the demonstration of the developed tool. A potential water supply project in southwest Ontario has been identified. As per the potential bid proposals, 3 manufactures from the EPD database were selected and their pipe prices were gathered from company websites. Five scenarios were defined whereas one is based on the traditional lowest cost evaluation concept and the rest were by using the proposed TBL-based proposal evaluation with various importance to the triple bottom line.

3.4 BIM Plugin Toolkit

The developed BIM plugin toolkit is an automated process. However, the pre-implementation configuration must be done in order to conduct the evaluation. The respective geographical model for the proposed geographical area was created in Infraworks before uploading the proposals into the model. Once the models are uploaded, all of them are configured under the extended schema *Pipelines_For_Proc* and the respective coordinate system for evaluation. Figure 3-4 is the plugin toolkit framework that conducts the automated SP bidder evaluation. This framework consists of 3 main phases including BIM data aggregation, optimized bidder evaluation, and output.

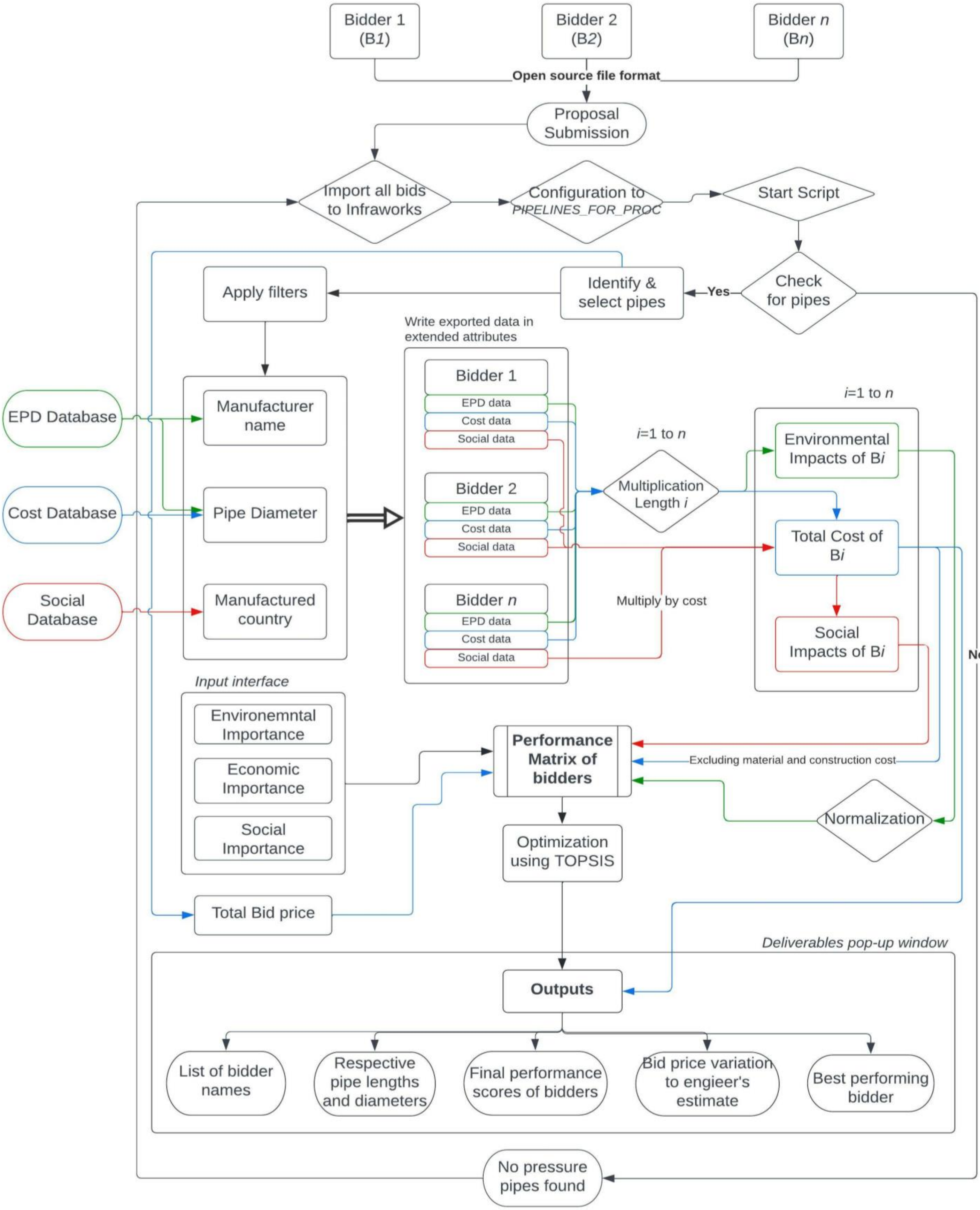

Figure 3-4: BIM Plugin toolkit framework

3.4.1 Phase 1: Exporting and linking external data sources

Once the BIM-based proposals are uploaded and configured, the data embedded in the BIM proposals were accessed using app.ActiveModelDb command line. As explained in section 3.4 embedded manufacturer name and pipe diameter in proposals were used as filters to import the respective KPI data from prototype databases. Imported data were written to the BIM objects using table.GetWriteRow command. At the end of phase 1, all the bid proposals contain sustainability KPI values alongside the bidder submitted data.

3.4.2 Phase 2: Optimized bidder evaluation

As per section 3.4, the using the bidder provided data and imported sustainability KPI data, the total KPIs for each proposal were calculated. The final data matrix consists of normalized environmental performance score, LCC, and social performance score for each bidder. User preferred importance for each aspect of TBL is gathered as per Figure 3-5 and converted into weightages using Equation 3-6 to conduct the weighted optimization. Optimization algorithm was coded as per Equation 3-13 to calculate the sustainability performance score of each bidder.

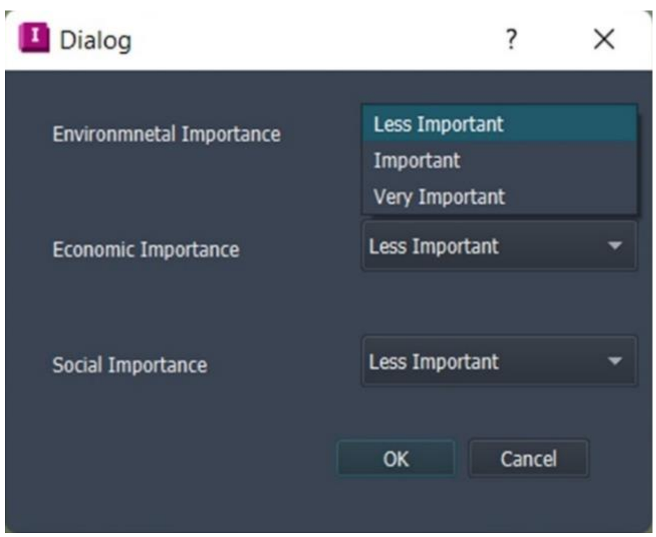

Figure 3-5: Parameter Importance window

Phase 3: Output

Based on environmental, economic, and social performance, this tool delivers the best performing proposal with the highest performance score, the information such as the bidders' names, and total pipe lengths as well as the cost variation of the bid price against the standard rates. The highest performing bidder is selected based on the final performance score of all the bidders, which consists of the environmental performance based on the respective EPDs, social performance based on the type of material and the country of manufacturing, and lastly, the LCC based on the bid price and repair and disposal costs imported from the cost database. The bid variation percentage is calculated by comparing the bid price with the standard material and labor costs imported from the cost database.

3.4.3 Best management practices for the proposed toolkit

There are several details that are necessary in executing the proposed BIM Toolkit. In the application of the developed BIM plugin toolkit the following best management practices should be followed by the evaluator and the bidder.

3.4.3.1 Bidder Instruction

Bidder should design the water network in BIM platform under *Pipe Network* class, in the instructed coordinate system and using Metric unit system. The pipe system should be designed as a network. The BIM model should be developed to a minimum level of development 300 including the information in Table 3-7. The final design shall be exported in .IFC or .IMX open source file format before submitting the bid.

Table 3-7: Bidder attribute definition

Data	**BIM class**
Pipe manufacturer name	NETWORKNAME
Construction costs including material, labor, profit, and overhead	DESCRIPTION
Pipe ID	NAME

3.4.3.2 Evaluator instruction

The evaluator shall prepare the geographical model through *Infraworks Model Builder.* Within the created model, as explained in section 3.3.3 *Pipelines* schema should be defined, and extended schema attributes should be defined as per Table 3-8. Attribute is the display name of the extended attribute, which can be modified by the evaluator. However, the Extended attribute schema class name should not be modified for the toolkit to run fluidly. When configuring the uploaded bidder proposal, the table ribbon of the configuration window should include the data source in shown extended schemas through the expression editor function. Lastly, the developed environmental, social, and costing databases are saved in a new folder called SP in local drive C, alongside the JavaScript code and the other toolkit files such as user interfaces. Following a successful configuration, the JavaScript code should be loaded into the Infraworks platform for execution.

Table 3-8: Evaluator attribute definitions

Attribute	Extended attribute schema class name	Data source
Ozone Depletion	OD	External databases (Automated identification by the tool)
Global Warming Potential	GWP	
Acidification	ACD	
Eutrophication	ETP	
Abiotic depletion potential	ADP	
Photochemical oxidation potential	POP	
Labor Rights & Decent Work	LDR	
Health & Safety	HSN	
Human Rights	HMR	
Governance	GVN	
Community	CMN	
Standard construction cost rate (Material & Labor)	RSCNC	

Standard repair cost rate	RSREP	
Standard disposal cost rate	RSDIS	
Pipe Length	LENGTH	Expression Editor (Geometry [2Dlength])
Bid price rate	CNC	Expression Editor (DESCRIPTION)

3.5 Tool Demonstration: A case study for southwestern Ontario

The tool developed in Section 3.4 was demonstrated by using a case study. Based on their master plan, a local government in Southwestern Ontario aims to deploy several water supply main lines within the city limits to cater to the forecasted demand. Therefore, depicts five selected main water lines over 500m long to be implemented by the end of 2022.

Table 3-9 depicts five selected main water lines over 500m long to be implemented by the end of 2022.

Table 3-9: Main water line to be procured

Street	From	To	Diameter (mm)	Length (m)
Glidden	Wyandotte	CNR	300	1100
George	Ontario	Tecumseh	200	2100
Argyle	Richmond	Ottawa	300	510
Tourangeau	Milloy	Tecumseh	300	550
Ellrose	Tecumseh	Milloy	200	620

This case study has considered potential contractors to bid for the project considering all the above five main lines. Since this project is delivered using Design-Bid-Build project delivery method, bidders are given the design of the pipeline with specification. Following Figure 3-6 is the geographical map and the proposed pipelines for this project.

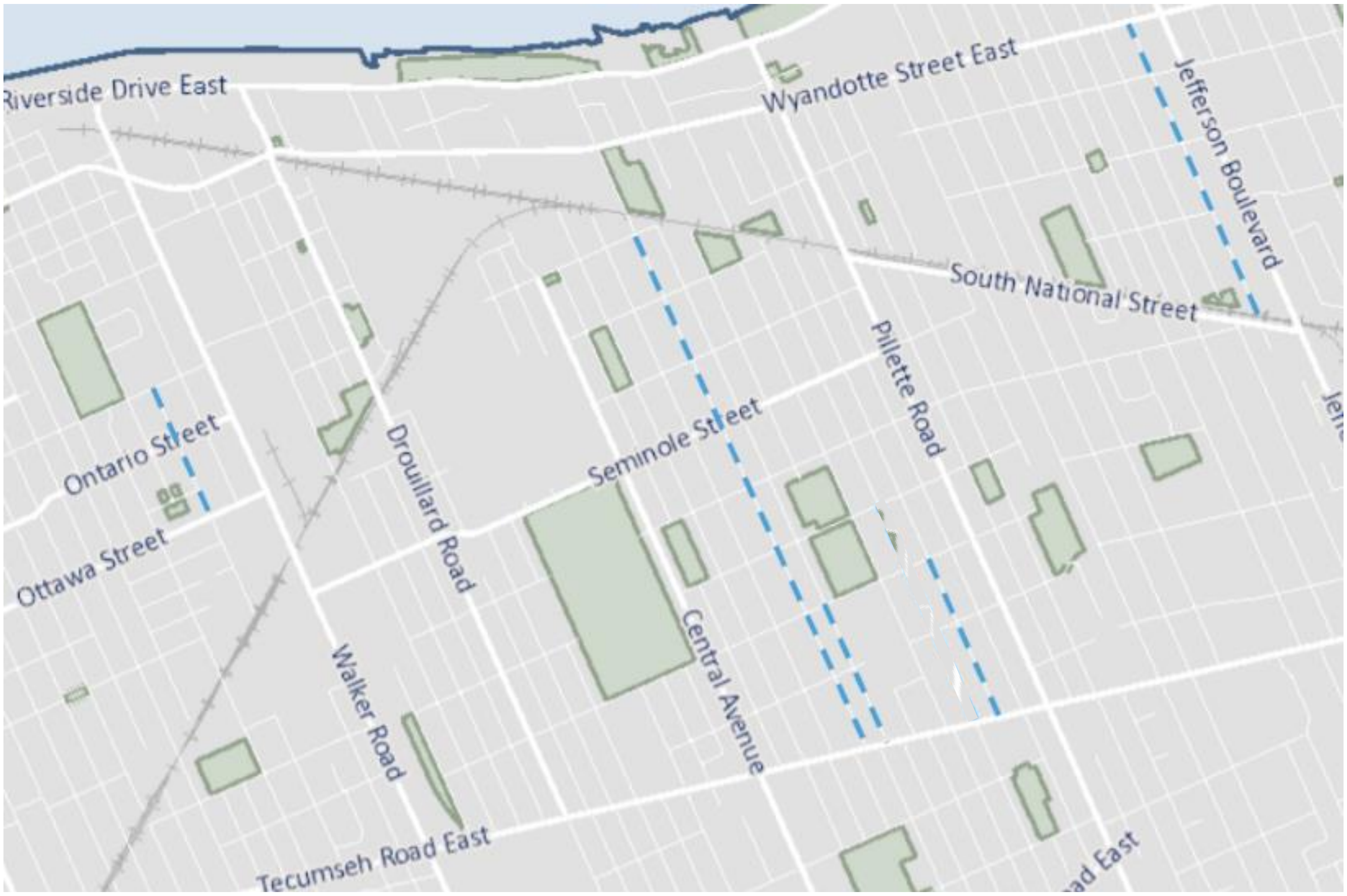

Figure 3-6: Proposed pipelines

For the purpose of this case study, the three pipe manufacturers considered in developing the EPD database have been considered as the bidders, and their unit bid prices are based on average market values. However, the environmental impacts, social impacts, and economic data are based on the actual values from the developed prototype databases.

The proposed toolkit is developed not only to conduct analysis but to embed the data from the databases into the respective pipe elements. Table 3-10 depicts all the values used for the evaluation parameters. User input weightage values are also considered as inputs in this evaluation tool. However, based on multiple combinations of weights, this case study is conducted under five scenarios as follows,

Scenario 1: Conventional lowest bid price

Scenario 2: Sustainable evaluation with the highest environmental importance

Scenario 3: Sustainable evaluation with the highest social importance

Scenario 4: Sustainable evaluation with the highest LCC importance

Scenario 5: Sustainable evaluation with equal importance

Table 3-10: Bidder Evaluation Data

	Environmental Impacts									**Economic Impacts (LCC)**			**Social**					**Unit Bid Price**
Bidder	Street	Length (m)	Diameter (mm)	POP (kg C2H4 eq)	OD (kg CFC-11 eq)	GWP (kg CO2 eq)	ETP (PO4 eq)	ADP (MJ)	ACD (mol H+ eq)	Material & labor cost	Repair cost	Disposal cost	LBR	HNS	HMR	GVN	CMN	
Bidder 1	Glidden	1100	300	3.28E-03	4.86E-05	5.12E+00	1.84E-04	1.35E+01	4.28E-03	77.34	3,222.73	14.55	8.302	8.064	5.241	5.200	5.393	94.35
	George	2100	200	2.18E-03	3.24E-05	3.41E+00	1.23E-04	9.02E+00	2.85E-03	56.76	2329.39	9.29						69.25
	Argyle	510	300	3.28E-03	4.86E-05	5.12E+00	1.84E-04	1.35E+01	4.28E-03	77.34	3,222.73	14.55						94.35
	Tourangeau	550	300	3.28E-03	4.86E-05	5.12E+00	1.84E-04	1.35E+01	4.28E-03	77.34	3,222.73	14.55						94.35
	Ellrose	620	200	2.18E-03	3.24E-05	3.41E+00	1.23E-04	9.02E+00	2.85E-03	56.76	2329.39	9.29						69.25
Bidder 2	Glidden	1100	300	1.17E-03	5.05E-12	2.38E+00	1.18E-03	4.01E+01	7.29E-03	77.34	3,222.73	14.55	4.583	4.336	3.834	4.769	4.023	96.67
	George	2100	200	7.78E-04	3.36E-12	1.59E+00	7.87E-04	2.67E+01	4.86E-03	56.76	2329.39	9.29						70.95
	Argyle	510	300	1.17E-03	5.05E-12	2.38E+00	1.18E-03	4.01E+01	7.29E-03	77.34	3,222.73	14.55						96.67
	Tourangeau	550	300	1.17E-03	5.05E-12	2.38E+00	1.18E-03	4.01E+01	7.29E-03	77.34	3,222.73	14.55						96.67
	Ellrose	620	200	7.78E-04	3.36E-12	1.59E+00	7.87E-04	2.67E+01	4.86E-03	56.76	2329.39	9.29						70.95

Bidder 3	Glidden	1100	300	6.76E-05	2.19E-08	2.28E-01	1.93E-04	6.44E+00	9.03E-04	77.34	3,222.73	14.55	36.77	39.49	20.43	49.77	25.46	100.54
	George	2100	200	4.51E-05	1.46E-08	1.52E-01	1.29E-04	4.29E+00	6.02E-04	56.76	2329.39	9.29						73.79
	Argyle	510	300	6.76E-05	2.19E-08	2.28E-01	1.93E-04	6.44E+00	9.03E-04	77.34	3,222.73	14.55						100.54
	Tourangeau	550	300	6.76E-05	2.19E-08	2.28E-01	1.93E-04	6.44E+00	9.03E-04	77.34	3,222.73	14.55						100.54
	Ellrose	620	200	4.51E-05	1.46E-08	1.52E-01	1.29E-04	4.29E+00	6.02E-04	56.76	2329.39	9.29						73.79

All the proposals were uploaded as per Figure 3-7, configured, and analyzed based on the sections mentioned beforehand. The environmental scores, social impact risks, life cycle cost, bid price, and the variation of the bid price to the standard rates of all bidders are depicted in the following in Table 3-11.

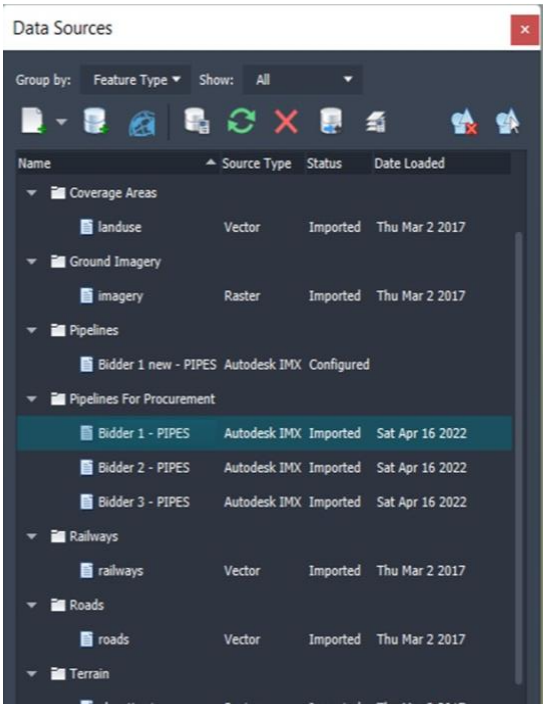

Figure 3-7: Proposal upload

Table 3-11: Bid information summary

Bidder	**Environmental performance score***	**Social impacts****	**Life cycle cost******(c$)**	**Total Bid Price**** **(c$)**	**Price variation (%)**
Bidder 1	3.95E-01	1.26E+07	13,745,915.63	392,147.46	22
Bidder 2	4.66E-01	8.66E+06	13,755,558.60	401,790.43	25
Bidder 3	9.97E-01	7.19E+07	13,771,630.21	417,862.05	30

Footnote: * beneficial score; ** non-beneficial score

In Table 3-11, the environmental performance scores were determined as per Equation 4 and Equation 5 from the EPD data. Even though the EPD data are considered as non-beneficial, the calculated environmental performance score is a beneficial score, whereas the most environmentally friendly alternative is the bidder with the highest score. However, the social impacts, life cycle cost, and the bid price are non-beneficial. Therefore, the best alternative is for the bidder with the lowest value. Furthermore, the variation between the bid price and the standard rates is also depicted as a percentage.

Since the scenario 1 is based on the lowest bid price approach, the toolkit was run only for the last 4 scenarios considering the sustainable procurement approach. Following Table 3-12 provides the linguistics terms used as the user input importance for each scenario.

Table 3-12: Scenario analysis

	Importance		
Scenario	**Environmental**	**Social**	**LCC**
2	Very important	Less important	Less important
3	Less important	Very important	Less important
4	Less important	Less important	Very important
5	Important	Important	Important

The output for each scenario is depicted in Table 3-13. Table 3-13 consists of optimized sustainability performances score of each bidder under scenario 2 through scenario 5. Furthermore, since the toolkit results aligned with manual calculation, the correctness of the JavaScript code can be confirmed.

Table 3-13: Case study results

Scenario	Bidder	Performance score	Best bidder
Scenario 1	Bidder 1	N/A	Bidder 1
	Bidder 2		
	Bidder 3		
Scenario 2	Bidder 1	3.8509e-1	Bidder 3
	Bidder 2	4.3486e-1	
	Bidder 3	5.9922e-1	
Scenario 3	Bidder 1	7.9119e-1	Bidder 2
	Bidder 2	8.2574e-1	
	Bidder 3	1.9304e-1	
Scenario 4	Bidder 1	6.0914e-1	Bidder 2
	Bidder 2	6.5509e-1	
	Bidder 3	3.7424e-1	
Scenario 5	Bidder 1	6.0914e-1	Bidder 2
	Bidder 2	6.5509e-1	
	Bidder 3	3.7424e-1	

Based on the results, scenario 1 selects Bidder 1 with the lowest bid price, while scenario 2 selects Bidder 3 with the highest environmental performance score. According to the results, Bidder 2 is selected in the other 3 scenarios. The performance scores in scenarios 4 and 5 are identical. Furthermore, the results revealed that Bidder 1 and Bidder 2 were the closest contenders with a slight variation in sustainability performance. Since the considered case study is a Design Bid

Build type project, the pipe diameters, lengths, and material are defined. Therefore, even though the bid price varies, the repair and disposal costs for each bidder will be the same.

Table 3-14 depicts the performance indicators of the selected bidder under each scenario and the variation of each performance indicator with respect to the traditional lowest cost evaluation concept (Scenario 1). Based on the scenario analysis, it can be determined that the traditional lowest cost method is not the most sustainable evaluation method.

Table 3-14: KPIs of scenario analysis

Scenario	**Environmental performance (Ep)**	**Social performance (SP)**	**Life cycle cost (LCC)**	**Variation to scenario 1 (%)**		
				EP	**SP**	**LCC**
1	3.95E-01	1.26E+07	13,745,915.63		N/A	
2	9.97E-01	7.19E+07	13,771,630.21	60.38	82.48	0.19
3	4.66E-01	8.66E+06	13,755,558.60	15.24	-45.50	0.07
4	4.66E-01	8.66E+06	13,755,558.60	15.24	-45.50	0.07
5	4.66E-01	8.66E+06	13,755,558.60	15.24	-45.50	0.07

3.6 Discussion

In this research a BIM plugin toolkit has been developed to aid TBL-based proposal evaluation for water supply infrastructure projects. The tool overcomes the transparency and efficiency barrier of public procurement and improves the overall sustainability of water supply infrastructure projects. The toolkit comprises prototype databases containing EPD, social impact risk values, and standard unit rates of pipes. The results of the case study revealed that TBL-based proposal evaluation positively impacts the environmental and social performance of water supply infrastructure projects at a reasonable increase in the bid price.

Five scenarios were considered in the case study. In scenario 1, the traditional low-cost evaluation method was used. Bidder 1 was selected in this scenario has a 60% lesser environmental performance than the most environmentally friendly bidder (Bidder 3) and a 45.5% higher life cycle social impacts risk than the other two bidders. Scenario analysis was conducted to analyze the sensitivity of the TBL weights. Scenario 2 provided higher importance to the environmental category where the proposal by bidder 3 was selected. This is evident as the Bidder 3 is the most environmentally friendly bidder. Social and economic categories were given higher importance as in scenarios 3 and 4 as well as equal importance to all the aspects given as in scenario 5. In all the three scenarios, bidder 2 was selected as the most sustainable bidder. Bidder 2 has a 15% higher environmental performance, 45.5% less social impact risks, a 6.55% high bid price, and 0.07% more LCC than the bidder selected from the traditional lowest bid concept. As per Rezaee et al. (2017) greener products are marginally expensive than less green products. Similarly, when the social performances indicators are ignored by manufacturers, they can provide a cheaper cost than their competitors (Toppinen et al., 2013). Hence, the case study results confirm with the above.

The result of scenario 2 is different from results of scenarios 3,4 and 5. This is because even though Bidder 3's environmental performance is extremely higher than the other two bidders, their social and economic performances are extremely low. Hence, despite being the most ecofriendly, Bidder 3`s proposal can't be considered as the most sustainable proposal. In conclusion, Bidder 2 can be considered as the most sustainable bidder since in 3 out 5 scenarios bidder 2 obtains the highest performance score.

3.6.1 Limitations and challenges of the plugin toolkit

The developed toolkit has several limitations, mainly due to the lack of interoperability in open-source file formats. One of the major limitations is that there is no object inheritance defined in the open-source file format architecture for pressure pipes as well as pipe fittings such as bends and tees and apparatuses such as valves and fire hydrants. Therefore, this tool is only applicable to main water distribution lines designed under the *PIPELINES* BIM schema. This tool does not consider the environmental and social impacts of the supporting equipment and material used during construction and maintenance. Furthermore, from an implementation perspective, the evaluator should define the extended schema class and the attributes classes before running the tool due to the limitations of object inheritance. The accuracy of the results significantly depends on the accuracy of the databases created. Hence, the authenticity and availability of the EPD data and SHDB data shall limit the wider application of the proposed toolkit. Lastly, the limited number of EPDs in pipes and fittings in the industry will limit the applications of this toolkit until EPDs become a mandate in the construction sector. The case study results are limited to Design-Bid-Build type projects and for the context of the project considered.

3.6.2 Practical implication

Since the developed toolkit automates proposal evaluation the time required in conventional proposal evaluation can be minimized. Furthermore, prior knowledge of coding, EPDs, or SHDB are not required to use the proposed tool. Automation addresses, the lack of experts for TBL-based proposal evaluation and avoids errors from human negligence. Furthermore, any changes in pipe materials, lengths, or diameters that applies during the negotiation phase of the procurement are automatically considered, given that the change is incorporated into the BIM model. The proposed toolkit can be used in any project delivery method. Lastly, the evaluator has the liberty to change the importance weightage by providing different importance to TBL criteria before making the final decision. The proposed tool kit can be combined with e-procurement and enterprise resource planning for a comprehensive BIM-based bid evaluation platform.

3.7 Summary

The water supply sector has gained paramount importance in infrastructure development, as it provides clean and accessible water to citizens. Despite its undeniable benefits, a massive environmental load is created during its life cycle. It has been identified that improving the procurement proposal evaluation process can address the environmental and social impacts caused by construction projects. Triple Bottom Line (TBL)-based project proposal evaluation is highly data-intensive and complex. State-of-the-art concepts in the construction industry such as Building Information Modeling (BIM) provide a data repository to aid the above process. More clients require contractors to submit their bids by using BIM. Yet, there is a lack to tools that aid sustainable procurement of infrastructure in the BIM environment. The objective of this study is to develop a BIM plugin toolkit to automate proposal evaluation of water supply infrastructure projects by considering the life cycle environmental performance, social impact risks, and life cycle cost. A demonstration was done for a potential water supply project with three proposals. The developed toolkit selected a proposal with expressively higher environmental, social performance and a significantly lower increment in bid price than the lowest cost proposal. The proposed method provides valuable data for proposal evaluation and promotes BIM implementation in the construction industry.

REFERENCES

The Brooks Act: FEDERAL GOVERNMENT SELECTION OF ARCHITECTS AND ENGINEERS, (1972). https://www.acec.org/advocacy/qbs/brooks2/

ADB. (2021). *Knowledge | Asian Development Bank*. https://www.adb.org/what-we-do/knowledge

Adeli, H., & Jiang, X. (2009). Intelligent Infrastructure. . In *CRC Press*. CRC Press.

Bataw, A., Kirkham, R., & Lou, E. (2016). The Issues and Considerations Associated with BIM Integration. *MATEC Web of Conferences*, *v 66*. https://doi.org/10.1051/matecconf/20166600005

Bjerkan, K. Y., Karlsson, H., Sondell, R. S., Damman, S., & Meland, S. (2019). Governance in maritime passenger transport: Green public procurement of ferry services. *World Electric Vehicle Journal*, *10*(4). https://doi.org/10.3390/wevj10040074

Bracht, M. K., Melo, A. P., & Lamberts, R. (2021). A metamodel for building information modeling-building energy modeling integration in early design stage. *Automation in Construction*, *121*, 103422. https://doi.org/10.1016/J.AUTCON.2020.103422

Chang, R.-D., Asce, S. M., Zuo, J., Soebarto, V., Zhao, Z.-Y., Zillante, G., & Gan, X.-L. (2017). Discovering the Transition Pathways toward Sustainability for Construction Enterprises: Importance-Performance Analysis. *Journal of Construction Engineering and Management*, *143*(6), 04017013. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001295

Chen, P. H., & Nguyen, T. C. (2019). A BIM-WMS integrated decision support tool for supply chain management in construction. *Automation in Construction*, *98*, 289–301. https://doi.org/10.1016/J.AUTCON.2018.11.019

Chiang, Y. H., Zhou, L., Li, J., Lam, P. T. I., & Wong, K. W. (2014). Achieving Sustainable Building Maintenance through Optimizing Life-Cycle Carbon, Cost, and Labor: Case in Hong Kong. *Journal of Construction Engineering and Management*, *140*(3), 05014001. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000823

Chigudu, D. (2014). PUBLIC PROCUREMENT IN ZIMBABWE: ISSUES AND CHALLENGES. *Journal of Governance and Regulation*, *3*(4), 21–26. http://www.virtusinterpress.org/IMG/pdf/JGR__Volume_3_Issue_4_2014.pdf#page=19

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2008). *BIM Handbook A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors BIM Handbook: A Guide to Building Informationn n Modeling for Owners, Managers*. www.wiley.com/go/permissions.

Feng, Y., Mohamed, S. A., Le, T., Zhang, P., Shou, W., Bevan, W., & S. Caldera. (2020). Sustainable Procurement: Literature Review. In *Western Sydney university research collection*. https://doi.org/10.2/JQUERY.MIN.JS

Gallastegui, I. G. (2002). The use of eco-labels: A review of the literature. *European Environment*, *12*(6), 316–331. https://doi.org/10.1002/EET.304

Gordian. (2022). *Heavy Construction Costs Book with RSMeans data* (D. Hale, Ed.; 36th ed.). https://www.rsmeans.com/products/books/2022-heavy-construction-costs-book

Government of Canada. (2021). *Infrastructure Canada - Investing in Canada plan*. Infrastructure Canada Bilateral Agreements. https://www.infrastructure.gc.ca/pt-sp/index-eng.html

Gransberg, D. D. (2015). *Major Equipment Life-cycle Cost Analysis*. http://www.lrrb.org/pdf/201516.pdf

Hall, J. N. (2010). Briefing: A practical initiative for the construction industry. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, *163*(4), 181–183. https://doi.org/10.1680/ensu.2010.163.4.181

Hampton, D. (1994). Procurement Issues. *Journal of Management in Engineering*, *10*(6), 45–49. https://doi.org/10.1061/(asce)9742-597x(1994)10:6(45)

Hardie, M., & Saha, S. (2012). Builders' Perceptions of Lowest Cost Procurement and Its Impact on Quality. *Construction Economics and Building*, *9*(1), 1–8. https://doi.org/10.5130/AJCEB.V9I1.3009

IEA. (2019). *Global Status Report for Buildings and Construction* . https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019

ISO. (2006). *ISO 14025: Environmental labels and declarations* . Standards. https://www.iso.org/standard/38131.html

Janajreh, I., Alshrah, M., & Zamzam, S. (2015). Mechanical recycling of PVC plastic waste streams from cable industry: A case study. *Sustainable Cities and Society*, *18*, 13–20. https://doi.org/10.1016/J.SCS.2015.05.003

Kankanamge, D. H., & Ruparathna, R. (2022). Adopting Ecolabels in the Construction Industry via Blockchain. *CSCE 2022 Annual Conference Whistler, British Columbia*, 1–15.

Laffont, J.-J., & Tirole, J. (1993). *A Theory of Incentives in Procurement and Regulation* . Massachusetts Institute of Technology.

Laosirihongthong, T., Samaranayake, P., & Nagalingam, S. (2019). A holistic approach to supplier evaluation and order allocation towards sustainable procurement. *Benchmarking*, *26*(8), 2543–2573. https://doi.org/10.1108/BIJ-11-2018-0360

Lee, G., Sacks, R., & Eastman, C. M. (2006). Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in Construction*, *15*(6), 758–776. https://doi.org/10.1016/j.autcon.2005.09.009

Lee, S. H., Hong, T., Piette, M. A., & Taylor-Lange, S. C. (2015). Energy retrofit analysis toolkits for commercial buildings: A review. *Energy*, *89*, 1087–1100. https://doi.org/10.1016/J.ENERGY.2015.06.112

Lin, Y. C., Chen, Y. P., Yien, H. W., Huang, C. Y., & Su, Y. C. (2018). Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital. *Advanced Engineering Informatics*, *36*, 130–145. https://doi.org/10.1016/J.AEI.2018.03.005

Lindsey, R., & Dahlman, L. (2022). Climate Change: Global Temperature. In D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, & T. K. Maycock (Eds.), *U.S. Global Change Research Program* (Vol. 1). https://doi.org/10.7930/J0J964J6

Mangal, M., Li, M., Gan, V. J. L., & Cheng, J. C. P. (2021). Automated clash-free optimization of steel reinforcement in RC frame structures using building information modeling and two-stage genetic algorithm. *Automation in Construction*, *126*, 103676. https://doi.org/10.1016/J.AUTCON.2021.103676

Meehan, J., & Bryde, D. (2011). Sustainable procurement practice. *Business Strategy and the Environment*, *20*(2), 94–106. https://doi.org/10.1002/bse.678

NewEarth B. (2022). *Social Hotspots Database*. http://www.socialhotspot.org/

Patel, K., & Ruparathna, R. (2021). Life cycle sustainability assessment of road infrastructure: a building information modeling-(BIM) based approach. *Https://Doi.Org/10.1080/15623599.2021.2017113*. https://doi.org/10.1080/15623599.2021.2017113

Pietroforte, R., & Miller, J. B. (2002). Procurement methods for US infrastructure: Historical perspectives and recent trends. *Building Research and Information*, *30*(6), 425–434. https://doi.org/10.1080/09613210210159875

Ren, G., Li, H., Liu, S., Goonetillake, J., Khudhair, A., & Arthur, S. (2021). Aligning BIM and ontology for information retrieve and reasoning in value for money assessment. *Automation in Construction*, *v 124*. https://doi.org/10.1016/j.autcon.2021.103565

Rezaee, A., Dehghanian, F., Fahimnia, B., & Beamon, B. (2017). Green supply chain network design with stochastic demand and carbon price. *Annals of Operations Research*, *250*(2), 463–485. https://doi.org/10.1007/S10479-015-1936-Z/FIGURES/9

Rodrigues, F., Antunes, F., & Matos, R. (2021). Safety plugins for risks prevention through design resourcing BIM. *Construction Innovation*, *21*(2), 244–258. https://doi.org/10.1108/CI-12-2019-0147/FULL/XML

Ruparathna, R., & Hewage, K. (2015). Sustainable procurement in the canadian construction industry: Challenges and benefits. *Canadian Journal of Civil Engineering*, *42*(6), 417–426. https://doi.org/10.1139/CJCE-2014-0376/ASSET/IMAGES/CJCE-2014-0376TAB10.GIF

Ruparathna, R., Hewage, K., & Sadiq, R. (2017). Economic evaluation of building energy retrofits: A fuzzy based approach. *Energy and Buildings*, *139*, 395–406. https://doi.org/10.1016/J.ENBUILD.2017.01.031

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM Handbook: A Guide to Building Information Modelling for Owners, Designers, Engineers, Contractors and Managers* (3rd ed.). John Wiley & sons.

Salehabadi, Z. M., & Ruparathna, R. (2022). User-centric sustainability assessment of single family detached homes (SFDH): A BIM-based methodological framework. *Journal of Building Engineering*, *50*. https://doi.org/10.1016/J.JOBE.2022.104139

Sharif, S., & Gentry, R. (2015). BIM for Masonry: Development of BIM Plugins for the Masonry Unit Database. *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe*, *1*, 567–576. https://doi.org/10.52842/CONF.ECAADE.2015.1.567

Smith, R., Ferrebee, E., Ouyang, Y., & Roesler, J. (2014). Optimal Staging Area Locations and Material Recycling Strategies for Sustainable Highway Reconstruction. *Computer-Aided Civil and Infrastructure Engineering*, *29*(8), 559–571. https://doi.org/10.1111/mice.12089

Su, S., Li, S., Ju, J., Wang, Q., & Xu, Z. (2021). A building information modeling-based tool for estimating building demolition waste and evaluating its environmental impacts. *Waste Management*, *134*, 159–169. https://doi.org/10.1016/J.WASMAN.2021.07.025

The world counts. (2022). *Child Labor Facts and Statistics*. From the Sweat of Our Children. https://www.theworldcounts.com/stories/Child-Labor-Facts-and-Statistics

Tien Doan, D., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ur Rehman, A., Tookey, J., & Ghaffarianhoseini, A. (2019). What is BIM? A Need for A Unique BIM Definition. *MATEC Web of Conferences*. https://doi.org/10.1051/matecconf/2019

United Nations. (2015). *THE 17 GOALS | Sustainable Development*. https://sdgs.un.org/goals

Velasquez, M., & Hester, P. T. (2013). An Analysis of Multi-Criteria Decision Making Methods. *International Journal of Operations Research*, *10*(2), 56–66.

Wang, B., Li, H., Rezgui, Y., Bradley, A., & Ong, H. N. (2014). BIM based virtual environment for fire emergency evacuation. *Scientific World Journal*, *2014*. https://doi.org/10.1155/2014/589016

Waste Management. (2022). *Waste Disposal & Recycling* . https://www.wm.com/

Windsor Utilities Commission. (2022). *Water Capital Projects Program*. https://enwin.com/water-capital-projects-program/

Yu, A. T. W., Yevu, S. K., & Nani, G. (2020). Towards an integration framework for promoting electronic procurement and sustainable procurement in the construction industry: A systematic literature review. In *Journal of Cleaner Production* (Vol. 250). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2019.119493

Zak, J., & Vitasek, S. (2018). Bim superior approach for infrastructure construction in the Czech Republic. *Engineering for Rural Development*, *v 17*, p 578-584. https://doi.org/10.22616/ERDev2018.17.N210

Zhong, Y., & Wu, P. (2015). *Economic sustainability, environmental sustainability and constructability indicators related to concrete-and steel-projects*. https://doi.org/10.1016/j.jclepro.2015.05.095

CHAPTER 4

ADOPTING ECOLABELS VIA BLOCKCHAIN TO AID SUSTAINABLE PROCUREMENT OF WATER SUPPLY INFRASTRUCTURE

A version of this chapter has been published and presented at the *Canadian Society of Civil Engineers annual conference 2022 (CSCE 2022)* as "Adopting Ecolabels in the Construction Industry via Blockchain" (Kankanamge & Ruparathna, 2022).

4.1 Introduction

Green procurement is a potential strategy to cater to the demand for water supply infrastructure in an eco-friendly manner (Ruparathna, 2013). Green procurement is an eco-conscious substitution to traditional low-cost project selection that incorporates environmental considerations into the procurement of goods, works, and services (Hollos et al., 2012; Reuter et al., 2010; Srivastava, 2007). Since this is a highly data-intensive process, the wider adaptation is hindered by data and implementation challenges.

Ecolabels are an incentive for green procurement. Environmental Product Declaration (EPD) is a type III ecolabel that contains quantified environmental impacts based on pre-set indices (Gallastegui, 2002). EPD is developed through a life cycle assessment (LCA) (ISO, 2006). The fidelity of an EPD heavily depends on the accuracy of the life cycle inventory. Ensuring the accuracy of a life cycle inventory is a challenge since less accurate data is available on a majority of backend processes.

Blockchain is a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network (Cachin et al., 2016). Blockchain can be a potential solution to enhance the accuracy of the life cycle inventory data. Blockchain allows multiple users in a supply chain to distribute the encrypted data via secure logging. It is a decentralized database that works on a network (e.g., Internet) (Nakamoto, 2008). Each new transaction (change) forms a new block with the updates if the transaction is validated, and the new blockchain is shared among all the users. This concept ensures the credibility and transparency of data, and it can be shared among all stakeholders instantaneously. Even though the blockchain concept is popular as the underlying technology in cryptocurrency, other industries, including the construction sector, have not acknowledged the full potential blockchain (Abou Jaoude & George Saade, 2019).

In order to incorporate EPDs in green procurement, a common data platform is required. Building Information Modelling (BIM) is an information repository that can serve as a common data platform for green procurement (Sacks et al., 2018). External data such as EPDs can be linked with the BIM environment to conduct eco-conscious evaluation (Farnsworth et al., 2015). Blockchain can be used for gathering entrusted, encrypted, up-to-date EPD data instantaneously.

According to Agarwal et al., (2016) construction industry is ranked at the second-lowest level to adapt to information technology. However, Rodrigo et al. (2020) have emphasized the potential uses of blockchain in the construction sector, such as asset management, file sharing for document management, and construction supply chain management. Kiu et al. (2020), Li et al. (2019), and Shojaei (2019) have also investigated the application of blockchain in the construction sector. Even though scholars have conducted reviews of blockchain adaptation for the construction sector, implementation frameworks for specific applications have not been researched.

The objective of this Chapter is to propose a conceptual framework architecture to integrate EPDs via blockchain to aid the BIM-based green procurement. The proposed approach will provide updated, transparent, and verified environmental impacts of infrastructure components. This study will advocate blockchain adaptation in the construction industry.

4.2 Eco-conscious purchasing in the infrastructure sector

Due to its magnitude, complexity, and various characteristics, construction of water supply, transportation, irrigation, & utility infrastructure requires close scrutiny (Dodanwala et al., 2021; Kankanamge & Santoso, 2021). The delivery of water supply infrastructure projects is within the mandate of federal, provincial, and municipal governments and international funding agencies (ADB, 2021; Government of Canada, 2021b; World Bank Group, 2021). However, environmental considerations of water supply infrastructure projects have been overlooked. Several previous studies have been conducted by previous researchers to enhance eco-conscious decision-making in the construction sector. Table 4-1 presents key focus areas of published literature in eco-conscious decision-making within 2019-2021.

According to Table 4-1, several researchers have developed innovative evaluation methods to assess environmental performance for eco-conscious decision making (Laosirihongthong et al., 2019; Pamučar et al., 2021). However, due to intensive data requirements, the infrastructure sector will not be able to apply the proposed methods without a common data platform. Several researchers have identified performance indicators to compare various suppliers, contractors, or products (Bjerkan et al., 2019; Cui et al., 2020; Kesidou & Sovacool, 2019; Pamučar et al., 2021). A comprehensive review of the above research has revealed that there is no consistency in the evaluation criteria. There are several studies that have identified the challenges pertaining to implementing eco-conscious project evaluation. Foo et al., (2019) and Lindblad & Gustavsson, (2018) have identified that financial capabilities of the manufacturers, Intra organizational integration, transparency, stakeholder influences are some of the challenges impacting eco-conscious decision-making. In order to address these gaps in the literature, ecolabels can be utilized as a standard set of performance indicators and BIM as a platform to conduct the data-driven evaluation.

Table 4-1: Published literature on eco-conscious decision making in the construction sector

	Innovative evaluation methods	**Performance indicator identification**	**Implementation challenges**
(Kesidou & Sovacool, 2019)		✓	
(Laosirihongthong et al., 2019)	✓		
(Pamučar et al., 2021)	✓	✓	
(Bjerkan et al., 2019)		✓	
(Cui et al., 2020)		✓	
(Lindblad & Guerrero, 2020)	✓		✓
(D'Amico et al., 2020)	✓		
(Foo et al., 2019)			✓

4.2.1 Ecolabeling

Ecolabels inform customers of the product's environmental impacts in the form of a descriptive label (Gallastegui, 2002). There are three types of ecolabels specified by the International Standards Association (ISO):

Type I: Type I ecolabel is standardized via ISO 14024, and it is a multi-criteria ecolabel program evaluated by an independent third-party organization (Government of Canada, 2021). It is also a self-styled environmental symbol, claim, or statement based on the full life cycle considerations (UNEP, 2022)

Type II: Type II ecolabel is a self-declared claim made by the manufacturers following ISO 14021, considering the selected aspects of the product's life cycle. Type II ecolabels are presented without impartial third-party auditing or verification (OECD, 1997).

Type III: Environmental Product Declaration (EPD) uses pre-set indices based on ISO 14025 or EN 15804 to provide quantified environmental information about a product. An impartial organization verifies EPD before disclosing it to the public (Gallastegui, 2002). Given that EPDs contain quantified data, a consumer may evaluate a product`s environmental performance with its competitors. EPD is an incentive for green procurement of the construction sector (Manzini et al., 2006). Figure 4-1 depicts the process for developing an EPD.

LCA and the approval for the LCA are the two main components of EPD development. This process involves extensive data sharing. In conducting the LCA, a life cycle inventory shall be conducted based on the data provided by a manufacturer (Guinée et al., 2011). The accuracy of life cycle inventory data should be ensured. Moreover, this data can vary with time as a result of changes to production methods, transportation modes and distances, and the type of raw material used. An established EPD does not regularly update by incorporating the time-varied parameters. Therefore, innovative measures such as blockchain can be utilized to verify the data used in conducting the LCA and automatically incorporate life cycle inventory changes into an EPD.

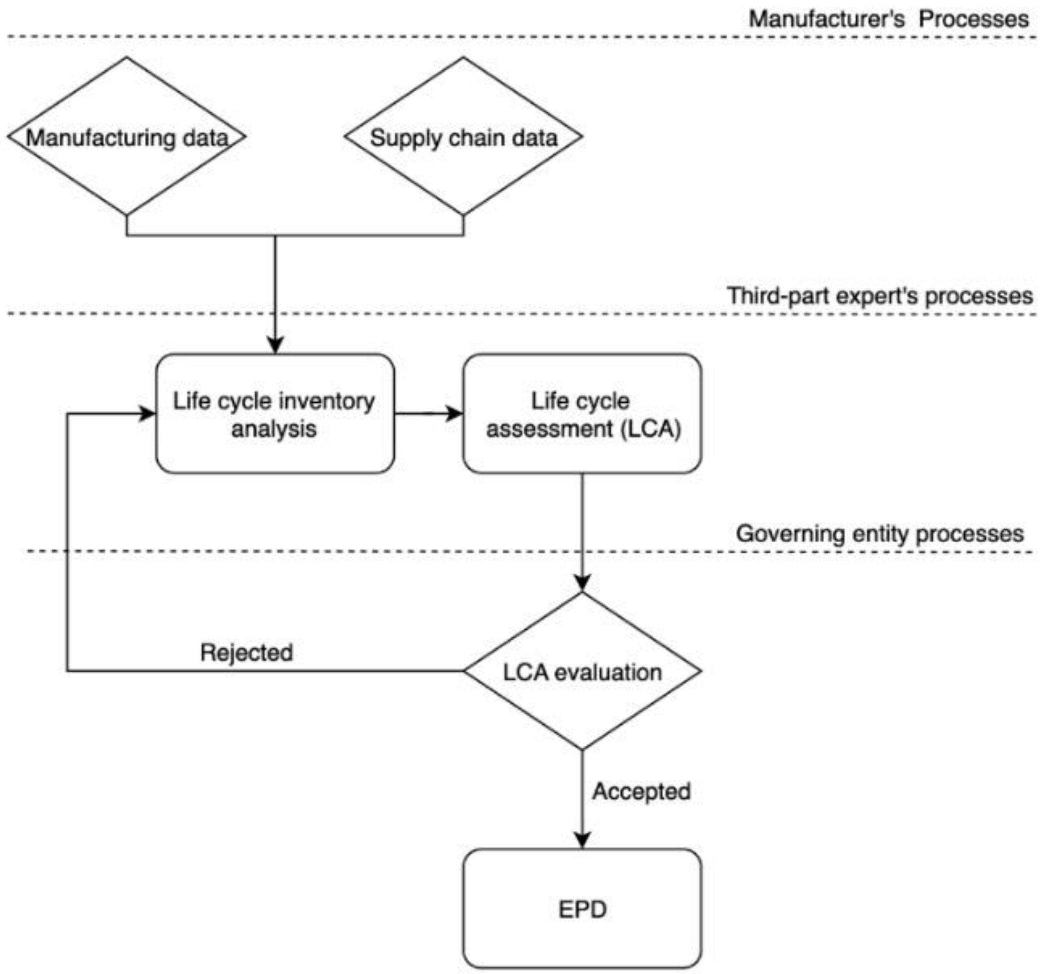

Figure 4-1: EPD Processes

4.2.2 Blockchain and its applications infrastructure

The blockchain concept was developed in 1991 and is widely practiced in the financial sector due to its speed, transparency, and encryption. Blockchain is defined as a decentralized electronic form of a database of blocks connected via chains (Tasatanattakool & Techapanupreeda, 2018). In a blockchain, the longest chain is identified as the main chain (also referred active chain), generated from the genesis block, and each block is connected with different information and encryption with specific authorization. The blockchain has four elements ledger, cryptography, consensus, and business logic. The ledger element is replicated and shared among all the participants in that blockchain domain (Cachin et al., 2016). The ledger contains the history of transactions, not necessarily in terms of money, while cryptography ensures the integrity of the ledge and the identity of the participants in the blockchain. Consensus is the decentralized protocol and business logic element that contains the logic embedded in the ledger, and it is executed together with the transactions. For each transaction, a new block is created and chained after verification, typically known as Proof of Work (POW), and once it is chained, it cannot be broken. Furthermore, each stakeholder in the blockchain has a private key and a public key in order to make a transaction (change) in the blockchain (Nakamoto, 2008). Once the transaction is approved, the entire chain is duplicated among every stakeholder involved (Turk & Klinc, 2017). The blockchain can be public, private, or hybrid based on the developer's requirement, and therefore, the application of blockchain has been extended into currency, healthcare, and supply chain. Similarly, the infrastructure sector can benefit from the blockchain concept in terms of eco-conscious decision-making via EPDs. Even though there wasn't any direct literature to support the possibility of using blockchain for eco-conscious decision-making via EPDs, Ølnes & Jansen (2017), Kiu et al. (2020), Li et al. (2019), (Rodrigo et al., 2020), and (Shojaei, 2019) stated that blockchain is evolving into a support infrastructure sector to aid secure documentation and provide entrusted data. Moreover, blockchain is positioned to positively influence future digital innovations, including in the public sector's e-governance.

The blockchain concept is developed for secure and transparent data sharing via duplication of its ledger between stakeholders. Infrastructure projects involve multiple stakeholders varying from suppliers to governmental authorities (Dodanwala & Santoso, 2021; Dodanwala & Shrestha, 2021), where the authenticity of the functional data has always been a major concern. Blockchain has the potential to address this challenge. In applying blockchain as a solution for EPDs' data challenges, all the life cycle inventory, including supply chain data, can be encrypted and shared block-wise to the LCA practitioner, the authority that approves the EPD, and the consumer. The authority will approve or reject the EPD and upload that data into the blockchain so that each party will have access to the most updated entrusted data. Since the supply chain is linked to the blockchain, sudden changes shall be shared instantaneously among the other stakeholders to provide the most updated EPD.

4.3 Conceptual Framework

This study focuses on water supply infrastructure projects and therefore considers the EPDs of PVC pipes and fittings as a case study for the framework. In order to develop a conceptual framework, life cycle processes in PVC pipes and fittings are identified. Based on the published literature, generalized life cycle processes and relevant stakeholders were identified Table 4-2.

Table 4-2: Pipes and fittings life cycle and EPD process, including the stakeholders. Adapted from Del-Borghi (2013), FPI (2021), and Government of Canada (2021)

Process	**Stakeholder**
Raw material extraction Manufacturing Transportation Operation (usage) End life disposal	Manufacturer
Conduct EPD	Expert
Verify EPD	Governing authority
Purchasing	Purchaser

Based on the life cycle processes and the stakeholders identified, a conceptual framework was designed to obtain a reliable and updated EPD via blockchain. The most updated EPD containing KPI values before the verification is denoted by uEPD in this framework. Once the uEPD is approved, it will become the EPD. In certain scenarios, uEPD may differ from the EPD based on the verification time lag. Figure 4-2 presents the architecture of the conceptual framework.

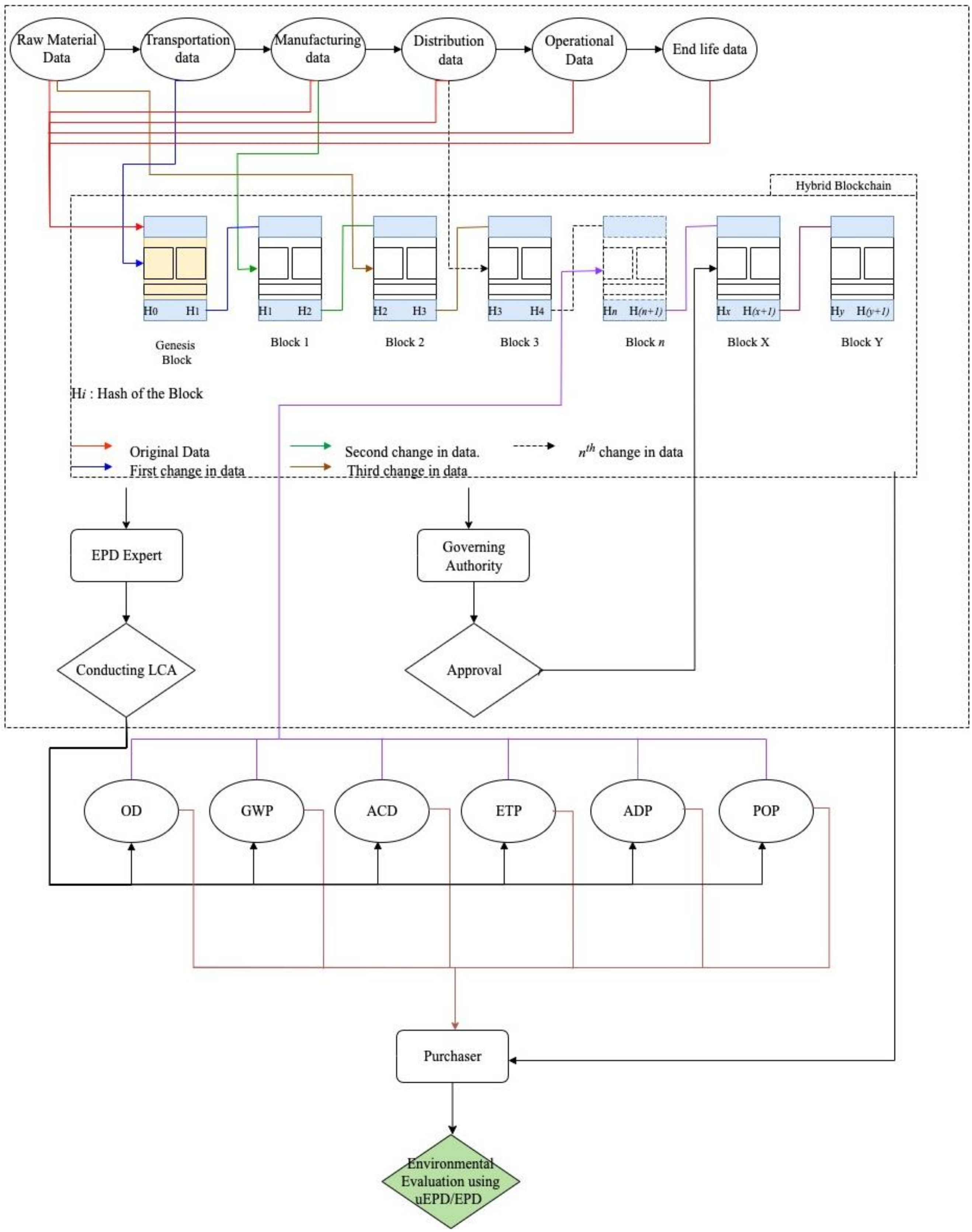

Figure 4-2: Blockchain based EPD conceptual framework

In this framework, the quantities, and qualities of each process of the life cycle of PVC pipes and fitting are shared among each stakeholder via blockchain. The initial data provided by the manufacturer is included in the Genesis block, and each modification that occurs within the life cycle is added to the blockchain. After the POW, a new block will be created and chained with the updates. An enhanced view of a block is presented in Figure 4-3.

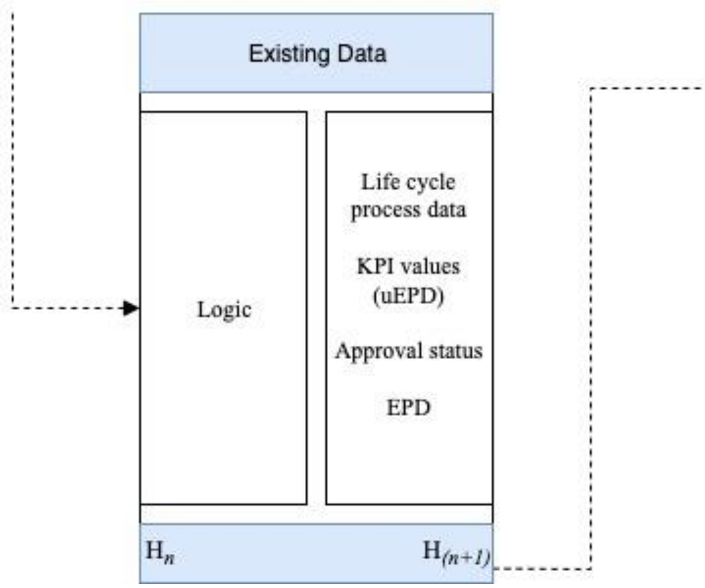

Figure 4-3: Enhanced view of Block *n*

The initial data provided in the Genesis block acts as the benchmark for the EPD. The *KPI values (uEPD), Approval status,* and the *EPD* appear as *Null* in the Genesis block. Any single transaction (change) in any of the *Life cycle process data, uEPD, approval status, and EPD* are added to the *logic element* in the block. In order to override existing data, each stakeholder has a private and public key; as an example, if the manufacturer's logistics department changes the mode of transportation to trucks from a rail, they add that change to the *Logic* using their private key and verify that change using their public key in order to confirm the authenticity. The signing using their keys is called the Hash, and it is a mathematical problem that must be solved to approve the transaction, which is the POW. Each block contains the Hash of the previous block, and therefore, any data tampering requires changing all the Hash in the succeeding blocks, which is impossible (Nakamoto 2008). The new *Life cycle process data, uEPD, Approval status,* and *EPD* are updated based on the logic provided and included in the blockchain as a new block. Furthermore, each change contains its timestamp to ensure the last update of data.

The expert obtains the last updated *Life cycle process data* and provides the uEPD and its KPI values by using their private and public keys. The governing authority verifies the last uEPD based on the timestamp and changes the approval status using their private and public keys to publish the EPD. However, to maintain consistency, the KPIs shall be predefined. Based on the EPD standards, ISO 14025 and EN 15804 KPIs vary. For the purposes of this case study, KPIs depicted in Table 4-3 are used.

Table 4-3: Key Performance Indicators

KPI	**Unit**
Ozone Depletion (OD)	kg CFC-11 eq
Global Warming Potential (GWP)	kg CO_2 eq
Acidification (ACD)	mol H+ eq
Eutrophication (ETP)	PO_4 eq / kg N eq
Abiotic depletion potential (ADP)	MJ
Photochemical oxidation potential (POP)	kg C_2H_4 eq

Since the purchaser has access the uEPD as well as the EPDs, the evaluation of manufacturers can be conducted. Even though the expert may take time in providing the uEPD or delays in approving an EPD, it will not cause any delays in decision-making due to the decentralized ledger with all the previous transactions. Therefore, the purchaser may still be able to make their decision based on previously approved EPD and the most updated KPI values in the uEPD.

4.4 Discussion

This research developed a conceptual framework to obtain the most updated and reliable EPD to aid the eco-conscious evaluation of water supply project proposals. Furthermore, through this framework, the client will have the opportunity to look into the backend of the supply chain and manufacturing information of the product before making a decision. This framework will deliver the following benefits to the construction industry as well as to the manufacturers.

- Considering the magnitude of investments for water supply infrastructure projects, implementing this framework will significantly lower the potential environmental impacts of the construction industry. Furthermore, since the EPD is conducted based on life cycling thinking, the overall environmental impacts can be minimized by adopting this framework.
- Since blockchain contains a decentralized database of all the transactions, the purchaser will have the ability to monitor and track the life cycle processes of a product. Hence, once the bidders are evaluated and the contract is awarded, the purchaser will be able to track the purchase order to ensure that the product is delivered according to the expected quality and environmental performance.
- The logistics information of the purchase order will also be shared with the purchaser. Therefore, once the order is placed, the purchaser will be able to track the status of the order and incorporate that data into the project scheduling process to make an accurate and precise project schedule.
- The proposed approach will aid contractors around the world in securely bidding for potential infrastructure projects. In fact, the data transparency is enhanced via blockchain; therefore, the purchaser will have no hesitation in the bidder's data. This will allow the manufacturers to expand their customer base on a global scale due to the blockchains' decentralized data sharing.

4.4.1 Implementation of the proposed framework

The manufacturers will develop a blockchain for their supply chain as well to transfer life cycle process data to other stakeholders. The manufacturer will appoint a control officer for each process in the product life cycle to monitor the changes happening in their respective process with a public and private key to update the information in the blockchain. Manufacturers can share the blockchain with their prospective buyers to emphasize their data credibility. The expert who develops the EPD and the approval authority will be provided with timeframes to consider the updates to the life cycle process in developing the EPD and approving it. The client will instruct all the manufacturers and experts to follow a single standard (e.g., ISO 14025) in developing the

EPD. Lastly, the client will gather the entrusted EPD and conduct the evaluation for eco-conscious decision-making.

4.4.2 Limitations of the proposed framework

Even though the proposed framework improves the eco-conscious decision-making for water supply infrastructure projects, implementation will be a challenge due to the knowledge and resource limitations of stakeholders. Furthermore, on a technical horizon, the blockchain process of hashing, which is solving the encryptions for validations of each block, requires a large amount lot of energy which is estimated to be 250-500MW (enough to power a major city to a small country) (Cachin et al., 2016). ICT solution providers such as IBM offers platforms to implement blockchain solutions for industries such as supply chain, food, oil, gas and etc. (Singh et al., 2019). However, since the blockchain solution providers are limited, there may be delays for manufacturers in developing countries to adopt blockchain. Lastly, the development of legislation for blockchain-based applications is pivotal. Due to the limitation of that, the contract administration between the stakeholders can create disputes. Another limitation of the proposed framework is the delays that may occur in developing and approving EPDs.

4.5 Summary

This chapter consists of a conceptual framework to enhance the data accuracy of EPDs. EPDs were utilized as an incentive to conduct the environmental impact evaluation within the comprehensive sustainable bid evaluation toolkit. However, the lack of trustworthiness of the EPD's backend data and the ineffective nature of the EPD's credibility during the long validation period has been identified as setbacks. Therefore, this chapter provides a blockchain based solution in terms of a conceptual framework to ensure the transparency of the product's backend data. Thus, the accuracy of the EPD and consequently the bid evaluation can be enhanced.

REFERENCES

Abou Jaoude, J., & George Saade, R. (2019). *Blockchain applications - Usage in different domains*. *7*, 45360–45381. https://doi.org/10.1109/ACCESS.2019.2902501

Cachin, C., Androulaki, E., de Caro, A., Osborne, M., Schubert, S., Sorniotti, A., Vukolic, M., & Weigold, T. (2016). Blockchain, cryptography, and consensus. *IBM Research - Zurich*.

Del-Borghi, A. (2013). LCA and communication: Environmental Product Declaration. In *International Journal of Life Cycle Assessment* (Vol. 18, Issue 2, pp. 293–295). Springer Verlag. https://doi.org/10.1007/s11367-012-0513-9

Dodanwala, T. C., & Santoso, D. S. (2021). The mediating role of job stress on the relationship between job satisfaction facets and turnover intention of the construction professionals. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-12-2020-1048

Dodanwala, T. C., & Shrestha, P. (2021). Work–family conflict and job satisfaction among construction professionals: the mediating role of emotional exhaustion. *On the Horizon*, *29*(2), 62–75. https://doi.org/10.1108/OTH-11-2020-0042

FPI. (2021). *Environmental Product Declaration*.

Gallastegui, I. G. (2002). The use of eco-labels: A review of the literature. *European Environment*, *12*(6), 316–331. https://doi.org/10.1002/EET.304

Government of Canada. (2021). *Environmental Labelling Programs* . Office of Consumer Affairs. https://ic.gc.ca/eic/site/oca-bc.nsf/eng/ca02742.html

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: Past, present, and future. *Environmental Science and Technology*, *45*(1), 90–96. https://doi.org/10.1021/ES101316V

Kankanamge, D. H., & Ruparathna, R. (2022). Adopting Ecolabels in the Construction Industry via Blockchain. *CSCE 2022 Annual Conference Whistler*, *British Columbia*, 1–15.

Kankanamge, D. H., & Ruparathna, R. (2022). *Life Cycle Thinking for Sustainable Public Procurement in Infrastructure Projects: A State-of-the-Art Review*.

Kiu, M. S., Chia, F. C., & Wong, P. F. (2020). Exploring the potentials of blockchain application in construction industry: a systematic review. *International Journal of Construction Management*. https://doi.org/10.1080/15623599.2020.1833436

Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction*, *102*, 288–307. https://doi.org/10.1016/J.AUTCON.2019.02.005

Manzini, R., Noci, G., Ostinelli, M., & Pizzurno, E. (2006). Assessing environmental product declaration opportunities: A reference framework. *Business Strategy and the Environment*, *15*(2), 118–134. https://doi.org/10.1002/BSE.453

Nakamoto, S. (2008). Bitcoin: A Peer-to-Peer Electronic Cash System. *Decentralized Business Review*. www.bitcoin.org

OECD. (1997). *Eco-Labelling: Actual Effects of Selected Programme*. https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=ocde/gd(97)105

Ølnes, S., & Jansen, A. (2017). Blockchain Technology as s Support Infrastructure in e-Government. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *10428 LNCS*, 215–227. https://doi.org/10.1007/978-3-319-64677-0_18

Rodrigo, M. N. N., Senaratne, S., & Weinand, R. (2020). Blockchain Technology: Is it Hype or Real in the Construction Industry? *Journal of Industrial Information Integration*. https://doi.org/10.1016/j.jii.2020.100125

Ruparathna, R. J. (2013). *Emergy based procurement framework to improve sustainability performance in construction.* [University of British Columbia]. https://doi.org/10.14288/1.0074139

Shojaei, A. (2019). Exploring applications of blockchain technology in the construction industry. *10th International Structural Engineering and Construction Conference*. https://doi.org/10.14455/ISEC.RES.2019.78

Singh, A. J., Cuomo, J., & Gaur, N. (2019). *Blockchain for Business*.

Tasatanattakool, P., & Techapanupreeda, C. (2018). Blockchain: Challenges and applications. *International Conference on Information Networking*, *2018-January*, 473–475. https://doi.org/10.1109/ICOIN.2018.8343163

Turk, Ž., & Klinc, R. (2017). Potentials of Blockchain Technology for Construction Management. *Procedia Engineering*, *196*, 638–645. https://doi.org/10.1016/J.PROENG.2017.08.052

UNEP. (2022). *Eco-labelling- UN Environment Programme*. Eco-Labelling. https://www.unep.org/explore-topics/resource-efficiency/what-we-do/responsible-industry/eco-labelling

CHAPTER 5

INVESTIGATING THE IMPLEMENTATION OF BIM-BASED SUSTAINABLE PROCUREMENT BY USING BAYESIAN BELIEF NETWORKS (BBN)

5.1 Background

The construction sector plays a key role in social and economic development (Ofori, 2012; Turin, 1980). Yet, it has been criticized for being inefficient and the lack of focus on TBL of sustainability (Adetunji et al., 2015; Hong et al., 2016). Out of many approaches, Building Information Modeling (BIM) has been identified as a promising solution to enhance the sustainability performance and efficiency of construction projects (Farnsworth et al., 2015). BIM is a collaborative platform that can contain a large amount of physical and functional data related to a project (Sacks et al., 2018). Despite the technological developments, implementation challenges still have been impacting the wider adaptation of BIM (Criminale & Langar, 2017). According to Steers, (2021), European countries are actively pursuing BIM implementation compared to the rest of the developed countries. In spite of several initiatives such as the introduction of implementation standards and guidelines (RAIC, 2021), Canada is yet to fully implement BIM in the construction industry. In fact, Canada is the only G7 country without a national BIM implementation mandate (Shahi & Lyall, 2019).

Implementing a novel technology such as BIM in a laid-back industry such as construction is a complex task (Dodanwala and Santoso, 2021). Challenges for BIM adaptation includes the lack of technical resources and knowledge persons (Ali et al., 2022; Criminale & Langar, 2017; Donato et al., 2017). Recently, there has been number of initiatives to address BIM implementation challenges. As an example, Zhu et al. (2019) have attempted to improve the interoperability between SHP files and IFC files. Zak & Vitasek, (2018) identified a financial threshold to decide if or not to implement BIM for a particular project. Due to the several shortcomings in the construction sector, it is vital to foresee the success of project-level BIM adaptation. As per author`s knowledge no study has been done on this topic for Canada.

Scholars have investigated on predictive models to determine the success of an event, process, or a product (Cooper et al., 2002; Zhang et al. 2016). Out of many approaches, Bayesian Belief Network (BBN) has been identified as one of the most sort afterapproachs to determine the success for a new process or a product (Guikema & Paté-Cornell, 2012). However, the accuracy of the

BBN relies on the precision of the input data. Obtaining accurate data, especially in construction sector can be difficult (Zarei et al., 2019). Moreover, construction process data can be qualitative, uncertain, and incomplete. Horčík (2008) suggested the use of fuzzy set theory to address above data challenges. A novel fuzzy-Bayesian belief network (FBN) approach can be used to incorporate data uncertainties associated predicting the success of BIM-based procurement implementation success.

This chapter addresses the above-mentioned gap in the literature by developing a model for predicting the success of BIM-based sustainable procurement in the Canadian construction sector. This study identifies the literature-based BIM-based procurement implementation drivers and predicts the overall probability of a successful BIM-based procurement implementation through an FBN. This study further identifies the factors that need immediate responses, considering the importance of it towards a successful BIM-based procurement implementation.

5.2 Literature review

Recently, BIM has expanded its application horizons from buildings to the infrastructure sector (Tien Doan et al., 2019). Recent updates to BIM software allow the construction sector to conduct specific analyses and improve stakeholder involvement for better decision-making. Many scholars have conducted research on manipulating the capabilities of BIM to aid various project activities throughout the project life cycle (e.g., sustainability analysis, procurement, cost analysis, and facilities management) (Hasan & Rasheed, 2019; Masood et al., 2014; Bradley et al., 2016). Patel & Ruparathna (2021) and Salehabadi & Ruparathna (2022) developed BIM-based frameworks to evaluate sustainability performance of the built environment. Similarly, Aguiar Costa & Grilo (2015) and Sloot et al. (2019) utilized BIM's 4D simulation capabilities to assist the project management decision-making. Yet, it is evident that previous BIM research is more biased towards technical innovations (Bradley et al., 2016).

5.2.1 Drivers of BIM implementation

Table 5-1 presents the identified drivers for BIM-based procurement implementation. Each driver was categorized based on the influence of the type of stakeholder or the type of application. Furthermore, certain drivers such as adequate amount of BIM experts, BIM related training for employees, affordable cost for implementation, BIM-related research, etc. are common for multiple categories.

Table 5-1: BIM implementation drivers

Driver category	Driver	Source
Client readiness	Affordable cost for implementation	(Criminale & Langar, 2017; Smith, 2014)
	Adequate BIM experts	(Migilinskas et al., 2013; Vass & Gustavsson, 2017)
	Government motivation	(Diaz, 2016; Lindblad, 2019)
	Training for employees	(Lindblad & Guerrero, 2020; Migilinskas et al., 2013)
	Advantages of implementing BIM	(Langar, 2017; Smith, 2014)
Industry readiness	Affordable cost for implementation	(Criminale & Langar, 2017)
	Adequate BIM experts	(Migilinskas et al., 2013)
	Client motivation	(Lindblad & Guerrero, 2020; Vass & Gustavsson, 2017)
	Government motivation	(Diaz, 2016; Lindblad, 2019)
	Training for employees	(Lindblad & Guerrero, 2020; Migilinskas et al., 2013)
	Advantages of implementing BIM	(Langar, 2017; Smith, 2014)
Technology compatibility	BIM product databases and libraries	(Criminale & Langar, 2017; Smith, 2014)
	BIM interoperability	(Eadie et al., 2013; Lindblad, 2019)

	BIM-related research	(Criminale & Langar, 2017; Migilinskas et al., 2013)
Contract management	BIM protocols and legal contracts	(Lindblad, 2019; Smith, 2014)
	BIM-based standards	(Miettinen & Paavola, 2014; Migilinskas et al., 2013)
	BIM implementation guidelines	(Miettinen & Paavola, 2014; Vass & Gustavsson, 2017)
	BIM-related research	(Criminale & Langar, 2017; Migilinskas et al., 2013)

As shown in Table 5-1, successful BIM-based procurement implementation in the construction industry is influenced by multiple factors. Client readiness is one such impact category identified in literature (Criminale & Langar, 2017; Vass & Gustavsson, 2017). In order for the clients to be ready to implement BIM in their projects, affordable BIM implementation costs, motivation from the government, and expert users are required (Criminale & Langar, 2017; Diaz, 2016; Vass & Gustavsson, 2017). Construction industry consisting of contractors, suppliers and etc. shall also have an adequate readiness level parallel to the clients to gain the full benefits of BIM. Similarly, in the client readiness category, client`s motivation for BIM adaptation is crucial (Vass & Gustavsson, 2017). Other impact categories for a successful BIM-based procurement implementation consist of technical capacity and contract management capacity. Technological readiness includes availability of adequate databases and open-source file formats as well as continuous improvement to enhance current technologies (Eadie et al., 2013; Migilinskas et al., 2013; Smith, 2014). Furthermore, Migilinskas et al. (2013), Smith (2014) and Vass & Gustavsson (2017) have identified standard contract documents, protocols, standards, and guidelines are essential ingredients for smooth BIM-based procurement implementation.

5.2.2 Evaluating the success of technology adaptation

Technology evaluation and new technology adaptation are two regular encounters in the contemporary world. Hence, it is vital to determine the success of new technology adaptation before its implementation. Simple assessment methods such as multi-dimensional scoring sheets or rating process is an approach conduct as a preliminary assessment to determine the readiness (Cooper et al., 2002). Many complex mathematical models can be used to evaluate the success of new technology adaptation (Mock et al., 1993). Table 5-2 shows various techniques used by previous researchers for the assessment of new technology success.

Table 5-2: New technology success evaluation techniques

Method	**Source**
System dynamic modelling	(Swiderski et al., 2012)
Bayesian belief networks	(Vens et al., 2008; Dueñas-Santana et al. 2021)
interviews	(Vinod et al., 2003)
Event tree analysis	(Ramzali et al., 2015)
Neural networks	(Ronzhina et al., 2012)

BBN is a plausible method for evaluating the successful implementation of a new technologies (Guikema & Paté-Cornell, 2012; Park & Kim, 2013). As an example, Dueñas-Santana et al. (2021) and Zhang et al. (2016) have used Fuzzy Set Theory (FST) and Bayesian Belief Network (BBN) to predict the failure probability of thermal radiation of a hydrocarbon storage and to predict the probability of gas pipeline failure.

5.2.2.1 Bayesian Belief Networks

BBN is a probabilistic method for establishing a set of random variables and their dependencies via an acyclic graph (Pearl, 1988). An engineering process can be analyzed by using BBN. As an example, various engineering-related analysis such as pipeline failures, safety analysis, and thermal radiation accident predictions have been performed by using BBN (Dueñas-Santana et al., 2021; Zarei et al., 2019; Zhang et al., 2016). BBN adopts relationships among multiple variables to predict the probability of an event's occurrence (Chen & Pollino, 2012). In BBN, events are represented in nodes that are connected to each other through links that represent the relationship as shown in Figure 5-1. In the figure independent nodes (A & B) are defined as parent nodes, while dependent nodes (C) as child nodes in a BBN (Chen & Pollino, 2012). Obtaining probabilities of child nodes is a difficult task in the construction sector due to the low response rates and the lack of accurate technical knowledge (Mentes & Helvacioglu, 2011). In such scenarios, expert opinion can be sought by using linguistic identifiers (Li et al., 2012).

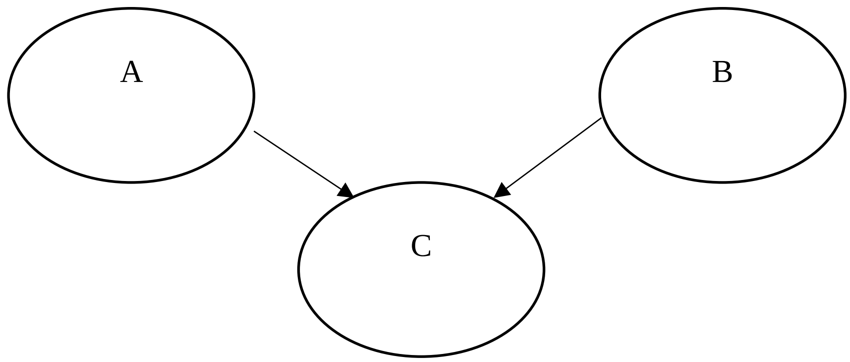

Figure 5-2: Typical BBN

5.2.2.2 Fuzzy set theory

According to Hanss (1999), FST can be used to explain engineering problems under uncertainty. The uncertainty is taken into consideration as fuzzy numbers (intervals) (Horčík, 2008). FST is used to convert vague linguistic terms into crisp numbers through a fuzzy membership function (Dubois et al., 2000). Fuzzy membership function consisting fuzzy numbers can take various geometric shapes (i.e., triangular, trapezoidal, Gaussian). Determining the fuzzy membership faction is a complex process. Cheng & Chen (1997) proposed a simulated annealing algorithm-based approach in determining the correct membership function. Barua et al., (2014) suggested that trapezoidal fuzzy membership function is a suitable approach for calculating the probability of an event's occurrence. Following Figure 5-2 is the trapezoidal membership function (a1, a2, a3, a4).

In FST the membership function is denoted as $\mu A(x)$; $x \rightarrow [0,1]$. If x is a universe of discourse and x is a particular element of X, then a fuzzy set A defined on X and can be written as a collection of ordered pairs as $A= \{(x, \mu A(x)), x \in X\}$.

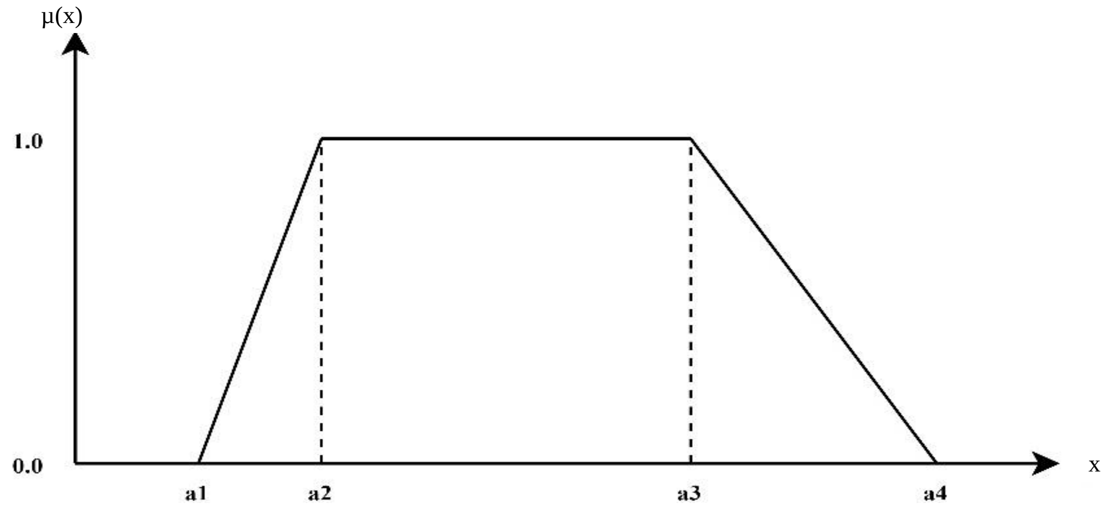

Figure 5-3:Trapezoidal membership function

FST has been used in previous research in determining the relative importance weights between dependent and independent variables, (Dueñas-Santana et al., 2021; Shahriar et al., 2012; Zarei et al., 2019). Since FST incorporates data uncertainty, there is no requirement for a large data sample (Zarei et al., 2019; Zhang et al., 2016).

5.2.2.3 Fuzzy Bayesian Belief Networks

Fuzzy BBN provides the means determining failure or success of an event when uncertain and vague data is available (Eleye-Datubo et al., 2008). Therefore, in order to predict the success or the failure of BIM-based procurement implementation in the construction sector, Fuzzy Bayesian Network (FBN) approach is much suited (Dueñas-Santana et al., 2021; Zhang et al., 2016). The independent probability values required in for the parent nodes of BBN can be computed via FST (Zhang et al., 2016). Thus, FBN can predict the probability of an event while considering the uncertainty. No previous study has focused on developing BBN for evaluating the success of BIM-based sustainable procurement in the construction sector.

5.3 Methodology

The methodology adopted here consists of 3 phases. Phase 1 consists of understanding the BIM-based procurement implementation process in the construction industry and data collection. Phase 2 consists of processing the collected raw data and converting them as the inputs to FBN. The last phase consists of developing the BBN to determine the probability of successful BIM-based procurement implementation in the current Canadian construction sector. Figure 5-3 illustrates the overall research methodology.

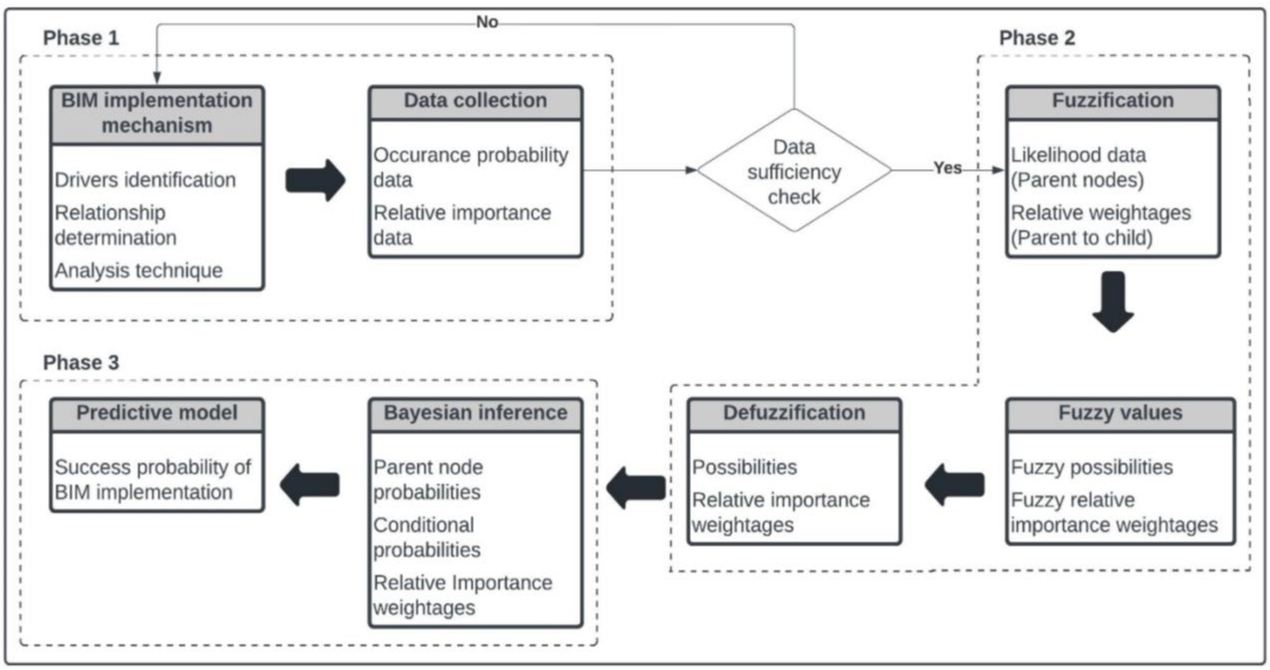

Figure 5-4: Workflow for the FBN predictive model for successful BIM-based procurement implementation

5.3.1 Phase 1: BIM implementation mechanism and data collection

The drivers of BIM-based procurement implementation and its relationships were identified, as depicted in Table 5-1. Altogether four main drivers (Child nodes) were identified for successful BIM-based procurement implementation as client readiness, industry readiness, technology compatibility, and contract management. Furthermore, 12 independent drivers (Parents nodes) were also identified that affect the probability of each four main drivers. Each child node consists of multiple parent nodes, and each parent node has one or more child nodes based on identified literature.

Data collection was conducted from case studies data in 3 stages. The first stage gathered data about the profiles of respondents. Each respondent shall be weighted based on the profile, suggested by Ramzali et al. (2015) and Zarei et al. (2019) (Table 5-3).

Table 5-3: Weighting score for respondents

Constitution	Classification	Score	Constitution	Classification	Score
Professional position (PP)	Senior academic/ Department head/ Project manager	5	Education level (EL)	PhD	5
	Junior academic/ Senior Engineer/ BIM coordinator	4		Masters	4
	Engineer	3		Bachelor	3
	Technician	2		Diploma/Certificate	2
	Worker	1		High school	1
Experience (years) (EP)	≥ 30	5	Age (years) (AG)	≥ 50	4
	20-29	4		40-49	3
	10-19	3		30-39	2
	6-9	2		≤ 30	1
	≤ 5	1			

The second stage gathered the likelihood of each parent node. Estimating the occurrence probability of vague and human error-dominated events via a single probability is error prone. Zadeh (1965) recommended the use of linguistic variables in such circumstances. Since the humans' memory capacity is limited, a suitable number of comparison variables vary between 5 and 9 (Huang et al., 2001; Miller, 1956). Therefore, a scale consisting of 9 linguistics terms was considered for estimating the occurrence probability (Table 5-4) (Chen & Hwang, 1992).

Table 5-4: Linguistic terms and fuzzy numbers to describe the occurrence probability

Linguistic term	Fuzzy sets ($\overline{a_1}, \overline{a_2}, \overline{a_3}, \overline{a_4}$)
Very High (VH)	(0.8,1, 1, 1)
High-Very High (H-VH)	(0.7,0.9,1,1)

High (H)	(0.6,0.8, 0.8,1)
Fairly High (FH)	(0.5,0.65, 0.65,0.8)
Medium (M)	(0.3,0.5, 0.5,0.7)
Fairly low (FL)	(0.2, 0.35, 0.35,0.5)
Low (L)	(0,0.2,0.2, 0.4)
Low-Very Low (L-VL)	(0,0,0.1,0.3)
Very Low (VL)	(0,0,0,0.2)

The stage 3 gathered the relative importance weightage of each independent variable (parent node) with reference to the dependent variable (child nodes). Fuzzy sets have been defined for each linguistic term as suggested by Dueñas-Santana et al. (2021) and Shahriar et al. (2012). However, the linguistic terms have been modified and reworded to suit the focus of this study. Table 5-5 represents the linguistic terms for respective fuzzy set.

Table 5-5: Relative importance weightage of independent variables

Linguistic term	**Fuzzy set** $(\dot{a}_1, \dot{a}_2, \dot{a}_3, \dot{a}_4)$
Not at all important (NI)	0, 0, 0, 0.25
Slightly important (SI)	0, 0.25, 0.25, 0.50
Moderately important (MI)	0.25, 0.50, 0.50, 0.75
Very important (VI)	0.50, 0.75, 0.75, 1.0
Extremely important (EI)	0.75, 1, 1, 1

5.3.2 Phase 2: Fuzzification

Equation 5-1 was used to provide a weight to the responses (aggregated fuzzy membership function) based on the profile of respondents. w_i is the aggregated value of expert *i* scored based on the criterion in Table 5-3.

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad \text{Equation 5-1}$$

W_i: Weight factor of respondent i $w_i: PP_i + EL_i + ES_i + AG_i$

PP, EL, ES, and AG are, respectively, professional position score, education level score, experience score, and age score for each respondent, as mentioned in Table 5-3.

Three data sets were gathered for this study. Consequently, using the data in Table 5-3 and Equation 5-1, the weightage factor for each respondent was calculated and depicted in Table 5-6 alongside the respondent profile.

Table 5-6: Expert weighting score

Expert No	**Title**	**Experience (Years)**	**Education level**	**Age (Years)**	**Score**
1	Junior academic/Senior Engineer/BIM coordinator	≤ 5	Masters	≤ 30	0.26
2	Junior academic/Senior Engineer/BIM coordinator	6-9	PhD	30-39	0.34
3	Junior academic/Senior Engineer/BIM coordinator	20-29	Masters	40-49	0.39

Aggregated membership functions of occurrence possibilities

Once the weights are determined, the aggregated membership function for each event were calculated. By considering the linear opinion pool approach (Clemen & Winkler, 1999), the aggregated weighted fuzzy values of event *i* were calculated as denoted in Equation 5-2 and aggregated weighted fuzzy membership functions were established for each event.

$$(a_1, a_2, a_3, a_4) = \sum_{i=1}^{m} W_j \times (\overline{a_1}, \overline{a_2}, \overline{a_3}, \overline{a_4})_{ij} \ , J = 1,2,3, \dots\dots, n \qquad \text{Equation 5-2}$$

a_i: Aggregated fuzzy value of event i m: Total number of events

W_j: Weighted score of response j n: Total number of responses

$(\overline{a_1}, \overline{a_2}, \overline{a_3}, \overline{a_4})_{ij}$: Fuzzy set corresponding to the linguistic value obtained from response j about event i

<u>Aggregated membership functions of relative importance weightages (RIW)</u>

FST was used in determining the relative importance weightage of each parent event with respect to the child nodes. Fuzzy values for the relative importance weightage were denoted as $\dot{a_1}, \dot{a_2}, \dot{a_3}, \dot{a_4}$ as depicted in Table 5-5. The aggregate fuzzy membership function of relative importance weightages is calculated using Equation 5-2.

Defuzzification

Out of many defuzzification methods, center of gravity (COG) method is the most widespread method (Sugeno & Kang 1986). This is due to its ability to represent the entire membership function (Lee, 1990; Takagi & Sugeno, 1985). COG approach was used for defuzzification as per Equation 5-4. The membership function of $\mu_A(x)$ is shown in Figure 5-5 and can be defined as following Equation 5-3.

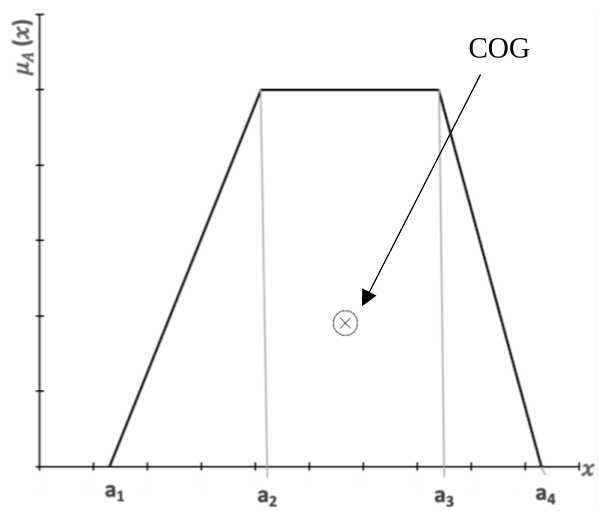

Figure 5-5: Trapezoidal membership function for fuzzy number A

$$\mu_A(x) = \begin{cases} 0 & , x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1} & , a_1 \le x \le a_2 \\ 1 & , a_2 \le x \le a_3 \\ \dfrac{a_4 - x}{a_4 - a_3} & , a_3 \le x \le a_4 \\ 0 & , x > a_4 \end{cases} \quad \text{Equation 5-3}$$

$$\bar{X} = \frac{\int \mu_i(x) X}{\int \mu_i(x)} dx \quad \text{Equation 5-4}$$

$\bar{X}$: COG of the membership function $\quad$ X: Output variable

$\mu_i(x)$: Aggregated weighted membership function

Using Equation 5-4 and

Equation 5-3, defuzzification of the trapezoidal fuzzy number A= (a_1, a_2, a_3, a_4) is calculated as per Equation 5-5.

$$\bar{X} = \frac{1}{3} \times \left[\frac{(a_4 + a_3)^2 - a_4 a_3 - (a_1 + a_2)^2 + a_1 a_2}{(a_4 + a_3 - a_1 - a_2)} \right] \qquad \text{Equation 5-5}$$

5.3.3 Phase 3: Fuzzy-Bayesian Network

The aggregated fuzzy membership function represents the fuzzy probability of each BIM driver (parent node). Thus, using COG defuzzification method, crisp probabilities (CPr) of each BIM driver being adequate were calculated.

Once the independent crisp probability values were computed, the conditional probabilities of each child node were determined. Binary values were used to compute the conditional probability for each given condition by multiplying each variable with the Defuzzified relative importance weightage (Equation 5-6). An independent variable with the condition *Adequate* was assigneda probability value 1.0, and for the condition *Not Adequate*, a probability value of 0 was assigned. Similarly, the final conditional probability for a given scenario is computed by considering all the parent nodes for a particular child node.

$$\text{Conditional probability} = \frac{\sum_i^n RI_i \times E_i}{n} \qquad \text{Equation 5-6}$$

RI_i: Defuzzified relative importance weightage of independent variable i

n: Number of parent nodes

E_i: Assigned conditional probabilistic value for event i $(0 \ or \ 1)$

During the last step, an acyclic diagram was developed by using the BIM drivers and their relationships depicted in Table 5-1. Norsys software corporation's Netica application was used to develop the BBN. Determined CPr, RIW, and conditional probabilities were used in determining the probability of successful BIM-based procurement implementation (Equation 5-7, Equation 5-7and Equation 5-9). Lastly, a sensitivity analysis was done to determine the fluctuation of the results under various controlled settings.

$$P(U) = \prod_{i=1}^{n} P(X_i | P_\alpha(X_i)$$ Equation 5-7

$P(U)$: Probability distribution of $\mathrm{U} = \{X_1, \ldots\ldots, X_n\}$

$P_\alpha(X_i)$: Parent set of variable X_i

$$P(X_i) = \sum_{X_{j,;J\neq 1}} P(U)$$ Equation 5-8

Following Equation 5-9 computes the probability of U given the evidence E.

$$P(U|E) = \frac{P(U,E)}{P(E)} = \frac{P(U,E)}{\sum_U (P(U,E)}$$ Equation 5-9

5.4 Results and discussion

Table 5-7 depicts the expert judgment (Exp*i*) for each independent driver, the aggregated fuzzy membership function, and the crisp probability of adequacy (CPr).

Table 5-7: Expert judgments and crisp probabilities

Driver	**Exp 1**	**Exp 2**	**Exp 3**	**Aggregated Membership function**	**CPr**
Government motivation	FH	FH	FL	(0.38, 0.53, 0.53, 0.68)	0.53
Client motivation	M	L	L	(0.08, 0.28, 0.28, 0.48)	0.28
BIM databases & libraries	L	M	M	(0.22, 0.42, 0.42, 0.62)	0.42
Protocols & legal contracts	L	L	L	(0.00, 0.20, 0.20, 0.40)	0.20

BIM Guidelines	L	M	M	(0.22, 0.42, 0.42, 0.62)	0.42
BIM Standards	L	L	L	(0.00, 0.20, 0.20, 0.40)	0.20
BIM implementation cost	L	FL	L	(0.07, 0.25, 0.25, 0.43)	0.25
BIM interoperability	L	FL	FL	(0.15, 0.31, 0.31, 0.47)	0.31
BIM implementation advantages	VH	VH	VH	(0.80, 1.00, 1.00, 1.00)	0.93
BIM-related research	FH	H-VH	FH	(0.57, 0.74, 0.77, 0.55)	0.74
Amount of BIM experts	M	FL	FL	(0.23, 0.39, 0.39, 0.36)	0.32
Employee training	M	M	FL	(0.26, 0.44, 0.44, 0.42)	0.38

5.4.1 Fuzzy relative importance weightages

Using the data in Table 5-1, Table 5-5, and Equations 5-2 through Equation 5-5, the Relative Importance Weightage (RIW) were calculated (Table 5-8). Table 5-8 further contains responses of each expert and the aggregated fuzzy membership function of each parameter.

Table 5-8: Expert judgment and Fuzzy relative importance weightages (RIW)

Child Nodes	**Parent Nodes**	**Exp 1**	**Exp 2**	**Exp 3**	**Aggregated Membership function**	**RIW (%)**
Industry readiness	Amount of BIM experts	EI	EI	VI	(0.39, 0.64, 0.64, 0.83)	14.74
	BIM implementation cost	MI	SI	VI	(0.35, 0.60, 0.60, 0.85)	14.17
	Government motivation	VI	VI	MI	(0.40, 0.65, 0.65, 0.90)	15.41
	Client motivation	VI	MI	VI	(0.41, 0.66, 0.37, 0.91)	16.25
	Employee training	VI	VI	VI	(0.50, 0.75, 0.75, 1.00)	17.75
	BIM implementation advantages	EI	EI	EI	(0.75, 1.00, 1.00, 1.00)	21.69
Client readiness	Amount of BIM experts	MI	EI	EI	(0.62, 0.87, 0.87, 0.93)	23.09
	BIM implementation cost	VI	SI	SI	(0.13, 0.38, 0.38, 0.63)	10.92
	Government motivation	VI	VI	VI	(0.50, 0.75, 0.75, 1.00)	21.46
	Employee training	VI	VI	VI	(0.50, 0.75, 0.75, 1.00)	21.46
	BIM implementation advantages	VI	EI	VI	(0.59, 0.84, 0.84, 1.00)	23.09
Technology readiness	BIM databases & libraries	EI	EI	VI	(0.65, 0.90, 0.90, 1.00)	35.63
	BIM-related Research	VI	MI	VI	(0.41, 0.66, 0.66, 0.91)	27.82
	BIM Interoperability	VI	EI	EI	(0.68, 0.93, 0.93, 1.00)	36.55
	BIM Guidelines	VI	EI	VI	(0.59, 0.84, 0.84, 1.00)	26.15

Contract management	BIM-related Research	VI	MI	VI	(0.41, 0.66, 0.66, 0.91)	21.54
	BIM standards	VI	EI	VI	(0.59, 0.84, 0.84, 1.00)	26.15
	Protocols & contracts	VI	EI	VI	(0.59, 0.84, 0.84, 1.00)	26.15
Implementation	Industry readiness	VI	VI	EI	(0.60, 0.85, 0.85, 1.00)	24.64
	Client readiness	VI	VI	VI	(0.50, 0.75, 0.75, 1.00)	22.65
	Technology readiness	VI	EI	EI	(0.68, 0.93, 0.93, 1.00)	26.36
	Contract management	VI	EI	EI	(0.68, 0.93, 0.93, 1.00)	26.36

5.4.2 Bayesian Belief Network

Figure 5-5 presents the developed BBN to predict the implementation success of BIM–based sustainable procurement in the Canadian construction sector. The results convey that there is a 51.4% probability of BIM-based procurement implementation failing in the current Canadian

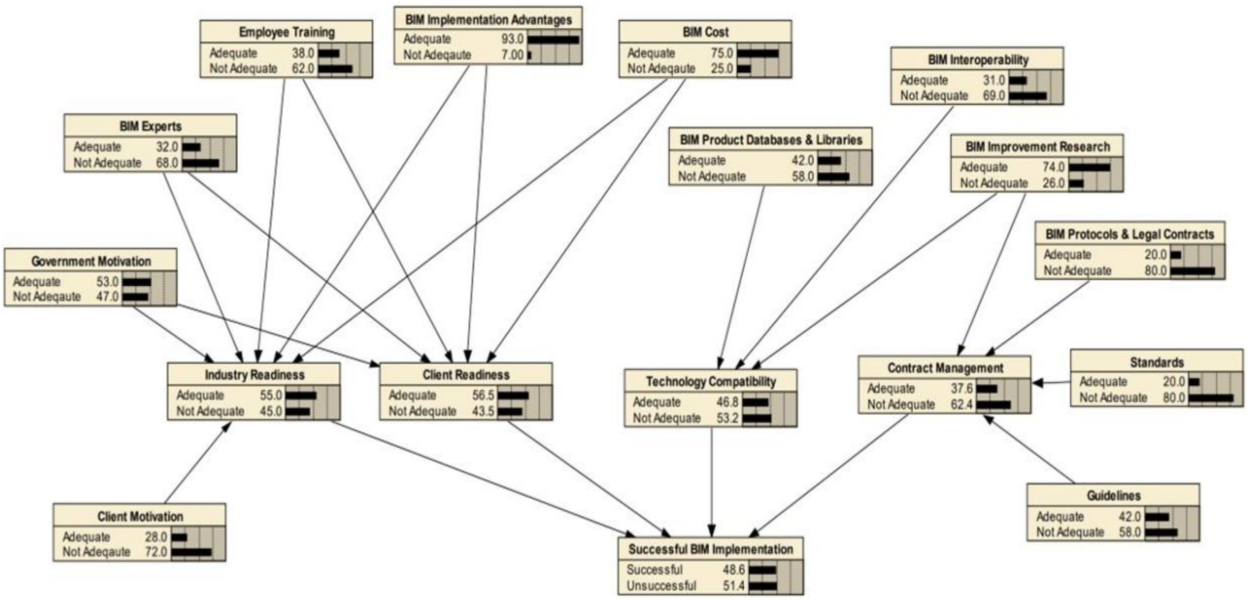

Figure 5-6: Bayesian belief network

construction sector.

Based on the results, the adequate amount of BIM advantages has the highest probability (93%). The BBN revealed that BIM-related standards, protocols, and contracts are currently insufficient. The probability of contract management readiness in the current Canadian construction sector has 37.6% probability of being adequate. Yet, both the industry and clients' readiness to be adequate to implement BIM within their organizations has a probability of over 55%.

5.4.3 Sensitivity analysis

A sensitivity analysis was conducted to determine the fluctuation of the results to draw theoretical and practical implications for the study. Table 5-9 depicts the results of the sensitivity analysis. Each variable was changed to 0% and 100% probability of being adequate while controlling the other variables to determine how much results fluctuated.

Table 5-9: Sensitivity Analysis

Variable	BIM Implementation success %			Original
	0% adequacy	100% adequacy	Difference	probability
Industry readiness*	33.5	61	27.5	55
Client readiness*	34	59.9	25.9	56.5
Technology readiness*	35.7	63.3	27.6	46.8
Contract management readiness*	38.3	65.9	27.6	37.6
Government motivation	44	52.7	8.7	53.2
Client motivation	47.5	51.5	4	27.9
BIM databases & libraries	44.7	54	9.3	42.1
Protocols &legal contracts	47.3	54.1	6.8	20.0
Guidelines	45.8	52.6	6.8	42.1
Standards	47.3	54.1	6.8	20.0
BIM cost	44.2	50.1	5.9	25.1
BIM interoperability	45.7	55.3	9.6	31.1
Implementation advantages	38.7	49.4	10.7	93.3
BIM research	39	52	13	74.3
BIM experts	45.8	54.7	8.9	32.4
Employee training	45.1	54.4	9.3	37.5

Note: Variable* are the child nodes of the drivers.

Table 5-8 contains the original probabilities of the parent nodes based on the FBN analysis. The overall probability of BIM-based procurement implementation success is evaluated by considering values between 0% and 100% adequacy probability.

5.5 Discussion

Based on the findings of this study, implementation of BIM-based sustainable procurement in the Canadian construction sector has a 48.6% probability of being successful. Nine drivers out of 12 (i.e., Protocols &legal contracts, BIM experts, Employee training) has less than 50% probability of being adequate. BIM implementation advantages have a 93% probability of being adequate, and this finding is confirmed by multiple literature by explaining various advantages of BIM (Sacks et al., 2018; Fargnoli & Lombardi, 2020; Criminale & Langar, 2017; Diaz, 2016). The amount of

BIM-related research has drastically increased over the last few years (Hasan & Rasheed, 2019). Thus, the probability of adequate amount of BIM-related research being done for successful BIM-based procurement implementation is at 74%. Even though Canada is yet to fully mandate BIM, the motivation provided by the government to implement BIM in Canada is at 53% probability.

As per the results of the sensitivity analysis, increasing the amount of BIM-related research has the strongest influence on providing a higher success probability of BIM-based procurement implementation. However, BIM-related research has a 74% probability of being adequate. Furthermore, the BIM implementation advantages have the second strongest influence on providing a higher success probability of BIM-based procurement implementation. Consequently, BIM implementation advantages has a 93% probability of being adequate. Hence, it is possible to deduce that, the most influential parameters for a successful BIM-based procurement implementation are adequate in the current Canadian construction industry.

BIM interoperability increases the success probability of BIM-based procurement implementation by 9.6%. Currently, the probability of having adequate amount of BIM interoperability resources for successful BIM-based procurement implementation is at 31.1%. BIM interoperability is reinforced by the availability of open-source file formats. According to Zhu et al. (2019), open-source file formats are yet to achieve its potential in terms of infrastructure definitions, sustainability-related definitions, safety definitions and etc.

Currently, the probability of having adequate number of BIM experts, databases and libraries, and BIM training provided for employees are at less than 50%, However, increasing the above to 100% individually will increase the chances of successful BIM-based procurement implementation respectively by 8.9%, 9.3%, and 9.3%. Expert knowledge is vital for the success of technology implementation in any sector (Mcarthur & Robin, 2019). Post-secondary education/research with a focus on BIM can increase the number of experts. Furthermore, databases and object libraries for BIM need to be expanded for the Canadian construction industry. Furthermore, AEC industry practitioners should receive training in modeling, analyzing, data sharing, simulation, and other features of BIM.

The parent nodes of successful BIM-based procurement implementation are the readiness of the industry, clients, technology, and contract management. Those four parameters directly influence the success of BIM implementation. However, as per the sensitivity analysis, all four parameters have a significantly similar influence on BIM-based procurement implementation success. Contract management readiness has the lowest adequate probability and is one of the strongest influences on the success of BIM-based procurement implementation. Therefore, BIM protocols such as when to use BIM, what kind of projects BIM should be used for should be defined. Furthermore, standard contracts and guidelines should be stipulated to increase the chances of BIM-based procurement implementation being successful.

5.5.1 Limitations

There are three main limitations that have affected the findings of this study.

Data uncertainties: Even though the data uncertainty was accounted for in this analysis, a smaller data sample is a limitation of this study. Furthermore, human errors in providing feedback have been minimized in data collection by using a 9-point scale. However, consistency of the responses will remain as a limitation.

Model uncertainties: The BBN model was prepared by using literature. There are drivers that may not have been included in the acyclic diagram. This limitation could impact the findings of this research.

The static nature of the evaluation: The result of this study is a snapshot view of the current Canadian construction sector. Due to the dynamic nature of the construction industry, the calculated probabilities may vary in the future.

5.6 Summary

This chapter developed a predictive model to identify the success of BIM-based sustainable procurement in the Canadian construction industry. Literature-based drivers for BIM-based procurement implementation were used to develop the acyclic diagram. Occurrence probability data were collected from the Canadian construction professionals and analyzed using a Fuzzy-Bayesian Belief Network. The result of this cross-sectional study revealed that the Canadian construction sector is not ready to implement BIM-based sustainable procurement successfully. Therefore, it is crucial to address the identified BIM-based procurement implementation challenges such as developing resources to increase the probability of successful implementation of BIM-based procurement in the Canadian construction sector.

REFERENCE

Adetunji, I., Price, A., Fleming, P., & Kemp, P. (2015). Sustainability and the UK construction industry—a review. *Http://Dx.Doi.Org/10.1680/Ensu.2003.156.4.185*, *156*(4), 185–199. https://doi.org/10.1680/ENSU.2003.156.4.185

Aguiar Costa, A., & Grilo, A. (2015). BIM-based e-procurement: An innovative approach to construction e-procurement. *Scientific World Journal*, *2015*. https://doi.org/10.1155/2015/905390

Ali, K. N., Alhajlah, H. H., & Kassem, M. A. (2022). Collaboration and Risk in Building Information Modelling (BIM): A Systematic Literature Review. *Buildings 2022, Vol. 12, Page 571*, *12*(5), 571. https://doi.org/10.3390/BUILDINGS12050571

Barua, A., Mudunuri, L., & Kosheleva, O. (2014). Why Trapezoidal and Triangular Membership Functions Work So Well: Towards a Theoretical Explanation. *Journal of Uncertain Systems*, *8*. https://scholarworks.utep.edu/cs_techrep/783

Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and constructor perspective. *Automation in Construction*, *71*, 139–152. https://doi.org/10.1016/J.AUTCON.2016.08.019

Cooper, R. G., Edgett, S. J., & Kleinschmidt, E. J. (2002). Optimizing the stage-gate process: What best-practice companies Do-I. Research Technology Management, 45(5), 21–27. https://doi.org/10.1080/08956308.2002.11671518

Chen, S. H., & Pollino, C. A. (2012). Good practice in Bayesian network modeling. *Environmental Modelling and Software*, *37*, 134–145. https://doi.org/10.1016/J.ENVSOFT.2012.03.012

Chen, S. J., & Hwang, C. L. (1992). *Fuzzy Multiple Attribute Decision Making Methods*. 289–486. https://doi.org/10.1007/978-3-642-46768-4_5

Cheng, H. D., & Chen, J. R. (1997). Automatically determine the membership function based on the maximum entropy principle. *Information Sciences*, *96*(3–4), 163–182. https://doi.org/10.1016/S0020-0255(96)00141-7

Clemen, R. T., & Winkler, R. L. (1999). Combining Probability Distributions From Experts in Risk Analysis. *Risk Analysis 1999 19:2*, *19*(2), 187–203. https://doi.org/10.1023/A:1006917509560

Criminale, A., & Langar, S. (2017). Challenges with BIM Implementation: A Review of Literature . *53rd ASC Annual International Conference Proceedings*. http://www.ascpro.ascweb.org

Diaz, P. M. (2016). Analysis of Benefits, Advantages and Challenges of Building Information Modelling in Construction Industry. *Journal of Advances in Civil Engineering*, *2*(2), 1–11. https://doi.org/10.18831/djcivil.org/2016021001

Dodanwala, T. C., and D. S. Santoso. (2021). "The mediating role of job stress on the relationship between job satisfaction facets and turnover intention of the construction professionals." *Engineering, Construction and Architectural Management*. Emerald Group Holdings Ltd. https://doi.org/10.1108/ECAM-12-2020-1048.

Donato, V., Biagini, C., Bertini, G., & Marsugli, F. (2017). Challenges and opportunities for the implementation of h-bim with regards to historical infrastructures: A case study of the ponte giorgini in castiglione della pescaia (grosseto - Italy). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *v 42*, *n 5W1*(5W1), p 253-260. https://doi.org/10.5194/isprs-Archives-XLII-5-W1-253-2017

Dubois, D., Ostasiewicz, W., & Prade, H. (2000). *Fuzzy Sets: History and Basic Notions*. 21–124. https://doi.org/10.1007/978-1-4615-4429-6_2

Dueñas-Santana, J. A., Orozco, J. L., Furka, D., Furka, S., Boza Matos, Y. C., Febles Lantigua, D., González Miranda, A., & Barrera González, M. C. (2021). A new Fuzzy-Bayesian approach for the determination of failure probability due to thermal radiation in domino effect accidents. *Engineering Failure Analysis*, *120*, 105106. https://doi.org/10.1016/J.ENGFAILANAL.2020.105106

Eadie, R., Browne, M., Odeyinka, H., Mckeown, C., & Mcniff, S. (2013). BIM implementation throughout the UK construction project lifecycle: An analysis. *Automation in Construction*, *36*, 145–151. https://doi.org/10.1016/j.autcon.2013.09.001

Eleye-Datubo, A. G., Wall, A., & Wang, J. (2008). Marine and offshore safety assessment by incorporative risk modeling in a fuzzy-Bayesian network of an induced mass assignment paradigm. *Risk Analysis*, *28*(1), 95–112. https://doi.org/10.1111/J.1539-6924.2008.01004.X

Fargnoli, M., & Lombardi, M. (2020). Building information modelling (BIM) to enhance occupational safety in construction activities: Research trends emerging from one decade of studies. *Buildings*, *10*(6). https://doi.org/10.3390/BUILDINGS10060098

Farnsworth, C. B., Beveridge, S., Miller, K. R., & Christofferson, J. P. (2015). Application, Advantages, and Methods Associated with Using BIM in Commercial Construction. *International Journal of Construction Education and Research*, *11*(3), 218–236. https://doi.org/10.1080/15578771.2013.865683

Guikema, S. D., & Paté-Cornell, M. E. (2012). Bayesian Analysis of Launch Vehicle Success Rates. Https://Doi.Org/10.2514/1.9268, 41(1), 93–102. https://doi.org/10.2514/1.9268

Hanss, M. (1999). On the implementation of fuzzy arithmetical operations for engineering problems. *Annual Conference of the North American Fuzzy Information Processing Society - NAFIPS*, 462–466. https://doi.org/10.1109/NAFIPS.1999.781736

Hasan, A. N., & Rasheed, S. M. (2019). The Benefits of and Challenges to Implement 5D BIM in Construction Industry. *Civil Engineering Journal*, *5*(2), 412. https://doi.org/10.28991/CEJ-2019-03091255

Hong, J., Shen, G. Q., Guo, S., Xue, F., & Zheng, W. (2016). Energy use embodied in China's construction industry: A multi-regional input-output analysis. *Renewable and Sustainable Energy Reviews*, *53*, 1303–1312. https://doi.org/10.1016/J.RSER.2015.09.068

Horčík, R. (2008). Solution of a system of linear equations with fuzzy numbers. *Fuzzy Sets and Systems*, *159*(14), 1788–1810. https://doi.org/10.1016/J.FSS.2008.01.018

Huang, D., Chen, T., & Wang, M. J. J. (2001). A fuzzy set approach for event tree analysis. *Fuzzy Sets and Systems*, *118*(1), 153–165. https://doi.org/10.1016/S0165-0114(98)00288-7

Kankanamge, D. H., & Ruparathna, R. (2022). *Life Cycle Thinking for Sustainable Public Procurement in Infrastructure Projects: A State-of-the-Art Review*.

Langar, S. (2017). *Challenges with BIM Implementation: A Review of Literature ollege Students' Perception of Household Energy Efficiency View project Residential Industry Perception for Resilience View project*. http://www.ascpro.ascweb.org

Lee, C. C. (1990). Fuzzy Logic in Control Systems: Fuzzy Logic Controller—Part I. *IEEE Transactions on Systems, Man and Cybernetics*, *20*(2), 404–418. https://doi.org/10.1109/21.52551

Li, P. cheng, Chen, G. hua, Dai, L. cao, & Zhang, L. (2012). A fuzzy Bayesian network approach to improve the quantification of organizational influences in HRA frameworks. *Safety Science*, *50*(7), 1569–1583. https://doi.org/10.1016/J.SSCI.2012.03.017

Lindblad, H. (2019). Black boxing BIM: the public client's strategy in BIM implementation. *Construction Management and Economics*, *v 37, n 1*(1), p 1-12. https://doi.org/10.1080/01446193.2018.1472385

Lindblad, H., & Guerrero, J. R. (2020). Client's role in promoting BIM implementation and innovation in construction. *Construction Management and Economics*, *v 38, n 5*(5), p 468-482. https://doi.org/10.1080/01446193.2020.1716989

Masood, R., Kharal, M. K. N., & Nasir, A. R. (2014). Is BIM Adoption Advantageous for Construction Industry of Pakistan? *Procedia Engineering*, *77*, 229–238. https://doi.org/10.1016/J.PROENG.2014.07.021

Mcarthur, J., & Robin, E. (2019). Victims of their own (definition of) success: Urban discourse and expert knowledge production in the Liveable City. *Article Urban Studies*, *56*(9), 1711–1728. https://doi.org/10.1177/0042098018804759

Mentes, A., & Helvacioglu, I. H. (2011). An application of fuzzy fault tree analysis for spread mooring systems. *Ocean Engineering*, *38*(2–3), 285–294. https://doi.org/10.1016/J.OCEANENG.2010.11.003

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. *Automation in Construction*, *43*, 84–91. https://doi.org/https://doi.org/10.1016/j.autcon.2014.03.009

Migilinskas, D., Popov, V., Juocevicius, V., & Ustinovichius, L. (2013). The Benefits, Obstacles and Problems of Practical Bim Implementation. *Procedia Engineering*, *57*, 767–774. https://doi.org/10.1016/j.proeng.2013.04.097

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81–97. https://doi.org/10.1037/H0043158

Mock, J. E., Kenkeremath, D. C., & Janis, F. T. (1993). Moving R&D to the Marketplace, A Guidebook for Technology Transfer Managers. https://doi.org/10.2172/860797

Ofori, G. (2012). New perspectives on construction in developing countries. *New Perspectives on Construction in Developing Countries*, 1–388. https://doi.org/10.4324/9780203847343

Park, H. J., & Kim, S. H. (2013). A Bayesian network approach to examining key success factors of mobile games. Journal of Business Research, 66(9), 1353–1359. https://doi.org/10.1016/J.JBUSRES.2012.02.036

Patel, K., & Ruparathna, R. (2021). Life cycle sustainability assessment of road infrastructure: a building information modeling-(BIM) based approach. *Https://Doi.Org/10.1080/15623599.2021.2017113*. https://doi.org/10.1080/15623599.2021.2017113

Pearl, J. (1988). Chapter 1 – UNCERTAINTY IN AI SYSTEMS: AN OVERVIEW. In *Probabilistic Reasoning in Intelligent Systems*.

RAIC. (2021). *BIM Explained* . http://www.buildingsmart-tech.org/

Ramzali, N., Lavasani, M. R. M., & Ghodousi, J. (2015). Safety barriers analysis of offshore drilling system by employing Fuzzy Event Tree Analysis. *Safety Science*, *78*, 49–59. https://doi.org/10.1016/J.SSCI.2015.04.004

Ren, J., Jenkinson, I., Wang, J., Xu, D. L., & Yang, J. B. (2009). An offshore risk analysis method using fuzzy Bayesian network. *Journal of Offshore Mechanics and Arctic Engineering*, *131*(4), 1–12. https://doi.org/10.1115/1.3124123/468241

Ronzhina, M., Janoušek, O., Kolářová, J., Nováková, M., Honzík, P., & Provazník, I. (2012). Sleep scoring using artificial neural networks. *Sleep Medicine Reviews*, *16*(3), 251–263. https://doi.org/10.1016/J.SMRV.2011.06.003

Ross, T. J. (2010). Fuzzy Logic with Engineering Applications. In *Fuzzy logic with engineering applications* (3rd ed.). John Wiley & Sons.

Ruparathna, R., & Hewage, K. (2015). Sustainable procurement in the Canadian construction industry: current practices, drivers and opportunities. *Journal of Cleaner Production*, *109*, 305–314. https://doi.org/10.1016/j.jclepro.2015.07.007

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM Handbook: A Guide to Building Information Modelling for Owners, Designers, Engineers, Contractors and Managers* (3rd ed.). John Wiley & sons.

Salehabadi, Z. M., & Ruparathna, R. (2022). User-centric sustainability assessment of single family detached homes (SFDH): A BIM-based methodological framework. *Journal of Building Engineering*, *50*. https://doi.org/10.1016/J.JOBE.2022.104139

Steers, S. (2021). *Which countries are leading the adoption of BIM?* . Digital Construction. https://constructiondigital.com/digital-construction/which-countries-are-leading-adoption-bim

Shahi, A., & Lyall, R. (2019). BIM can transform the Canadian construction and design industry . *Daily Commercial News*. https://canada.constructconnect.com/dcn/news/government/2019/10/bim-can-transform-the-canadian-construction-and-design-industry

Shahriar, A., Sadiq, R., & Tesfamariam, S. (2012). Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis. *Journal of Loss*

Prevention in the Process Industries, *25*(3), 505–523. https://doi.org/10.1016/J.JLP.2011.12.007

Sloot, R. N. F., Heutink, A., & Voordijk, J. T. (2019). Assessing usefulness of 4D BIM tools in risk mitigation strategies. *Automation in Construction, v 106*. https://doi.org/10.1016/j.autcon.2019.102881

Smith, P. (2014). BIM implementation - Global strategies. *Procedia Engineering*, *85*, 482–492. https://doi.org/10.1016/j.proeng.2014.10.575

Sugeno, M., & Kang, G. T. (1986). Fuzzy modelling and control of multilayer incinerator. *Fuzzy Sets and Systems*, *18*(3), 329–345. https://doi.org/10.1016/0165-0114(86)90010-2

Takagi, T., & Sugeno, M. (1985). Fuzzy Identification of Systems and Its Applications to Modeling and Control. *IEEE Transactions on Systems, Man and Cybernetics*, *SMC-15*(1), 116–132. https://doi.org/10.1109/TSMC.1985.6313399

Tien Doan, D., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ur Rehman, A., Tookey, J., & Ghaffarianhoseini, A. (2019). What is BIM? A Need for A Unique BIM Definition. *MATEC Web of Conferences*. https://doi.org/10.1051/matecconf/2019

Turin, D. A. (1980). What do we mean by building? *Habitat International*, *5*(3–4), 271–288. https://doi.org/10.1016/0197-3975(80)90023-5

Vass, S., & Gustavsson, T. K. (2017). Challenges when implementing BIM for industry change. *Construction Management and Economics*, *v 35, n 10*(10), p 597-610. https://doi.org/10.1080/01446193.2017.1314519

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, *8*(3), 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X

Zak, J., & Vitasek, S. (2018). Bim superior approach for infrastructure construction in the Czech Republic. *Engineering for Rural Development*, *v 17*, p 578-584. https://doi.org/10.22616/ERDev2018.17.N210

Zarei, E., Khakzad, N., Cozzani, V., & Reniers, G. (2019). Safety analysis of process systems using Fuzzy Bayesian Network (FBN). *Journal of Loss Prevention in the Process Industries*, *57*, 7–16. https://doi.org/10.1016/J.JLP.2018.10.011

Zhang, L., Wu, X., Qin, Y., Skibniewski, M. J., & Liu, W. (2016). Towards a Fuzzy Bayesian Network Based Approach for Safety Risk Analysis of Tunnel-Induced Pipeline Damage. *Risk Analysis*, *36*(2), 278–301. https://doi.org/10.1111/RISA.12448

Zhu, J., Wang, X., Chen, M., Wu, P., & Kim, M. J. (2019). Integration of BIM and GIS: IFC geometry transformation to shapefile using enhanced open-source approach. *Automation in Construction*, *106*, 102859. https://doi.org/10.1016/J.AUTCON.2019.102859

CHAPTER 6
CONCLUSIONS

The vision of this research is to enhance the BIM-based sustainable procurement of water supply infrastructure projects. This thesis developed several implementation tools and analyzed the construction industry's readiness for BIM-based sustainable procurement. The conclusions, recommendations, contributions, and future research are explained in the following sections.

6.1 Conclusions

The main conclusions of this research are as follows:

The proposed BIM-toolkit provides a direct link in the BIM platform for TBL performance evaluation of water supply project proposals. The framework adopts EPDs, life cycle social impact data, and life cycle cost data. The proposed method enables obtaining a comprehensive evaluation of proposed water supply infrastructure.

The case study results revealed that the optimal project proposal identified by the developed BIM plugin toolkit had a 15.24% higher increase in environmental and 45.5% increase in social performance. However, the bid price was 6.55% higher than the lowest cost bid.

Blockchain can be used to mitigate data inaccuracies, enhance transparency, and maintain the data security of EPDs. The proposed framework linked EPDs, BIM, and blockchain. By implementing this technology, the reliability of the results in the proposed sustainable procurement plugin toolkit can also be enhanced. Furthermore, blockchain can be used to enhance the accuracy environmental labeling in general.

BBN was used to determine the success of the implementation of BIM-based sustainable procurement in the Canadian construction sector. By considering the drivers of BIM implementation in the Canadian construction sector, the results revealed that there is a 48.6% probability of successfully implementing BIM-based sustainable procurement.

6.2 Recommendations

Based on this research, the following recommendations are made for BIM-based sustainable procurement.

- TBL-based proposal evaluation enabled identifying a proposal with higher environmental and social performance than the lowest cost bid. Hence it is recommended to incorporate TBL of sustainability into the project proposal evaluation. This approach will assist enhancing the sustainability performance of the construction sector as a whole.
- Traditionally, an approved EPD is valid for a period of 3-5 years. This approach disregards the possible changes to the life cycle inventory during the above time period. Incorporating blockchain into environmental labeling is recommended to mitigate the above drawback.
- The BBN model revealed that the with current status, BIM-based procurement in the Canadian construction sector has a higher probability of failure. Hence, it is recommended to develop BIM-related standards, protocols, guidelines, and contract agreements to ensure a successful BIM implementation.

6.3 Contributions

Main contributions of this research are as follows:

Implementation support tools for BIM-based sustainable procurement: This research contributes to the infrastructure sector by developing a BIM plugin toolkit to assist sustainable procurement. This will improve the efficiency of the proposal evaluation so that the construction industry can minimize delays in the procurement process. Furthermore, the BIM-plugin toolkit contributes to the accuracy of the evaluation as well as improves the transparency.

This research proposed solutions to smoothen the industrial implementation of the BIM plugin toolkit. These tools contribute to the construction industry to improve the accuracy of EPD data via blockchain integration.

BBN model for assessing BIM implementation: A BBN model was developed to analyze the implementation success of BIM-based procurement in the construction sector. This model allows construction organizations to understand about the success of BIM-based procurement implementation. Furthermore, the use of fuzzy-set theory incorporates data uncertainties into the evaluation.

6.4 Future research

The following research could extend the findings of this research.

The proposed proposal evaluation platform can be extended as a BIM-based e-procurement platform. Further research is required to develop a comprehensive database including EPD data S-LCA and cost data. Further research is required to analyze the construction industry perception for such framework.

State-of-the-art technology can be used to enhance implementation of BIM-based sustainable procurement. As an example, blockchain can used to enhance data accuracy and smart contract can be embedded in blockchain to automate contract management. Further research is required to develop required resources for the above.

It is vital to determine threshold values for each TBL KPI for regional specificity. Further research is required to study TBL performance values in previous water supply projects and determine a threshold range.

VITA AUCTORIS

NAME:	Dilusha Hemal Kankanamge
PLACE OF BIRTH:	Sri Jayawardenapura, Sri Lanka
YEAR OF BIRTH:	1994
EDUCATION:	Royal College, Colombo, Sri Lanka, 2013
	Asian Institute of Technology, BSc., Pathum Thani, Thailand, 2018.
ACHIEVEMENTS:	Recipient of the CSA graduate scholarship
	Winner of the 3MT thesis competition in the Faculty of Engineering
INDUSTRIAL PROJECTS:	MITACS research intern for the project Assessing the Validity and Reliability of a Client Risk Profile Assessment Method
	MITACS research intern for the project Investigating the industrial greenhouse gas (GHG) emissions in Greater Toronto and Hamilton Area (GTHA).