A Quantitative Assessment of Cost and Carbon Dioxide Emissions Associated with Industrialized Concrete Basements in Cold-climate Regions

by

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ABSTRACT

The building and construction industry aims to reduce its CO_2 emissions to reach Net-Zero goals by the year 2050. However, the industry faces the challenge of a possible increase in its CO_2 emission levels due to rapid global population growth. Consequently, researchers and practitioners have devised strategies to reduce the CO_2 emissions generated during the operational phase of a building's life cycle. However, other phases with emission reduction potential, including the construction phase, have been largely overlooked. The construction phase generates between 10% and 20% of the total CO_2 emissions generated during a building's life cycle, and these emissions are expected to increase due to rapid global population growth and the corresponding need for additional residential housing. Furthermore, construction material manufacturing, including concrete and cement manufacturing, accounts for approximately 6% of the total CO_2 emissions attributable to human activity. In this context, industrialized construction has emerged as an alternative construction method capable of reducing both the overall project duration and the total quantity of materials used in construction projects. These reductions, in turn, can lead to a decrease in the CO_2 emissions generated during the construction phase. Despite the potential environmental benefits, though, the high cost of this alternative construction method remains an impediment to its adoption. Moreover, due to the lack of a quantitative method by which to objectively compare the financial and environmental benefits between traditional and industrialized construction methods, decision makers struggle to make sound decisions when selecting the construction method that most closely aligns with their financial and environmental targets. In light of this, this thesis presents a quantitative assessment method for conducting cost and environmental tradeoff analysis between cast-in-place and industrialized (precast) concrete basements for residential buildings in cold-climate regions. Three construction scenarios are considered in the tradeoff analysis: the traditional cast-in-place construction method and two industrialized construction

methods, solid-wall precast and ribbed precast structure. Moreover, three criteria are selected for quantifying and comparing the cost and CO_2 emissions between these methods: concrete, temporary heating, and site inspections. Simulation models are developed in Simphony.NET to recreate the project schedule for the on-site construction of concrete basements for both the cast-in-place and the two precast construction scenarios. The total cost and CO_2 emissions resulting from the use of temporary heating, concrete, and site inspections are then calculated for each of the three scenarios. Finally, a tradeoff analysis is conducted to determine the cost and environmental implications between cast-in-place and industrialized (precast) concrete construction. The key contribution of this thesis is a quantitative method by which to objectively estimate and compare the cost and environmental benefits between traditional and industrialized construction methods. This will aid decision makers in making sound decisions based on empirical information when choosing the most appropriate construction method for a given project.

PREFACE

This thesis is an original work by Valeria Veronica Vecchio Castillo. The research process and components conducted for this thesis received approval from the University of Alberta Research Ethics Board, under the project name "A Quantitative Assessment of Carbon Dioxide Emissions Associated with Industrialized Concrete Structures for Basements in Cold-Climate Regions", No. Pro00133346, on November 28, 2023. This thesis is organized in a paper-based format, and it follows the University of Alberta's guidelines for a paper-based thesis. One journal paper and two conference papers associated with the research developed for this thesis have been submitted, accepted, or published, as follows:

1. **Vecchio Castillo, V**., Dias Barkokébas, R., Barkokébas, B., Al-Hussein, M. "A Quantitative Assessment of Carbon Dioxide Emissions Associated with Temporary Heating in Residential Housing." *Proceedings, Canadian Society for Civil Engineering (CSCE) Annual Conferenc*e, Moncton, NB, Canada, May 24–27, 2023 (Accepted, 2023).

This conference paper appears as Chapter 3 of this thesis. Valeria Vecchio Castillo was responsible for leading the execution of the proposed methodology, data collection and analysis, and the composition of the research paper. Dr. Dias Barkokébas and Dr. Barkokébas were responsible for assisting in the conceptualization and development of the methodology and analysis, as well as for the revision of the research paper. Dr. Dias Barkokébas and Dr. Al-Hussein were the supervisory authors of the manuscript and were involved in the conceptualization of the research methodology and the revision of the research paper.

2. **Vecchio, V**., Barkokébas, E., Días Barkokébas, R., Barkokébas, B., Al-Hussein, M. "A Systematic and Bibliometric Review of Greenhouse Gas Emissions in the Construction Phase of Residential Buildings." Proceedings, Construction Research Congress: Sustainability, Resilience,

Infrastructure Systems, and Materials Design in Construction, Des Moines, IA, USA, Mar. 20–23, 2024, pp. 568–577.

This conference paper appears as Chapter 2 of this thesis. Valeria Vecchio Castillo was responsible for leading the execution of the proposed methodology, data collection and analysis, and the composition of the research paper. Enric Barkokébas Martins assisted in the filtering of the research papers included in the literature review and in the development of the research methodology. Dr. Dias Barkokébas and Dr. Barkokébas were responsible for assisting in the conceptualization of the methodology, as well as for the revision of the research paper. Dr. Dias Barkokébas and Dr. Al-Hussein were the supervisory authors of the manuscript and were involved in the conceptualization of the research methodology and the revision of the research paper.

3. **Vecchio, V**., Barkokébas, E., Días Barkokébas, R., Barkokébas, B., & Al-Hussein, M. "Environmental and Financial Tradeoff Analysis of Industrialized Construction Methods in Cold Climate Regions." *Journal of Cleaner Production* (Submitted, 2024).

This journal paper appears as Chapter 4 of this thesis. Valeria Vecchio Castillo was responsible for leading the execution of the proposed methodology, data collection and analysis, and the composition of the research paper. Enric Barkokébas Martins assisted in the data analysis phase and in the development of the graphics presented in this paper. Dr. Dias Barkokébas and Dr. Barkokébas were responsible for assisting in the conceptualization of the methodology and the revision of the research paper. Dr. Dias Barkokébas and Dr. Al-Hussein were the supervisory authors of the manuscript and were involved in the conceptualization of the research methodology and the revision of the research paper.

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The completion of this thesis and my master's program was possible thanks to the unconditional love and support of my family. I would like to dedicate this thesis to my role models and greatest source of inspiration—my parents, Orlando Vecchio Nero and Julia Castillo. Thank you so much for your unconditional love, for instilling in me the values of hard work and responsibility, and for teaching me the importance of education. Thanks for always believing in me and for teaching me that I am capable of achieving all of my goals. I also want to dedicate this thesis to Osis, one of the people I love the most on this planet. Thanks for your unconditional love and support, for always taking care of me, for believing in me, even when I did not do it myself, and for shaping me into the person I am today. I would also like to thank my siblings, Orly, Isa, Christian, and Juni, for being an important influence in my life and for always supporting me. I want to also thank my friends, both in Panama and Canada, for being my support system during this period.

I also want to express my gratitude to Sol for always believing in my potential and for providing me with the tools and resources I needed to make the transition to living by myself in Canada and navigating the master's experience. Thank you for the weekly meetings and for always providing a safe space for me to share my thoughts and feelings.

I cannot finish the acknowledgments without thanking myself for all the effort I made to develop this thesis. I want to thank myself for not giving up despite the adversity, for being extremely committed to the completion of this thesis, and for always pushing through despite the inherent uncertainties that come with the research process and the feelings of fear and loneliness that come with being an immigrant. Thank you, little Valeria, for having big dreams of studying abroad from a very early age and for working so hard to make that dream a reality.

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LIST OF ABBREVIATIONS

BIM	Building Information Modelling
CIP	Cast-in-Place
CO_2	Carbon Dioxide
CO_2 kg-eq	Kilograms of Carbon Dioxide Emission Equivalent
CRMCA	Canadian Ready-Mix Concrete Association
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analysis
RP	Ribbed Precast
SCC	Self-Compacting Concrete
SOG	Slab-on-Grade
SW	Solid-Wall Precast

CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

The increase in greenhouse gas (GHG) emissions present in the atmosphere is a substantive environmental concern due to the significant contribution of these emissions to global warming and climate change (IPCC, 2022). A further increase in GHG emission levels is expected as a result of population growth and increased fossil fuel-dependent human activities (Tao et al., 2018; Fang et al., 2018). Consequently, policymakers and governments are encouraging industries to adopt environmental strategies to reduce their GHG emission levels and prevent irreversible changes to the climate (Global Alliance for Buildings and Construction, 2022; IPCC, 2022; Scherz et al., 2023).

In this regard, the building and construction industry has been attempting to reduce its carbon dioxide (CO_2) emissions—CO_2 being the predominant form of GHG emissions attributed to human activity (Jiang et al., 2019)—in order to reach Net-Zero goals by the year 2050 (Global Alliance for Buildings and Construction, 2022). On the other hand, there is pressure on the building construction industry to meet the high housing demand that is accompanying rapid global population growth (Global Alliance for Buildings and Construction, 2022; United Nations Department of Economic and Social Affairs, 2022). Therefore, the building and construction industry faces the challenge of meeting the housing demands of the world's growing population while also complying with the policies and regulations established by international entities and governments to develop strategies to reduce global CO_2 production.

In Canada, there is a growing emphasis on reducing CO_2 emissions to reach the environmental goals established by Canada's 2030 Emission Reduction Plan. This plan targets a 40% reduction in GHG emissions, considering the emission levels from the year 2005 as the baseline (Environment and Climate Change Canada, 2022). The plan calls on various industrial sectors, including the building construction industry, to implement alternatives to reduce the GHG emissions generated. In the context of the building construction industry in Canada, there has been an increase in housing demand in the largest urban centres in the country as a result of rapid population growth and urbanization in recent years (Canada Mortgage and Housing Corporation, 2023; Carter, 2005). According to the Canada Mortgage and Housing Corporation (2023), an additional 3.5 million residential buildings will be required in Canada by 2030 to compensate for the current and projected housing shortage. As a result, residential construction is expected to increase in scale, underscoring the urgent need to reduce the GHG emissions generated by this industry on a per-unit basis.

However, researchers and industry experts have primarily focused their attention on reducing the CO_2 emissions generated during the operational phase of a building's life cycle while largely overlooking the emissions from other phases, such as the construction phase (Tao et al., 2018). The construction phase accounts between 10% and 20% of the total CO_2 emissions being generated during the building's life cycle, with approximately 9%–11% of these emissions attributed to the embodied emissions of construction materials (Ji et al., 2018; Global Alliance for Buildings and Construction, 2020; Global Alliance for Buildings and Construction, 2022). In this regard, the manufacture of construction materials such as concrete and steel was found to have generated approximately 6% of the total global CO_2 emissions attributed to the building sector in 2022 (Global Alliance for Buildings and Construction, 2022). Because of the construction industry's comparably high CO_2 emission levels, the research gaps related to emissions reduction in construction, the predicted population growth, and the corresponding increased demand for housing, it is imperative that alternative construction techniques be explored aimed at reducing the CO_2 emissions generated during the construction phase (Tao et al., 2018; Jiang et al., 2019).

It is also worth noting that single-family detached houses represent 52.6% of all residential buildings in Canada (Statistics Canada, 2021). These buildings utilize concrete as the primary construction material for the below-ground portion of the house, while the majority of the above-ground portion is built using structural wood. Previous research conducted by Mah et al. (2011) identified the construction of traditional cast-in-place concrete basements as a significant source of CO_2 emissions in comparison to other phases of the construction process for single-family detached houses. These emissions further increase during construction operations in the winter due to the requirement of temporary heating during the construction of concrete basements for curing purposes (Mah et al., 2011; Vecchio Castillo et al., 2023) and during the installation of underground utilities. The resulting emissions can be difficult to predict beforehand, because weather and usage duration, which largely govern emission levels, are highly variable. These emissions, in combination with the embodied CO_2 emissions associated with the concrete used in cast-in-place construction for single-family detached house basements, represent a significant source of CO_2 emissions in the construction phase. As such, it is imperative that alternative construction methods that lessen the CO_2 emissions generated in the construction of residential buildings be investigated.

Industrialized construction is an alternative construction method that lessens the environmental impact compared to traditional construction methods by reducing project completion time, mitigating the generation of material waste, and decreasing the usage of construction materials (Dong et al., 2015; Dou et al., 2019; Luo et al., 2021; Xu et al., 2022). Industrialized construction, also known as prefabrication, is an alternative construction method in which structural components of a building, such as wall panels and slabs, are manufactured in a controlled environment outside of the construction site and subsequently transported and assembled on site (Tam et al., 2007; Mao et al., 2013; Teng et al., 2018; Du et al., 2019). Although the previously listed environmental and project duration benefits have been widely documented in the literature, its adoption in practice has been limited due to its higher cost compared to the traditional approach (Zhang et al., 2018; Xue et al., 2018).

Despite the high initial cost for a construction enterprise of shifting to industrialized construction operations, major cost reductions can be achieved through decreased material use, reduced on-site labour requirements, and less material waste compared to on-site construction (Zhang et al., 2018). These reductions translate to a decrease in the amount of CO_2 emissions generated during the construction phase (Dou et al., 2019; Luo et al., 2021; Xu et al., 2022). Nonetheless, decision makers are not well-positioned to make sound decisions when choosing the most appropriate construction method for a project due to the lack of reliable, empirical methods for comparing the financial and environmental advantages and disadvantages of traditional and industrialized construction. There is thus a pressing need for an objective quantitative method by which decision makers can compare the cost and environmental implications between these two construction methods in order to achieve the cost and environmental targets for a given project.

In this context, the research presented in this thesis develops a quantitative assessment method for conducting cost and environmental tradeoff analysis between traditional cast-in-place and industrialized construction methods for residential houses in cold-climate regions. Three criteria are selected to showcase the effectiveness of the analysis: (1) temporary heating, (2) concrete usage, and (3) site inspections. These criteria are selected due to the cost and environmental uncertainties linked to these elements and their significant contribution to the generation of CO_2 emissions on the construction site.

Chapter 2 of this thesis presents a systematic and bibliometric literature review outlining state-of-the-art strategies for reducing GHG emissions in residential construction and identifying gaps in the literature. Chapter 3, meanwhile, describes a quantitative analysis method, based on a Monte Carlo simulation, for estimating the cost and CO_2 emissions associated with the use of temporary heating and concrete during the construction of a cast-in-place concrete basement typical of single-family detached houses in cold-climate regions. The study considers the project schedule of previous cast-in-place concrete basement projects for single-family detached houses built in the winter season in order to develop a simulation model in Simphony.NET. This simulation model estimates the overall project duration and propane consumption from the use of temporary heating during the construction of concrete basements. The model also estimates the total project duration based on empirical data, taking into consideration the inherent uncertainties linked to construction operations on site. Similarly, Chapter 4 makes use of the quantitative method and simulation model presented in Chapter 3 to develop a second simulation model that represents the on-site construction operations for industrialized concrete basements. This simulation is subsequently used to estimate the cost and CO_2 emissions of two different industrialized construction methods for concrete basements: solid-wall precast and ribbed precast. The cost and CO_2 emissions results from this quantitative assessment are then compared to cost and CO_2 emissions data from cast-in-place construction projects as a tradeoff analysis between traditional and industrialized construction methods. The purpose of this comparison is to determine whether industrialization is a viable construction method capable of reducing the cost and environmental impact of construction operations on site compared to traditional methods.

This thesis contributes to the body of knowledge by developing an objective quantitative assessment method by which to conduct cost and environmental tradeoff analysis between traditional and industrialized construction methods. This analysis will assist construction practitioners and decisions makers in making well-informed decisions when selecting the most appropriate construction method for a given project, based on empirical data and in alignment with the financial and environmental targets of the project.

1.2 Hypothesis and Research Objectives

The present study tests the following hypothesis:

"The implementation of industrialization in the construction of residential buildings results in favourable tradeoff outcomes in terms of cost and CO_2 emissions."

To verify the validity of this hypothesis, three objectives are pursued:

Objective 1: Quantify the cost and environmental impact of traditional cast-in-place concrete structures for basements.

Objective 2: Estimate the cost and environmental impact of industrialized concrete structures for basements by considering two different industrialized construction methods.

Objective 3: Conduct a cost and environmental tradeoff analysis between cast-in-place and industrialized (precast) concrete structures for basements.

The research conducted in pursuit of the first objective is described in Chapter 3 of this thesis, while the remaining objectives are addressed in Chapter 4.

1.3 Thesis Organization

This thesis consists of five chapters. Chapter 1 describes the motivation underlying the research, as well as the hypothesis and objectives of the study. Chapter 2 consists of a systematic review and bibliometric analysis that identifies state-of-the-art approaches to reducing GHG emissions in the construction of residential buildings. The literature search portion of the systematic review is conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (Moher et al. 2009). The PRISMA statement provides a guideline for documenting the purpose of the systematic review, the methodology to conduct the research, and the results of the literature search (Moher et al. 2009; Page et al. 2021).Moreover, the PRISMA 2020 guidelines are considered for this study to document the literature search process of the systematic review in order to minimize biases from the author's perspective when conducting the research, provide transparency by reporting the details of the literature search, and ensure that the search strategy can be replicable by other researchers (Page et al. 2021; Rethlefsen et al., 2021). Chapter 2 also discusses the gaps yet to be addressed regarding the current strategies to reduce GHG emissions in the construction phase of residential buildings.

Chapter 3 describes the cost and environmental impact of traditional cast-in-place concrete basements for single-family detached houses by considering the use of concrete and temporary heating during construction operations in the winter as significant sources of CO_2 emissions. This chapter uses Monte Carlo simulation and the simulation computer software, Simphony.NET, to represent the construction schedule for a cast-in-place concrete basement project for a single-family detached house in Edmonton, Canada. A simulation model is built based on the construction schedules of seven actual concrete basement projects, where the data from actual projects helps to represent the inherent uncertainties of construction operations on site that can lead to project delays.

Furthermore, the chapter describes the methods applied to validate the simulation model based on the validation techniques established by Sargent (2010). These techniques are utilized to validate computerized simulation models to ensure that the models closely represent the activities that occur in real-life scenarios. The validation techniques used in this chapter include historical data validation, face validity, comparison to other models, and event validity. The simulation model obtained from this chapter was considered validated once an acceptable margin of accuracy was obtained through low error percentages when considering quantitative validation techniques (i.e., historical data validation and event validity).

Chapter 4 presents a quantitative assessment, along with a cost and environmental tradeoff analysis between cast-in-place construction and two different methods of industrialized construction for concrete basements in cold-climate regions. For this chapter, a simulation model based on the model described in Chapter 3 is developed to represent the construction schedule of industrialized concrete basement projects for single-family detached houses. As with the simulations presented in Chapter 3, here concrete and temporary heating are used as the basis of the cost and environmental tradeoff analysis due to their considerable impact on the overall cost and CO_2 emissions of a concrete basement project. Moreover, site inspections are selected as an additional criterion for the cost and environmental tradeoff analysis. This is because various construction methods for a concrete basement will result in different project durations, which will in turn govern the cost and environmental impact resulting from site inspections.

Chapter 5 outlines the conclusions drawn, the research contributions made, the limitations of the study, and the recommendations for future research on the decarbonization of building construction through the adoption of industrialized construction methods.

CHAPTER 2: A SYSTEMATIC AND BIBLIOMETRIC REVIEW OF GREENHOUSE GAS EMISSIONS IN THE CONSTRUCTION PHASE OF RESIDENTIAL BUILDINGS[1]

2.1 Introduction

The building and construction sector is a significant contributor to GHG emissions, accounting for 37% of total energy-related emissions worldwide (Global Alliance for Buildings and Construction, 2022). As a result, efforts have been focused on reducing GHG emissions from the operational phase of a building's life cycle while the emissions from other phases, such as the construction phase, have been largely overlooked (Tao et al., 2018). Although it generates less emissions than the operational stage, the construction phase still accounts for between 10% and 20% of overall GHG emissions generated during a building's life cycle, with approximately 9% and 11% of this being embodied emissions of construction materials (Global Alliance for Buildings and Construction, 2020; Ji et al., 2018). Meanwhile, residential buildings are the most common type of structure being built worldwide, and further growth of the residential construction sector is expected amid growing housing demand due to rapid urbanization and population growth (Jiang et al., 2019; Tao et al., 2018). Thus, there is a pressing need for strategies to prevent a rapid increase in the GHG emissions tied to the residential construction sector in the coming years.

It should be noted that, although previous studies have identified key factors contributing to GHG emission during the construction phase (e.g., selection of building materials, construction equipment, uncertainty during the construction process), this area of research remains relatively underdeveloped in comparison to research targeting the operational phase of the building life cycle

[1] Chapter 2 of this manuscript was originally published as Vecchio, V., Barkokébas, E., Dias Barkokébas, R., Barkokébas, B., and Al-Hussein, M. (2024). "A systematic and bibliometric review of greenhouse gas emissions in the construction phase of residential buildings." Proceedings, Construction Research Congress: Sustainability, Resilience, Infrastructure Systems, and Materials Design in Construction, Des Moines, IA, USA, Mar. 20–23, 2024, pp. 568–577

(Sandanayake et al., 2016; Wang et al., 2016). Furthermore, little has been done by way of an inventory of existing strategies available in the literature for reducing the GHG emissions generated during the construction phase, particularly for residential construction. In this context, the objective of this study is to conduct a systematic review and bibliometric analysis identifying state-of-the-art approaches to reduce the GHG emissions generated during the construction phase of residential buildings. This study uses the database Scopus to find existing publications in this area of research while also carrying out a literature search based on The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al. 2009). The key contribution of this study is a comprehensive view of existing strategies and trends related to GHG emissions reduction in the construction phase of residential buildings.

2.2 Methodology

As noted above, a systematic literature review was conducted to explore existing methods and potential strategies to reduce the GHG emissions generated during the construction phase of residential buildings. Figure 1 shows the methodology underlying both the systematic literature review and the bibliometric analysis. The methodology and results were documented based on the PRISMA 2020 guideline, a reporting system that provides a framework for presenting the purpose of the given systematic review, the methodology followed to conduct the search, and the results of the systematic literature review (Moher et al. 2009; Page et al., 2021). The PRISMA 2020 guideline was considered as it includes an updated list of the information required to be documented in systematic literature reviews compared to its original edition (Page et al., 2021). Moreover, the PRISMA 2020 guideline is used to minimize biases from the author's perspective and ensure replicable search strategies to demonstrate transparency in the results of the systematic literature review.

Finally, a bibliometric analysis was performed using VOSviewer, a software used to characterize relationships between research topics by developing "clusters" based on the author keywords and establishing linkages among the studies selected for analysis (Too et al., 2022).

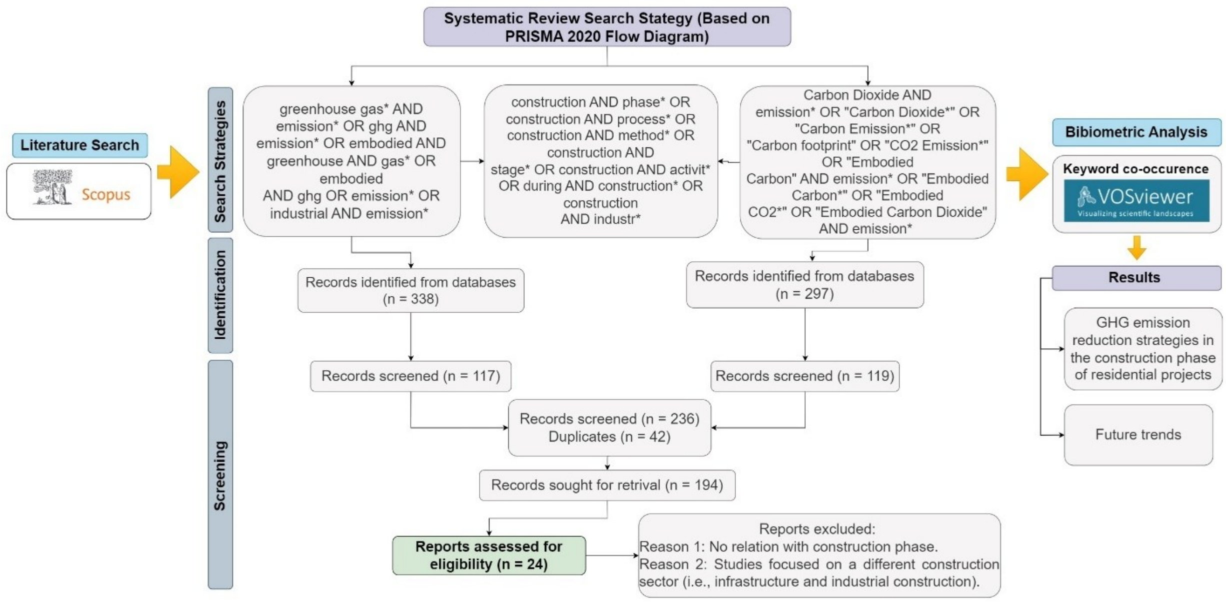

Figure 2.1: Methodology for literature search and bibliometric analysis.

The systematic review was conducted using the Scopus database. This database was chosen as it is one of the most complete and reliable sources of academic literature (Singh et al., 2021; Sabri et al., 2022), containing more journal publications than other commonly used databases in the field of construction and technology (Martinez et al., 2019; Singh et al., 2021).

The literature search began with keyword selection. Keywords were selected for the initial evaluation as they represent the key topics a given publication encompasses (Lu et al., 2020; Too et al., 2022). As mentioned above, this study focuses on GHG emission reduction in the construction phase of residential buildings. As such, the keywords chosen were "GHG emissions", "Carbon Dioxide", and "Construction Phase". The keyword, "Carbon Dioxide", was selected in addition to the more general “GHG emissions”, as CO_2 is the most prevalent type of GHG emission attributable to human activities (Jiang et al., 2019). To ensure comprehensive search results, two literature searches were conducted on Scopus: (1) considering the keywords “GHG emissions” and “Construction Phase”, and (2) considering the keywords “Carbon Dioxide” and “Construction Phase”, (see Figure 2.1). In the figure, the asterisk (“*”) is employed to denote variations of keywords.

The search in Scopus began with a query searching for the chosen keywords using the default search settings (i.e., searching article titles, abstracts, and keywords). The search process was limited to English-language publications. Moreover, since the aim was to evaluate the state of the art and recent trends, only documents from the past ten years (2013 to 2023) were included to analyze the most common strategies in the construction phase of residential buildings from the past ten years. In terms of source type, the search was limited to peer-reviewed journals and conference proceedings. To ensure alignment with and relevancy to the study objectives, the subject area was limited to Engineering, Environmental Science, and Energy. Finally, in terms of document type, the search was limited to Articles and Reviews. These search criteria, based on a previous work by Martinez et al. (2019), were applied to both literature searches.

The first literature search (i.e., “GHG emissions” and “Construction Phase”) was carried out on April 12, 2023, and the second (i.e., “Carbon Dioxide” and “Construction Phase”) was carried out on May 5, 2023. Figure 2.1 shows the publications obtained in the initial screening based on the abovementioned criteria. The first literature search yielded 117 documents while the second 119 documents, for a total of 236 documents. Bibliographic information for these 236 documents was then downloaded from Scopus in the form of CSV files in order to search for any duplicates using

MS Excel. In total, 42 duplicates were found, and the resulting 194 unique documents were selected for the subsequent manual filtering process.

The manual filtering process entailed filtering documents by evaluating the relevancy of each document to the study objectives based on its title and abstract. A few studies focused on commercial construction were included due to the similarities between commercial and residential construction. Additionally, studies reviewing the impact of building codes, policies, and regulations on the construction of residential buildings were also included. This filtering process resulted in a total of 38 documents being selected for an in-depth review in which the introduction, the methodology, the results, and the conclusion were analyzed. As a result of the in-depth review, finally, 24 documents were deemed to be directly related to the study objectives and were thus selected for bibliometric analysis.

2.3 Results and Discussion

The 24 documents remaining after this filtering process were then analyzed, examining the methodology and results presented in each in order to gain insights concerning GHG emission reduction strategies for the construction phase of residential buildings. Table 2.1 lists the four academic journals accounting for the most publications among the 24 documents analyzed.

Table 2.1: Academic journal sources with the most publications related to GHG emission reduction during the construction phase of residential buildings (2013 to 2023).

Journal Article	Number of Articles Found	% of Total Publications
Journal of Cleaner Production	8	33.33%
Sustainability	4	16.67%

Automation in Construction	2	8.33%
Journal of Building Engineering	2	8.33%
Other sources	8	33.33%

As shown in Table 2.1, *Journal of Cleaner Production* was found to be the academic source best represented, followed by *Sustainability*, *Automation in Construction*, and *Journal of Building Engineering*.

The change over time in the number of articles published over the course of the study period (2013 to 2023) is shown in Figure 2.2. As can be seen, there were significant fluctuations, with relatively little attention given to this topic over the study period.

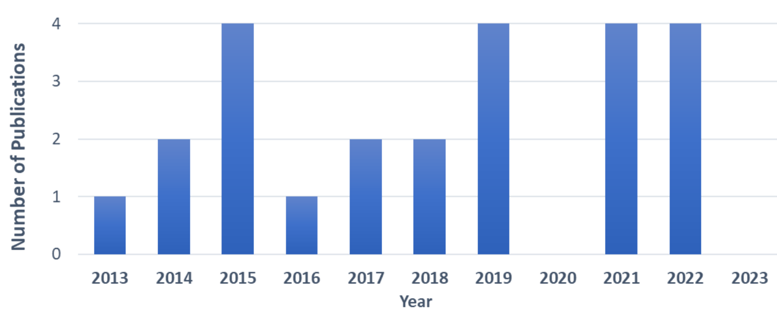

Figure 2.2: Historical trends in terms of scholarship related to GHG emission reduction strategies during the construction phase of residential buildings.

A bibliometric analysis based on keyword co-occurrence using the VOSviewer software was conducted in order to identify the common strategies and trends regarding GHG emission reduction as discussed in the selected articles, following the strategy implemented by Martinez et al. (2019). Author keywords were chosen for evaluation, as these are established by the authors themselves (Lu et al., 2020; Too et al., 2022). In the graphics visualizing the results, it should be noted, each research topic is defined by a specific cluster colour (Yin et al., 2019). Considering the number of papers that qualified for further analysis and the resulting number of author keywords (43), a minimum of 2 occurrences of a given keyword was selected as the threshold for the assessment, with 16 keywords being found to meet this threshold. The keyword co-occurrence results for the 24 publications selected for the systematic review using VOSviewer are depicted in Figure 2.3.

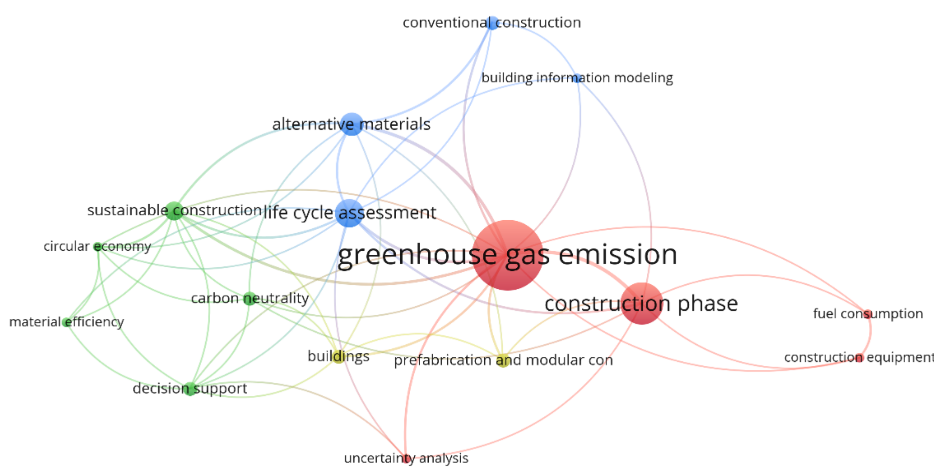

Figure 2.3: Keyword co-occurrence in academic articles on GHG emission reduction strategies for the construction phase of residential buildings.

All keywords related to CO_2 emissions were combined with the GHG emission cluster to eliminate any distinction between them. The most frequently used terms were "Greenhouse Gas Emission", with 15 occurrences, and "Construction Phase", with 9 occurrences. The outcome analysis and interpretation of results focused on the clusters displayed in Figure 2.3.

2.3.1 Life Cycle Assessment and Alternative Construction Materials (Blue Cluster)

Life Cycle Assessment. Life Cycle Assessment (LCA) is a widely used tool for calculating the total environmental impacts across a building's life cycle. LCA can be used to identify potential sources of GHG emissions based on project specifications and details such as location, building dimensions, and selection of construction materials (Sandanayake et al., 2019). Moreover, buoyed by specialized software, it can be used to compare embodied emissions between different construction materials and structural components in order to select the most sustainable option for a construction project (Marzouk et al., 2017). Other studies have employed a similar approach by linking Building Information Modelling (BIM) models to embodied emissions databases for detailed evaluation of environmental impact (Gu et al., 2021).

Despite wide usage, LCA is not able to accurately quantify the emissions from on-site construction activities due to discrepancies between the planned and actual quantity of materials (Hong et al., 2017). As a result, LCA-based GHG emissions could be underestimated or overestimated (Lee et al., 2019). Consequently, predictive systems that consider the emissions generated during on-site construction operations, as well as the variability and uncertainty of the building process, are gaining prominence.

Alternative Construction Materials. The literature search identified selection of construction materials as an important factor governing the rate of GHG emissions tied to the construction phase of residential buildings. Wang et al. (2016) noted that material selection can influence the total GHG emissions in a building's life cycle due to the embodied emissions of the selected material. Selection of materials with a high-manufacturing environmental footprint, such as concrete or steel, will result in an increase in the overall GHG emissions associated with the construction phase of a project (Younis & Dodoo, 2022). Consequently, the use of low-carbon construction materials is viewed as a promising solution for reducing embodied emissions. Alternative construction materials such as fly ash bricks and cellular concrete blocks for masonry walls (Naveen Kishore & Chouhan, 2014), concrete mixes with lower cement proportions and containing recycled materials (Orsini & Marrone, 2019), and cross-laminated timber (Gu et al., 2021; Younis & Dodoo, 2022) have been shown to significantly reduce GHG emissions compared to traditional construction materials. However, despite the potential advantages of these alternative construction materials, there is a degree of uncertainty concerning their strength capacity compared to conventional construction materials, the possibility of higher manufacturing costs, and the lack of technical expertise and experience in the practical use of these materials (Orsini & Marrone, 2019).

2.3.2 Sustainable Construction (Green Cluster)

A sustainable construction approach involves not only the use of low-carbon construction materials, but also the implementation of project logistics strategies intended to reduce the GHG emissions incurred during the construction phase (Hong et al., 2015). In this regard, construction planners make use of predictive decision-support tools to estimate GHG emissions on the construction site (Too et al., 2022). For instance, Sandanayake et al. (2019) developed a predictive decision-support tool that estimates GHG emissions by identifying primary sources of emissions in the construction phase. Similarly, on-site monitoring tools are being used to assess GHG emissions in real time during construction operations and to obtain more conclusive GHG emission estimations using the Internet of Things (IoT) and Radio Frequency Identification (RFID) sensors to monitor real-time emissions at the assembly line of a prefabrication factory. They demonstrated that on-site monitoring tools could be used to detect irregular GHG emission levels during the manufacture of prefabricated components and to facilitate intervention to prevent excessive emissions in real time.

Other environmental strategies have been applied to reduce GHG emissions at the construction site. For instance, Christensen et al. (2022) applied circular economy principles to evaluate the feasibility and GHG emission reduction potential of repurposing demolished materials. Their findings demonstrated that not every construction material is equally suitable for recycling after the demolition phase. Their study also emphasized the unlikelihood of construction enterprises adopting circular economy practices. Indeed, construction enterprises are often hesitant to apply sustainable construction alternatives due to the novelty and high cost of these alternatives compared to traditional practices (Christensen et al. 2022). Further research is required in order to verify the non-financial benefits of sustainable construction compared to the traditional approach.

2.3.3 Fuel Consumption and Construction Equipment (Red Cluster)

As mentioned above, predictive systems or simulation models have been used to detect significant sources of GHG emission generation during construction. One use of these tools has been to detect the emissions resulting from the fuel consumption of construction equipment and specific construction operations. For instance, Hong et al. (2017) used a multi-method-based uncertainty analysis framework to detect, quantify, and mitigate sources of uncertainty during the construction phase of a mixed-use project in China. Fang et al. (2021) developed a predictive model using a Random Forest approach to estimate the environmental impact of electricity and fossil fuel consumption on construction equipment. They found that design parameters and construction site conditions are key factors influencing the generation of GHG emissions. Virtual prototyping technology and simulation were applied by Wong et al. (2013) to identify CO_2 emission peaks and to design proactive measures based on the predicted emissions generated by construction equipment during on-site operations. Likewise, Trani et al. (2016) focused on the CO_2 emissions generated by construction equipment, using a predictive model based on cluster analysis and linear regression to estimate fuel consumption during earthwork activities for a residential project. What these predictive models have in common is the ability to identify significant sources of emissions in order to mitigate them. However, the use of predictive models to measure GHG emissions is a relatively new technique, and specialized expertise concerning data handling and machine learning is required in order for the model to accurately estimate emissions. Consequently, decision makers remain reluctant to adopt this approach.

Another approach to reducing the GHG emissions resulting from the fuel consumption of construction equipment is to use either machinery that uses alternative fuel sources with low-environmental impact or hybrid construction equipment (Mok et al., 2014). However, the acquisition cost of this type of equipment surpasses that of traditional construction equipment, and this could be considered a limiting factor.

2.3.4 Prefabrication and Modular Construction (Yellow Cluster)

Prefabrication is an alternative to traditional on-site construction in which structural components or modules are manufactured and assembled in an off-site factory and then transported to the construction site for assembly (Du et al., 2019; Tam et al., 2007). An attractive aspect of this alternative construction method is that it provides the opportunity to capitalize on the inherent efficiencies of manufacturing principles. As a result, prefabrication reduces material waste, reduces construction time, and minimizes the intrinsic uncertainty and variability of the on-site construction process (Hong et al., 2017).

Previous studies have shown that waste minimization and resource optimization resulting from prefabrication in construction can reduce the embodied GHG emissions associated with construction materials (Fang et al., 2021; Gan et al., 2017; Hong et al., 2017). According to a study by Jiang et al. (2019), the benefits of prefabrication are especially evident in on-site construction operations, with their study finding that CO_2 emissions were reduced by 44.7% when using prefabricated rebar cage in place of traditional in-situ rebar in high-rise building construction. However, despite this significant reduction in CO_2 emissions during on-site construction operations, their study also identified increased emissions resulting from the manufacture and transport of the prefabricated components when compared to the traditional scenario (Jiang et al., 2019). Despite these findings, numerous countries, such as China, are encouraging the use of prefabrication as it is easier to monitor and reduce GHG emissions due to there being fewer uncertainties in off-site manufacturing compared to on-site operations and less variability with respect to resource consumption (Tao et al. 2018).

2.4 Future Research Trends

Efforts to reduce GHG emissions in construction have tended to focus on the operational phase of the building life cycle, mainly because this phase is subject to stringent environmental regulations as laid out in building codes and construction standards. There has been comparably less progress made with respect to reducing the GHG emissions generated in the construction phase at least partially due to the lack of established benchmarks or limits on the generation of GHG emissions with which construction enterprises are compelled to comply (Too et al., 2022). This gap is often attributed to the inherent uncertainty of the on-site construction phase, where there is often a significant discrepancy between actual consumption of construction materials and the quantity of materials reflected in the bill of quantities (Hong et al., 2017). Likewise, it is challenging to monitor the actual fuel consumption by the construction equipment used on site (Trani et al., 2016). Material use and equipment use demonstrated to be significant sources of GHG emissions. As such, emission reduction efforts should focus on developing tools that can accurately monitor and detect reduction opportunities with respect to these emissions sources.

The research trends identified regarding strategies for reducing the GHG emissions generated during the construction phase are: (1) including a mandatory GHG emission cap to limit the emissions generated during the construction phase of residential buildings in accordance with government strategies and targets related to sustainability, and (2) the use of monitoring tools in conjunction with the use of prefabrication as an alternative construction method to effectively monitor, regulate, and reduce the GHG emissions generated during the construction phase of residential buildings.

2.5 Conclusion

A systematic review of the literature on GHG emission reduction strategies in the construction phase of residential buildings was conducted based on the PRISMA 2020 systematic review guidelines. The database, Scopus, was searched to find articles on this research topic. Following a series of screening processes, 24 academic documents were ultimately selected for further analysis. The bibliometric analysis used Scopus software to examine and visualize the interrelationships among subtopics as represented in these 24 articles. The results indicated that there are relatively few publications available on the topic of GHG emission reduction strategies for the construction phase of residential buildings. For instance, in the past ten years, no more than four scientific articles on this topic have been published in any given year. Furthermore, the marked fluctuation in the number of articles published from year to year reflects an inconsistency in research efforts to mitigate the GHG emissions generated during the construction phase of residential buildings. The study found that strategies for reducing the GHG emissions generated in the construction phase of residential buildings are typically aimed at reducing the embodied emissions associated with traditional construction materials and minimizing the GHG emissions resulting from the fossil fuel consumption of construction equipment. Accordingly, strategies such as using alternative construction materials, implementing predictive models to identify and estimate GHG emissions prior to the commencement of on-site construction operations, and employing alternative construction methods such as prefabrication and modular construction are suggested.

This study was subject to some limitations that should be acknowledged. First, the scope of this research was limited to the residential construction sector and a few commercial projects; and to the construction phase of the building life cycle. Consequently, other construction sectors, such as infrastructure (e.g., bridges, railways, highways, etc.) were not considered in this research.

Future trends were also identified, including implementing national building codes and construction regulations to establish a GHG emission benchmark during construction operations (Too et al. 2022). Additionally, low-emission design and sustainable construction logistics are suggested to delineate a construction project with low carbon emissions. Despite the limitations, the results from the systematic review and bibliometric analysis described upcoming trends in the technology and public policy fields that could address the uncertainty linked to the previously mentioned factors of the construction phase. Moreover, the compilation of state-of-the-art approaches documented in this study will help construction practitioners to effectively address and mitigate GHG emissions during the construction phase of residential buildings.

CHAPTER 3: A QUANTITATIVE ASSESSMENT OF CARBON DIOXIDE EMISSIONS ASSOCIATED WITH TEMPORARY HEATING IN RESIDENTIAL HOUSING[2]

3.1 Introduction

The building and construction sectors are expected to drastically reduce their CO_2 emissions due to their impact on overall emissions worldwide. Indeed, both the building and construction sectors are responsible for producing 38% of the total CO_2 emissions related to energy consumption (Global Alliance for Buildings and Construction, 2020) while having a predicted growth of 85% by the year 2030 (Robinson, 2015). In this context, researchers have been seeking solutions to reduce the emissions resulting from the operational phase of the building life cycle. However, the construction phase, which represents up to 20% of the CO_2 emissions in the building life cycle, has been neglected by researchers and building experts (Ji et al., 2018). Moreover, approximately 75% of the CO_2 emissions generated during the construction phase of the building life cycle are attributed to the building materials being selected for construction projects (Falliano et al., 2022). The concrete industry, responsible for producing the most commonly used construction material worldwide (Adesina, 2020; Ni et al., 2022), is accountable for generating approximately 8–9% of the total CO_2 emissions attributed to human activity (Falliano et al., 2022; Ni et al., 2022). Consequently, there are opportunities for research and innovation in the construction phase to reduce the environmental footprint associated with the use of concrete in construction (Ji et al., 2018).

[2] Chapter 3 of this manuscript was originally published as Vecchio Castillo, V., Dias Barkokébas, R., Barkokébas, B., Al-Hussein, M. "A quantitative assessment of carbon dioxide emissions associated with temporary heating in residential housing." *Proceedings, Canadian Society for Civil Engineering (CSCE) Annual Conference,* Moncton, NB, Canada, May 24–27, 2023 (Accepted, 2023).

Temporary heaters are applied when performing concrete-related construction activities to ensure a specific design temperature for curing in cold weather conditions (National Research Council of Canada, 2019a). As such, it is a resource commonly used in cold-climate regions (i.e., regions with below freezing conditions) to provide heat during construction operations (Ferreira et al., 2018; Zhuravlev et al., 2020). Additionally, temporary heating is required to provide heat to the basement foundation in order to prevent the structure from freezing and potentially cracking (National Research Council of Canada, 2019b).

Previous studies have evaluated the impact of temporary heating in the form of CO_2 emissions generated during the construction phase. Al-Hussein et al. (2009) and Li et al. (2014) identified the adverse environmental impact of using temporary heaters during winter construction when comparing alternative construction methods, such as modular and panelized construction, to conventional construction methods for residential buildings. Both studies observed an increase in CO_2 emissions regardless of the construction technique, attributed to the use of temporary heating during winter construction. Mah et al. (2011) further emphasized the adverse environmental effects of temporary heating as a contributor to CO_2 emissions in a study monitoring emissions from the construction of single-family houses. They concluded that the basement foundation wall phase was associated with higher CO_2 emission levels compared to other construction phases as a result of the use of temporary heating. Furthermore, they observed a 6-tonne increase in CO_2 emission for residential construction in the winter season due to the continuous use of temporary heating throughout the entire concrete basement construction.

Ferreira et al. (2018) demonstrated the impact of temporary heating on the overall cost of residential projects by evaluating the factors governing its use, such as the weather, project delays, and thermal resistance of the building envelope during construction. They applied simulation to assess the impact of alternative construction methods in terms of reducing the use of temporary heating, taking into account the above factors. Their results indicated that the cost of temporary heating is largely a function of the project duration and the set-point of heaters.

Nevertheless, few studies have focused on the impact of temporary heating on construction operations, thus leaving important research gaps addressed.

Indeed, temporary heating is often overlooked as a significant resource during construction (Ferreira et al., 2018) and as a significant contributor to CO_2 emissions. In particular, there is a lack of information regarding the environmental impact and cost of temporary heating, specifically for concrete basements in single-family detached houses—the part of the house with the highest heating requirement (Mah et al., 2011). In this context, the objective of the present research is to quantify the environmental impact and cost of temporary heating for concrete basement construction in cold-climate regions. The contribution of this study is a quantitative assessment of the impact that temporary heating represents in terms of cost and CO_2 emissions for concrete components of residential projects in cold-climate regions. The cost and CO_2 emissions of temporary heating are compared to the embodied emissions of concrete used during construction operations for basements of single-family detached houses in order to obtain the total cost and emissions resulting from the two sources.

3.2 Methodology

This research applies simulation to quantify the environmental impact of the current practice of concrete basement construction through the estimation of the propane consumed in the operation of temporary heaters during concrete basement construction in cold-climate regions. Figure 3.1

shows the steps followed to obtain the CO_2 emissions based on the estimation of propane consumption for concrete basement construction in single-family detached houses.

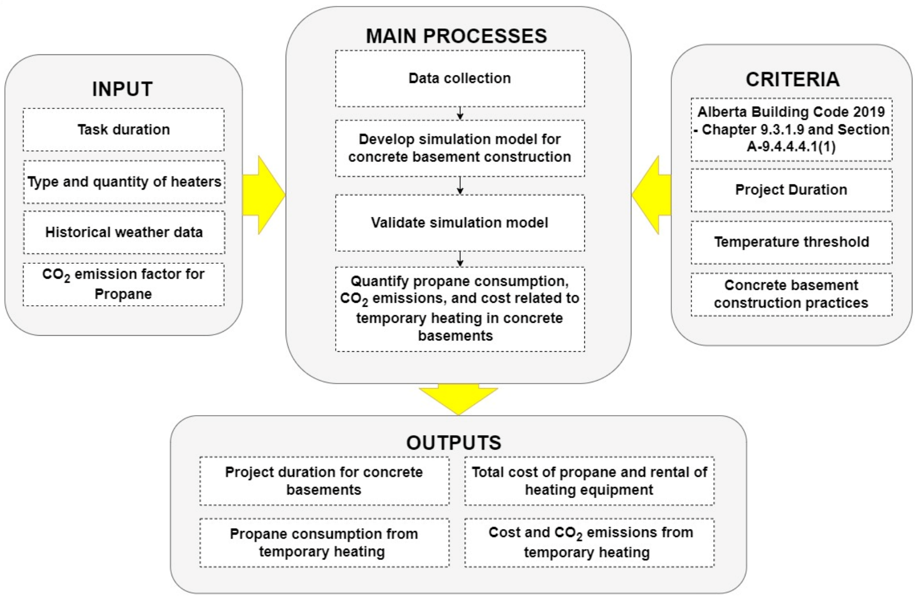

Figure 3.1: Overview of the methodology.

The first step is to collect data, where actual project information, such as task duration and sequences involved in concrete basement construction during winter, is obtained from a construction company based in Edmonton, Canada. Additionally, interviews with five construction experts and three equipment rental company representatives are conducted to collect information regarding the use of temporary heaters during winter construction operations.

Simphony.NET is then applied to develop a simulation model for predicting the average daily propane consumption based on the tasks involved in the construction of a concrete basement for a single-family detached house, resulting in the total project duration for the aforementioned construction.

The third step is to validate the simulation by considering the techniques established by Sargent (2010). These techniques are utilized to validate computerized simulation models to ensure that the models closely represent the activities that occur in real-life scenarios (Sargent, 2010). After validating the simulation model, the cost of propane is then estimated based on the total propane consumption for the project, cost of propane per litre, and the rental cost for the heating equipment.

Finally, the environmental impact is calculated based on the total propane consumption associated with the construction of a concrete basement. The cost and CO_2 emissions resulting from temporary heating are compared to those resulting from concrete usage to better comprehend the cost and environmental impacts of temporary heating in contrast to those from concrete, one of the most energy-intensive construction materials used during construction projects and linked to high levels of embodied CO_2 emissions (Global Alliance for Buildings and Construction, 2020; Falliano et al., 2022).

As noted above, the dataset used to determine the propane consumption and project duration is obtained from a residential construction company operating in Edmonton, Canada. Single-family detached houses are selected in this study, as they are the most common type of residence, representing 52.6% of all private dwellings in Canada (Statistics Canada, 2021). Conventional stick-built construction for these types of houses results in the release of approximately 45-tonnes of CO_2 per single-family house on average (Al-Hussein et al., 2009). These emissions increase further during the winter due to the continuous use of propane heating during construction of the concrete basement (Mah et al., 2011). Consequently, the construction of single-family home basements was selected as the scope of this research, since this portion of the house has the highest heating requirements due to its concrete usage and to protect the basement foundation from freezing (National Research Council of Canada, 2019a, 2019b).

3.3 Case Study

3.3.1 Data Collection

To address the research gap identified in this study concerning the environmental impact and cost of temporary heating, actual data from seven concrete basement construction projects conducted during winter months is selected for this study. The projects selected for evaluation occurred during the winter of 2021/2022, when temporary heating was required for construction projects due to extreme cold weather conditions. The construction schedules from actual projects included a list of tasks necessary to complete the construction of concrete basements and the duration of each activity; this information served as the basis for building the simulation model.

The total duration of concrete basement construction is defined by the task sequence and durations for the given project (see Figure 3.2). A total of seven concrete basement projects for single-family detached houses were considered for this research, and 13 tasks were identified as essential components of the concrete basement construction process.

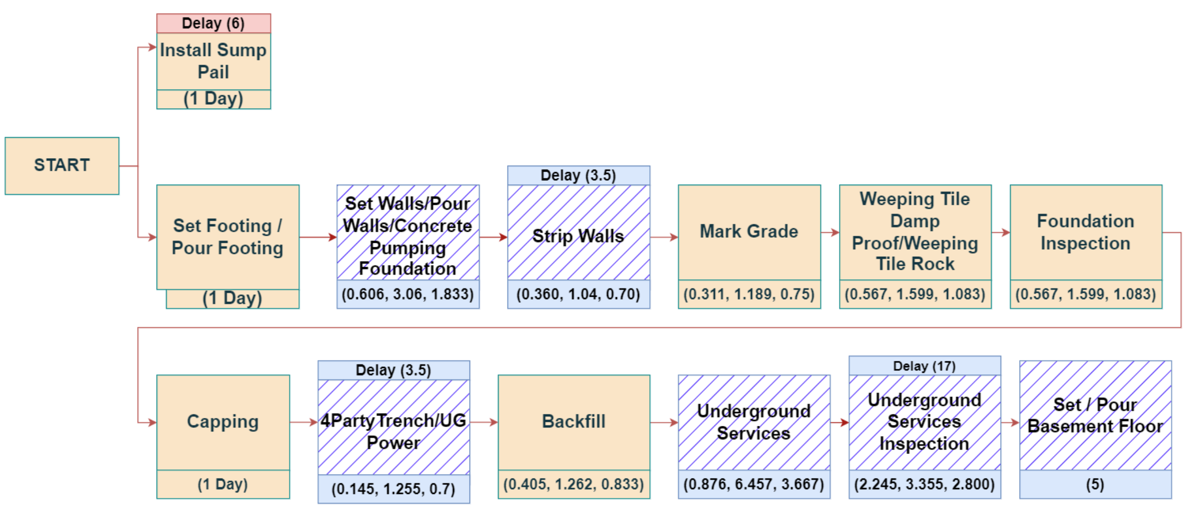

Figure 3.2: Schedule for concrete basement construction operations in a single-family detached house.

Considering the small sample size and the variation in task duration for each project, the Student's Distribution technique (Barkokébas et al., 2022) was applied to establish a lower and upper bound to guarantee that the mean of the sample during each simulation run would fall within the established limits. A confidence interval of 95% was considered for this purpose. The values obtained for each task that demonstrated considerable variations (i.e., the average duration and the upper and lower bounds) were added to the simulation model as triangular distributions to estimate individual task durations and, consequently, the overall project duration for the construction of concrete basements as shown in Figure 3.2.

The propane consumption associated with the use of temporary heating is dependent on weather conditions, project duration, the number of heaters used, and the set temperature threshold at which the heaters begin operating (Ferreira et al., 2018). Multiple rental equipment companies and construction experts in Edmonton were consulted to solicit information about the types of heaters and models used for basement construction—particularly in terms of their fuel consumption and the temperature setpoint at which they begin operating—for comparison purposes. The most common temporary heating setup was determined based on this expert feedback, and this information was implemented in the simulation model. In the simulation, one heater was used in the construction of concrete basements. The heater operated for 24 h, seven days a week , except when the outdoor temperature was above the set temperature threshold of 0 °C. This threshold was considered because it is the most common temperature set point for heating operations, according to the consulted experts.

It should be noted that there were some inconsistencies in the expert feedback concerning the timing of heater operations. Although there was consensus that temporary heating is required prior to pouring concrete for the basement floor, some of the experts suggested that temporary heaters should begin operating one week prior to pouring the basement slab, while others suggested heater operations should begin as early as three weeks prior to pouring the floor. In light of this, the case study considered four different heater operation scenarios: the use of the resource during the entire basement construction operations after the first basement construction task begins, as well as three, two, and one week prior to pouring the basement floor. The inputs used in the case study are shown in Table 3.1.

Table 3.1. Simulation inputs for case study

Simulation Inputs for Case Study	
Temperature threshold	0 °C
125,000 Btu radiant heater fuel consumption	5L/h
Number of heaters	1
Average cost of propane (per L)	$0.73
Average cost of concrete (per m^3)	$262.50
Emission factor of propane (kg G CO_2/L) (Env and Climate Change Canada, 2022)	1.515
Emission factor of concrete (CO_2 kg/m^3) (Gomes et al., 2019)	418.783
Average volume of concrete for one basement (m^3)	35

The temperature threshold, fuel consumption from radiant heaters, average cost of propane per litre, average cost of concrete per m^3, and the average volume of concrete for single-family house basements (m^3) was determined by interviewing construction and heating equipment experts.

3.3.2 Simulation Model

Simphony.NET was used to calculate the project duration and average daily propane consumption associated with the use of temporary heaters for concrete basement construction throughout the winter.

The simulation model was created by implementing the tasks with their respective task sequences and durations (based on triangular distributions) in the software to obtain the overall project duration based on the information provided by the construction company that participated in this study. The time unit selected for the simulation was "day" since the propane consumption was to be evaluated based on calendar days (Ferreira et al., 2018). Figure 3.2 shows the sequence and duration of tasks for the construction of a concrete basement for a single-family detached house. These tasks were selected based on their link to temporary heating usage. It should be noted that the framing activity was considered to be outside of the scope of this research since framing is performed by a third-party. Moreover, the curing time for concrete-related activities was included in the triangular distributions observed in Figure 3.2 for the foundation walls and basement floor tasks (i.e., pouring the foundation walls, strip walls, and pouring the basement floor) to determine the total duration of such activities. The overall project duration was determined by simulating the durations of the individual tasks making up the concrete basement construction process.

It should be noted that some tasks demonstrated significant delays in their durations, which were observed in the samples obtained for this research and represented in Figure 3.2. As such, the simulation model included a "probabilistic" element to calculate task durations considering the number of concrete basement samples that demonstrated a delay in a certain task.

The propane consumption was calculated using Equation 3.1, which is a variation of an equation used by Ferreira et al. (2018) to calculate the propane consumption for a four-storey residential building.

$$24\text{ h} \times \text{number of heaters} \times \text{beginning of heating} \times \text{hourly fuel consumption} \qquad (3.1)$$

The hourly fuel consumption was based on the consumption rate of a 125,000 Btu radiant heater. In this equation, the beginning of heating operations is represented by the value 1 when the average daily temperature is below 0 °C and by the value 0 when the temperature is above this threshold. This means that propane consumption is accounted by the simulation model whenever the average daily temperature is below freezing conditions. The expected average daily temperature was obtained from historical weather data for the City of Edmonton available in the Simphony.NET environment.

A total of 1,000 runs were executed on the simulation model, resulting in the average project duration and average daily propane consumption for concrete basement construction operations in single-family detached houses.

3.3.3 Validation

The small sample size used for this study necessitated multiple validation techniques to ensure that the results from the simulation model were reflective of the average propane consumption per day and project duration for the construction of concrete basements. Since the total propane consumption is a function of the project duration, the total project duration was validated using a number of different validation techniques. The series of validation techniques proposed by Sargent (2010), which included historical data validation, face validity, comparison to other models, and event validity, were used to demonstrate the accuracy of the results obtained through simulation.

The first validation technique, historical data validation (Sargent, 2010), consists of building a simulation model based on an existing database and comparing the results obtained through the simulation model with actual historical data. To that end, the task and project duration observed through the simulation model were compared to the actual durations of the seven concrete basement projects included in the data provided by the case company. The average total project duration from the simulation model was compared to each of the seven actual projects collected as a dataset for the research. The average error between the simulation results and actual projects was found to be −4.12% within the acceptable margin of error, as specified in the relevant literature (Altaf et al., 2018; Bhatia et al., 2019, 2022). Using the second validation technique, face validity, the simulation model was validated based on consultation with a construction expert with several years of experience in concrete basement construction.

The event validity technique (Sargent, 2010) was also applied. This technique, it should be noted, consists of verifying the accuracy of the results obtained from the historical validation technique. Iterations were conducted for each of the observations collected for this study, as shown in Table 3.2, in order to obtain the project duration from the simulation model with the lowest error when compared to actual project durations. For each iteration, six projects were used to acquire the task duration to be included in the simulation model, while the remaining project was compared with the simulation results in terms of total duration. The iteration that resulted in the project duration with the lowest error was selected as the simulation model that will be used for the study.

Table 3.2. Iterations for historical data validation.

Project ID	Actual Duration (Workdays)	Simulation Mean (Workdays)	Error (%)
D1	21	24.401	−16.20%
D2	18	24.620	−36.78%
D3	30	22.813	23.96%
D4	23	24.503	−6.53%

D5	17	25.234	−48.44%
D6	23	24.517	−6.60%
D7	39	21.643	44.51%
		Average Error	**−6.58%**

As shown in Table 3.2, D4 had the lowest error with a difference of −6.53% compared to the project duration that was left out of for comparison purposes. D4 was then compared to the actual project durations of the seven observations, resulting in an average error of −7.81%, which is considered to be within the acceptable margin of error. Accordingly, task distributions from D4 were selected, as this was the simulation model with the most accurate results. These task distributions were selected in order to obtain the average project duration and propane consumption results for the study. The total project duration, as well as its propane consumption from temporary heaters, can be considered validated after concluding the aforementioned validation techniques with an acceptable margin of error.

The propane consumption from the temporary heaters, which is a function of project duration, was forecasted with the consideration of the results from the validated simulation model. The results show a project duration of 34.195 calendar days. Additionally, the average propane consumption for the concrete basement project was found to be 118.206 L/day.

3.4. Results

3.4.1 Propane Consumption

Once the simulation model had been validated, four different temporary heating scenarios were analyzed: (1) using temporary heating throughout the entire basement construction operation, starting once the first task "Set Footing/ Pour Footing" begins, while following the Canadian

National Building Code – Alberta Edition standard for concrete temperature requirements (National Research Council of Canada, 2019a) (i.e., the base scenario for this study), (2) starting temporary heating three weeks prior to pouring the basement floor, (3) starting temporary heating two weeks prior to pouring the basement floor, and (4) starting temporary heating one week prior to pouring the basement floor. Figure 3.3 shows the cost and propane consumption for each of the four temporary heating scenarios considered.

The propane consumption for the base scenario was found to be 4,043.90 L. Scenario 2 achieved a 14.62% reduction in propane consumption compared to the base scenario when using the temporary heaters three weeks prior to pouring the basement floor. Scenarios 3 and 4 resulted in reductions of 35.09% and 55.56% respectively, compared to the base scenario.

3.4.2 Cost of Temporary Heating

In concrete basement construction for single-family detached houses, the use of temporary heating was found to increase the average total cost of concrete basement construction. Projects that required temporary heating as soon as the first task, "Set Footing/ Pour Footing" begins cost up to 19.31% more than projects that do not require temporary heating (i.e., summer projects). A 16.56% cost increase was found to be associated with Scenario 2, while increases of 12.70% and 8.84% were associated with Scenarios 3 and 4, respectively. The cost of temporary heating was then compared to the cost of concrete, the predominant building material for basement construction in single-family detached houses. The cost of concrete was found to represent between 25.24% and 30.80% of the overall project cost for concrete basements built in the winter—a significant portion of the total cost of concrete basements for single-family detached houses. Figure 3.3 illustrates the cost percentage breakdown for building concrete basements for single-family detached houses considering the housing starts in Alberta in 2022, in which the cost of one concrete basement was multiplied by the number of housing starts each month (Statistics Canada, 2024). According to the Alberta Economic Dashboard website developed by the Government of Alberta, housing starts refers to the moment at which construction operations begin for a project, with the construction of the basement foundation being the indicator of the start of the construction process in urban areas (Government of Alberta, 2024). Considering this information, it was assumed that the monthly number of housing starts for single-family detached houses for the year 2022 reflected that construction permits had already been granted for the housing starts each month, in addition to reflecting the projects in which the construction process for concrete basements had already started. Moreover, the construction cost of one concrete basement was assumed to be the same for all housing starts in 2022 with the exemption of the temporary heating costs, which are not considered during projects executed when temperatures are above freezing conditions. Consequently, the monthly variation of the overall concrete basement cost is a result of the number of housing starts being built each month.

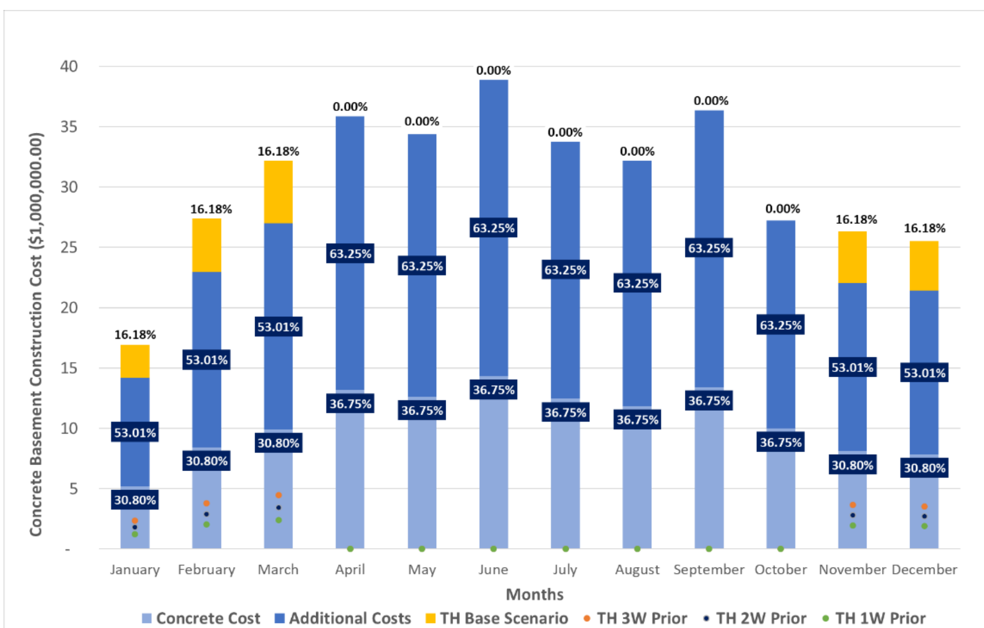

Figure 3.3: Concrete basement construction cost versus temporary heating cost.

3.4.3 CO_2 Emissions from Temporary Heating

The CO_2 emissions associated with the use of temporary heating were then quantified based on the propane consumption of the heaters by using the same four scenarios for temporary heater operation that were considered in estimating the fuel consumption and cost. The scenario in which temporary heating is applied throughout the entire process of concrete basement construction (i.e., the base scenario) was found to produce up to 6,126.510 kg of CO_2 emissions. Scenario 3 achieved a 14.62% emission reduction compared to the base, with reductions of 35.09% and 55.56% for Scenarios 3 and 4, respectively.

To better comprehend the impact of the CO_2 emissions resulting from the use of temporary heating during the construction of concrete basements, the emissions derived from the concrete usage of single-family house basements were quantified for this study. Considering the CO_2 emission factor for concrete (Gomes et al., 2019) from Table 3.1, an estimated 14,657.405 kg of CO_2 was found to be attributable to the embodied emissions from concrete as a building material. Temporary heating was found to represent 29.48% of the total CO_2 emissions resulting from concrete and temporary heating usage for the base scenario, whereas it was found to represent 26.30%, 21.34%, and 15.66% in Scenarios 2, 3, and 4, respectively.

The impact of CO_2 emissions from temporary heating is further illustrated in Figure 3.4, representing the CO_2 emissions resulting from the use of temporary heating considering housing starts in Alberta in 2022 (Statistics Canada, 2024). Similarly to Figure 3.3, the CO_2 emissions generated by the use of temporary heating for one concrete basement were multiplied by the single-family detached housing starts each month. Figure 3.4 shows that the total CO_2 emissions resulting from the use of temporary heating ranged from 26,356,244.129 kg (base scenario) to 11,711,745.27

kg (Scenario 4). These emissions are equivalent to the embodied emissions in concrete from the construction of 1,798 and 799 concrete basements, respectively. The emissions for Scenarios 2 and 3, meanwhile, were found to be 22,502,428.640 kg and 17,107086.96 kg, respectively, and were equivalent to the embodied emissions in concrete from the construction of 1,535 and 1,167 basements, respectively. Figure 3.4 also illustrates the significant difference between the monthly CO_2 emissions from temporary heating and the embodied CO_2 emissions from concrete usage per year. Concrete represents 87.03% more CO_2 emissions each year compared to the emissions from the base scenario of temporary heating usage, which is the case with the highest emissions coming from the heating source. If the embodied emissions from concrete are compared to the emissions resulting from using temporary heating one week before pouring the basement floor, which is the case with the lowest emissions, the annual CO_2 emissions from concrete are 94.24% higher than the emissions resulting from temporary heating. These results further demonstrate that, although temporary heating represents a considerable portion of the CO_2 emissions generated in the construction of concrete basements, the concrete material itself accounts for a significant share of CO_2 emissions due to its embodied emissions.

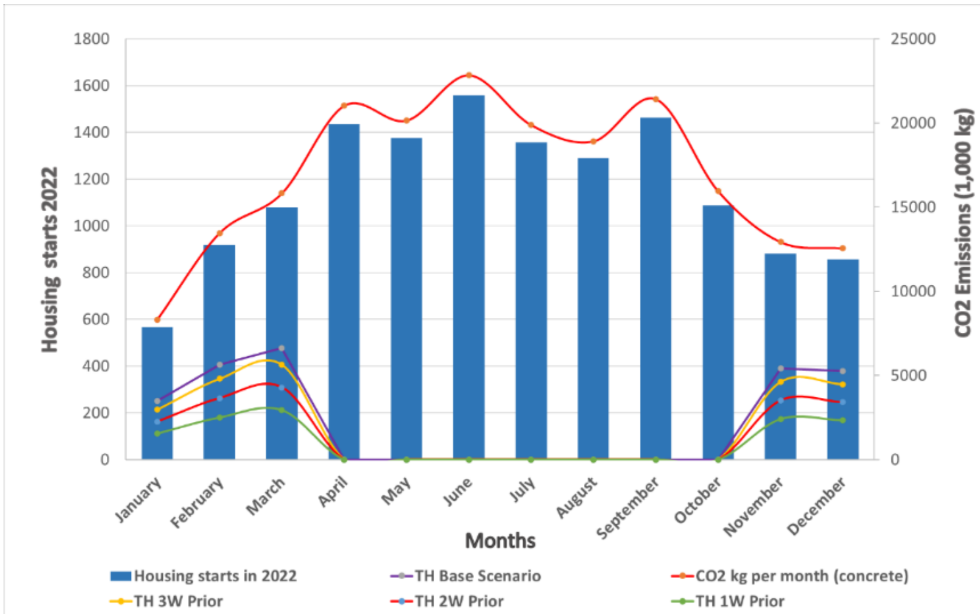

Figure 3.4: CO_2 emissions from propane consumption vs concrete usage throughout the year 2022 for housing starts in Alberta.

3.5 Conclusion

The purpose of this study was to evaluate the environmental impact of temporary heating during concrete construction projects. Temporary heating was shown to be a significant contributor to CO_2 emissions, with the construction of a concrete basement for a typical single-family detached dwelling in Canada representing between 2,722.395 kg and 6,126.510 kg of CO_2 emissions. It was also found that temporary heating can increase the average total cost of concrete basement construction, compared to concrete basement projects conducted in the summer season with no heating requirement. Temporary heating can increase costs by 8.84% to 19.31%, depending on when the operation begins relative to the concrete pouring task.

This research also identified uncertainties related to the use of temporary heaters. The temperature threshold at which temporary heater operation is triggered was one of the variables identified when consulting construction practitioners. A second variable of note was the timing of when temporary heating begins relative to when the concrete for the basement slab is poured.

Despite temporary heating being an additional source of cost and the increasing of CO_2 emissions during winter construction, the concrete material itself represents between 25.24–30.80% of the total cost of concrete basement projects developed during the winter. The embodied emissions of concrete represent between 70.52%–84.34% more CO_2 emissions compared to the emissions from temporary heating for a single-family house basement.

Future research could include the evaluation of construction alternatives for concrete basements that reduce the project duration and thus, the use of temporary heating in the construction site (Ferreira et al., 2018). Construction methods such as prefabrication significantly reduce project duration and, as a result, reduce the total CO_2 emissions for the construction phase of a project (Al-Hussein et al., 2009; Li et al., 2014). Additionally, prefabricated structures may reduce the total embodied concrete emissions by using less concrete to build structural elements. The authors of this paper intend to further explore this topic in future publications.

CHAPTER 4: ENVIRONMENTAL AND FINANCIAL TRADEOFF ANALYSIS OF INDUSTRIALIZED CONSTRUCTION METHODS IN COLD-CLIMATE REGIONS[3]

4.1 Introduction

The building and construction industry faces the challenge of reducing its Carbon Dioxide (CO_2) emission levels to reach Net-Zero targets by the year 2050 while still meeting the construction demands of a growing population worldwide (Zhang et al., 2023). This industry is responsible for producing nearly 40% of the total CO_2 emissions from energy usage globally, and this could further increase with the projected population growth in the coming years (Global Alliance for Buildings and Construction, 2022; United Nations Department of Economic and Social Affairs, 2022). Consequently, a growing emphasis exists within the building and construction sectors on implementing environmental strategies to reduce CO_2 emissions.

In this context, the construction phase has been a focus of attention in recent years, as this phase contributes approximately 10–20% of the total CO_2 emissions attributed to buildings (Guggemos & Horvath, 2006; Ji et al., 2018; Sandanayake et al., 2016). Additionally, this phase accounts for the embodied CO_2 emissions of construction materials, which contribute 9–11% of the total CO_2 emissions from this phase (Global Alliance for Buildings and Construction, 2020, 2022). Moreover, high carbon-intensive construction materials, such as concrete and steel, represented 6% of the overall CO_2 emissions generated by the building construction industry in 2022 (Global Alliance for Buildings and Construction, 2022). Indeed, despite the construction phase accounting for a considerable portion of the overall CO_2 emissions generated throughout a building's life cycle, this phase has often been overlooked in environmental efforts to reduce emissions in favour of

[3] Chapter 4 of this manuscript was originally submitted as Vecchio, V., Barkokébas, E., Días Barkokébas, R., Barkokébas, B., & Al-Hussein, M. "Environmental and financial tradeoff analysis of industrialized construction methods in cold climate regions." Journal of Cleaner Production (Submitted, 2024).

efforts to reduce the CO_2 emissions associated with the operational phase (Mao et al., 2013; Sandanayake et al., 2016). Therefore, given the relative shortage of research on the construction phase and the expected increase in construction activities to meet the housing demands of a growing population, there is an evident need to explore alternative construction methods aimed at reducing the CO_2 emissions resulting from the construction phase of buildings' life cycle.

Single-family detached houses are one of the most popular types of residential buildings around the world (Berrill et al., 2021; Lavagna et al., 2018; Saldaña-Márquez et al., 2019; Statistics Canada, 2021). However, this type of residential building has been identified as a significant contributor to CO_2 emissions, with the embodied emissions of construction materials being one of the primary factors driving the adverse environmental impact of this housing type (Lavagna et al., 2018; Soust-Verdaguer et al., 2016). In cold-climate regions, such as Canada and the United States, these types of houses are primarily built using timber frames for much of the above-ground structure, while concrete is typically used for the basement construction (Yu et al., 2008). This makes basements the part of the house with the highest concrete usage, potentially increasing the overall CO_2 emissions for this type of project (Mah et al., 2011). These emissions further increase during the winter as a result of the continuous use of temporary heating, a resource commonly used during construction projects that are exposed to freezing conditions (Mah et al., 2011; Vecchio Castillo et al., 2023). The use of temporary heating, particularly during the construction of residential buildings, results in higher costs and increased CO_2 emissions compared to the same type of projects executed in the summer due to the propane consumption of temporary heaters (Al-Hussein et al., 2009; Li et al., 2017; Mah et al., 2011). In light of this, it is crucial to explore alternative construction methods to reduce the CO_2 emissions resulting from construction materials and fossil-fuel-dependent construction equipment, particularly for the construction phase of residential houses.

In this context, industrialized construction, also known as prefabrication, is an alternative construction method that can decrease the CO_2 emissions generated compared to traditional construction methods due to its shorter project duration, lower material waste, and a reduction in the quantity of building materials used (Dong et al., 2015; Dou et al., 2019; Luo et al., 2021; Xu et al., 2022). According to Teng et al. (2018), prefabrication can decrease the embodied CO_2 emissions of buildings by an average of 15.6% when compared to traditional methods. Similarly, Mao et al. (2013) noted that prefabrication is capable of reducing embodied emissions by 86.5% when compared to traditional residential construction. However, despite the documented benefits of implementing industrialized methods for the construction of residential houses, construction enterprises remain hesitant to adopt this alternative construction method due to its perceived higher cost, preventing them from objectively assessing the non-financial and environmental benefits of industrialized construction (Jiang et al., 2018; Xue et al., 2018). Moreover, the absence of a quantitative approach by which to objectively weigh the financial and environmental benefits and drawbacks of industrialized construction hinders decision makers from making sound, unbiased decisions when selecting a construction method for a given residential project.

In this context, this study presents a quantitative assessment method for conducting analyses of the cost and environmental tradeoff between traditional and industrialized construction methods for residential buildings in cold-climate regions. A concrete basement for a single-family detached house is used as a case study to demonstrate the effectiveness of the proposed method in quantifying and comparing the costs and CO_2 emissions associated with traditional and industrialized construction methods. Three criteria are used in the tradeoff analysis: concrete, temporary heating, and site inspections. The key contribution of this study is that it provides an objective, quantitative method of analysis by which to evaluate the cost and environmental tradeoff between traditional and industrialized construction methods. This assessment method will allow decision makers to make well-informed decisions based on empirical data when selecting a construction method for a given project.

4.2 Background

4.2.1 CO_2 Emissions in the Construction Phase of Residential Buildings

Although the literature concerning this topic remains scarce compared to that of the operational phase, researchers have identified significant sources of CO_2 emissions in the construction of residential buildings. For instance, the embodied emissions of construction materials have been identified as a significant source of CO_2 emissions during this phase (Environment and Climate Change Canada, 2022). In this regard, concrete has been identified as a carbon-intensive construction material due to the energy that is used to manufacture some of the product's constituent elements (e.g., cement) (Lehne & Preston, 2018; Younis & Dodoo, 2022; Curmi et al., 2022; United Nations Environment Programme, 2022). Wang et al. (2016) identified concrete-related components as significant contributors to an increased carbon footprint in their quantification and comparison of the life cycle greenhouse gas (GHG) emissions of two green buildings. Similarly, Hong et al. (2015), whose study examined a residential complex in China, observed that the embodied emissions of construction materials, along with on-site electricity, were the primary sources of GHG emissions during the construction phase, with concrete and steel identified as the main contributors of these embodied emissions. In a follow-up study, Hong et al. (2017) not only identified the high environmental footprint of concrete, but also described the high levels of uncertainty related to material handling on the construction site, an aspect that strongly influences the accuracy of the calculation of the environmental impact of concrete for a given construction project. In this regard, alternative construction methods, such as industrialized construction, have the potential to minimize the intrinsic uncertainty related to material handling in the construction site, thereby improving the accuracy of construction materials and emission estimates.

4.2.2 Estimation of CO_2 Emissions in the Construction Site Using Uncertainty Analysis

Predictive models have frequently been used to estimate the CO_2 emissions resulting from the construction phase, using uncertainty analysis to account for the intrinsic variability of this particular phase (Hong et al., 2017). For instance, Wong et al. (2013) used virtual prototyping and mixed reality to virtually recreate construction works in order to predict the CO_2 emissions resulting from a residential project. Hajji (2015) developed a framework that uses multiple linear regression analysis to determine the productivity of construction equipment during earthwork operations as the basis for estimating their fuel consumption and corresponding CO_2 emissions. Likewise, Trani et al. (2016) developed a numerical evaluation to estimate fuel consumption for earthwork-related equipment, considering the load factor in order to quantify the expected CO_2 emissions resulting from this source prior to commencing construction operations. Lee et al. (2019) used a probabilistic approach applying Monte Carlo simulation to consider the intrinsic variability of construction operations on site and, therefore, improve the accuracy of CO_2 emission estimations for concrete pouring. Similarly, Vecchio Castillo et al. (2023) used a discrete-event simulation (DES) model in Simphony.NET to account for the variability in project duration and weather forecast when estimating the CO_2 emissions resulting from the use of propane for temporary winter heating and the embodied emissions of concrete for the construction of a traditional concrete basement for a single-family detached house. The study suggested that using prefabricated components could reduce project duration and concrete usage for concrete basements and, as a result, reduce CO_2 emissions when compared to cast-in-place basement construction. It should be noted that this study was based on a previous study conducted by Ferreira et al. (2018) that deployed a DES model in Simphony.NET in order to capture uncertain factors such as project duration and weather forecast, along with the thermal resistance of the building envelope of a multi-storey residential building. This study aimed to quantify and compare the costs associated with temporary heating for different types of construction methods. The findings demonstrated that the use of industrialized construction methods can significantly reduce costs related to temporary heating by virtue of a shorter project duration, and, therefore, a decrease in propane consumption for temporary heating when compared to traditional construction.

In this regard, using predictive models and uncertainty analysis to account for the variability of construction operations and material handling on site is one of the most commonly used methods to enhance the precision of the estimations regarding CO_2 emissions during construction activities (Hong et al., 2017). However, despite its potential benefits, industrialized construction has yet to be widely adopted due to complexities related to data analysis and the need for technical expertise in order to accurately predict the CO_2 emissions using predictive models.

4.2.3 Industrialized Construction

Industrialized construction is a construction approach in which building components are manufactured off site and then transported to the construction site for assembly (Tam et al., 2007; Mao et al., 2013; Teng et al., 2018). This results in a shorter project duration, reduced material usage, and lower material waste throughout the construction project (Du et al., 2019; Luo et al., 2021).

In addition to the aforementioned benefits, industrialized construction is also considered a more sustainable approach to construction in comparison to traditional methods, as it decreases CO_2 emissions due to its lower material usage (Hong et al., 2015; Xu et al., 2022). For instance, Jiang et al. (2019) found that industrialized construction methods decreased on-site CO_2 emissions by 44.7% for a multi-storey residential building compared to the traditional stick-built construction approach, while Li et al. (2014) obtained similar results. Du et al. (2019) demonstrated that implementing an industrialized construction approach for residential projects can reduce CO_2 emissions by nearly 18% in comparison to traditional construction methods. Their study also found that, although the CO_2 emissions generated by this alternative method fluctuate based on the prefabrication rate, the associated emissions are still lower than those generated by traditional construction. Dong et al., (2015) found that precast concrete generated approximately 10% less CO_2 emissions than cast-in-place construction when building a multi-storey residential building. Likewise, Mao et al. (2013) found that applying a partially industrialized construction approach for a residential project reduced CO_2 emissions by nearly 9% when compared to traditional construction. The decrease in emissions was mainly attributed to the reduction in construction material use (and associated embodied emissions).

In contrast to the aforementioned studies, other researchers have addressed the disadvantages of industrialized construction. For instance, Ji et al. (2018) found that the precast construction method only resulted in a 3.1% reduction in GHG emissions when compared to traditional construction methods between two high-rise residential buildings in China. They concluded that the environmental impact reduction from precast is relatively minor and could be considered negligible. Zhang et al. (2018) identified the higher cost of prefabricated components, the lack of flexibility in design, limited on-site storage for these components, and the prolonged design process as key limitations inhibiting the adoption of prefabrication. Similarly, Jiang et al. (2018) identified higher costs, inadequate logistics, low supply chain capacity, and insufficient technical expertise in prefabrication as the predominant factors limiting the adoption of prefabrication in China. Xue et al. (2018) also identified the higher cost of prefabrication as a significant constraint to implementing this construction method. Their results also indicated that construction material and labour costs highly affect the overall cost of industrialized construction alternatives. Considering the financial effects that influence the adoption of prefabrication, Chauhan et al. (2022) applied a multi-criterion decision analysis method based on cost–benefit analysis in order to compare the financial and non-financial implications of prefabrication to traditional construction. Their study sought to improve decision-making processes by considering individual criteria and preferences, and by providing an evaluating method to estimate the financial and non-financial advantages of each construction method. However, their study focused particularly on modular bathrooms and did not weigh the overall environmental benefits of adopting prefabrication in construction. Therefore, there is an evident gap with regard to quantitative assessment methods for conducting cost and environmental tradeoff analysis between industrialized and traditional construction methods. Due to this gap, construction decision-makers lack a reliable tool by which to identify the non-financial benefits of industrialized construction.

Considering the aforementioned studies, three gaps are identified: (1) limited research concerning CO_2 emissions mitigation alternatives in the construction phase of residential buildings, (2) the reluctancy of construction enterprises to adopt industrialized construction due to its perceived higher cost, and (3) the lack of a quantitative analysis method that addresses the cost and environmental tradeoff between different construction methods for residential projects. The present study aims to fill these gaps by proposing a quantitative assessment and cost and environmental tradeoff analysis method by which to objectively compare the cost and environmental implications of industrialized and traditional construction, particularly for residential buildings in cold-climate regions.

4.3 Methodology

In this research, a quantitative assessment method is developed for conducting cost and environmental tradeoff analysis between industrialized and traditional construction methods in cold-climate regions. A detailed representation of the methodology is provided in Figure 4.1. Three criteria are selected for the analysis: concrete, temporary heating, and site inspections. As mentioned in the Introduction section, single-family detached houses are selected for the case study due to this being one of the predominant types of residential buildings in cold-climate regions such as Europe, Canada, and the United States (Berrill et al., 2021; Lavagna et al., 2018; Statistics Canada, 2021). Moreover, concrete basements in particular are considered due to the high quantity of concrete required to build this section of the house and due to the extensive use of temporary heating for this phase of construction (Mah et al., 2011).

Concrete is considered one of the most accessible and widely used construction materials around the world (Adesina, 2020; Ni et al., 2022). As mentioned in the Introduction section, this building material is commonly used in the construction of basements for single-family detached houses in North America (Mah et al., 2011; Yu et al., 2008). Concrete is mainly used to form the foundation walls and slab-on-grade structures that constitute the basement area. Temporary heating, another comparison criterion for this study, is a resource used to provide heat during construction operations throughout the winter season in regions where temperatures drop below freezing conditions (Ferreira et al., 2018; Zhuravlev et al., 2020). This resource is chosen as one of the criteria for this study, considering that research on the use of temporary heating during residential construction operations remains scarce and is considered a source of financial and environmental uncertainty (Vecchio Castillo et al., 2023). Both of these construction resources are selected for the study due to their being required during winter construction operations, regardless of the chosen construction method. Additionally, the costs associated with the construction manager's site inspections are included given that this metric is affected by the overall project duration, being directly influenced by the number of daily site inspection trips (Al-Hussein et al., 2009).

In addition to their widespread use, concrete, temporary heating, and site inspections have been identified as significant sources of CO_2 during on-site construction operations. As mentioned in the Background section above, concrete production entails a substantial amount of energy use, leading to significant embodied emissions (Lehne & Preston, 2018; Younis & Dodoo, 2022; Curmi et al., 2022). Similarly, the use of temporary heating during the winter season significantly increases the CO_2 emissions associated with residential construction in Canada, in comparison to the same type of projects executed during the summer season (Al-Hussein et al., 2009; Li et al., 2014; Mah et al., 2011). Likewise, the cost and CO_2 emissions associated with site inspections depend on the project duration, leading to increased costs and CO_2 emissions in the case of extended projects (Al-Hussein et al., 2009).

To demonstrate the effectiveness of the quantitative assessment and tradeoff analysis, the cost and CO_2 emissions associated with concrete usage, temporary heating, and site inspections resulting from two separate industrialized construction scenarios are compared to those resulting from the cast-in-place construction scenario.

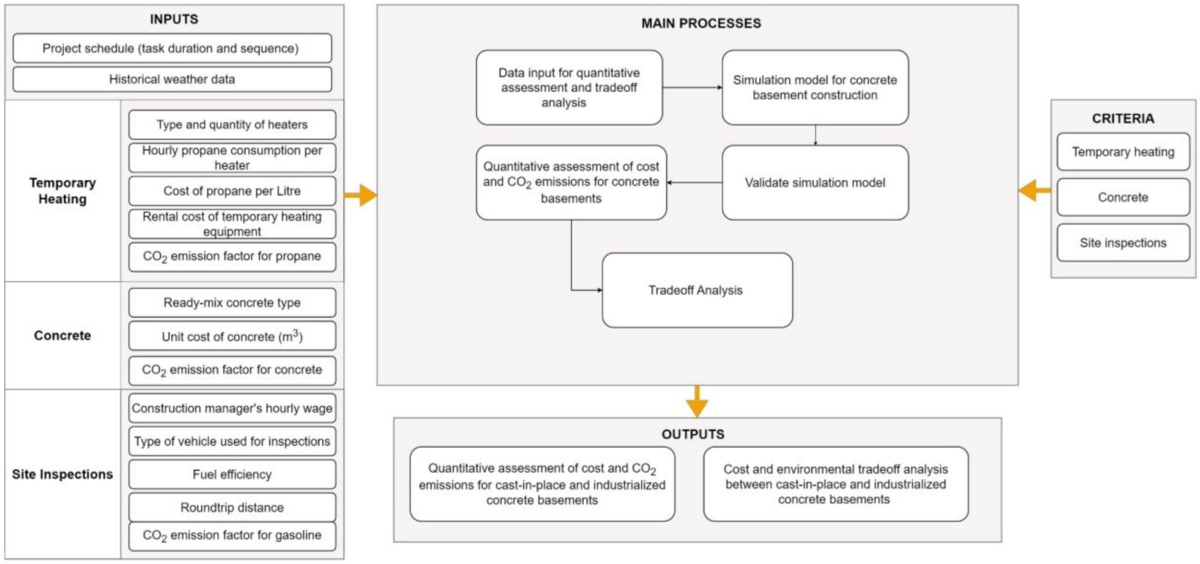

Figure 4.1: Overview of methodology for case study.

4.3.1 Data Collection for Quantitative Assessment and Tradeoff Analysis

This study considers data inputs such as project schedule, historical weather data, and propane consumption in order to obtain the overall costs and CO_2 emissions resulting from the three criteria selected for this study: concrete, temporary heating, and site inspections. Figure 4.1 provides a detailed list of the inputs considered in this study. The project schedule for the cast-in-place basement construction scenario, as well as the historical weather data and propane consumption, are drawn from a previous study conducted by Vecchio Castillo et al. (2023) and from publicly available data (e.g., Statistics Canada). The cast-in-place construction method is used as the baseline scenario against which the cost and CO_2 emissions resulting from the industrialized construction method are compared in the tradeoff analysis. The industrialized construction scenario's project schedule is based on the baseline scenario from Vecchio Castillo et al. (2023), as well as from the information provided by a construction manager from an industrialized construction company operating in Edmonton, Canada. The CO_2 emissions for the two different types of concrete considered for this study are obtained from the Environmental Product

Declaration (EPD) for ready-mixed concrete, published by the Canadian Ready-Mixed Concrete Association (CRMCA), and from the EPD of the Ready-Mixed Concrete Association of Ontario Both EPD reports having been prepared by the Athena Sustainable Materials Institute. The cost of concrete used for the cast-in-place and the industrialized construction scenarios is determined based on invoice data from a ready-mix concrete supplier in Edmonton, Alberta, as well as invoice data from two suppliers of self-compacting concrete (SCC), (used in industrialized concrete construction), operating in Edmonton, Alberta.

The information related to the cost and CO_2 emission associated with site inspections is collected from publicly available data and from a previous study conducted by Al-Hussein et al. (2009).

4.3.2 Simulation Model for Concrete Basement Construction

Simphony.NET is used as the simulation environment to determine the tasks and project durations associated with on-site construction operations. Researchers have previously used this simulation environment to represent and predict events occurring at the production line of an offsite facility (Barkokébas et al., 2022; Bhatia et al., 2019; Li et al., 2017) and to replicate and enhance on-site construction operations (AbouRizk et al., 2016). Simphony.NET is used in this study to develop a Monte Carlo simulation to account for the intrinsic variability of on-site construction operations. Because the tasks associated with on-site construction operations have variable durations, the total project duration is determined through probabilistic analysis based on estimated ranges of individual task durations.

4.3.3 Quantitative Assessment and Tradeoff Analysis

This study builds upon the results of a quantitative assessment by Vecchio Castillo et al. (2023) for quantifying the costs and CO_2 emissions resulting from on-site construction operations for a traditional cast-in-place concrete basement in a cold-climate region. The results of the study were obtained through a validated simulation model developed by the authors to represent the on-site construction schedule for a traditional cast-in-place concrete basement. For the present study, a layer of complexity is added by comparing the cost and CO_2 emissions between the traditional cast-in-place method and two industrialized construction methods. Therefore, an additional simulation model is incorporated based on the original validated simulation model in order to account for the two industrialized construction scenarios addressed in the present study. Furthermore, the accuracy of the initial analysis is improved upon by accounting for the fact that temporary heating is required for concrete-related activities and for the installation of underground services. Finally, the CO_2 emission factor for the cast-in-place concrete construction scenario considered in this study is based on the technical specifications of the particular type of concrete used in Edmonton, Canada, for the construction of basements for single-family detached houses.

4.4 Case Study

4.4.1 Data Input for Quantitative Assessment and Tradeoff Analysis

As mentioned above, concrete basements for single-family detached houses are used as the case study for the quantitative assessment and tradeoff analysis between cast-in-place and industrialized construction methods. For this study, two industrialized construction methods, solid-wall precast and ribbed precast structures, are compared to the baseline scenario, the cast-in-place construction method, in order to determine whether industrialization achieves positive tradeoff results in terms of the cost and CO_2 emissions associated with residential construction. The simulation model built to replicate the industrialized concrete basement construction scenario is used to represent the project schedule for the two types of industrialized concrete basement construction methods being observed in this study.

To conduct the quantitative assessment and tradeoff analysis between the three construction methods, a simulation model is developed to replicate the on-site operations in the construction of an industrialized concrete basement. This model collects data concerning the task durations of the activities required to build a concrete basement, resulting in the total project duration for this type of project (Vecchio Castillo et al., 2023). As mentioned in the Methodology section, this simulation model is based on a previously validated simulation model developed by Vecchio Castillo et al. (2023) in which the construction schedule for a conventional cast-in-place concrete basement was recreated to reflect the tasks and overall project duration for this type of project while taking into account the uncertainty and variability concerning the durations of activities on the construction site. This simulation model was validated using four different validation techniques established by Sargent (2010): historical data validation, face validity, comparison to other models, and event validity. The comparison of project schedules between traditional cast-in-place and industrialized concrete basement construction operations is shown in Figure 4.2. The project durations obtained for these methods are subsequently used to compare the cost and CO_2 emissions resulting from cast-in-place and industrialized construction methods for concrete basements.

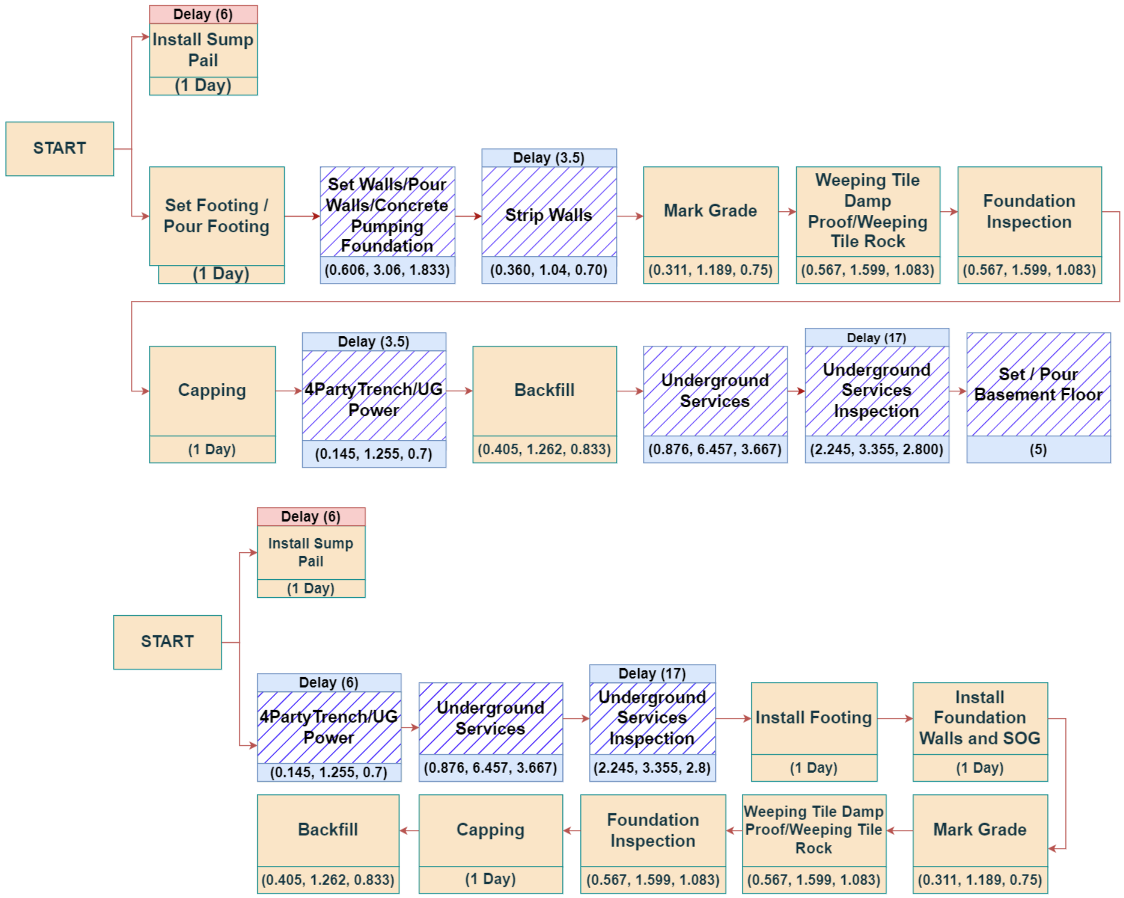

Figure 4.2: Project schedule for a cast-in-place concrete basement (top) (Vecchio Castillo et al., 2023) and a precast concrete basement (bottom).

The project schedule and task duration for the construction of an industrialized concrete basement are obtained from a construction expert from a precast concrete company in Edmonton, Canada, who has several years of experience working in the construction of both industrialized and traditional residential developments. For the industrialized scenario, the installation of the precast foundation walls and slab-on-grade (SOG) occurs on the same day. This differs from the cast-in-place scenario, in which the foundation walls and SOG-related tasks take multiple days to be completed. Additionally, in the industrialized scenario, the installation of the underground services, and their subsequent inspection, take place prior to the installation of the industrialized concrete structures. The remaining activities involved in completing an industrialized concrete basement project are the same as in the case of the cast-in-place basement, so the same durations are considered for both scenarios for these activities. The overall project duration resulting from both simulation models is determined in calendar days.

4.4.2 Propane Consumption

The estimated propane consumption is based on a temporary heating setup, in which temporary heating is used whenever the temperature drops to 0 °C and runs continuously for as long as the temperature remains at or below 0 °C. The expected average daily temperature was obtained from historical weather data for the City of Edmonton available in the Simphony.NET environment. The temperature threshold and the simulation inputs used to calculate propane consumption, depicted in Table 4.1, are based on the simulation inputs previously considered by Vecchio Castillo et al. (2023). It should be noted that the amount of propane consumed is dependent on both the weather conditions and the type of task being performed.

Table 2.1: Simulation inputs to estimate propane consumption for traditional cast-in-place and industrialized basement construction (Vecchio Castillo et al., 2023)

Input	Unit
Temperature threshold	0 °C
Fuel consumption for a 125,000 Btu radiant heater	5 L/h
Number of heaters	1

To identify the tasks that require temporary heating during winter for both cast-in-place and industrialized concrete basement construction, several construction experts were interviewed. It was determined based on these consultations that temporary heating is used primarily during the construction of basement foundation walls and SOG for concrete curing purposes, and during the installation of underground services. As such, the temporary heating time and estimated propane consumption are dependent on the duration of the particular tasks that require the resource, represented by a hatched pattern in Figure 4.2.

It can be observed from Figure 4.2 that the use of temporary heating differs between the cast-in-place and industrialized construction methods. Although both construction methods require temporary heating for the installation of the underground services, the industrialized construction method does not require the use of temporary heating for curing purposes during the installation of the foundation walls and SOG. This is because these components are manufactured outside of the construction site and later brought to the site for their final placement. Hence, temporary heating is not considered for these two tasks.

4.4.3 Simulation Model for Industrialized Concrete Basements

The project schedule information for an industrialized concrete basement having been collected and the tasks that require temporary heating during winter construction for this type of project having been identified, a simulation model is built using Simphony.NET to represent the project schedule and construction operations on site. Due to the intrinsic variability and uncertainty of operations in the construction site, triangular distributions are developed for each of the tasks in industrialized concrete basement construction exhibiting significant variations in completion time. Consequently, a lower bound, upper bound, and mean duration are designated for these tasks based on actual task duration values in order to account for possible delays in the project (Vecchio Castillo et al., 2023).

The equation used to estimate propane consumption during the construction of concrete basements was originally developed by Ferreira et al., (2018) to estimate the fuel consumption of temporary heaters used for the construction of a multi-storey residential building. This equation was later modified by Vecchio Castillo et al. (2023) to consider the specific scenario of propane consumption during the construction of concrete basements. Equation 1 shows the modified equation by which to estimate propane consumption in this scenario.

$$24 \text{ h} \times \text{number of heaters} \times \text{beginning of heating} \times \text{hourly fuel consumption} \tag{4.1}$$

The simulation is run 1,000 times, with December 1, 2024, selected as the project start-date for the simulation. This date was chosen because December is one of the coldest months of the year in Edmonton, Canada, with average daily high temperatures lower than 0 °C (Statistics Canada, 2023). This means that temporary heating would certainly be used on the construction site during this time of the year. Moreover, December is selected for the case study considering that more houses are built during this month compared to January (Statistics Canada, 2023b). The simulation is run 1,000 times in order to collect the average task durations and overall project duration. The simulation software considers the mean values for these two durations for each run to account for any possible delays associated with the tasks involved in the project. This process helps to account for uncertainties related to possible delays in task completion.

The baseline simulation model for cast-in-place concrete basement construction was previously validated using several validation methods as part of a previous study. Therefore, only the face validity and comparison to other model validation techniques are employed for the present study. The project duration from the industrialized construction simulation model is validated in consultation with an expert construction manager experienced with both cast-in-place and industrialized construction. The industrialized simulation model is compared to the baseline simulation model in order to observe similarities between the simulation models.

4.4.4 Quantitative Assessment—Temporary Heating

The cost associated with temporary heating is based on the total propane consumption throughout the duration of the concrete basement project, as well as the total cost related to the rental of the temporary heating equipment for the duration of the project (Ferreira et al., 2018). Similarly, the level of CO_2 emissions generated by the use of temporary heating during the construction of industrialized concrete basements is governed by the propane consumption throughout the project. The cost related to renting the temporary heating equipment is determined by reviewing invoice data from a residential construction company in Edmonton, Canada, following the methodology previously conducted by Ferreira et al. (2018) and Vecchio Castillo et al. (2023). These invoices include the rental cost of the temporary heater and other related items at the construction site. Table 4.2 shows a detailed list of the items considered as part of the rental equipment package. This table also shows the CO_2 equivalent (CO_2-eq) emission factor for propane, which is used to calculate the total CO_2 emissions resulting from the use of temporary heating (Environment and Climate Change Canada, 2022).

Table 4.2: Temporary heating costs and CO2-eq emission factor for propane (Vecchio Castillo et al., 2023)

Temporary Heating and Concrete Costs and CO_2-eq Input	
Item	**Unit Price ($)**
Temporary Heating	
Average cost of propane (per L)	0.73
125,000 Btu radiant heater	22.00

Propane tank	5.00
Heater thermostat	5.00
Environmental fees	0.10
Duct hose	5.00
Connector double tank propane	2.00
Extension cord	8.00
Delivery charge	60.00
Pick-up charge	60.00
Emission factor for propane (CO_2 kg-eq/L)	1.515
Concrete	**Unit Price ($) per m^3**
Winter handling	25.00
Environmental charge	11.00
Alberta government carbon tax	5.00
Fuel sub charge	4.00

4.4.5 Quantitative Assessment— Concrete

The inputs to quantify the cost and CO_2 emissions of concrete for the cast-in-place and the two industrialized concrete basement scenarios observed in this study are based on an Autodesk Revit model of a single-family detached project located in Edmonton, Canada. The original Revit model, shown in Figure 4.3, which considers the ribbed precast construction method for basements, is used to represent the cost and CO_2 emissions associated with concrete, temporary heating, and site inspections for the two industrialized scenarios.

To conduct the quantitative assessment and tradeoff analysis between the three construction scenarios, the original Autodesk Revit model is altered to resemble the structural conditions of a traditional cast-in-place basement while also considering the dimensions and specifications of the original model (see Figure 4.4). It should be noted that the ribbed precast construction method uses less concrete than the cast-in-place and solid-wall precast basements as a result of its particular engineered design, which uses other construction materials, such as rigid insulation, to improve the thermal and moisture properties of the building. Consequently, the thickness of the concrete layer for the basement walls for this particular scenario is thinner than for a cast-in-place or solid-wall precast basement, and this is reflected in the Revit model of the cast-in-place basement. This model is used to estimate the concrete usage for the cast-in-place and solid-wall precast concrete basement scenarios, considering that both construction methods use the same quantity of concrete for this particular type of project, with only the concrete waste on site varying between the two methods. The concrete waste for the cast-in-place, solid-wall precast, and ribbed precast concrete basements is found to be 5%, 3%, and 3%, respectively. The concrete waste is greater in the cast-in-place scenario due to the inherent challenges with handling the material on site, as opposed to in a controlled factory environment. The concrete usage for the three previously described scenarios is shown in Table 4.3.

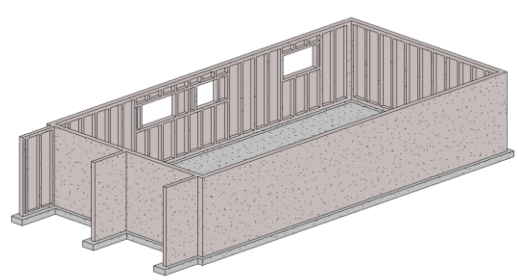

Figure 4.3: Industrialized concrete basement model.

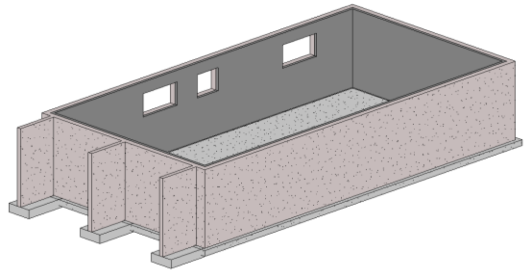

Figure 4.4: Cast-in-place concrete basement model.

Based on the concrete usage for each scenario and the type of concrete being used for each construction method, the unit cost of concrete per cubic metre (m^3) is determined. The type of concrete used for a cast-in-place concrete basement is assumed to be 35 MPa General Use (GU) concrete mix with air and 0–14% fly ash (FA) / slag cement (SC) based on invoice data from a ready-mix concrete supplier in Edmonton, Canada. For the industrialized scenarios, the type of concrete used is 35 MPa SCC with 5–8% air. This information is collected through consultations with a construction expert who works for a residential construction company, as well as from invoice data from two different ready-mix concrete suppliers. In addition to the unit cost of concrete per m^3, other costs such as the winter handling, environmental charge, and carbon tax are incorporated in order to calculate the total cost of concrete for the construction of basements, as shown in Table 4.2.

As previously mentioned, the CO_2 emissions information used in the analysis is drawn from the EPD for concrete developed by the Athena Sustainable Materials Institute. The CO_2 emission factor used to calculate the concrete-related emissions is selected based on the concrete strength and technical specifications of the type of concrete selected for each construction scenario. These emission factors are shown in Table 4.3.

Table 4.3: Concrete usage and CO_2 emission factor for different basement construction methods

Concrete Usage, Unit Cost, and CO_2 Emission Factor			
Construction Method	**Concrete usage (m^3)**	**Unit cost**	**CO_2 –eq. Emission Factor**
Traditional Cast-In-Place	42.488	$235.00	449.790
Traditional Precast	41.678	$246.00	377.330
Ribbed Precast Structure	25.668	$246.00	377.330

4.4.6 Quantitative Assessment—Site Inspections

As mentioned above, costs related to site inspections are based on a construction manager's daily wage and the cost of fuel. The cost of the fuel is calculated based on the number of trips to the construction site for inspection purposes. The amount of CO_2 emissions resulting from these inspections is governed by the fuel consumption, which in turn is determined based on the number of trips made to the construction site (Al-Hussein et al., 2009). The cost and CO_2 emissions inputs, shown in Table 4.4, are selected due to the variability of these metrics resulting from the differences in the total duration of concrete basement projects.

Table 4.4: Concrete usage and CO_2 emission factor for different basement construction methods

Cost and CO_2 Emission Inputs for Construction Managers		
Construction Manager's Wage		**Cost of Fuel (per L)**
Average annual wage	$108,142.00	1.4114 $/L

Taxes	30%	Regular gasoline
Average daily wage	$286.74	

The annual wage of a construction manager is obtained from a Government of Alberta webpage (Government of Alberta, 2021). A 30% portion of the total wage is subtracted to account for provincial taxes. Accordingly, the total cost of the construction manager's wage throughout the project is calculated by multiplying the manager's daily average salary by the project duration in terms of working days for each of the three scenarios.

The overall cost of fuel for site inspections, meanwhile, is quantified by multiplying the working days by the quantity of fuel used per roundtrip. It should be noted that a conventional pick-up truck using regular gasoline is selected as the vehicle type, since this is the type of vehicle commonly used by construction managers for transportation purposes (Al-Hussein et al., 2009). The fuel efficiency per 100 km for the selected type of truck is obtained from the given automobile's technical specifications and publicly available data (Natural Resources Canada, 2022), while the roundtrip distance is assumed to be 40 km (Al-Hussein et al., 2009).

The fuel consumption per roundtrip is multiplied by the total working days for each of the concrete basement construction scenarios in order to obtain the total fuel consumption for each construction method. This value is subsequently multiplied by the average price per litre of regular gasoline in order to obtain the total cost of fuel for each scenario. It should be noted that the average price of regular gasoline per litre used in the calculation is based on the average price of regular gasoline between the years of 2022 and 2023 in Edmonton, Canada.

The cumulative CO_2 emissions based on trips to the construction site are calculated by multiplying the CO_2 emission factor for regular gasoline per kilometre by the total roundtrip distance. This result is then multiplied by the total number of working days for each basement construction scenario in order to obtain the total CO_2 emissions resulting from trips to the construction site for inspection purposes for each project (Al-Hussein et al., 2009).

4.5. Results

4.5.1 Project Duration and Average Propane Consumption

The simulation results show that industrialized construction methods reduce the overall project duration by 27.62% when compared to the cast-in-place method for concrete basement projects. Moreover, the simulation model is used to estimate the average reduction in propane consumption during the winter months of November to March, when the daily average temperature in Edmonton is below 0 °C. Figure 4.5 shows the decrease in propane consumption throughout the winter months. An average decrease of 22.81% in propane consumption compared to the cast-in-place method is observed when industrialized construction is used for concrete basement projects.

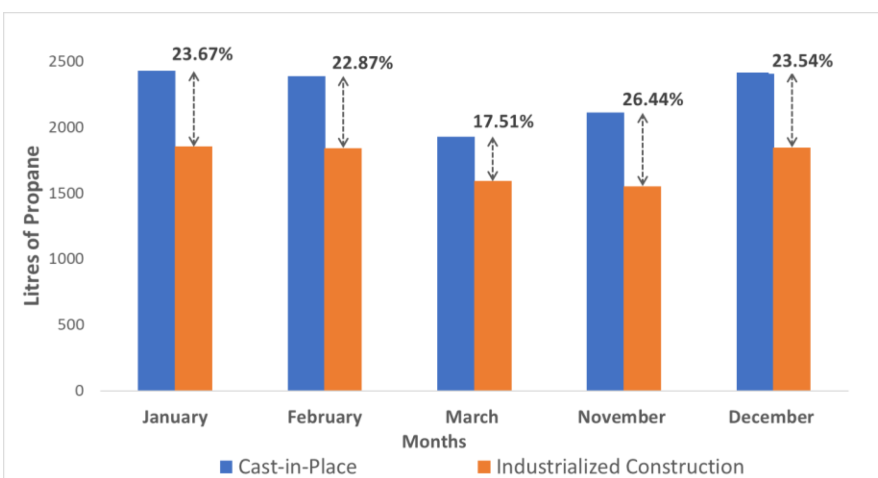

Figure 4.5: Cast-in-place versus industrialized propane consumption during winter months.

4.5.2 Cost Breakdown for Concrete Basements

With regard to quantifying the total cost related to concrete basements in terms of the criteria selected for this study (i.e., temporary heating, concrete, and site inspections), it is worth noting that the costs associated with these resources may vary depending on the season. For instance, once temporary heating is no longer required due to warmer temperatures, the winter handling fee is not included in the cost of concrete from ready-mix concrete manufacturers. For the purpose of this study, the time period described as "summer" refers to the months of the year in which the average temperature is above 0 °C (i.e., April to October in the case of Edmonton, Canada). This information is considered when comparing the cost of the selected criteria between construction methods.

In order to determine the cost differences between the three construction methods, the costs associated with the cast-in-place concrete basement scenario are used as a reference point to estimate the variations between this and the two industrialized construction methods being evaluated.

The solid-wall precast construction method is found to have an average concrete cost during the winter months $189.37 higher than that of the cast-in-place basement construction method due to the higher unit cost of concrete and lower material waste due to mishandling. However, the solid-wall precast scenario reduces temporary heating costs by $666.61 due to a reduced heating time, and reduces site inspection costs by $1,956.49 due to a shorter project duration. As a result, the average total cost difference between the cast-in-place and solid-wall precast scenario per concrete basement for single-family detached houses is $2,433.73. This represents an average cost reduction of 10.98% when compared to the cast-in-place scenario, as depicted in Figure 4.6. During the summer months, the cost of concrete for the solid-wall precast scenario increases by $209.61 on average compared to the baseline scenario due to the exclusion of the winter handling fees, while the cost reduction from site inspections remains the same as for the winter months. As previously mentioned, temporary heating costs are not applicable during the summer, as the resource is not required during this season. Consequently, the average cost reduction per concrete basement considering the solid-wall precast scenario is approximately $1,746.88. This represents an overall cost decrease of 9.67% compared to the cast-in-place scenario, as shown in Figure 4.6.

Similarly to the solid-wall precast scenario, the ribbed precast construction method reduces concrete costs by $4,469.75 compared to the cast-in-place scenario during the winter months, despite the higher unit price of precast concrete. This is due to a 39.59% reduction in concrete usage for the ribbed precast method when compared to the traditional cast-in-place method. The average cost reductions associated with the use of temporary heating and site inspections are found to be $666.61 and $1,956.49, respectively, which is similar to the cost savings observed in the solid-wall precast construction method relative to the baseline method. In total, the ribbed precast construction method represents an average cost reduction of $7,092.85 per concrete basement project—a 32.00% decrease in basement construction costs compared to cast-in-place for construction operations occurring in the winter, as shown in Figure 4.6. During the summer months, the ribbed precast scenario reduces concrete costs by $4,049.25 due to the exclusion of the winter handling fees and reduced concrete usage compared to the baseline scenario, while the cost reduction from site inspections is the same as for the winter months. The total cost of a concrete basement is reduced by $6,005.74, a cost reduction of 33.25% when compared to the cast-in-place method, as observed in Figure 4.6.

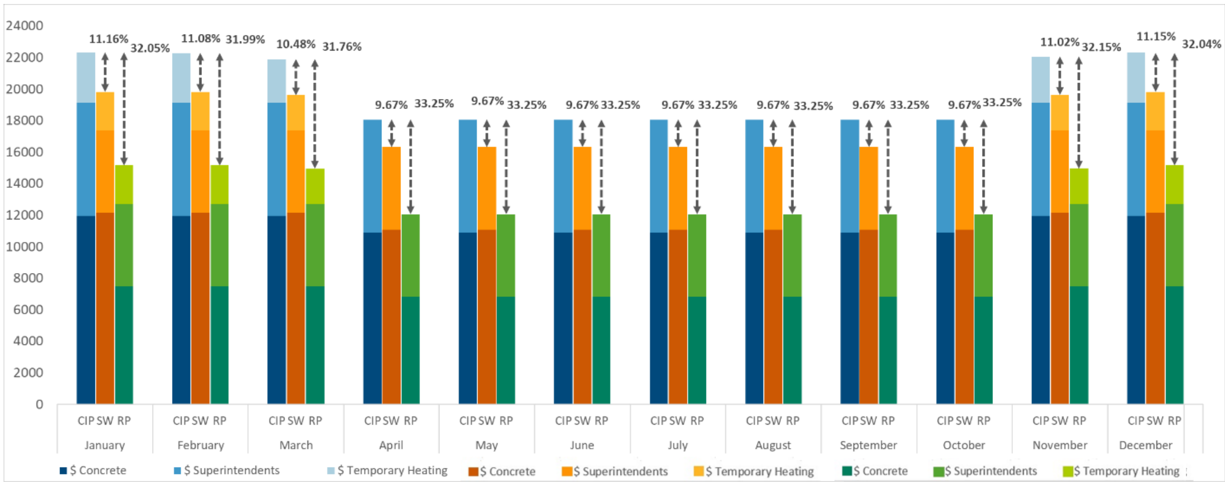

Figure 4.6: Monthly difference in cost per concrete basement.

4.5.3 CO_2 Emissions Breakdown per Concrete Basement

The CO_2 emissions for the cast-in-place and industrialized concrete basement construction scenarios are analyzed in a manner similar to the cost analysis described above. The CO_2 emissions for the winter and summer months are estimated in terms of the three criteria considered, and the CO_2 emissions resulting from the cast-in-place construction method for concrete basements are considered as the reference point for calculating the emission difference between construction methods.

The solid-wall precast construction method is found to reduce the CO_2 emissions associated with concrete usage during the winter months by approximately 17.71% compared to the cast-in-place scenario. This emission reduction is a result of a lower concrete emission factor corresponding to the SCC compared to the emission factor of conventional ready-mix concrete used for cast-in-place basement projects. The solid-wall precast scenario is also found to result in a 22.81% reduction in the CO_2 emissions generated by the use of temporary heating compared to the cast-in-place method due to a shorter project duration and fewer tasks requiring the use of temporary heating. Moreover, the CO_2 emissions resulting from site inspections are reduced by 27.21% due to a shorter project duration (i.e., fewer trips to the construction site and lower fuel consumption compared to the baseline scenario). The same emission reduction percentages for concrete and site inspections are observed during the summer months. CO_2 emissions from temporary heating, on the other hand, are not accounted for the summer season since this resource is not used during the summer.

Similarly to the solid-wall precast scenario, the ribbed precast method is found to result in a 49.32% reduction in CO_2 emissions resulting from concrete usage compared to the cast-in-place construction method for concrete basements during the winter months. This is attributable to the lower emission factor considered for the SCC precast concrete and a lower quantity of concrete being used during the construction of concrete basements. The CO_2 emission percentage difference between the cast-in-place and ribbed precast construction methods for basements with regard to temporary heating and site inspections is 22.81% and 27.21%, respectively. The same emission reductions for concrete and site inspections are observed during the summer months, whereas the reduction of CO_2 emissions from temporary heating is not applicable during this time of the year.

4.5.4 Monthly Breakdown and Cumulative CO_2 Emissions Based on the Number of Housing Starts in 2022

In order to understand the impact of the CO_2 emissions generated during the construction of concrete basements on a larger scale, the amount of emissions expressed in kg resulting from the construction of one concrete basement and the criteria selected for this study is multiplied by the number of housing starts in Alberta in 2022 (Statistics Canada, 2024). Similar to Chapter 3, it was assumed that the monthly number of housing starts for single-family detached houses for the year 2022 reflected the projects in which the construction process for concrete basements had already started (Government of Alberta, 2024). It is also assumed that the total number of housing starts had the same concrete volume requirements for the basement portion of these houses as the case study for this research, considering each of the concrete basement scenarios evaluated in this study. Figure 4.7 shows the CO_2 emissions generated by each construction method for concrete basements for the year 2022, as well as the breakdown of the sources of emissions for each construction method. The figure shows that both industrialized construction methods result in a significant CO_2 emission reduction for the construction of concrete basements for single-family detached houses when compared to the cast-in-place scenario. The solid-wall precast scenario is capable of reducing by between 17.79% and 19.05% the CO_2 emissions attributed to the use of concrete, temporary heating, and construction site inspections. The ribbed precast method, meanwhile, is capable of reducing between 44.93% and 49.07% of the CO_2 emissions resulting from the aforementioned criteria for concrete basements.

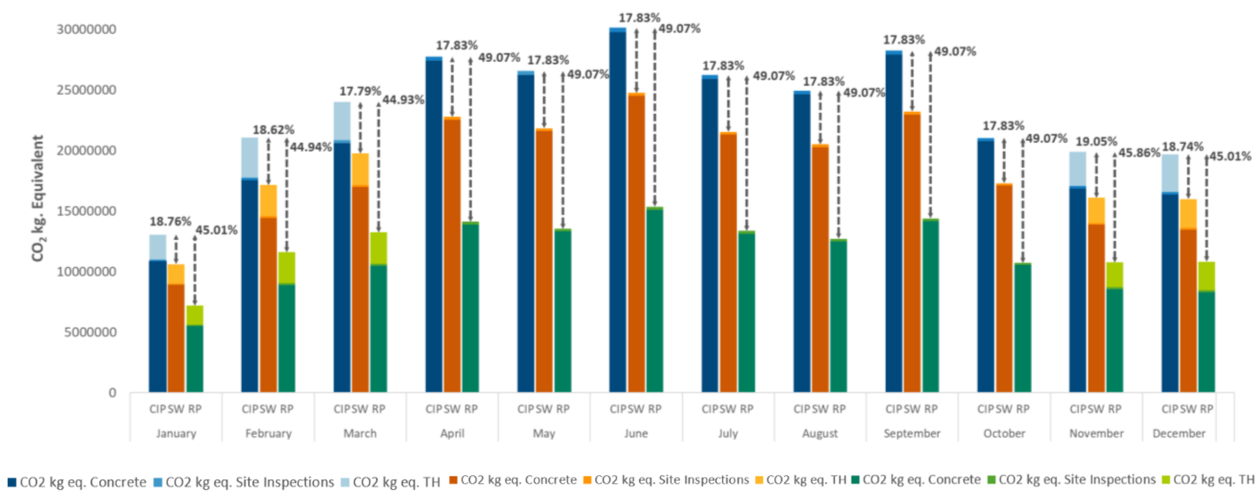

Figure 4.7: Monthly difference of CO_2 emissions based on the number of housing starts in Alberta in 2022.

In addition to the emissions breakdown, the cumulative CO_2 emissions generated by each method for the criteria examined in this study are quantified based on the number of housing starts in

Alberta in 2022 for single-family detached houses (Statistics Canada, 2024). The results of this analysis are presented in Figure 4.8 considering the total CO_2 kg equivalent throughout the year. The figure illustrates the approximate 282,617,488 kg of CO_2 emissions that the cast-in-place construction method generates throughout the year. To put this into perspective, this is equivalent to the CO_2 emissions generated by concrete usage, temporary heating, and site inspections for the construction of 13,612 cast-in-place concrete basements for single-family detached houses. The solid-wall precast scenario generates approximately 231,526,387 kg of CO_2 emissions throughout the year, which is the equivalent of building 11,151 cast-in-place concrete basements for single-family detached houses. The ribbed precast construction method produces approximately 147,775,490 kg of CO_2 emissions throughout the year, which is the equivalent of the CO_2 emissions generated by the construction of 7,118 cast-in-place concrete basements. Consequently, it can be determined that the solid-wall precast construction method generates approximately 51,091,101 fewer kg of CO_2 emissions compared to the traditional cast-in-place method, representing an 18.08% reduction in CO_2 emissions. Moreover, the ribbed precast method generates approximately 134,841,998 fewer kg of CO_2 emissions, representing a 47.71% emissions reduction compared to the traditional cast-in-place construction method for concrete basements. These reductions demonstrate that the solid-wall precast construction method is capable of reducing the CO_2 emissions equivalent to 2,461 cast-in-place concrete basements, while the ribbed precast method reduces the CO_2 emissions equivalent to 6,494 cast-in-place concrete basements for single-family detached houses.

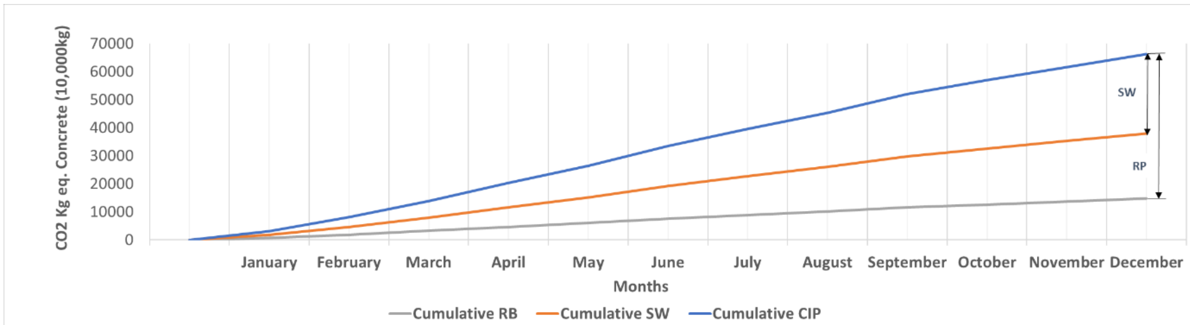

Figure 4.8: Cumulative difference of CO_2 emissions per construction method based on the number of housing starts in Alberta in 2022.

4.6 Conclusion

This study presented a quantitative assessment to conduct cost and environmental tradeoff analysis between traditional and industrialized construction methods. The purpose of this study was to address the gap in the literature regarding the lack of an objective method of quantitative analysis by which to compare the financial and environmental implications of selecting industrialized construction for building concrete basements for single-family detached houses. To demonstrate the effectiveness of the quantitative assessment, three construction methods were analyzed and compared using both cost and CO_2 emissions as metrics. The methods included the traditional cast-in-place method, as well as two types of industrialized construction methods: solid-wall precast and ribbed precast construction. Concrete usage, temporary heating, and site inspections were considered as the criteria by which the overall cost and CO_2 emissions for each method were determined. A single-family detached concrete basement in Edmonton, Canada was selected as the case study to test the validity of the quantitative and tradeoff analysis.

The results of this study show that both industrialized construction methods are capable of reducing the overall cost related to the use of temporary heating, concrete usage, and site inspections when compared to the traditional cast-in-place construction method for concrete basements. The solid-wall precast method demonstrated a decrease in concrete basement costs mainly attributable to a shorter project duration and lower propane consumption for winter-time concrete basement construction. Similarly, the ribbed precast construction method demonstrated a significant decrease in concrete basement costs, attributed to a reduction in concrete usage in the case of this particular method (i.e., 39.59% lower than that used in the traditional cast-in-place method), as well as a shorter project duration and lower propane usage for on-site winter heating.

In terms of CO_2 emissions, both industrialized construction methods demonstrated significant emission reductions compared to the cast-in-place scenario. In the case of the solid-wall precast construction method, the reduction in CO_2 emissions was achieved due to a shorter project duration, which led to a reduced number of site inspections and less propane consumption for winter heating. Additionally, the carbon emission factor of the type of concrete used in industrialized construction represents a lower environmental impact in comparison to that of the traditional ready-mix concrete used for cast-in-place construction. Consequently, there is a decrease in the associated embodied CO_2 emissions. The ribbed precast construction method in particular demonstrated a significant reduction in CO_2 emissions when compared to the cast-in-place construction method due to the reasons previously mentioned for the solid-wall precast construction scenario, as well as a 49.32% emission reduction resulting from lower concrete usage.

The CO_2 emissions for the construction of one concrete basement were multiplied by the number of housing starts in Alberta in 2022 in order to provide a macro perspective on the environmental impact of each construction method. The results demonstrated that the solid-wall precast construction method is capable of reducing the CO_2 emissions equivalent to building 2,461 cast-in-place concrete basements, while the ribbed precast method reduces the CO_2 emissions equivalent to 6,494 cast-in-place concrete basements for single-family detached houses. The main contribution of this research is the development of an objective quantitative analysis method that compares the financial and environmental aspects of choosing industrialization as the construction method for concrete basements for single-family detached houses. This assessment will aid construction practitioners in making well-informed decisions when choosing the most appropriate construction method for a given project based on financial and environmental targets.

4.7 Limitations and Future Research

This study is subject to some limitations. First, the cost and CO_2 emissions associated with the construction of a concrete basement were determined based solely on the selected criteria for this study (i.e., concrete usage, temporary heating, and site inspections). Therefore, the total cost for a concrete basement project, considering labour and production costs, was not included (with the exception of the wage for a construction manager). Second, this study only considered the cost and CO_2 emissions related to the construction phase of a concrete basement project. Other phases of a building's life cycle, such as the operational phase, were not included. Third, the quantitative assessment and cost and environmental tradeoff analysis were conducted solely based on the concrete basement of a single-family detached house.

These study limitations leave an opportunity for future research to be conducted in this field. For instance, future studies could include the development of a quantitative and tradeoff analysis comparing the cost and CO_2 emissions for the entirety of a single-family detached house project (i.e., not the basement only) while considering the three construction scenarios addressed in this study. This would provide a better understanding of the financial and environmental benefits of industrialized construction for an actual single-family detached house project when compared to cast-in-place construction. Moreover, future studies could implement the quantitative assessment presented in this study to estimate the cost and CO_2 emissions resulting from single-family detached houses, considering all phases of a building's life cycle. This would provide additional information by which to accurately quantify and compare the cost and CO_2 emissions resulting from each of the phases of the life cycle of a single-family detached house, therefore identifying the overall life cycle cost and environmental implications of adopting industrialized construction for a residential building. Finally, the results of this study could be improved upon by using automation during the data collection portion of the quantitative assessment. Some resources, such as RFID sensors, could be implemented at the offsite manufacturing facility to collect real-time data with higher accuracy in order to obtain the total cost and environmental impact for each construction method from cradle to grave.

4.8 Acknowledgments

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CHAPTER 5: CONCLUSIONS

5.1. Key Study Conclusions Drawn

The aim of this research was to develop a quantitative assessment method for conducting cost and environmental tradeoff analyses between different construction methods for concrete basements. The effectiveness of industrialized concrete construction methods (i.e., precast) in reducing the CO_2 emissions generated during the construction phase of concrete basements in comparison to the traditional cast-in-place construction method was evaluated while also considering the financial implications of both construction approaches. To this end, the cost and CO_2 emissions resulting from the cast-in-place method of concrete basement construction were compared with those of two industrialized construction methods: solid wall precast and ribbed precast construction. Three indicators were selected for the cost and environmental tradeoff analysis between these methods: temporary heating, concrete usage, and site inspections. These were considered because they are representative of significant generators of CO_2 emissions in the construction phase and of the effect of project duration on cost and CO_2 emissions. A single-family concrete basement project in Edmonton, Canada, was considered as a case study in order to quantify the emissions resulting from concrete construction operations in cold-climate regions.

A stochastic simulation model was developed in Simphony.NET to represent the on-site construction schedule for a cast-in-place concrete basement, the potential delays that could arise during the project, and the estimated propane consumption based on project duration and weather conditions. The simulation model was validated using the validation strategies proposed by Sargent (2010), which include historical data validation, face validity, comparison to other models, and event validity. This simulation model was then used, as described in Chapter 4, as the baseline in the development of a simulation model representing the industrialized construction scenarios, in which the project schedule and task durations were determined based on empirical data and consultations with a construction manager with experience in industrialized residential construction. This simulation model was designed to represent the on-site construction operations for industrialized concrete basements in order to determine the overall project duration and propane consumption based on uncertainty analysis.

The results in terms of project duration and the resulting propane consumption, presented in Chapters 3 and 4, enabled the development of the quantitative assessment method for cast-in-place and industrialized construction methods based on the criteria selected for this study. This assessment method was employed in the tradeoff analysis examining these two construction approaches (cast-in-place versus precast). The results of this analysis indicated that both industrialized construction scenarios (i.e., solid wall precast and ribbed precast structures) were able to significantly reduce the costs and CO_2 emissions associated with concrete, temporary heating, and site inspections compared to the cast-in-place construction method for concrete basements. This was mainly due to the shorter project duration from the industrialized construction scenarios, which governed factors such as the use of propane consumption throughout the project and reduced the number of inspections at the construction site. Moreover, in the ribbed precast scenario, the decrease in overall costs and CO_2 emission was more pronounced than for the solid wall precast method due to less concrete being used, and this had a significant impact on the total cost and CO_2 emissions resulting from the construction of concrete basements for single-family detached houses. Based on the results, it can be concluded that the use of industrialized concrete components for the construction of concrete basements for single-family houses can significantly reduce the costs and CO_2 emissions associated with the use of concrete, temporary heating, and site inspections, despite the perception that it is more expensive than the traditional cast-in-place method.

5.2. Research Contributions

In this research, a quantitative assessment method for conducting cost and environmental tradeoff analysis between traditional and industrialized construction methods in cold-climate regions was developed. The main contribution of this research is the development of a quantitative method that allows decision makers to objectively weigh the financial and environmental implications of different construction methods based on empirical evidence in order to avoid biases when choosing the most appropriate construction method for a given project. Additional contributions of this research are summarized below:

1) State-of-the-art approaches and emerging trends for reducing the GHG emissions resulting from the construction phase of residential buildings were identified, as were the limiting factors constraining the adoption of these techniques. It was determined that strategies to minimize the GHG emissions generated during the construction phase remain underdeveloped in comparison to strategies for other phases of the building's life cycle. As such, there is an opportunity for extensive research in this area.
2) A quantitative method for assessing the cost and CO_2 emissions associated with the use of concrete and temporary heating in the construction of residential buildings in cold-climate regions was proposed (Chapter 3). This quantitative assessment was implemented to determine the financial and environmental impact of the continuous use of temporary heating, particularly for the construction of cast-in-place concrete basements. Despite the significant costs and CO_2 emissions associated with temporary heating, the cost and CO_2 emissions resulting from the use of traditional cast-in-place concrete structures for

basements surpassed those associated with the use of temporary heating. This finding underscores the potential benefits to be realized in terms of a reduction in the costs and CO_2 emissions associated with these two resources through the application of industrialized construction methods.

3) This study proposed a quantitative assessment method for conducting cost and environmental tradeoff analysis in order to quantify and compare the cost and CO_2 emissions between traditional and industrialized construction methods (Chapter 4). The tradeoff analysis was conducted based on the quantitative assessment method presented in Chapter 3, which was adapted to reflect the on-site construction operations for industrialized concrete basements. This assessment method will aid decision makers in selecting the most suitable construction method by quantitatively evaluating and comparing the financial and environmental implications of traditional and industrialized construction methods for a given residential construction project.

5.3. Limitations and Future Research

Although the research objectives of this study were successfully achieved, it was subject to some study limitations that could be addressed in future research:

1) The quantitative assessment method for evaluating the cost and CO_2 emissions associated with the use of concrete and temporary heating for the construction of residential buildings in cold-climate regions, described in Chapter 3 of this thesis, was developed using data and project schedules from seven actual concrete basement projects. Although several validation techniques were implemented to validate the simulation model, future research could expand the dataset on which the simulation model is based in order to increase the accuracy and reliability of the assessment tool.

2) The quantitative assessment tool developed and the cost and environmental tradeoff analysis between traditional and industrialized concrete basements were based solely on the three comparison criteria selected for this study: concrete, temporary heating, and site inspections. As such, the overall cost of cast-in-place versus industrialized construction methods was not addressed. Future studies could evaluate this, as well as assess other costs and other generators of CO_2 emissions during the construction of residential projects (e.g., labour, on-site construction equipment, etc.) as the basis for a comprehensive quantification and tradeoff analysis that takes into account all of the resources utilized in on-site construction operations.
3) The cost and CO_2 emissions attributed to concrete were solely based on the construction material itself. The cost and CO_2 emissions resulting from the equipment used while pouring concrete to the foundation walls and SOG for the cast-in-place scenario (e.g., concrete mixer, vibrator, concrete pump, etc.), and during the installation of the concrete structures for the industrialized construction scenarios (e.g., cranes) were not considered for this study. Consequently, future research could include the cost and CO_2 emissions attributed to such equipment for each of the construction scenarios evaluated in this study. This could be achieved by quantifying the fuel consumed by the concrete equipment based on the duration of the tasks where the equipment is being used, which would have to be represented in the simulation model.
4) This research examined only the cost and CO_2 emissions associated with the construction phase of residential projects in cold-climate regions. Future work could include a tradeoff analysis based on the life cycle assessment (LCA) and Life Cycle Cost Analysis (LCCA) of traditional cast-in-place versus industrialized (precast) concrete construction methods. Such an assessment would encompass the total cost and CO_2 emissions throughout the

building's life cycle, from the production phase to the end-of-life phase. Such a tool would enable decision makers to make well-informed decisions when choosing the most suitable construction method for a given project based on financial and environmental targets.

5) The case studies used to test the effectiveness of the quantitative assessment method and tradeoff analysis were based on concrete basements for single-family detached houses. Future research could consider the entire house rather than just the basement in order to evaluate the cost and environmental benefits of applying industrialization in the construction of a complete residential unit.

6) The project schedule observed for the cast-in-place concrete basement construction scenario presented in Chapter 3 of this thesis was based on actual concrete basement projects collected from a residential construction company in Edmonton, Canada. Therefore, the tasks represented in the project schedule were obtained through the data collected by this company during the construction process for these types of projects. The observations obtained from the company did not specify the installation of frost walls as one of the main tasks during the construction of cast-in-place concrete basements. Consequently, the installation of frost walls was not considered as one of the tasks included in the project schedule to build cast-in-place or industrialized concrete basements. Future research could include this task as part of the construction process for single-family detached houses in cold-climate regions, as these types of structures are used in such regions to prevent the ground underneath the SOG from freezing.

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APPENDIX A

The list of research papers selected for the bibliometric analysis described in Chapter 2 is presented in Figure A.1.

Figure A.1.

Name of Research Paper		Source	Year of Publication
1	Mass timber building life cycle assessment methodology for the U.S. regional case studies	Sustainability Journal	2021
2	Reprint: Uncertainty analysis for measuring greenhouse gas emissions in the building construction phase: a case study in China	Journal of Cleaner Production	2017
3	Building information modeling-based model for calculating direct and indirect emissions in construction projects	Journal of Cleaner Production	2017
4	Greenhouse gas emission monitoring system for manufacturing prefabricated components	Journal of Automation in Construction	2018
5	Approaches for a low-carbon production of building materials: A review	Journal of Cleaner Production	2019
6	The implementation of clean development mechanism (CDM) in the construction and built environment industry	Energy Policy Journal	2014
7	A random forest-based model for the prediction of construction-stage carbon emissions at the early design stage	Journal of Cleaner Production	2021
8	Real-time emissions from construction equipment compared with model predictions	Journal of the Air & Waste Management Association	2015
9	Framework for standardising carbon neutrality in building projects	Journal of Cleaner Production	2022
10	Estimation of environmental emissions and impacts of building construction – A decision making tool for contractors	Journal of Building Engineering	2019
11	Cross-laminated timber for building construction: A life-cycle-assessment	Journal of Building Engineering	2022
12	Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock	Journal of Industrial Ecology	2021
13	Toward low-carbon construction processes: The visualisation of predicted emission via virtual prototyping technology	Journal of Automation in Construction	2013
14	Greenhouse gas emissions during the construction phase of a building: A case study in China	Journal of Cleaner Production	2015
15	Global Policy Review on Embodied Flows: Recommendations for Australian Construction Sector	Sustainability Journal	2022
16	Quota-based carbon tracing model for construction processes in China	Journal of Cleaner Production	2018
17	Energy-related carbon emissions mitigation potential for the construction sector in China	Environmental Impact Assessment Review	2021
18	Embodied Energy Assessment and Comparisons for a Residential Building Using Conventional and Alternative Materials in Indian Context	Journal of The Institution of Engineers (India) Series A	2014
19	The use of construction equipment productivity rate model for estimating fuel use and carbon dioxide (CO_2) emissions Case study: bulldozer, excavator and dump truck	International Journal of Sustainable Engineering	2015
20	Cradle-to-site carbon emissions assessment of Prefabricated Rebar Cages for high-rise buildings in China	Sustainability Journal	2018
21	Greenhouse Gas Emissions Management in Prefabrication and Modular Construction Based on Earned Value Management	Journal of Construction Engineering and Management	2022
22	Carbon footprint assessment of a typical low rise office building in Malaysia using building information modelling (BIM)	Journal of Sustainable Building Technology and Urban Development	2015
23	Predicting fuel energy consumption during earthworks	Journal of Cleaner Production	2016
24	Stochastic analysis of embodied carbon dioxide emissions considering variability of construction site	Sustainability Journal	2019

APPENDIX B

The list of questions posed to construction experts and rental equipment representatives regarding the use of temporary heating equipment during the construction of concrete basements for single-family detached is provided below. The information obtained using these questions was used to estimate the propane consumption from temporary heaters as described in Chapters 3 and 4 above, as well as to quantify the cost and environmental impact of using temporary heating in the construction of residential buildings in cold-climate regions. It should be noted that the questions pertaining to the use of temporary heating for groundwork operations relate to the work presented in Chapter 4 of this thesis, while the questions pertaining to the use of temporary heating for concrete curing purposes relate to the work presented in both Chapters 3 and 4.

Interview Guide

1. Why is it necessary to use temporary heating during the construction of concrete basements for single-family detached houses?
2. When is it considered necessary to use temporary heating? How many days before the start date of the construction of a concrete basement, and for how long a total duration, is the temporary heating required?
3. Is temporary heating required for groundwork tasks? If so, why is it needed?
4. When is it necessary to start using temporary heating specifically for groundwork tasks? Is it used a few days prior to these tasks or is it used beginning on the day when the tasks begin? If temporary heating has to commence in advance of when these tasks begin, how many days in advance of these tasks does the heating commence?
5. Is temporary heating required for concrete pouring and curing tasks? If so, why is it needed?
6. When is it necessary to start using temporary heating specifically for concrete pouring and curing tasks? Does it commence a few days prior to these tasks or on the day when the tasks

begin? If temporary heating has to commence in advance of when these tasks begin, how many days in advance of these tasks does temporary heating begin?

7. What type of temporary heating is used for basement construction?
8. What type of temporary heating is used for groundwork purposes?
9. What type of temporary heating is used for pouring/curing purposes related to the concrete basement walls and the slab on grade?
10. What is the temperature threshold at which temporary heating starts?
11. How many heaters are used for the construction of a concrete basement in a single detached family house?
12. What types of heaters are used? What are the capacity and the fuel consumption per unit rate?
13. What is the approximate rental cost for each piece of equipment?
14. What is the approximate cost of propane per litre?
15. What is the heating setup during workdays versus weekends?