Evaluating Time-Cost-Carbon Emission Trade-Offs in Construction: A Study of Onsite Optimization and Offsite Prefabrication Methods

by

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Abstract

This research investigates strategies to accelerate construction projects while balancing cost and environmental considerations, using a single-family house construction project in Edmonton, Canada, as a case study. Two strategies are examined: onsite trade-off optimization and offsite prefabrication. The first strategy employs a Non-dominated Sorting Genetic Algorithm (NSGA-II) to optimize the time, cost, and carbon emissions of a stick-built construction process. By inputting data on activities, costs, and carbon emissions at normal and crash levels, the model generates optimal trade-off solutions through iterative selection, crossover, and mutation, offering a range of shortened project durations based on budget and sustainability goals. The second strategy focuses on scheduling the offsite construction process, where portions of the project are prefabricated in a factory and installed onsite. This method enhances schedule predictability and reduces build time, resulting in an 18% reduction in project duration, a 24.89% decrease in costs, and a 31.67% reduction in carbon emissions. Combining these strategies can significantly improve project efficiency in terms of time, cost, and environmental impact, even under construction uncertainties. These findings highlight the potential for improved construction project management through innovative optimization and prefabrication techniques.

Acknowledgments

I am deeply grateful to my supervisor, Dr. Mohamed Al-Hussein, and my co-supervisor, Dr. Ahmed Bouferguene, for their unwavering academic support towards the completion of my master's degree program. I also extend my heartfelt appreciation to the construction engineering and management professors, Dr. Yasser Mohamed, Dr. Ming Lu, Dr. Farook Hamzeh, and Dr. Ahmed Hammad, for their invaluable teachings, guidance, and academic support. The significant funding from the Natural Science and Engineering Research Council of Canada (NSERC) grant has been instrumental in the successful completion of this research. I am also thankful to Temitope Adebanjo, my twin sister, Juliet Taiwo OIuyale, and my parents, Mr. and Mrs. OIuyale, for their constant encouragement and support.

Dedication

I dedicate this thesis to Almighty God, the author and finisher of my faith, who has been my source of inspiration throughout my master's degree program. Additionally, I dedicate this thesis to my parents, Mr. and Mrs. Oluyale, for their unwavering emotional and mental support throughout my program.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The construction industry faces many challenges hindering the achievement of successful project outcomes. Among these challenges, meeting project budgets and durations is a significant concern when initiating new projects. Despite proper planning, the industry confronts complex and multifaceted issues, including uncertainties such as unpredictable weather conditions, unexpected fluctuations in market prices, or equipment breakdowns, all of which significantly affect project outcomes. One implication of these challenges is a reduction in productivity levels. For instance, delays triggered by supply chain disruptions or labour shortages can disrupt project timelines and inflate expenses. Furthermore, project delays can lead to the underutilization of equipment, thereby incurring additional costs. Additionally, as projects encounter delays, equipment costs may rise due to disruptions in the supply chain, resulting in additional project expenses.

Most importantly, adjusting project schedules to reduce project duration necessitates an efficient method to minimize durations at the lowest cost. The number of resources assigned to activities influences the relationship between construction time and cost. The relationship between time and cost is known as time-cost trade-off decisions, and these trade-off decisions influence other project objectives such as quality, safety, and environment. The purpose of time-cost trade-off analysis is to reduce project duration from a critical path to meet specific deadlines with the least cost (Elbeltagi, 2009).

However, previous studies on time-cost trade-offs explore other project objectives such as safety, quality, and sustainability. Inyim (2015) conducted research to analyze and identify the relationships between time, cost, and environmental impact in terms of carbon emissions throughout the life cycle of a building. Results showed a direct trade-off between cost and time and carbon emissions and time, indicating that increased costs and carbon emissions correspond to shortened project durations. However, in the construction phase, findings indicate an indirect correlation between cost and carbon emissions, as increased direct costs due to an increase in the number of resources can also impact carbon emissions. This implies that higher costs due to increased resources might be associated with increased carbon emissions.

Wang et al. (2021) also identified and analyzed the trade-offs among the project objectives of time, cost, and construction quality, and the result showed that minimizing project durations will result in additional costs, whereas reducing expenses will result in additional project duration, jeopardizing quality; also increasing quality will result in additional cost and time; hence depicting trade-off behaviours between time, cost, and quality. These planning methods can allow construction managers to make reasonable adjustments to the project so that it will not jeopardize time, cost, and other project objectives. Understanding the trade-off behaviours between time, cost, and other project objectives will allow construction managers to be aware of how their trade-off decisions on time and cost can affect other factors such as quality, safety, and the environment, such as carbon emissions, hence driving them to identify the optimal feasible solution of achieving an objective without jeopardizing other objectives.

However, studies have proven that reducing time, cost, and carbon emissions in construction relies on the construction method and technology adopted (Guo et al., 2023). For example, some studies have argued that offsite construction has the potential benefit of reducing carbon emissions in the construction phase of the building life cycle due to its advanced technology and controlled environment. Several studies have assessed the carbon footprint of different construction methods (Mah, 2011; Seo, 2020; Ji et al., 2018). Results showed that the precast-in-situ construction method produces lower carbon emissions than the cast-in-situ construction method (Ji et al., 2018), while the wood-based panelized construction method produces lower carbon emissions than the stick-built construction method (Li et al., 2014). Carbon emissions for each construction method are influenced by the amount of waste generated, transportation of equipment and materials, operation of construction equipment, and construction technique (Mao et al., 2013).

Studies have also suggested that offsite construction has the potential to reduce material waste, multiple trips for material delivery, and energy consumption (Mofolasayo, 2023). Additionally, Mah (2011) mentioned that offsite construction can reduce the construction time of a residential construction project by 40%, thereby reducing costs. It is crucial to understand that extending project durations, especially in cold regions, can increase the demand for temporary heating during construction and resource utilization, resulting in higher costs and carbon emissions (Shahin et al., 2007). The outcome of a project mostly relies on the priorities of the project stakeholders; therefore, an efficient planning method is crucial to ensure that a project objective is achieved without jeopardizing other objectives (Dwivedi, 2021).

1.2 Research Motivation and Scope

Construction projects often encounter time and cost overruns, necessitating schedule adjustments to meet project deadlines. Over the years, the construction industry has been striving to handle the dynamic nature of construction projects, requiring more efficient planning and effective decision-making to ensure projects remain within scope, schedule, budget, quality, and environmental standards throughout the construction process. These changes result from complexities, uncertainties, and a shortage of skilled labour in the construction industry, disrupting workflow and productivity. This often causes project delays, necessitating schedule adjustments and leading to time and cost overruns.

Accelerating the construction process to adhere to these schedules requires increasing productivity and project workflow by employing more resources. This research emphasizes on trade-offs between time, cost and carbon emissions in construction projects, highlighting that while increasing productivity and workflow in construction projects can expedite work, it has the downside of increased costs and potentially higher carbon emissions. The research builds on the existing knowledge of scheduling optimization, particularly using the crashing technique and considering offsite construction methods to deliver projects more cost-effectively and carbon-efficiently. Nasiri et al. (2019) proposed a time-cost trade-off optimization and developed an integer programming algorithm to facilitate this process. By adopting this technique, construction project durations were shortened at minimal cost. Seo (2020) and Ji et al. (2018) explored carbon emission reduction strategies in construction projects, and the results indicated that carbon emissions during construction are influenced by the amount of waste generated, transportation distance of materials, equipment, and workers to the construction site, energy consumption and the construction method adopted. While this is true, there is a minimum study on how the dynamism of construction projects regarding scheduling change impacts carbon emissions. This study addresses the criticism that the construction industry faces regarding environmental issues. It aims to explore methods to reduce carbon emissions while meeting project deadlines and budget constraints. Beyond meeting project timelines and budgets, reducing carbon emissions has become an important goal in construction projects (Ozcan-Deniz, 2011). However, limited research exists on strategies that improve and facilitate project management practices to reduce the impacts of scheduling adjustments on cost and carbon emissions.

This research introduces two methods for balancing time, cost, and carbon emissions of construction projects. The first method involves optimizing the onsite construction process through trade-off optimizations between time, cost, and carbon emissions (efficient resource utilization). The second method is a study on the offsite construction method, which involves transferring a portion of onsite construction activities to an offsite factory for prefabrication and then transporting the prefabricated panels or modules for installation, aiming to improve efficiency and reduce environmental impact. These two methods yield different project outcomes. This study examines the effectiveness and capabilities of these two project management strategies: the trade-off optimization of the onsite stick-built construction process and the adoption of the offsite panelized construction method, using a single-family home as a case study. Employing multi-objective optimization through a non-dominated sorting genetic algorithm (NSGA-II) alongside exploring the offsite construction method can significantly reduce the duration of a construction project while minimizing costs and carbon emissions. These strategies yield optimal solutions that balance project time, cost, and environmental impact, providing construction stakeholders with valuable insights for informed decision-making.

1.3 Research Objectives

The research aims to develop and propose methods that facilitate efficient planning and decision-making in construction projects, ensuring they remain within scope, schedule, budget, and environmental standards while addressing the industry's challenges of time and cost overruns, resource utilization, and environmental impact in terms of carbon emissions, through the following objectives:

1. Compute a critical path analysis of the case study construction project to determine the original project duration
2. Analyze the carbon emissions of each activity at both normal and crash levels
3. Conduct a time-cost-carbon emission trade-off optimization for the on-site construction project to shorten project duration at minimum costs and carbon emissions.
4. Analyze the time, cost, and carbon emissions for the panelized construction method.
5. Examine the effectiveness and potential of these two project management strategies: optimizing the on-site construction process through trade-off optimization and implementing an off-site construction method.

1.4 Significance of the Study

By optimizing the construction process through trade-off optimizations and embracing the offsite construction method, a world of possibilities for addressing the challenges of construction project management is opened. This research emphasizes the trade-offs between time, cost, and carbon emissions in construction projects. It highlights that while increasing productivity and workflow can expedite the construction process, it often results in increased costs and potentially higher carbon emissions due to the additional resources needed. The study builds on existing knowledge of scheduling optimization, particularly utilizing the crashing technique and considering offsite construction methods to deliver projects more cost-effectively and carbon-efficiently. With its unique strategies, this method can be particularly effective in meeting project deadlines, managing costs, and mitigating carbon emissions. The study of these two approaches and their effectiveness in achieving project objectives, such as shortened project duration, minimized costs, and reduced carbon emissions, provides a comprehensive understanding of their respective attributes. This knowledge can empower construction stakeholders in their decision-making processes, helping them determine which approach may best align with their specific project requirements, constraints, and sustainability goals.

1.5 Thesis Organization

This thesis comprises five chapters. Chapter One introduces the background study of typical construction projects, their scheduling challenges, and potential resolutions. It also presents the motivation, scope, objectives, and significance of the study. Chapter Two reviews the challenges faced in a construction project: onsite and offsite construction methods, Time-Cost Trade-off Optimization, Carbon Emissions and Environmental Sustainability, Trade-off Optimization Algorithms, and Industrialization of the Construction Process. Chapter Three outlines the research methodology employed to achieve the study's goals, detailing the project objectives, followed by the case study and data collection. Chapter Four conducts the research analysis and interprets the results. Chapter Five discusses the project’s findings and recommendations based on the results, highlighting the research's limitations and suggesting opportunities for future work. Finally, chapter six presents the study's conclusion based on its objectives, analysis, and results.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Researchers have extensively studied how construction project duration and costs critically influence project success and company performance (Aghasizadeh et al., 2022). The primary objectives of project scheduling include achieving the shortest possible duration and minimizing costs for project completion (Baptiste & Demassey, 2004). With the increasing number of construction projects and financial turnover, coupled with technological advancements, there is now greater awareness of the trade-off between time, cost, and carbon emissions within the context of sustainable development (Aghasizadeh et al., 2022). Various approaches have been suggested to balance time and cost in construction projects to meet customer standards (Zhang and Xing, 2010). However, these methodologies often overlook environmental issues such as carbon emissions. Therefore, construction planners and decision-makers must strive to achieve a balance among the various aspects of a project, optimizing time, cost, and carbon emissions simultaneously in the time-cost-environment trade-off (TCET) problem, which is increasingly important in today's world (Cheng & Tran, 2015). This chapter covers the discussion of the challenges being faced in a construction project, the two methods of construction: onsite and offsite construction methods, Time-Cost Trade-off Optimization, Carbon Emissions, and Environmental Sustainability, Trade-off Optimization Algorithms and Industrialization of the Construction Process.

2.2 Construction Project Management Challenges

Construction projects often encounter time and cost overruns. To achieve timely project completion and meet the budget, a construction project must maintain consistency in workflow and efficiency. According to Adel et al. (2022), overruns in construction projects are mostly caused by prevailing factors such as poor planning, unforeseen site conditions, inadequacy of resources, poor cash flow management, and lack of project coordination. In addition, Judson et al. (2022) highlighted other common factors influencing project outcomes, such as risks, stakeholders' conflicts, administration issues, variability, misrepresentation, omissions, negligence, mistakes and errors, complexity, experience/capability of construction workers, market conditions, weather conditions, and rework. According to Adel et al. (2022), these factors affect construction productivity, resource utilization, and project workflow, influencing project outcomes. For example, variability in construction projects can impact material prices and resource utilization. Misrepresentation of contracts and stakeholder objectives through estimation errors, quality issues, and flawed bidding processes can lead to increased costs (Newton et al., 2014). Human errors and uncertainties arising from design flaws, construction errors, and technical issues can lead to rework, directly affecting project outcomes (Adriana et al., 2023). Project complexity, such as geotechnical conditions and funding sources, can influence project outcomes if not managed properly (Dao, 2016). Conflicts between stakeholders and local authorities can delay construction projects, and weather conditions often disrupt onsite construction activities, leading to idling resources (Mohammad et al., 2019). Understanding construction project challenges is vital for facilitating project success and attaining desired outcomes.

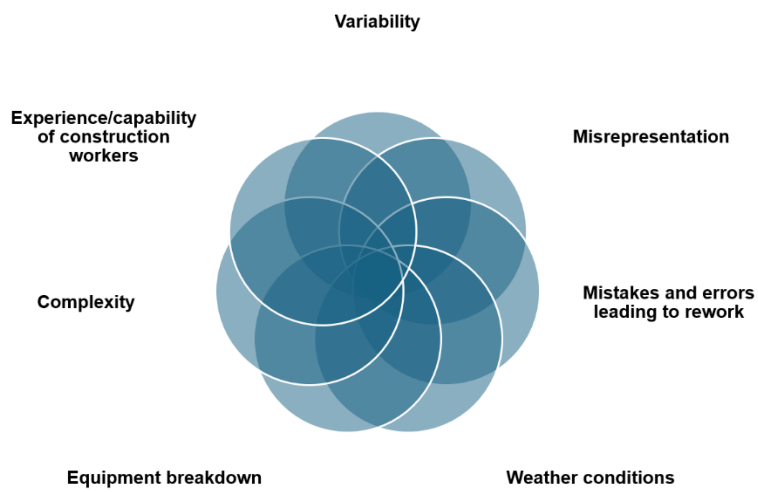


Figure 2.1. Factors impacting project outcomes (Source: Judson et al., 2022).

Effective project management practices are essential to overcome these challenges and achieve project objectives. Phasha (2022) suggests that implementing strategic planning, risk management, cost management, and project monitoring and control can mitigate the impact of construction challenges and enhance project outcomes. Construction risk management entails assessing and implementing measures to minimize the impact of risks in construction projects (Malsam, 2022). This can help plan for uncertainties and reduce their impacts when they arise. Strategic planning of construction projects refers to outlining the project goals and determining the necessary actions and resources to achieve them. Cost management within a construction project encompasses professional proficiency and expertise in planning, estimating, controlling, and managing costs (Ronald & Agung, 2018). Project monitoring and control involve overseeing, evaluating, and managing a construction project as it progresses to ensure the achievement of its objectives (Hassan, 2023).

2.3. Onsite and Offsite Construction Methods

The choice between onsite and offsite construction methods has an influence on project outcomes in terms of time, cost, and environmental impact (Ferrada & Serpell, 2013). However, several studies have compared the characteristics of onsite and offsite construction methods (Mah, 2011; Seo, 2020; Ji et al., 2018). Onsite construction is defined as a traditional approach to construction, where structures are built at their permanent location. In contrast, offsite construction involves designing and prefabricating building elements in a controlled environment, such as a factory, and transporting the prefabricated elements to the construction site for installation (Seo, 2020). Mofolasayo (2023) highlighted the advantages and disadvantages of onsite and offsite construction methods. As the offsite construction method involves the transportation of large modules or panels to the construction site, the onsite construction method may be suitable where there is a space constraint for module or panel delivery (Veiskarami, 2020). . The onsite construction method requires multiple trips for material delivery, whereas the offsite construction method is advantageous regarding material efficiency (Quale, 2017). Prefabricated buildings generate less construction waste than conventional methods due to efficient procurement, the reuse of waste materials in offsite facilities, and easier recycling compared to onsite construction (Jayawardana et al., 2023).

Figure 2. 2. Offsite Construction Method (Source: Iko team, 2024)

Previous studies indicate that the precast-in-situ method produces lower carbon emissions than the cast-in-situ method (Seo, 2020), and the wood-based panelized method produces lower emissions than the stick-built method (Li et al., 2014). Carbon emissions for each method are influenced by waste generation, transportation of equipment and materials, construction equipment operation, and techniques used (Mao et al., 2013). Studies also suggest that offsite construction can reduce material waste, multiple trips for material delivery, and energy consumption (Jin et al., 2018). Additionally, Broadhead et al. (2023) noted that offsite construction can reduce project durations as well as costs progressively.

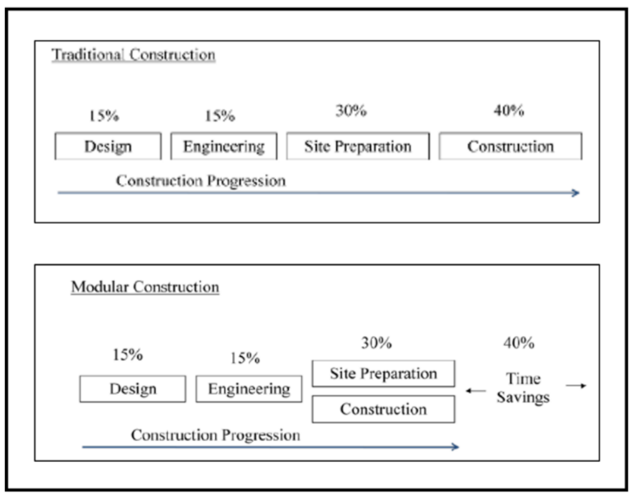


Figure 2. 3. Time savings of Modular Construction (Mah, 2011)

The adoption of the offsite construction method addresses the limitations of onsite construction. The primary advantage of offsite construction lies in the time saved. Contractors commonly report that transferring a substantial portion of construction work to an off-site facility reduces overall project schedules and construction durations, directly contributing to time efficiency (Alazzaz & Whyte, 2014). Prefabrication has the potential to enhance efficiency, mitigate safety risks, and reduce both the cost and duration of tasks conducted onsite (Mah, 2011). Quality improvement is another significant benefit highlighted by project stakeholders (Saxena, 2022). Offsite construction offers tighter control over quality than onsite methods, with elements manufactured in factories perceived as more consistent and subjected to rigorous quality control and testing (Egege, 2018). Additionally, the reduced need for remedial or snagging work further underscores the quality advantages of offsite construction (Ayinla et al., 2021). Moreover, offsite construction's standardized approach allows for continuous improvement and quality management over time, unlike the limitations posed by traditional onsite construction's unique project approach (Durdyev & Ismail, 2019).

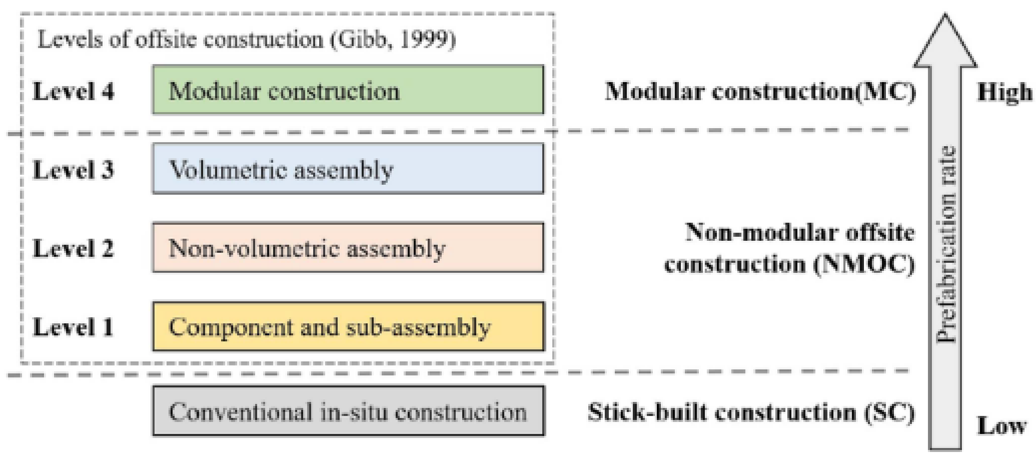


Figure 2. 4. Level of Prefabrication Rate of Construction Methods (Source: Zhang et al., 2024)

Another significant benefit of offsite construction is its ability to alleviate skills shortages in the construction industry (Almughrabi et al., 2021). Offsite construction allows the construction process to be 'outsourced' to another environment, reducing the need for labour in traditional onsite processes and addressing labour shortage in the construction sector (Alazzaz & Whyte, 2014). Cost reduction is another benefit of offsite construction, with enhanced cost certainty being a significant motivator for its adoption by house-building companies (Wuni & Shen, 2019). This can be attributed to the predictability of offsite construction, which is less prone to cost overruns stemming from uncertainties like weather conditions (Alazzaz & Whyte, 2014). The control and predictability offered by offsite construction instill confidence in its adoption, as it provides a clear and manageable path for construction projects. Most importantly, offsite construction has the potential benefit of reducing carbon emissions by utilizing green technologies incorporating energy-efficient design, and implementing green building practices (Mao et al., 2013). Offsite construction facilities, with their controlled environment, enable more efficient resource utilization and effective waste management (Seo, 2020). This, in turn, contributes to reducing overall emissions when compared to traditional onsite construction activities. Moreover, offsite methods often integrate carbon emission-reducing strategies, such as leveraging renewable energy sources, optimizing production processes, and selecting sustainable materials (Kamali et al., 2018). These combined efforts mitigate environmental impacts and promote a greener approach to construction.

Figure 2. 5. Construction Waste Generation (Source: https://bit.ly/3VnrhOs)

2.4. Time-Cost Trade-off Optimization

Time-cost tradeoff analysis is a fundamental technique in construction projects where it is crucial to complete a project within budget and on schedule (Ballesteros-Perez, et al., 2020). It enables a contractor to construct a project using an optimal schedule that minimizes costs (Alavipour & Arditi, 2019). Schedulers can conduct a time-cost tradeoff analysis to determine the most cost-effective project duration (Elbeltagi, 2009). It involves the relationship between the required project duration and their associated cost and, therefore, finding an efficient balance between time and cost (Feylizadeh et al., 2018). This technique allows project stakeholders to make informed adjustments to the project schedule with minimum cost. The empowerment that comes with time-cost trade-off optimization is significant, as it equips project managers with the tools to make informed decisions and manage their projects effectively. Time-cost trade-off analysis involves accelerating the construction process by assigning more resources to activities for shorter project durations at the expense of higher direct costs (Alavipour & Arditi, 2019). The common technique used in the trade-off analysis to accelerate the construction process is the crashing technique, which involves identifying critical activities in the construction project that greatly impact the project duration and cost, allocating additional resources such as manpower or equipment to these activities (Inyim, 2015). This technique will help project managers avoid delays and associated costs in the long run.

Project schedules may need to be compressed to meet construction deadlines and recover from early delays (Pablo et al., 2019). Schedule compression typically involves either crashing or fast-tracking techniques. Crashing entails adding resources to activities on the critical path to shorten the overall project duration, while fast-tracking involves overlapping critical path activities that would normally be performed sequentially (Feylizadeh et al., 2018). Crashing activity durations can increase direct costs, while fast-tracking may heighten project risks and lead to rework. Fast-tracking is effective only when critical path activities can be overlapped. If fast-tracking is not feasible, the project manager may resort to the crashing technique. As illustrated in figures 1 and 2, unlike crashing, fast-tracking does not require additional resources to shorten project duration; instead, it advances the start of subsequent activities (activity B with a lead of 2 days), reducing the overall time required for completion by 2 days. However, fast-tracking may not always be feasible for all activities, as some activities (like activity B) may depend on the completion of preceding activities (like activity A). Additionally, fast-tracking alters the sequence of activities compared to the crashing method, while crashing maintains the original sequence.

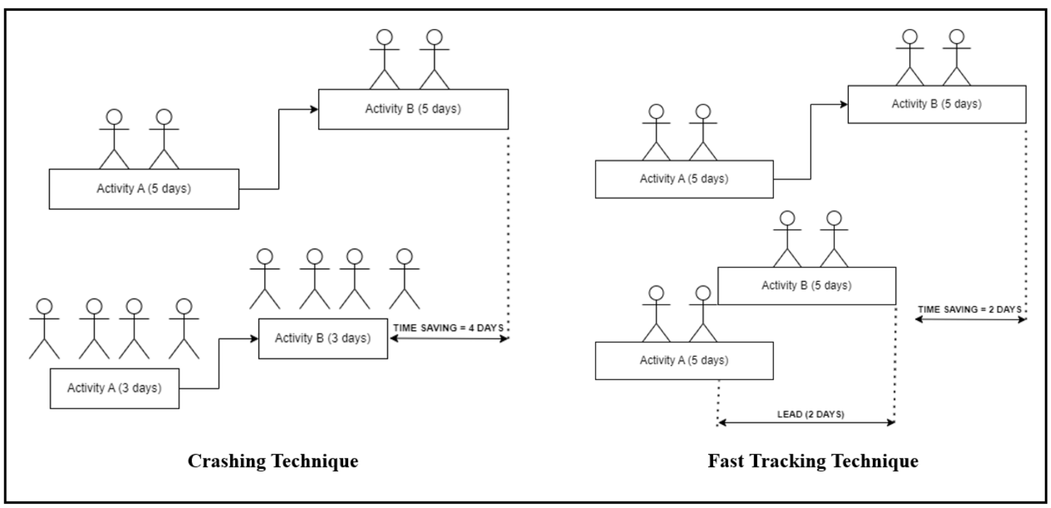


Figure 2. 6. Illustration of Two Different Techniques Employed during Construction to Speed up Construction Activities

It is crucial to understand that there is a limit to compressing activity durations to reduce project durations. Crashing activities too much to shorten project duration can result in a diminishing return of negative impact on cost, safety, quality, and the environment (Wang et al., 2021). Crashing activities aggressively, there might be some project constraints, such as resource availability and contractual obligations, that limit the options for other acceleration strategies. Crashing an activity by allowing workers to work overtime can jeopardize the quality of the work and lead to safety issues, as well as additional costs on lighting equipment and the premium rate of workers (Wang et al., 2021). Another important aspect to consider when conducting a time-cost trade-off analysis is considering indirect cost and direct costs. Indirect costs are costs that depend on the project duration, such as utility costs and administration expenses. In contrast, direct costs are total costs used in all construction activities, such as materials, labour, and equipment (Elbeltagi, 2009). A project manager who decides to shorten the project duration might reduce the indirect costs but at the expense of higher direct costs due to the additional resources required (Ballesteros-Perez, et al., 2019). Therefore, time-cost trade-off analysis allows project managers to make informed decisions on resource allocation and scheduling, delivering construction projects within budget and time.

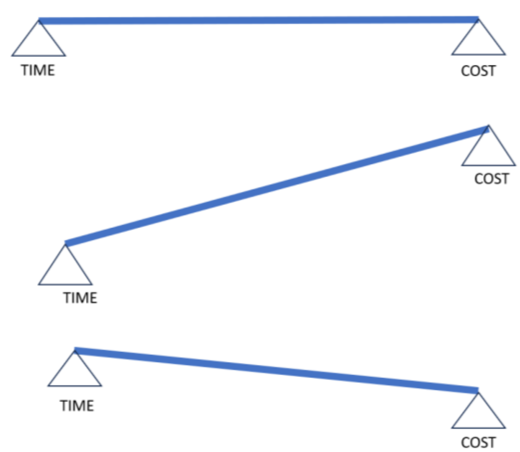


Figure 2. 7. Illustration of Time-Cost Trade-off Behaviours

However, it is important to understand that assigning more resources to reduce the project duration can also increase carbon emissions. Carbon emission during construction arises from energy consumption from equipment and transportation. However, it is nearly impossible to satisfy all the objectives: reduction in time, cost, and carbon emissions. Shortening project duration will increase direct costs and carbon emissions, due to assigning more resources. Previous findings reveal an indirect correlation between cost and carbon emissions due to the initial nature of direct costs, such as materials, equipment, and labour, but increasing resources can lead to elevated cost and carbon emissions, thus potentially linking higher costs with increased carbon emissions (Inyim, 2015).

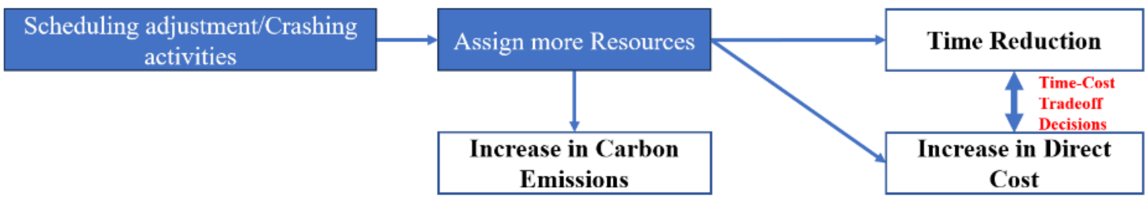


Figure 2. 8. Time, Cost, CO_2 emission Trade-off Relationships

2.5. Carbon Emissions and Environmental Sustainability

The construction industry significantly impacts the environment, contributing to carbon emissions, energy consumption, and resource depletion. Therefore, a growing interest is in mitigating carbon emissions and environmental impact. Mah (2011) discusses the environmental impact of construction activities and the role of carbon emissions in contributing to climate change. The factors contributing to carbon emissions during construction activities stem from the equipment used, material, equipment, and labour transportation, material waste, and the use of temporary heating in cold regions (Mah, 2011). Studies have shown that the various contributing factors must be revised to reduce carbon emissions in the construction phase. For example, in the aspect of transportation, considering building materials that are locally processed, reduces the transportation distance and energy consumption, hence the reduction in carbon emission. Also, selecting the transportation vehicles is essential in transportation planning. For example, selecting vehicles with a large carrying capacity, lightweight, low energy consumption, and low carbon emissions is preferable. Also, lightweight trucks are preferable for short-distance transportation within the city. In contrast, heavy-duty trucks, having larger carrying capacity, high transportation efficiency, and minimal carbon emissions, are suitable for long-distance transportation outside urban areas. Specialized trucks can be employed in unique situations, or a combination of vehicles can be utilized based on specific project requirements (Cheng et al., 2023). Furthermore, integrating green construction technology aims to optimize resource conservation and reduce environmental impacts while maintaining quality, safety, and energy efficiency and ensuring environmental protection (Alazzaz & Whyte, 2014). Examples of such technology include adopting prefabricated components and promoting offsite construction, a growing trend in the construction industry known for its enhanced environmental friendliness and high production efficiency compared to traditional onsite construction methods (Seo, 2022).

Figure 2. 9. Sources of Carbon Emission (Source: Stacy, 2024)

It is also important to know that sometimes decision-makers do not realize or often overlook the environmental effects of construction projects (Inyim, 2015). Recently, the construction industry has been charged with causing many environmental issues, like excessive resource use, polluting the environment, and producing greenhouse gases (Farazmand & Beheshtinia, 2018). So, in this study, besides aiming to meet the project timeline and budget, reducing carbon emissions from the project is also seen as a third important goal to achieve (Ozcan-Deniz, 2011). Therefore, incorporating environmental sustainability into project management decisions with respect to time and cost is paramount in achieving sustainability goals.

2.6 Trade-off Optimization Algorithms

Trade-off Optimization algorithms are essential tools in project management that facilitate balancing multiple competitive objectives such as time, cost, and carbon emissions. Nasiri et al. (2019) proposed a time-cost trade-off optimization and developed an integer programming algorithm to streamline the optimization process. However, time and cost trade-off decisions impact other project objectives, such as carbon emissions, quality, and safety. Many algorithms that handle multi-objective optimization exist, such as heuristic methods, mathematical programming, and evolutionary algorithms like genetic and ant colony optimization algorithms (Ballesteros-Perez et al., 2019).

Researchers have developed trade-off optimization algorithms that balance other objectives with time and cost. Farazmand & Beheshtinia (2018) developed a Reference Group Genetic Algorithm for multi-optimization between time, cost, quality, and carbon emissions. Huynh (2021) developed a multiple objective social group optimization (MOSGO) to balance time, cost, quality, and carbon dioxide emission (TCQC) factors in generalized construction projects. Wang et al. (2021) used Non-Dominated Sorting Genetic Algorithms II (NSGA II) to balance time, cost, and quality trade-offs. Vijayan et al. (2023) explored time-cost-risk optimization with the Ant Colony Algorithm.

Afshar and Dolabi (2014) employed a genetic algorithm to optimize time-cost-safety trade-offs. The evolutionary algorithms, with their search-based features, offer flexibility compared to heuristic or mathematical programming methods, which may struggle with a large number of variables or nonlinear objective functions (Inyim, 2015).

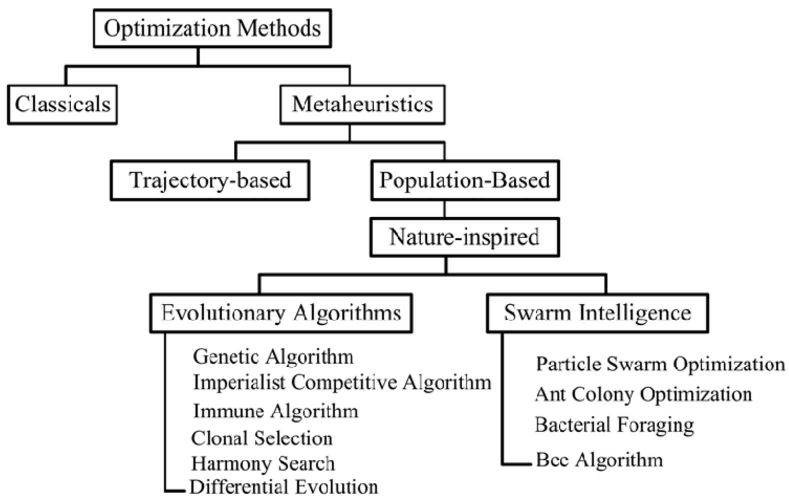


Figure 2. 10. Optimization Algorithms (Source: https://bit.ly/OptimizationAlgorithms)

Incorporating these optimization algorithms into project management practices will provide project managers with optimum solutions that balance conflicting project objectives. The construction industry is currently charged with excessive resource use, environmental pollution, and greenhouse gas emissions. It is crucial to incorporate environmental sustainability into project management decisions alongside time and cost objectives to reduce carbon emissions (Ozcan-Deniz, 2011). However, by incorporating these algorithms into project management practices, construction stakeholders can make informed decisions prioritizing project objectives while minimizing carbon emissions.

2.7 Industrialization of the Construction Process

Construction industrialization involves enhancing productivity in construction through increased mechanization and automation, typically achieved through practices such as modularization, prefabrication, preassembly, and mass production (Mah, 2011). Industrializing the construction process involves prefabricating the building structure and its systems in a factory and transporting it to the construction site for assembly (Goh & Loosemore, 2017). This approach offers benefits such as cost and time savings, improved production and quality control, and opportunities for innovation (Gunawardena & Mendis, 2022). While traditional design and construction prioritize cost, performance, and quality objectives, sustainable design and construction through industrialization integrate considerations of minimizing resource depletion and environmental degradation and fostering a healthy built environment (Opoku & Ahmed, 2015). Previous research has demonstrated that offsite construction provides advantages to the built environment, including reduced labour requirements, lower onsite Greenhouse Gas (GHG) emissions, and enhancements in construction scheduling and product quality (Mah, 2011). Adopting construction industrialization is a viable means to assist the construction industry in attaining sustainable development amidst rapid urbanization.

Figure 2. 11. Pictures of Prefabricated Panels (Mah, 2011).

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

This research aims to examine two strategies that can be adopted to shorten project duration while minimizing cost and carbon emissions. Gaining insight into these strategies will enable construction practitioners to make informed decisions and understand the impact of accelerating the construction process and adjusting schedules on cost and carbon emissions. To investigate these trade-offs, the study conducts a trade-off optimization of a construction project to minimize project duration, cost, and carbon emissions. The second approach is offsite prefabrication, which involves reducing the workload of onsite construction and shortening project duration by transferring certain onsite activities to an offsite factory for prefabrication and later installation at the construction site. To support this analysis, this chapter outlines the research methodology, including a project case study, data collection methods for the trade-off optimization technique and offsite prefabrication, and parameters for quantifying CO2 emissions. Additionally, this chapter explains the trade-off optimization process of the case study construction project.

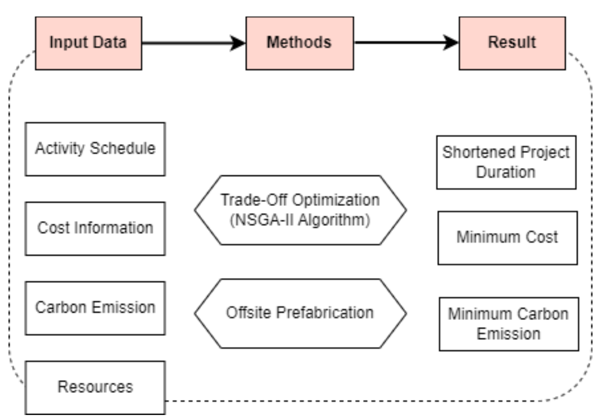


Figure 3.1. Research Methodology Framework

3.2 Case Study

The case study of the proposed construction of a single-family house located in Edmonton, Canada, covers a building area of 1750 square feet (162.58 m^2), a two-storey building comprising three bedrooms and two bathrooms. The single-family house is designed for wood framing. The construction, which is to start in July 2024, was postponed to October 2024 due to administrative issues such as late document approvals and delays in the design stage. Due to time constraints, the project manager decides to shorten the project duration to meet a predefined timeline while minimizing costs and carbon emissions. To achieve this, a trade-off optimization between time, cost, and carbon emissions is necessary to efficiently manage activity durations and resource utilization, which significantly impact cost and carbon emissions. This study examines two approaches to expedite the construction project. The first approach involves multi-objective optimization using a non-dominated sorting genetic algorithm (NSGA II) to minimize project durations, costs, and carbon emissions. The second approach explores the offsite construction method, which transfers a portion of onsite activities (such as framing activities) to be prefabricated offsite and then transported to the construction site for assembly. Additionally, based on existing literature, Lopez and Froese (2016) and Li et al. (2014), analyzed the cost per square foot and carbon emission per cubic meter of the offsite construction process, respectively. This provides a basis for evaluating the costs and carbon emissions associated with this method. This study offers valuable insights for construction stakeholders, aiding their decision-making processes by helping them explore different options best suited to their specific project requirements, constraints, and sustainability goals.

3.3 Data Collection

The proposed analysis for the two construction acceleration strategies must be conducted with a large network to ensure its practicality. A list of 85 construction activities was collected from existing papers by Yu (2010) and Mah (2011), along with their respective activity durations, quantity, and resources, as shown in Table 3.1 to Table 3.5. The panelized construction method is divided into onsite and offsite activities. The offsite activities of the panelized construction method are represented in Table 3.7. To implement the proposed non-dominated sorting genetic algorithm (NSGA II), each activity has its original and available crash durations, along with their respective costs and resources. Dormant, non-critical, and less labour-intensive activities have no crash durations available. This comprehensive data collection process ensures that the research findings are not just theoretical but can be directly applied to real-world construction projects, providing practical solutions to the industry's challenges. Based on the available data, labour, and equipment costs and carbon emissions will be computed for normal and crash levels. The costs and carbon emissions for materials are fixed and do not change with schedule adjustments. According to marketing articles, the minimum material cost to build a single stick-built home in Canada is $100 per square foot (https://bit.ly/Stick-builtHomes), which forms the basis for material cost in this study. The indirect cost is assumed to be 20% of the direct cost, covering overhead and profits.

3.4 Onsite Construction Activities

Table 3.1 to Table 3.5 list 85 construction activities, with their respective duration, quantity, predecessors, and resources. The resource types and respective costs from each activity were extracted from RS means construction data (https://www.rsmeansonline.com), and the number of resources decided for the available crashed durations was simulated based on the quantity and productivity of the original activity durations. For instance, while one person may finish a task in five weeks, it does not mean five people can complete it in one week. Therefore, the deployment of resources and activity durations are directly linked to the quantity of work and productivity, as expressed in Equation i and Equation ii.

$$\text{Productivity}_{\text{Activity}} = \frac{\text{Quantity}}{\text{Duration}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

$$\text{Resources}_{\text{CrashedActivity}} = \frac{\text{Resources (Normal duration) } X \text{ Productivity (Crashed duration)}}{\text{Productivity (Normal duration)}} \quad \ldots\ldots\ldots \text{(ii)}$$

Table 3.1. Construction Activities for Stage 1: Site Preparation and Excavation (Yu, 2010; Mah, 2011; Rs means)

Activity	Unit	Qty	Predecessors	Duration (days)		Crew type		Equipment	
				Normal	Crash	Normal	Crash	Normal	Crash
1. Site Preparation and Excavation									
A. Stake-out	m2	82.3	-	1	1	1 Rodman Instrument man	1 Rodman Instrument man		
B. Excavation	m3	298.1	A	2	2	3 labourers 1 operator	3 labourers 1 operator	1excavator	1 excavator
C. Install concrete walls	m2	18.88	B	4	3	1 foreman 2 labourers	1 foreman 4 labourers	1 generator concrete mixer	1 generator concrete mixer
D. Install damp proofing and weeping tile	linear ft	128	C	2	1	1 plumber	3 plumbers		
E. City Inspection	-	-	D	1	1	-	-		
F. Install electric meter	ea	1	K	1	1	1electrician	1 electrician		
G. Deep Services	ea	1	F	1	1	1 foreman 2 labourers 1 operator	1 foreman 2 labourers 1 operator	1excavator	1 excavator
H. Trench-in Shallow services	ea	1	G	1	1	1 foreman 2 labourers 1 operator	1 foreman 2 labourers 1 operator	1 backhoe	1 backhoe
I. Install precast products and window wells	m3	0.11	K	2	1	1technician	2 technicians		
J. Drill & pour slab and sidewalk piles	m2	82.3	H,I	2	1	1bricklayer 1 helper	2bricklayers 1 helper		
K. Main Floor Capping	m2	82.3	L	3	2	1 carpenter	2 carpenters	1generator, 1compressor	1 generator 2 compressors
L. Backfill Foundation	m3	62.4	E	1	1	1 operator 2 labourers	1 operator 2 labourers	1 backhoe	1 backhoe
M. Pregrade lot	m2	82.3	L	1	1	1 operator	1 operator	1 bobcat	1 bobcat
N. Inspection for gas line	-	-	M	1	1		-		
O. Install gasline	ea	1	N	2	1	1 plumber	3 plumbers		
P. Install gas meter	ea	1	O	1	1	1 plumber	1 plumber		

Table 3.2. Construction Activities for Stage 2: Structural Framing (Yu, 2010; Mah, 2011; Rs means)

Activity	Unit	Qty	Predecessor	Duration (days)		Crew type		Equipment	
				Normal	Crash	Normal	Crash	Normal	Crash
2. Structural Framing									
Q. Framing main floor	m2	82.3	J,P	2	1	1 carpenter 1 helper	3 carpenters 2 helpers	1 generator 1compressor	1 generator 3compressors
R. Framing main floor walls	linear m	63.1	Q	3	1.5	1 carpenter 1 helper	3 carpenters 2 helpers	1 generator 1compressor	1 generator 3compressors
S. Second floor joists & stairs	m2	82.3	R	2	1	1 carpenter	3carpenters	1 generator 1compressor	1 generator 3compressors
T. Framing second floor walls	linear m	78.9	S	3	1.5	1 carpenter 1 helper	3 carpenters 2 helpers	1 generator 1compressor	1 generator, 3compressors
U. Roof trusses & sheating	m2	112.6	T	5	3	1 carpenter 1 helper	2 carpenters 2 helpers	1 generator 1compressor	1 generator 3compressors
V. Windows, details & backing	m2	112.6	U	2	1	1 technician	3 technicians	-	-
W. Misc & final framing check	-	-	V	1	1		-		
X. Load roof material	-	-	W	1	1		-		
Y. Roofing	m2	112.6	X	3	2	1 carpenter 2 helper	3 carpenters 2 helpers	20 t crane 1 generator 1compressor	20 t crane 1 generator 2compressors
Z. Smart Trim & siding	m2	199	Y	8	6	2 carpenters 1 helper	3 carpenters 2 helpers	1 generator, 1compressor	1 generator 2compressors
AA. HVAC mark-out	ea	1	U	1	1	1 plumber	1 plumber		
AB. City frame inspection	-	-	W	1	1		-		

Table 3.3. Construction Activities for Stage 3: Mechanical/Electrical Installations (Yu, 2010; Mah, 2011; Rs means)

Activity	Unit	Qty	Predecessor	Duration (days)		Crew type		Equipment	
				Normal	Crash	Normal	Crash	Normal	Crash
3. Mechanical/Electrical Installations									
AC. Install Mechanical insulation	ea	1	AB	2	1	1 technician	3 technicians		
AD. Install fireplace	ea	1	AC	1	1	1 technician	1 technician		
AE. plumbing rough-in	ea	1	AD	3	2	1 plumber	2 plumbers	1 generator 1 compressor	1 generator 2 compressors
AF. Basement & garage slab	m2	82.3	AE	4	3	1 bricklayer 1 helper	2 bricklayer 1 helper	1 generator 1 vibrator 1 concrete mixer	1 generator 1 vibrator 1 concrete mixer
AG. HVAC rough-in	ea	1	AF	4	3	1 technician	2 technicians	1 generator 1compressor	1 generator 2compressors
AH. Electrical rough-in	ea	1	AG	4	3	1 electrician	2 electricians	1 generator 1compressor	1 generator 2compressors
AI. Structural wire rough-in	ea	1	AH	2	1	1 electrician	3 electricians	1 generator 1compressor	1 generator 1 compressor
AJ. City rough-in inspection			AI	1	1		-		
AK. Install insulation	ea	1	AJ	2	1	1 skilled worker/technician	2 skilled worker/technician		
AL. Frost walls & poly (vapour barrier)	m2	184	AK	2	1	1 carpenter	3 carpenters		
AM. City insulation inspection			AL	1	1		-		
AN. Drywall boarding	m2	606	AM	7	4	1 carpenters 1 helper	2 carpenters 2 helpers		
AO. Attic insulation	ea	1	AM	2	1	1 carpenter	3 carpenters		
AP. Drywall tapping	m2	606	AN,AO	6	5	2 carpenters 2 helpers	3 carpenters 2 helpers		

Table 3.4. Construction Activities for Stage 4: Finishes (Yu, 2010; Mah, 2011; Rs means)

Activity	Unit	Qty	Predecessors	Duration (days)		Crew type		Equipment	
				Normal	Crash	Normal	Crash	Normal	Crash
4. Finishes									
AQ. Prime vaccum	m2	163	AP	2	1	1 plumber	3 plumber		
AR. Prime	m2	606	AQ	2	1	1 plumber	3 plumbers		
AS. Texture	m2	192	AR	2	1	1 technician	2 technicians		
AT. Stage 1 finishing vacuum	m2	163	AS	2	1	1 technician	3 technician		
AU. Stage 1 finishing	ea	1	AT	5	3	1 skilled worker/technician	2 skilled workers/technician		
AV. Electrical rough final	ea	1	AS	2	1	1 electrician	3 electricians		
AW. Install cabinet	ea	1	AU	3	2	1 carpenter	2 carpenters		
AX. Railing	ea	1	AW	3	2	1 carpenter	2 carpenters		
AY. Paint vaccum	m2	163	AX	2	1	1 painter	3 painters		
AZ. Pour driveway & sidewalk	m3	4.3	AY	1	1	2 bricklayers	2 bricklayers	vibrator (gas)	vibrator (gas)
						1 equipment operator	1 equipment operator	bobcat	bobcat
BA. Parging	m2	28	AZ	2	1	1 bricklayers	3 bricklayers	1 concrete mixer	1concrete mixer
						1 helper	2 helpers		
BB. Rough grade site	m2	372	BA	1	1	1 equipment operator	1 equipment operator	1 bobcat	1 bobcat
BC. Interior painting	m2	414	AY	6	3	2 painters	4 painters		
						1 helper	3 helpers		
BD. Exterior painting	m2	184	BC,BA	2	1	1 painter	3 painter		
						1 helper	2 helper		
BE. Electrical Final	ea	1	BD	1	1	1 electrician	1 electrician		
BF. Structural wiring final	ea	1	BD	2	1	1 electrician	3 electrician		
BG. Hard flooring vacuum	m2	163	BE,BF	2	1	1 carpenter	3 carpenters		
						1 helper	2 helpers		
BH. Granite countertops	ea	1	BG	1	1	1 carpenter	1 carpenter		
BI. Laminate countertops	ea	1	BH	1	1	1 carpenter	1 carpenter		

Table 3.5. Construction Activities for Stage 5: Finals and Occupancy (Yu, 2010; Mah, 2011; Rs means)

Activity	Unit	Qty	Predecessors	Duration (days)		Crew type		Equipment	
				Normal	Crash	Normal	Crash	Normal	Crash
5. Finals and Occupancy									
BJ. Tile backslah & tub surrounds	ea	1	BG	4	2	1 tiler	2 tilers		
						1 helper	2 helpers		
BK. Sheet vinyl flooring	m2	33	BJ	2	1	1carpenter	3 carpenters		
						1 helper	1 helper		
BL. Laminate flooring	m2	163	BK	2	1	1carpenter	3 carpenters		
						1 helper	1 helper		
BM. Hardwood flooring	m2	50	BL	4	2	1carpenter	3 carpenters		
						1 helper	2 helpers		
BN. Stage 2 finishing	ea	1	BM	2	1	1 skilled worker	3 skilled workers		
BO. Plumbing final pressure test water line	ea	1	BN	1	1	1 plumber	1 plumber		
BP. Carpet vac & sweep basement	m2	82	BN	1	1	1 carpenter	1 carpenter		
						1 helper	1 helper		
BQ. carpet flooring	m2	82	BO	2	1	1 carpenter	3 carpenters		
						1 helper	1 helper		
BR. wire shelving	ea	1	BQ	1	1	1 carpenter	1 carpenter		
BS. Heating final	ea	1	BR	1	1	1 technician	1 technician		
BT. Full clean	m2	162	BS	2	1	1 labourer	3 labourers		
BU. Final site and garage clean	m2	372	BV	2	1	1 labourer	2 labourers		
BV. Clean & wash basement floor & stairs	m2	82	BT	2	1	1 labourer	3 labourers		
BW. Window final	ea	1	BV	1	1	1 carpenter	1 carpenter		
BX. Mirror and shower doors	ea	1	BV	1	1	1 carpenter	1 carpenter		
BY. Paint touch-ups	m2	414	BW	3	2	1 painter	2 painters		
BZ. Cabinet final	ea	1	BY	1	1	1 carpenter	1 carpenter		
CA. City final inspection	-	-	BZ	1	1		-		
CB. Reclean	m2	162	CA	2	1	1 labourer	3 labourers		
CC. Pre-occupancy orientation	-	-	CB	1	1		-		
CD. Do all repairs	ea	1	CC	3	2	1 technician	2 technicians		
CE. Furnace ductwork clean	ea	1	CD	1	1	1 technician	1 technician		
CF. Fireplace start-up	ea	1	BS	1	1	1 technician	1 technician		
CG. 2nd Reclean	ea	1	CD	2	1	1 labourer	3 labourers		
CH. Occupation	-	-	CG	-			-		

3.4.1 Quantification of Carbon Emission

In terms of carbon emissions, a reduced project duration might imply less energy consumption. However, assigning more resources to accelerate a construction process can significantly increase carbon emissions. Likewise, an increase in the workforce contributes to an increase in carbon through transportation. In this study, a 40km round trip distance and car vehicle type are assumed for the transportation of workers to the construction site. The equations for calculating the emissions of resources and labour transportation for the on-site construction process are represented below.

3.4.1.1 Emission from Construction Equipment

The emission factor of different types of equipment varies. For the on-site construction process, the equipment type and hours of operation on-site are recorded for CO_2 quantification. The mathematical formula is expressed below:

$$CO_2 = H_E \times EF_N \quad \text{(iii)}$$

Where H_E represents the equipment-use hours, and EF_N represents the carbon emission factor of equipment type "N" which is highlighted in Table 3.6 for different equipment types.

3.4.1.2 Emission from Transportation

The transportation of materials, construction equipment, and employees to the construction site contributes to carbon emissions. Since material transportation is not directly influenced by increased or shortened project duration, this study will focus on the transportation of employees to the onsite construction site. Embodied emissions from transportation are impacted by the transportation distance in km (D), the emission factor of the vehicle type (EF_T) in CO_2kg/km, and the number of round trips required from one point to the construction site (N_T).

$$CO_2 = N_T \times D_T \times EF_T \quad \text{(iv)}$$

Table 3.6. Emission Rates per Vehicle and Equipment Type (Mah, 2011)

Vehicle/Truck	CO2 (kg/km)	Equipment	CO2 (kg/hr)
Car/van	0.23	Compressor	2.68
Concrete mixer	1.16	Generator	2.68
		Excavator/backhoe	40
		Crane	16

3.5 Panelized Construction Method

3.5.1 Panelized Construction Activity Durations and Sequencing

According to previous studies, the panelized construction method has the potential to reduce project duration by 20% to 40%. It is capable of overlapping construction phases. This approach involves transferring some onsite activities that can be prefabricated to an offsite factory, allowing construction to progress offsite while site preparation and excavation proceed. The prefabricated components are later transported to the construction site for installation, as illustrated in Figure 3.2.

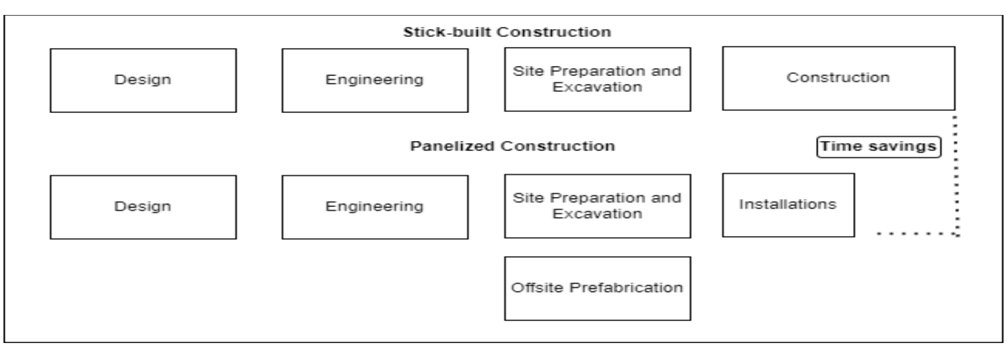


Figure 3.2. Phases of construction for stick-built and panelized

The table below shows the list of offsite activities and respective durations.

Table 3.7. Offsite Construction Activities and Duration (Yu et al., 2007).

Task	Duration (days)
Marking	2.6
Cutting for wall panel	2.2
Making components	1.3
1st-floor walls prefabrication	1.8
2nd-floor walls prefabrication	1.5
Wall move-out	0.5
1st-floor prefabrication	1.4
1st-floor move-out	0.1
2nd-floor prefabrication	1.5
2nd-floor move-out	0.1
Roof prefabrication	1.4
Roof move-out	0.2
Material moving	1.0
Load trailer	0.6
Transportation	0.5
Erection preparation	1.0
1st-floor erection	1.0
1st-floor walls erection	1.0
2nd-floor erection	1.0
2nd-floor wall erection	1.0
Roof installation	1.0

However, Lopez and Froese (2016) conducted a cost analysis of prefabricated construction methods, including the panelized method, based on the cost per square foot of construction that could serve as a valuable tool for estimating other similar construction projects. As shown in Table 3.8, the cost analysis in Canadian dollars involves the panelized construction process from the manufacturing stage to on-site installation, including direct (materials, labour, and equipment costs) and indirect costs (utilities). The cost for the construction's site preparation and excavation phase is sourced from the original activity duration data source in Table 4.1.

Table 3.8. Cost Breakdown for Panelized Construction (Lopez & Froese, 2016)

Stages	**$ CAD/ft^2**
Framing Activities (Manufacturing)	74.60
Customization	4.80
On-site interior work	29.60
Other on-site work and utilities	7.00
Total	**$116.00/ft**

According to Li et al. (2014), the table below shows the carbon footprint (kg/m^2) of the framing activities of a single-family house panelized construction method used for this case study.

Table 3.9. Carbon Emission Intensity for a Single-Family House Panelized Construction Method (Li et al., 2014).

Emission Element	**Carbon intensity (kg/m^2)**
Plant utility - Electricity	5.549
Plant utility – Natural Gas	2.680
Panel Transportation	3.418
Factory Workers	0.953
Site workers	0.959
Office staff	0.384
Site generators	1.338
Winter heating	10.793
Wood waste	1.581
Vehicle usage	0.710
Crane usage	0.311
Fuel	1.186

3.6 Genetic Algorithm

The genetic algorithm was inspired by evolutionary theory. Holland and his colleagues developed the concept in the 1960s and 1970s. The theory explains how natural selection leads to the extinction of weak species and allows stronger ones to reproduce and dominate. Random genetic mutations that offer survival advantages can lead to the evolution of new species, while unsuccessful mutations are eliminated. The components of the genetic algorithm are chromosomes, population, parent, and offspring. The chromosome is represented by a unique solution vector X and is encoded by the algorithm. Chromosomes are made of discrete units called genes, which are assumed to be binary digits. The features of the chromosome are controlled by each gene. The collection of chromosomes, which the genetic algorithm encodes, is called a population. The population is typically initialized randomly, and as the search progresses, it evolves to include increasingly fit solutions, eventually converging and becoming dominated by a single solution.

The genetic algorithm uses two operators to generate new solutions from existing ones, which are crossover and mutation. The crossover operator, the most important operator in the algorithm, combines two chromosomes together to form new chromosomes called offspring. The two chromosomes combined are the parent. Parents are selected from the existing population of chromosomes, favoring those with higher fitness to ensure offspring inherit good genes. Through repeated application of the crossover operator, good genes from fit chromosomes become more common in the population, ultimately leading to a highly fit solution convergence. The mutation operator introduces random changes to the characteristics of chromosomes, usually at the gene level. In typical GA implementations, the mutation rate is very low and depends on the chromosome's length, so the resulting chromosome is usually similar to the original. The mutation is crucial because it reintroduces genetic diversity, helping the population escape local optima, whereas crossover tends to make chromosomes more alike, leading to convergence. Reproduction in genetic algorithms involves selecting chromosomes for the next generation based on their fitness, with various selection methods like proportional selection, ranking, and tournament selection determining the probability of survival, as outlined in the following generic GA procedure (Konak et al., 2006):

Step 1: Set t = 1. Randomly generate N solutions to form the initial population, P_1, and evaluate their fitness.

Step 2: Crossover: Generate an offspring population Q_t by selecting two solutions, x and y, from P_t based on fitness and applying a crossover operator to produce offspring and add them to Q_t.

Step 3: Mutation: Mutate each solution in Q_t with a predefined mutation rate.

Step 4: Fitness assignment: Evaluate and assign a fitness value to each solution in Q_t based on its objective function value and infeasibility.

Step 5: Selection: Choose N solutions from Qt based on their fitness and copy them to P_{t+1}.

Step 6: If the stopping criterion is met, terminate the search and return the current population; otherwise, set t = t + 1 and repeat from Step 2.

Genetic algorithms (GAs) are not only efficient but also highly adaptable. They are well-suited for multi-objective optimization problems, which allows a single run to find multiple non-dominated solutions. GAs can explore diverse regions of the solution space, making them effective for problems with non-convex, discontinuous, and multi-modal solution spaces. The crossover operator, a key feature of GAs, can create new non-dominated solutions by leveraging good structures from different objectives, all without requiring the user to prioritize or weigh objectives. This adaptability is further demonstrated by the many developed multi-objective evolutionary algorithms, each with its own unique strengths and applications, including the Multi-objective Genetic Algorithm (MOGA), Random Weighted Genetic Algorithm (RWGA), Non-dominated

Sorting Genetic Algorithm (NSGA-II), Niched Pareto Genetic Algorithm (NPGA), Dynamic Multi-objective Evolutionary Algorithm (DMOEA) and many more.

3.6.1 Multi-Objective Optimization

Multi-objective optimization (MOO) problems involve conflicting objective functions, and the solutions are a set of Pareto optimal solutions that represent the best trade-offs between these objectives. In this study, the Non-Dominated Sorting Genetic Algorithm (NSGA-II) is used to optimize time, cost, and carbon emissions. The optimization model formulation consists of objectives, decision variables, and constraints.

3.6.1.1 Decision variables

The decision variables are unknown changeable parameters in the optimization model that determines the objective function value. In this model, the activity durations are the decision variables that should be changed within each activity's original project duration and available crash duration. It is represented mathematically below, where D_N represents the duration of an activity:

$$x = D_A, D_B, D_C \ldots D_N \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(v)}$$

3.6.1.2 Objective Functions

The model's optimization process aims to minimize project duration, total cost, and total carbon emissions simultaneously by selecting the appropriate execution options for the decision variables. The optimization model requires a range for activity durations with their respective cost and carbon emissions, termed normal and crash, as shown in Figure 3.3.

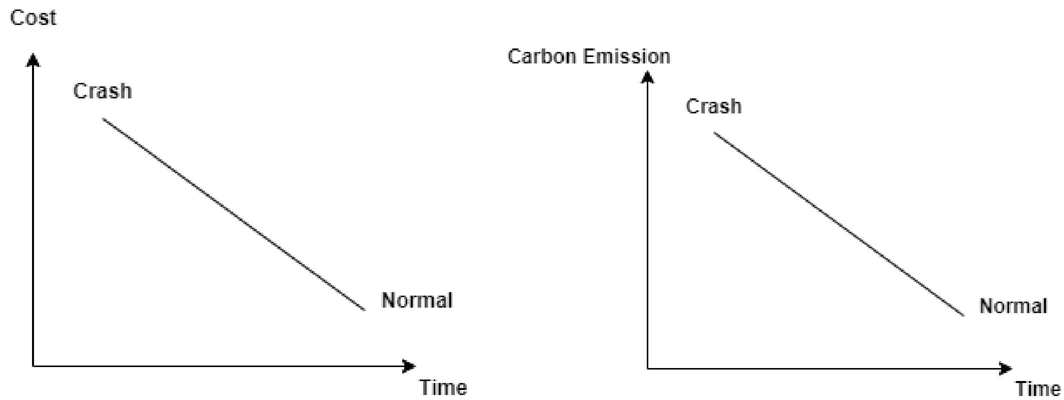


Figure 3.3. Illustration of linear time/cost and time/carbon emissions trade-off for an activity

Minimization of project duration:

The first objective function of the model is to minimize project duration, as shown in the following equation:

$$D = \min\left(\underset{a=1,\ldots M}{\mathrm{Max}}(FT_a)\right) = \min\left(\underset{a=1,\ldots M}{\mathrm{Max}}(ST_a + D_a)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(vi)}$$

Where ST_a and FT_a represent the activity start and finish time. D_a represents the activity duration, which is limited to its normal and crash duration range.

Minimization of total project cost

The total project cost is the summation of the total direct cost and indirect cost of a project. The direct cost refers to the cost attributed to each activity, such as labour, equipment, and material costs. In contrast, the indirect costs represent additional costs corresponding to the project duration, such as project overhead and general overhead. The indirect cost of a project can be represented by a fixed amount or percentage of the direct cost.

The second objective function is to minimize total project cost, as shown in the following equation:

C_{total} = Direct cost + Indirect cost…………………………………………………….. (vii)

$C_{total} = \sum_{a=1,\ldots M}((C_a + C_{slope(a)}.\ (D_a - d_{a2})) + C_{a(I)})$ ……………………………..…. (viii)

Where C_a is the normal direct cost of an activity, $C_{a(I)}$ is the indirect cost of an activity. D_a and d_{a2} are the normal activity duration and selected crash duration for the activity, respectively, if any. If an activity remains uncrashed after the optimization, the normal project cost (C_a) is returned. $C_{slope(a)}$ represents the direct cost slope of an activity, as shown in the equation below:

$C_{slope(a)} = \frac{C_{a2} - C_a}{D_a - D_{a2}}$…………………………………………………………………...……(ix)

Where D_{a2} is the crashed duration of an activity, and C_{a2} is its respective direct cost.

Minimization of total project carbon emissions:

The third objective function is the minimization of the total carbon emissions, as shown in the following equation:

$E_{total} = \sum_{a=1,\ldots M}((E_a + E_{slope(a)}.\ (D_a - d_{a2}))$……………………………………...….(x)

Where E_a is the normal carbon emission of an activity, D_a and d_{a2} are the normal activity duration and selected crash duration for the activity, respectively, if any. If an activity remains uncrashed after the optimization, the normal carbon emission (E_a) is returned. $E_{slope(a)}$ represents the emission slope of an activity, as shown in the equation below:

$E_{slope(a)} = \frac{E_{a2} - E_a}{D_a - D_{a2}}$…………………………………………………………………...…….(xi)

Where D_{a2} is the crashed duration of an activity, and E_{a2} is its respective carbon emission.

3.6.1.3 Constraints

A comprehensive project schedule with generalized precedence relations among activities encompasses all network components, including preceding and succeeding activities and their logical relationships. The precedence relationship of each activity is the model's constraints, which denotes which activity should start first before another. This is represented in the following equation:

$$ST_a \geq \max_{p \in P(a)} ST_p + d_p \quad \text{(xii)}$$

Where ST_a is the start time of an activity, ST_p is the start time of its preceding activity and d_p is the duration of the preceding activity.

3.6.2 Implementation of the model

The optimization computations were conducted using the Non-dominated Sorting Genetic Algorithm (NSGA-II) due to its efficacy in handling multi-objective optimization and addressing non-linear objective functions and constraints (Konak et al., 2006). NSGA-II incorporates an elitist principle, carrying over the best-performing individuals to maintain diversity and accelerate convergence (Fu & Liu, 2019). It also uses a Crowding Distance mechanism to ensure solutions are spread across the Pareto front and emphasizes finding non-dominated solutions that balance conflicting objectives (Pourtakdoust & Zandavi, 2016). NSGA-II facilitates the identification of optimal trade-offs among the objectives of time, cost, and carbon emissions by generating high-quality solutions. The optimization model operates in three phases, as illustrated in Figure 3.4.

In the first phase, the model searches for and integrates input and project data. It then determines key parameters such as population size (P), termination conditions, crossover rate (C), and mutation rate (M). The second phase involves randomly generating an initial population from feasible solutions, ensuring diversity to avoid premature convergence on suboptimal solutions. Increasing the initial population size can enhance convergence to a global optimum but also significantly lengthen the computational time.

The third phase evaluates the fitness of the generated population based on project time, cost, and carbon emissions. Solutions with minimal project duration, total cost, and carbon emissions are classified as high fitness, while those with higher values are deemed low fitness and dominated by higher fitness solutions. Non-dominated solutions are then processed by NSGA-II operators for selection, crossover, and mutation to create a new population. A rank-based mechanism involving non-dominated sorting and crowding distance is applied to include and exclude criteria. The non-dominated sorting algorithm ranks solutions based on their proximity to global optimality and crowding distance, selecting the closest solutions first. In cases where solutions are equally close, the one with lower density is chosen. The model's computations terminate upon reaching a predefined number of generations; otherwise, the third phase is repeated.

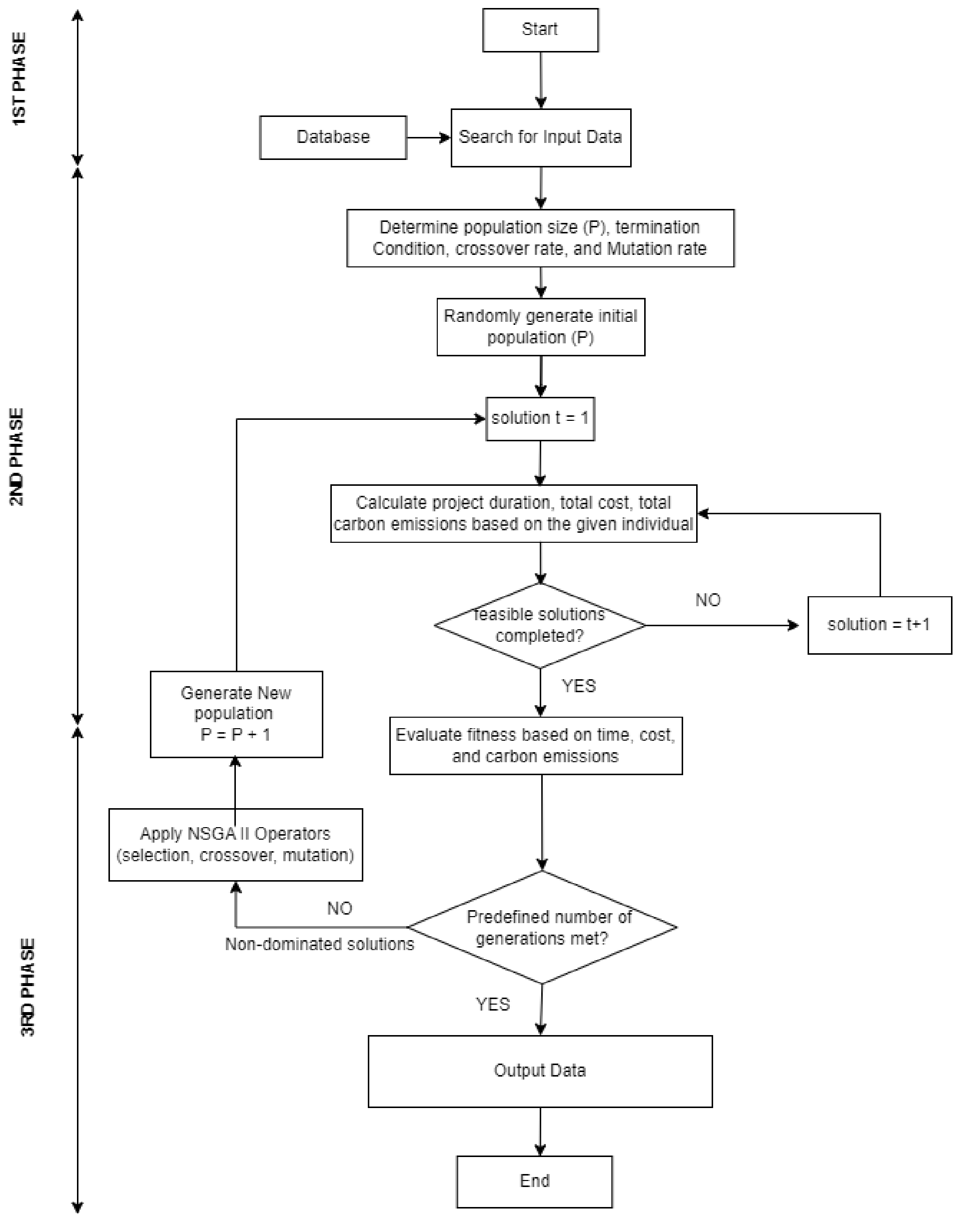


Figure 3. 4. Process map of the NSGA II Optimization process

3.6.2.1 Model input data

The model requires the following input data to begin the optimization process: a list of activities, predecessor(s) of each activity, normal and available crash duration for each activity, normal and available crash direct cost for each activity, normal and available crash carbon emissions for each activity and Indirect cost (cost/project duration) as illustrated in Tables 4.1 to Tables 4.5.

3.6.2.2 Model output

Once the data are input into the optimization model, the model outputs a set of Pareto front solutions: the non-dominated optimal trade-offs among the project objectives of time (project duration), total cost, and total carbon emissions with their respective newly selected activity durations. This set of Pareto front solutions will enable the user to select the desired solution based on the specific project requirements and sustainability goals. As mentioned earlier, the number of resources assigned to each activity influences the relationship between time, cost, and carbon emissions. Therefore, the new activity durations correspond to the number of resources required to achieve that minimum project duration, total cost, and carbon emissions.

3.6.3. Time, Cost, and Carbon Emission Trade-off Relationship

To crash an activity's duration, more resources must be assigned to that activity to increase its productivity and workflow, leading to increased costs and carbon emissions for that activity. Critical activities influence the project duration and are the target activities for crashing. Randomly crashing an activity will adversely affect costs and carbon emissions, making it necessary to optimally reschedule the project within the constraints and available crash duration to shorten the project duration. The optimized technique and random selection of activities to crash with respect to time, cost and carbon emissions are compared with the baseline which is the original (normal) project duration, cost and carbon emissions before the activity schedules are altered, as illustrated in Figure 3.5. Although shortening a project duration increases cost and carbon emissions above the baseline (normal level), the optimization method results in a more cost-effective approach and lower carbon emissions while shortening the project duration than crashing activities randomly without optimization. :

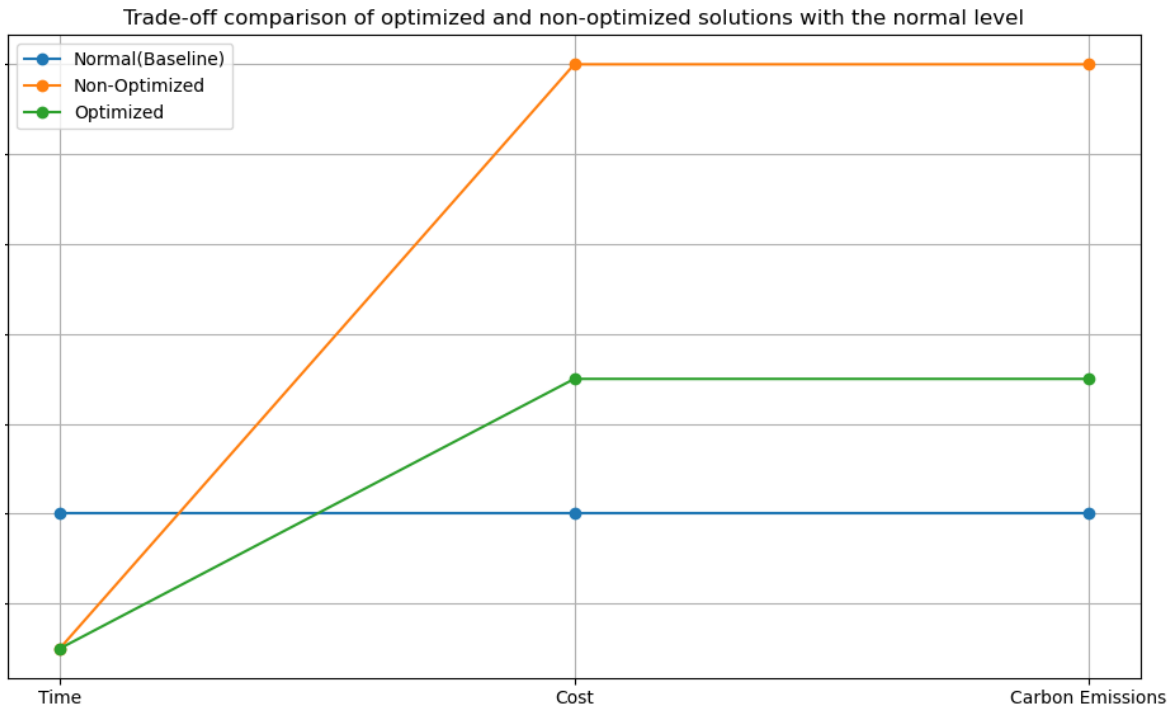


Figure 3. 5. Illustration of the effect of optimal and non-optimized solutions on time, cost, and carbon emissions.

CHAPTER FOUR

DATA ANALYSIS AND RESULT

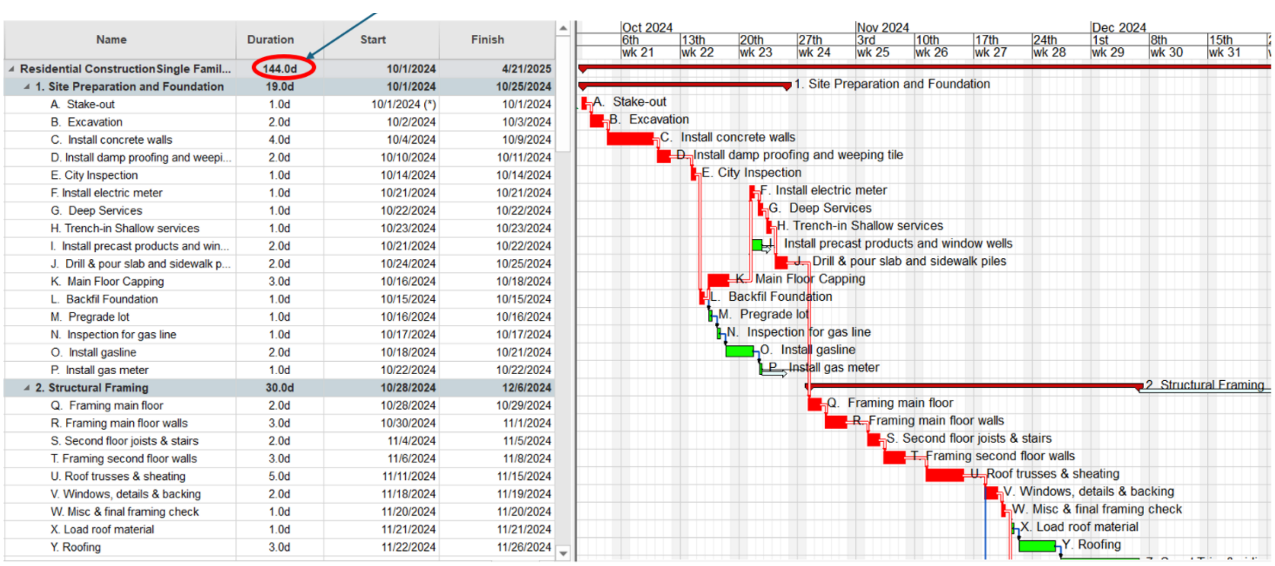
4.1 Introduction

Accelerating the construction process of a project requires assigning more resources to the construction activities to increase productivity and complete the project within a short period. The time reduction goal at the expense of high resource demand, increased cost, and environmental impact in terms of carbon emission poses a great concern to construction practitioners on which activity to crash and which not to crash. This decision on which activity to crash to achieve a shortened project duration is a critical decision that can incur additional costs and intensify the impact on carbon emissions if managed improperly. Therefore, construction practitioners must understand the trade-off behaviours between time, cost, and carbon emission and find an optimal solution that will help achieve a shortened duration in a more cost-efficient and with less impact on carbon emission.

This chapter is divided into two analyses: on-site optimization and off-site prefabrication. This study uses the non-dominated sorting genetic algorithm (NSGA-II) to optimize trade-offs between time, cost, and carbon emissions of an onsite construction project. The optimization process requires a range of values for each parameter: time, cost, and carbon emissions for each activity, termed normal and crash, in this study. Providing this range will enable trade-off optimization within the available crashing limits. The panelized construction method involves transferring some onsite activities, like framing activities, to an offsite factory for prefabrication, which is then transported to the site for installation. Offsite prefabrication addresses labour shortages and enhances schedule predictability by mitigating issues such as weather disruptions and site conditions. Using Synchro Scheduler software, onsite activities were rescheduled so that wall, floor, and roof elements were prefabricated concurrently with site preparation and foundation construction. Onsite trade-off optimization and offsite prefabrication are effective strategies for shortening project duration cost-efficiently and with less environmental impact.

4.2 Onsite Optimization

Figure 4.1 shows a Gantt chart representing construction activities with their original durations. The original project duration, which serves as the baseline, is 144 days. The optimization process is reliant on the data being fed into the system. The input data required are a list of activities, precedence relationships of the activities, durations, cost, and carbon emissions of each activity at both normal and crash levels. Therefore, the required data must be complete and available before being fed into the optimization process. Given the list of activities and their respective resources, each activity's direct cost and carbon emissions at both normal and crash levels were computed as shown in Tables 4.1 to 4.5.



Name	Duration	Start	Finish
Residential Construction Single Famil...	144.0d	10/1/2024	4/21/2025
1. Site Preparation and Foundation	19.0d	10/1/2024	10/25/2024
A. Stake-out	1.0d	10/1/2024 (*)	10/1/2024
B. Excavation	2.0d	10/2/2024	10/3/2024
C. Install concrete walls	4.0d	10/4/2024	10/9/2024
D. Install damp proofing and weepi...	2.0d	10/10/2024	10/11/2024
E. City Inspection	1.0d	10/14/2024	10/14/2024
F. Install electric meter	1.0d	10/21/2024	10/21/2024
G. Deep Services	1.0d	10/22/2024	10/22/2024
H. Trench-in Shallow services	1.0d	10/23/2024	10/23/2024
I. Install precast products and win...	2.0d	10/21/2024	10/22/2024
J. Drill & pour slab and sidewalk p...	2.0d	10/24/2024	10/25/2024
K. Main Floor Capping	3.0d	10/16/2024	10/18/2024
L. Backfil Foundation	1.0d	10/15/2024	10/15/2024
M. Pregrade lot	1.0d	10/16/2024	10/16/2024
N. Inspection for gas line	1.0d	10/17/2024	10/17/2024
O. Install gasline	2.0d	10/18/2024	10/21/2024
P. Install gas meter	1.0d	10/22/2024	10/22/2024
2. Structural Framing	30.0d	10/28/2024	12/6/2024
Q. Framing main floor	2.0d	10/28/2024	10/29/2024
R. Framing main floor walls	3.0d	10/30/2024	11/1/2024
S. Second floor joists & stairs	2.0d	11/4/2024	11/5/2024
T. Framing second floor walls	3.0d	11/6/2024	11/8/2024
U. Roof trusses & sheating	5.0d	11/11/2024	11/15/2024
V. Windows, details & backing	2.0d	11/18/2024	11/19/2024
W. Misc & final framing check	1.0d	11/20/2024	11/20/2024
X. Load roof material	1.0d	11/21/2024	11/21/2024
Y. Roofing	3.0d	11/22/2024	11/26/2024

Figure 4. 1. Gantt Chart Representation of Construction Activities

4.2.1 Data Input Preparation: Computation of Cost and Carbon Emission

The carbon emission and cost computation for each activity is sampled below using Activity C (Install concrete walls) at a normal level, as an example:

CO_2Kg (Labour and equipment) = (trip numbers × vehicle type × distance) + (duration × equipment type)

COST $ (Labour and equipment) = number of crew × duration × cost/day

The construction workers' vehicle type is assumed to be a car or van, and the average distance is assumed to be 40 km. Each employee's transportation distance to the construction site is assumed to be 40 km daily. Additionally, it is summed that construction activities are carried out 8 hours/day. The carbon emission factors for vehicle and equipment types and the daily cost of crew members are shown in Table 3.6.

Since it is assumed all crew members use the same vehicle type (car/van), round trip numbers are calculated as:

Round trip numbers = number of crews × duration.

Therefore, the cost and carbon emission computation of Activity C at normal level (Install concrete walls) is as follows:

242.56 CO_2Kg = (12 round trips × 0.23kg/km × 40km) + ((4 days × 8hrs/day × 2.68 kg/hr) + (1 round trip × 1.16 kg/km × 40 km))

$4814.4 = (1 foreman × 4 days × $530/day) + (2 labourers × 4 days × $336.8)

The computation process for cost and carbon emissions is done for other activities at both normal and crash levels, as represented in Tables 4.1 to 4.5.

Table 4. 1. Construction Activities for Stage 1: Site Preparation and Excavation

Activity	Predecessor	Duration (days)		Crew type		Equipment		Cost ($)		Carbon Emissions (CO2Kg)	
		Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash
1. Site Preparation and Foundation											
A. Stake-out	-	1	1	1 Rodman	1 Rodman			846.8	846.8	18.4	18.4
				Instrument man	Instrument man						
B. Excavation	A	2	2	3 laborers	3 laborers	1 excavator	1 excavator	4753.5	4753.5	713.6	713.6
				1 operator	1 operator						
C. Install concrete walls	B	4	3	1 foreman	1 foreman	1 generator	1 generator	4814.4	5631.6	242.56	248.72
				2 laborers	4 laborers	concrete mixer	concrete mixer				
D. Install damp proofing and weeping til	C	2	1	1 plumber	3 plumber			1164.7	1613.55	18.4	27.6
E. City Inspection	D	1	1	-	-					-	-
F. Install electric meter	K	1	1	1 electrician	1 electrician			490.8	490.8	9.2	9.2
G. Deep Services	F	1	1	1 foreman	1 foreman	1 excavator	1 excavator	2569.95	2569.95	356.8	356.8
				2 laborers	2 laborers						
				1 operator	1 operator						
H. Trench-in Shallow services	G	1	1	1 foreman	1 foreman	1 backhoe	1 backhoe	2096.15	2096.15	356.8	356.8
				2 laborers	2 laborers						
				1 operator	1 operator						
I. Install precast products and window v	K	2	1	1 technician	2 technicians			877.6	1316.4	18.4	18.4
J. Drill & pour slab and sidewalk piles	H,I	2	1	1 bricklayers	2 bricklayers			1500.8	1917.2	36.8	27.6
				1 helper	1 helper						
K. Main Floor Capping	L	3	2	1 carpenters	2 carpenters	1 generator,	1 generator	1275	1700	156.24	165.44
						1 compressor	2 compressors				
L. Backfill Foundation	E	1	1	1 operator	1 operator	1 backhoe	1 backhoe	1566.15	1566.15	347.6	347.6
				2 laborer	2 laborers						
M. Pregrade lot	L	1	1	1 operator	1 operator	1 bobcat	1 bobcat	856.35	856.35	329.2	329.2
N. Inspection for gas line	M	1	1		-					-	-
O. Install gasline	N	2	1	1 plumber	3 plumbers			1458.7	1760.55	18.4	27.6
P. Install gas meter	O	1	1	1 plumber	1 plumber			515.6	515.6	9.2	9.2

Table 4.2. Construction Activities for Stage 2: Structural Framing

Activity	Predecessor	Duration (days)		Crew type		Equipment		Cost ($)		Carbon Emissions (CO2Kg)	
		Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash
2. Structural Framing											
Q. Framing main floor	J,P	2	1	1 carpenter	3 carpenters	1 generator	1 generator	1518	1943	122.56	131.76
				1 helper	2 helpers	1 compressor	3 compressors				
R. Framing main floor walls	Q	3	1.5	1 carpenter	3 carpenters	1 generator	1 generator	2277	2914.5	183.84	197.64
				1 helper	2 helpers	1 compressor	3 compressors				
S. Second floor joists & stairs	R	2	1	1 carpenter	3 carpenters	1 generator	1 generator	850	1275	104.16	113.36
						1 compressor	3 compressors				
T. Framing second floor walls	S	3	1.5	1 carpenter	3 carpenters	1 generator	1 generator,	2277	2914.5	183.84	197.64
				1 helper	2 helpers	1 compressor	3 compressors				
U. Roof trusses & sheating	T	5	3	1 carpenter	2 carpenters	1 generator	1 generator	3795	4554	306.4	367.68
				1 helper	2 helpers	1 compressor	3 compressors				
V. Windows, details & backing	U	2	1	1 technician	3 technicians	-	-	877.6	1316.4	18.4	27.6
W. Misc & final framing check	V	1	1		-					-	-
X. Load roof material	W	1	1		-					-	-
Y. Roofing	X	3	2	1 carpenter	3 carpenters	20 t crane	20 t crane	6897	7148	595.44	648.16
				2 helper	2 helpers	1 generator	1 generator				
						1 compressor	2 compressors				
Z. Smart Trim & siding	Y	8	6	2 carpenters	3 carpenters	1 generator,	1 generator	9472	11658	563.84	661.92
				1 helper	2 helpers	1 compressor	2 compressors				
AA. HVAC mark-out	U	1	1	1 plumber	1 plumber			515.6	515.6	9.2	9.2
AB. City frame inspection	W	1	1		-			-	-	-	-

Table 4.3. Construction Activities for Stage 3: Mechanical/Electrical Installations

Activity	Predecessor	Duration (days)		Crew type		Equipment		Cost ($)		Carbon Emissions (CO2Kg)	
		Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash
3. Mechanical/Electrical Installations											
AC. Install Mechanical insulation	AB	2	1	1 technician	3 technicians			877.6	1316.4	18.4	27.6
AD. Install fireplace	AC	1	1	1 technician	1 technician			438.8	438.8	9.2	9.2
AE. plumbing rough-in	AD	3	2	1 plumber	2 plumbers	1 generator	1 generator	1546.8	2062.4	156.24	165.44
						1 compressor	2 compressors				
AF. Basement & garage slab	AE	4	3	1 bricklayer	2 bricklayer	1 generator	1 generator	3001.6	3500.4	291.52	322.16
				1 helper	1 helper	1 vibrator	1 vibrator				
						1 concrete mixer	1 concrete mixer				
AG. HVAC rough-in	AF	4	3	1 technician	2 technicians	1 generator	1 generator	1755.2	2632.8	208.32	248.16
						1 compressor	2 compressors				
AH. Electrical rough-in	AG	4	3	1 electrician	2 electricians	1 generator	1 generator	1963.2	2944.8	208.32	248.16
						1 compressor	2 compressors				
AI. Structural wire rough-in	AH	2	1	1 electrician	3 electricians	1 generator	1 generator	981.6	1472.4	104.16	113.36
						1 compressor	1 compressor				
AJ. City rough-in inspection	AI	1	1		-					-	-
AK. Install insulation	AJ	2	1	1 skilled worker/technician	2 skilled worker/technician			877.6	1755.2	18.4	18.4
AL. Frost walls & poly (vapour barrier)	AK	2	1	1 carpenter	3 carpenters			850	1275	18.4	27.6
AM. City insulation inspection	AL	1	1		-					-	-
AN. Drywall boarding	AM	7	4	1 carpenters	2 carpenters			5313	10626	128.8	147.2
				1 helper	2 helpers						
AO. Attic insulation	AM	2	1	1 carpenter	3 carpenters			850	1275	18.4	27.6
AP. Drywall tapping	AN,AO	6	5	2 carpenters	3 carpenters			9108	11658	220.8	230
				2 helpers	2 helpers						

Table 4.4. Construction Activities for Stage 4: Finishes

Activity	Predecessors	Duration (Days)		Crew type		Equipment		Cost ($)		Carbon Emissions (CO2Kg)	
		Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash
4. Finishes											
AQ. Prime vaccum	AP	2	1	1 plumber	3 plumber			1031.2	1546.8	18.4	27.6
AR. Prime	AQ	2	1	1 plumber	3 plumbers			1031.2	1546.8	18.4	27.6
AS. Texture	AR	2	1	1 technician	2 technicians			877.6	1755.2	18.4	18.4
AT. Stage 1 finishing vacuum	AS	2	1	1 technician	3 technician			877.6	1316.4	18.4	27.6
AU. Stage 1 finishing	AT	5	3	1 skilled worker/technician	2 skilled workers/technician			2194	2632.8	46	55.2
AV. Electrical rough final	AS	2	1	1 electrician	3 electricians			981.6	1472.4	18.4	27.6
AW. Install cabinet	AU	3	2	1 carpenter	2 carpenters			1275	1700	27.6	36.8
AX. Railing	AW	3	2	1 carpenter	2 carpenters			1275	1700	27.6	36.8
AY. Paint vaccum	AX	2	1	1 painter	3 painters			710	1065	18.4	27.6
AZ. Pour driveway & sidewalk	AY	1	1	2 brick layer	2 bricklayers	vibrator (gas)	vibrator (gas)	1689.15	1689.15	70.48	70.48
				1 equipment operator	1 equipment operator	bobcat	bobcat				
BA. Parging	AZ	2	1	1 bricklayers	3 bricklayers	1 concrete mixer	1 concrete mixer	1780.8	2057.2	83.2	92.4
				1 helper	2 helpers						
BB. Rough grade site	BA	1	1	1 equipment operator	1 equipment operator	1 bobcat	1 bobcat	856.35	856.35	30.64	30.64
BC. Interior painting	AY	6	3	2 painters	4 painters			6264	7266	165.6	193.2
				1 helper	3 helpers						
BD. Exterior painting	BC,BA	2	1	1 painter	3 painter			1378	1733	36.8	46
				1 helper	2 helper						
BE. Electrical Final	BD	1	1	1 electrician	1 electrician			490.8	490.8	9.2	9.2
BF. Structural wiring final	BD	2	1	1 electrician	3 electrician			981.6	1472.4	18.4	18.4
BG. Hard flooring vacuum	BE,BF	2	1	1 carpenter	3 carpenters			1518	1943	36.8	46
				1 helper	2 helpers						
BH. Granite countertops	BG	1	1	1 carpenter	1 carpenter			425	425	9.2	9.2
BI. Laminate countertops	BH	1	1	1 carpenter	1 carpenter			425	425	9.2	9.2

Table 4.5. Construction Activities for Stage 5: Finals and Occupancy

Activity	Predecessors	Duration (Days)		Crew type		Equipment		Cost ($)		Carbon Emissions (CO2Kg)	
		Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash	Normal	Crash
5. Finals and Occupancy											
BJ. Tile backslah & tub surrounds	BG	4	2	1 tiler	2 tilers			2920	5840	73.6	73.6
				1 helper	2 helpers						
BK. Sheet vinyl flooring	BJ	2	1	1 carpenter	3 carpenters			1518	1609	36.8	36.8
				1 helper	1helper						
BL. Laminate flooring	BK	2	1	1 carpenter	3 carpenters			1518	1609	36.8	36.8
				1 helper	1 helper						
BM. Hardwood flooring	BL	4	2	1 carpenter	3 carpenters			3036	3886	73.6	92
				1 helper	2 helpers						
BN. Stage 2 finishing	BM	2	1	1 skilled worker	3 skilled workers			877.6	1316.4	18.4	27.6
BO. Plumbing final pressure test water line	BN	1	1	1 plumber	1 plumber			515.6	515.6	9.2	9.2
BP. Carpet vac & sweep basement	BN	1	1	1 carpenter	1 carpenter			759	759	18.4	18.4
				1 helper	1 helper						
BQ. carpet flooring	BO	2	1	1 carpenter	3 carpenters			1518	1609	36.8	36.8
				1 helper	1 helper						
BR. wire shelving	BQ	1	1	1 carpenter	1 carpenter			425	425	9.2	9.2
BS. Heating final	BR	1	1	1 technician	1 technician			438.8	438.8	9.2	9.2
BT. Full clean	BS	2	1	1 laborer	3 laborers			673.6	1010.4	18.4	27.6
BU. Final site and garage clean	BV	2	1	1 laborer	2 laborers			673.6	1347.2	18.4	18.4
BV. Clean & wash basement floor & stairs	BT	2	1	1 laborer	3 laborers			673.6	1010.4	18.4	27.6
BW. Window final	BV	1	1	1 carpenter	1 carpenter			425	425	9.2	9.2
BX. Mirror and shower doors	BV	1	1	1 carpenter	1 carpenter			425	425	9.2	9.2
BY. Paint touch-ups	BW	3	2	1 painter	2 painters			1065	1420	27.6	36.8
BZ. Cabinet final	BY	1	1	1 carpenter	1 carpenter			425	425	9.2	9.2
CA. City final inspection	BZ	1	1		-					-	-
CB. Reclean	CA	2	1	1 laborer	3 laborers			673.6	1010.4	18.4	27.6
CC. Pre-occupancy orientation	CB	1	1		-					-	-
CD. Do all repairs	CC	3	2	1 technician	2 technicians			1316.4	1755.2	27.6	36.8
CE. Furnace ductwork clean	CD	1	1	1 technician	1 technician			438.8	438.8	9.2	9.2
CF. Fireplace start-up	BS	1	1	1 technician	1 technician			438.8	438.8	9.2	9.2
CG. 2nd Reclean	CD	2	1	1 laborer	3 laborers			673.6	1010.4	18.4	27.6
CH. Occupation	CG	-			-			-	-	-	-

4.2.2 Non-dominated Sorting Genetic Algorithm (NSGA-II)

The input data consisting of 86 activities, with their corresponding predecessors, duration, cost, and carbon emissions at both normal and crash levels, were fed into the optimization model to identify the trade-off optimal solutions between time, cost, and carbon emissions of each activity. The NSGA-II optimization model was coded using Python programming. The model was set to have a population size of 250, a crossover rate of 0.8, a mutation rate of 0.1, and several trials (ngen) of 1000 generations. The model then generates its initial population from feasible solutions and calculates the project duration, total cost, and carbon emissions. Among the set of feasible solutions generated, their fitness was evaluated. Minimum project duration, cost, and carbon emissions were classified as high fitness. In contrast, solutions with increasing project duration, total cost, and carbon emissions were classified as low fitness and dominated by higher fitness. The NSGA-II operators (selection, crossover, and mutation) process the non-dominated solutions to generate a new population. The process is iterated, and generated populations are classified based on their fitness level until the number of trials of 1000 is reached; then, the model terminates and outputs the trade-off optimization results between time, cost, and carbon emissions. The model generated several optimal trade-off solutions that can be selected based on project constraints, such as the available budget and sustainability goals, some of which are shown in Table 4.6. The model iterates and shortens the original project duration of 144 days up to 94 days with their updated activity schedule until there is no possible shortened duration that minimizes cost and carbon emissions. All optimal trade-off solutions (224 optimal trade-off solutions) from the original project duration of 144 days to 94 days with their respective optimal cost and carbon emissions are graphically represented in Figure 4.2 and Figure 4.3.

Table 4.6. Model Output of Pareto Front Solutions (Optimal Trade-off Solutions)

<u>Up to 94 days of shortened project duration is possible, according to the model output. All optimal trade-off solutions are represented graphically in Figure 4.2 and Figure 4.3</u>

Project Duration (Days)	Cost ($)			Total Carbon Emissions	Activity Schedule
	Direct Cost	Indirect Cost	Total Cost	(CO2Kg)	
144	128319	25663.8	153982.8	7316.56	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 2, K: 3, L: 1, M: 1, N: 1, O: 2, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 2, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 5, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 2, BG: 2, BH: 1, BI: 1, BJ: 4, BK: 2, BL: 2, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 2, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 3, CE: 1, CF: 1, CG: 2, CH: 0
140	129499.2	25899.84	155399.04	7307.36	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 1, K: 3, L: 1, M: 1, N: 1, O: 2, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 2, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 5, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 1, BG: 2, BH: 1, BI: 1, BJ: 4, BK: 1, BL: 1, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 1, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 3, CE: 1, CF: 1, CG: 2, CH: 0
139	129801.05	25960.21	155761.26	7316.56	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 1, K: 3, L: 1, M: 1, N: 1, O: 1, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 2, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 5, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 1, BG: 2, BH: 1, BI: 1, BJ: 4, BK: 1, BL: 1, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 1, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 3, CE: 1, CF: 1, CG: 2, CH: 0
139	130376.8	26075.36	156452.16	7307.36	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 1, K: 3, L: 1, M: 1, N: 1, O: 2, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 1, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 5, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 1, BG: 2, BH: 1, BI: 1, BJ: 4, BK: 1, BL: 1, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 1, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 3, CE: 1, CF: 1, CG: 2, CH: 0
138	129521.6	25904.32	155425.92	7325.76	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 2, K: 3, L: 1, M: 1, N: 1, O: 2, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 2, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 3, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 1, BG: 2, BH: 1, BI: 1, BJ: 4, BK: 1, BL: 1, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 1, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 3, CE: 1, CF: 1, CG: 2, CH: 0
138	129938	25987.6	155925.6	7316.56	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 1, K: 3, L: 1, M: 1, N: 1, O: 2, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 2, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 3, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 1, BG: 2, BH: 1, BI: 1, BJ: 4, BK: 1, BL: 1, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 1, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 3, CE: 1, CF: 1, CG: 2, CH: 0
137	129946.6	25989.32	155935.92	7334.96	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 2, K: 3, L: 1, M: 1, N: 1, O: 2, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 2, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 3, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 1, BG: 1, BH: 1, BI: 1, BJ: 4, BK: 1, BL: 1, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 1, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 3, CE: 1, CF: 1, CG: 2, CH: 0
137	130376.8	26075.36	156452.16	7325.76	A: 1, B: 2, C: 4, D: 2, E: 1, F: 1, G: 1, H: 1, I: 2, J: 1, K: 3, L: 1, M: 1, N: 1, O: 2, P: 1, Q: 2, R: 3, S: 2, T: 3, U: 5, V: 2, W: 1, X: 1, Y: 3, Z: 8, AA: 1, AB: 1, AC: 2, AD: 1, AE: 3, AF: 4, AG: 4, AH: 4, AI: 2, AJ: 1, AK: 2, AL: 2, AM: 1, AN: 7, AO: 2, AP: 6, AQ: 2, AR: 2, AS: 2, AT: 2, AU: 3, AV: 2, AW: 3, AX: 3, AY: 2, AZ: 1, BA: 2, BB: 1, BC: 6, BD: 2, BE: 1, BF: 1, BG: 2, BH: 1, BI: 1, BJ: 4, BK: 1, BL: 1, BM: 4, BN: 2, BO: 1, BP: 1, BQ: 1, BR: 1, BS: 1, BT: 2, BU: 2, BV: 2, BW: 1, BX: 1, BY: 3, BZ: 1, CA: 1, CB: 2, CC: 1, CD: 2, CE: 1, CF: 1, CG: 2, CH: 0

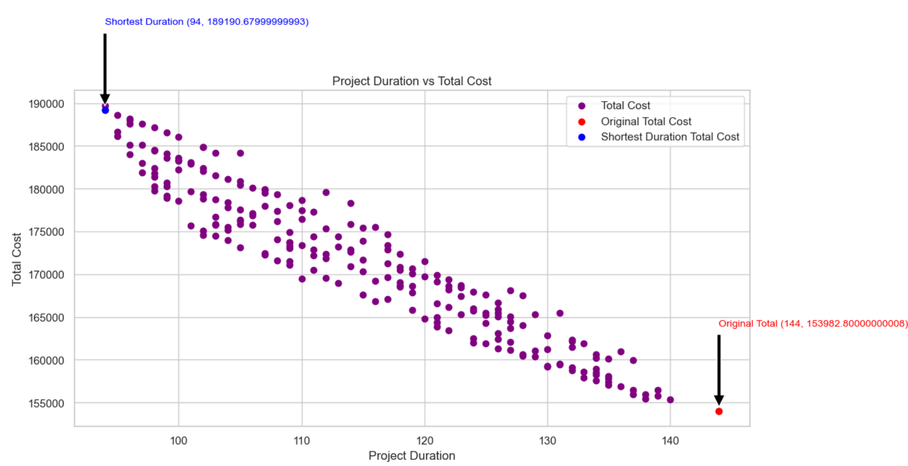


Figure 4.2. Graphical representation of total project cost as the project duration is shortened

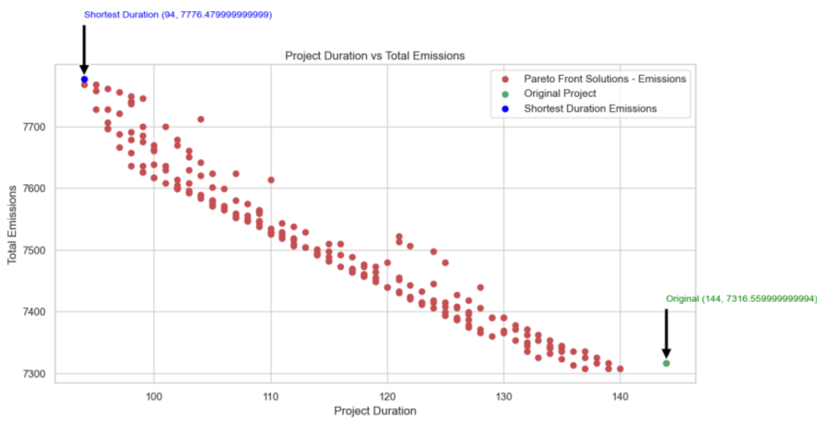


Figure 4.3. Graphical representation of total carbon emissions as the project duration is shortened

The relationship between time, cost, and carbon emissions is key to our optimization process. As the NSGA-II model shortens the project duration, the total cost increases, as represented in Figure 4.2. This is because direct costs are attributed to activities and their respective resources, so changes in activity schedules and the number of resources influence these costs. Also, the total carbon emissions increase as the project duration is shortened, graphically represented in Figure 4.3. This is because carbon emissions are attributed to resources and influenced by activity schedule changes. Therefore, the optimal trade-off solutions are determined by the least total project cost and total carbon emissions, striking a balance between time, cost, and carbon emissions. In practice, the optimization model can identify the shortest project duration within the specified budget and carbon emission constraints of the project, making it a valuable tool for project managers and stakeholders. For example, the optimization result indicates that the shortest possible project duration is 94 days if the budget and carbon emissions are limited to $189,190 and 7776.48 CO_2 kg, respectively. Another practical example is that if the project budget and carbon emissions are limited to \$168,527.64 and 7476.05 CO_2 kg, the project can be completed in 118 days.

As previously stated, the number of resources assigned to each activity influences the relationship between time, cost, and carbon emissions. The optimization results update the activity schedules for each optimal solution, balancing time, cost, and carbon emissions. This enables project managers to determine the productivity and resources required for the selected project duration that meets the budget and carbon emission constraints, as illustrated in Equation i and Equation ii.

Decision-makers cannot identify optimal solutions based on experience alone. The case study analyzed the performance and practicality of the developed optimization model by comparing the optimization model's result with the results of manually and randomly crashing the activities. For example, Table 4.7 shows a non-optimal crashing technique, which results in spending extra costs and carbon emissions for the same project duration or additional duration for the same project cost and carbon emissions. This random crashing of selected activities shortens the original project duration from 144 days to 118 days, resulting in additional cost and carbon emissions of \$176284.50 and 7636.92 CO_2Kg, respectively, compared with the optimized. Although the shortening of the project duration leads to an increase in total cost and carbon emissions above the normal level, the optimized approach could minimize the effect of schedule change on cost and carbon emissions, as graphically shown in Figure 4.4 and Figure 4.5.

Table 4.7. Non-optimized and Optimized result comparison

	Project Duration	Cost	Carbon emissions (CO2Kg)
Non-Optimized	118 days	$176284.50	7636.92 CO2Kg
Activities randomly crashed (these activities crashed randomly by their available crash time): C, R, U, V, Z, AE, AH, AI, AK, AL, AN, AP, BC, BD, BF, BJ, BM, BV, BY			
Optimized	118 days	$168,527.60	7476.05 CO2Kg
Original	144 days	$153,982.80	7316.56 CO2Kg

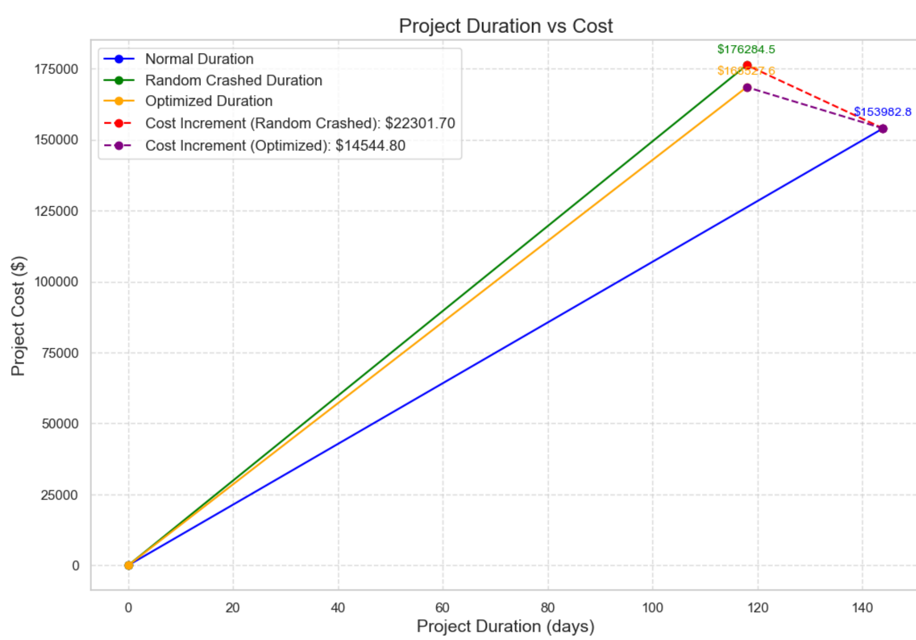


Figure 4. 4. Cost comparison between optimized and non-optimized

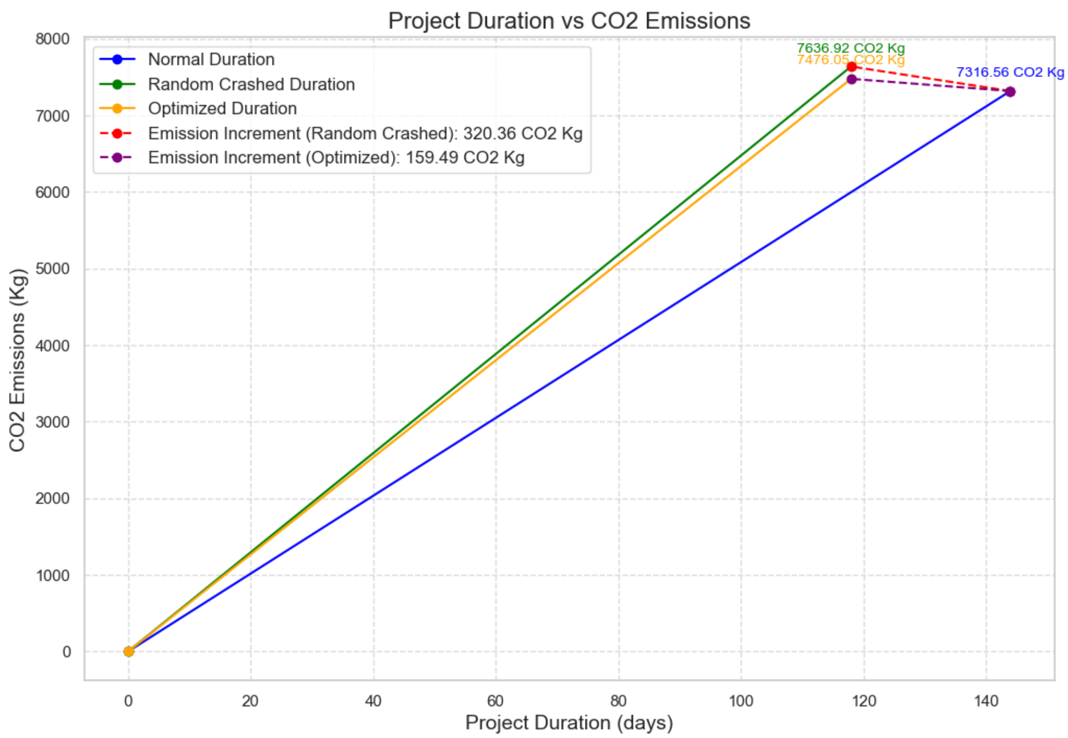


Figure 4. 5. CO2 Emission comparison between optimized and non-optimized

4.3. Offsite Prefabrication

The offsite construction method involves transferring a portion of on-site construction activities to an off-site factory for prefabrication and transporting them to the construction site for installation. Adopting offsite prefabrication, the construction process can be controlled despite unpredictable weather, site conditions, and crew availability, leading to more predictability in schedule than traditional onsite construction methods. Many builders overlook other cost benefits, such as reduced build time, which can lower overhead supervision costs and utility costs associated with longer construction financing periods of onsite construction. The prefabrication process follows the same procedures as the traditional wood frame houses, except that prefabricated frames are produced with more quality control and less physical demand for labour. The primary goal of using a prefabrication system is to enhance operational efficiency.

Using the stick-built construction process as a case study, this study analyzes the time efficiency, cost benefits, and carbon emissions that can be achieved if the panelized construction method were adopted. As mentioned, to handle the schedule adjustments of the stick-built construction process, resources must be utilized optimally to reduce the impact on cost and carbon emissions. But in most cases where there is a labour shortage, the panelized construction method offers the potential benefit of reducing time without much labour demand. However, the time reduction of the construction process will reduce the cost of supervision, resources and utilities of the onsite construction process in the long run. The panelized construction method is a construction method that should be considered because it offers more predictability in schedules, quality control, and environmental protection in terms of less impact on carbon emissions.

4.3.1 Construction Scheduling for Panelized Construction Method

Using the Synchro scheduler software, the construction process is rescheduled into the panelized construction as shown in Figure 4.6, depicting the Gantt chart representation of the panelized construction method. It illustrates how site preparation/excavation and framing activities are overlapped. This means that on-site framing activities are prefabricated in an off-site factory while the site is prepared for excavation and foundation construction. After being prefabricated offsite and completing the site excavation and foundation construction, the framing elements will be transported to the construction site for installation using a crane. By doing this, the construction duration was shortened, reducing the original project duration of the case study from 144 days to 118 days, as shown in Figure 4.6. Also, the panelized construction method reduces the stick-built construction workload, leading to a time reduction of 18% as illustrated in Figure 4.7 and Figure 4.8.

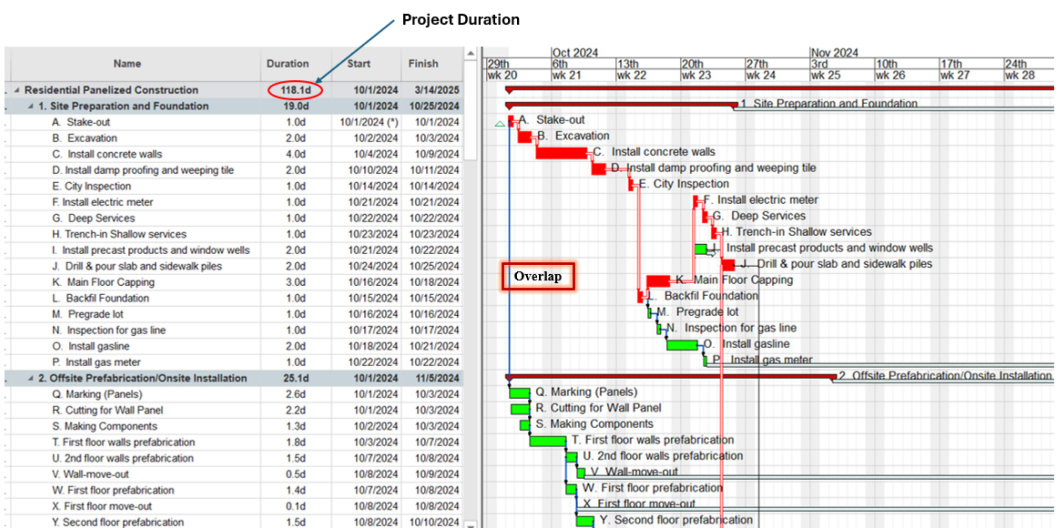


Figure 4. 6. Gantt Chart Representation of Panelized Construction Method

$$\textbf{Percentage Workload} = \frac{\text{Duration of each stage}}{\text{Project duration}} \times 100$$

$$\textbf{Percentage Reduction} = \frac{\text{New duration of each stage}}{\text{Original project duration}} \times 100$$

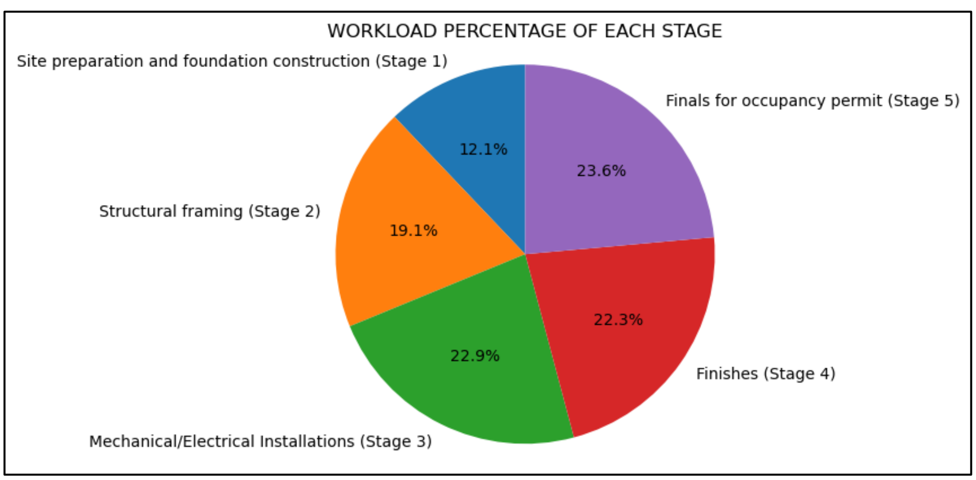


Figure 4.7. Stick-built Construction workload for each stage of construction

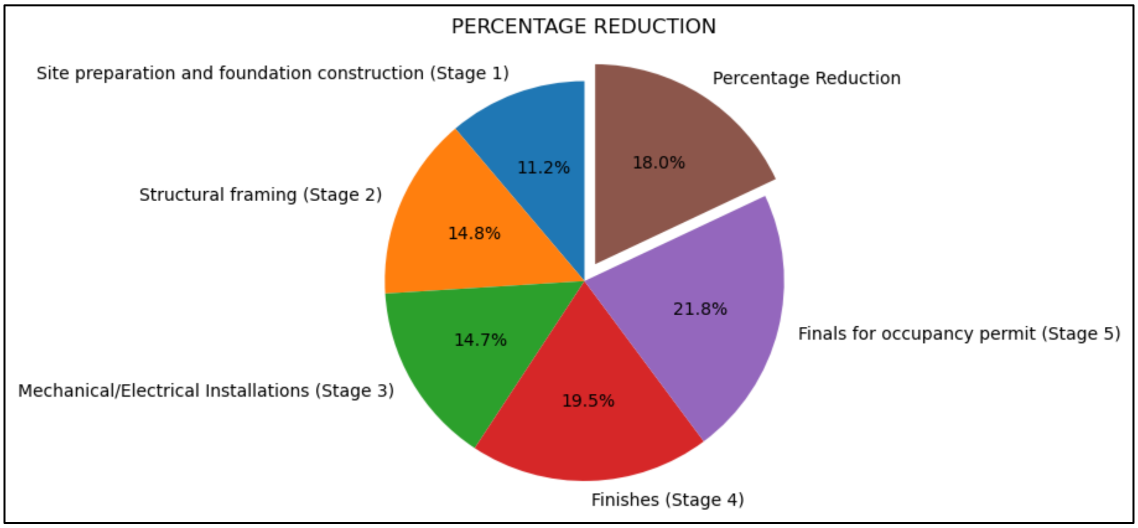


Figure 4.8 Construction workload reduction for panelized construction

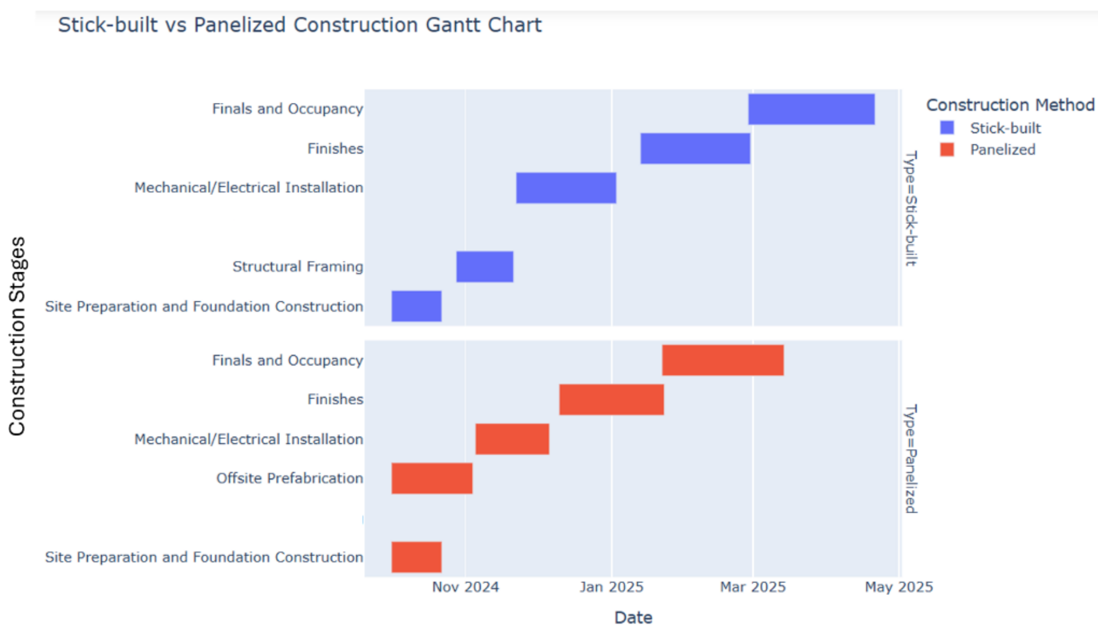


Figure 4.9. Gantt Chart Representation between Stick-built and Panelized Construction Method

4.3.2 Cost Analysis

Lopez and Froese (2016) conducted a cost analysis in Canadian dollars examining the cost per square foot of construction for the panelized construction method, which is a valuable tool for decision-makers to estimate similar construction projects and is suitable for this case study. The cost covers materials, offsite prefabrication, utilities, and onsite activities, except for site preparation and foundation construction. Therefore, the site preparation and foundation construction costs are extracted from the stick-built construction process case study in Table 4.1. Based on this analysis, the panelized construction cost is estimated at $232,743.80. In addition to the stick-built cost in Table 4.8, the minimum material cost is estimated at $100/sf in this study; also, an assumed indirect cost of 20% direct cost is added at each stage of the construction. Compared with the stick-built construction method analyzed in Table 4.8, a cost reduction of 24.89% was achieved for the panelized construction method, as shown in Figure 4.9.

Table 4.8. Stick-built Construction Cost Analysis (1750 ft^2)

Cost Breakdown	**Direct Cost**	**Cost (Direct + Indirect Cost)**
Site Preparation/Foundation Construction	24786.5	29,743.80
Onsite Framing	28479.20	34,175.04
Mechanical/Electrical Installations	13142.40	15,770.88
Finishes	24543.90	29,452.68
Finals and Occupancy	21428	25,713.60
Material cost ($100/sf)	-	175,000
Total:		**309,856**

Table 4.9. Panelized Construction Cost Analysis (1750 ft^2)

Cost Breakdown	**Cost**
Site Preparation/Foundation Construction ($24786.5 + Indirect cost (20% direct cost))	29,743.80
Manufactured elements ($74.60)	130,550
Customization ($4.80)	8,400
On-site interior work ($29.60)	51,800
Other on-site work and utilities ($7.00)	12,250
Total:	**232,743.80**

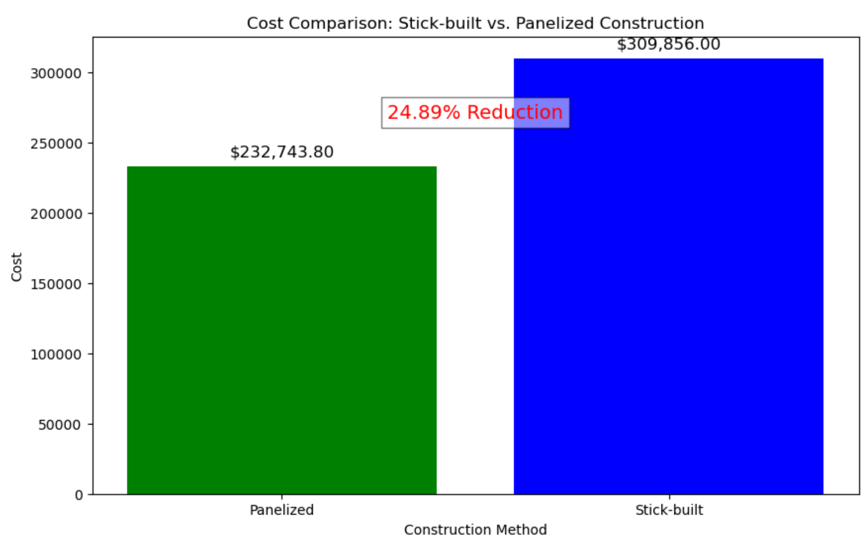


Figure 4.10. Panelized Construction Cost Reduction

4.3.3 Carbon Emission Quantification

The carbon emissions during the framing stage of stick-built and panelized construction methods are shown in Table 4.10. Li et al. (2014) quantified the carbon emissions of panelized and stick-built construction methods in kg/m², providing a means for assessing the carbon footprint of similar construction projects, which is suitable for this case study. For the stick-built construction method, the framing activity results in a total carbon emission of 2087.86 kg, as analyzed in Table 4.2. It is assumed the framing activities were done during the winter period, with a need for temporary heating. In addition to the framing activities, the carbon emissions from material waste and winter heating are quantified as 3.027 kg/m² and 27.834 kg/m² (Li et al., 2014), respectively. The carbon emissions include emissions from energy use of resources, transportation of workers, winter heating, and material waste. Based on this analysis, the panelized construction method (Table 4.11) has a percentage carbon emission reduction of 31.67, as represented in Figure 4.10.

Table 4.10. Stick-built CO_2 Emission Quantification (1750 ft^2 = 162.58 m^2)

Emission Element	**Carbon Emission (CO_2Kg)**
Structural Framing	2087.86
Material waste (3.027 kg/m^2)	492.13
Winter heating (27.834Kg/m^2)	4525.25
Total	**7105.24**

Table 4.11. CO_2 Emission Quantification for Panelized Construction Method (1750 ft^2 = 162.58 m^2)

Emission Element	**Carbon Intensity (kg/m^2)**	**Carbon Emission (CO_2Kg)**
Plant utility-Electricity	5.549	902.16
Plant utility – Natural Gas	2.680	435.71
Panel transportation	3.418	555.70
Factory workers	0.953	154.94
Site workers	0.959	155.91
Office staff	0.384	62.43
Site generators	1.338	217.53
Winter heating	10.793	1754.73
Wood waste	1.581	257.04
Vehicle usage	0.710	115.43
Crane usage	0.311	50.56
Fuel	1.186	192.82
	Total	**4854.96**

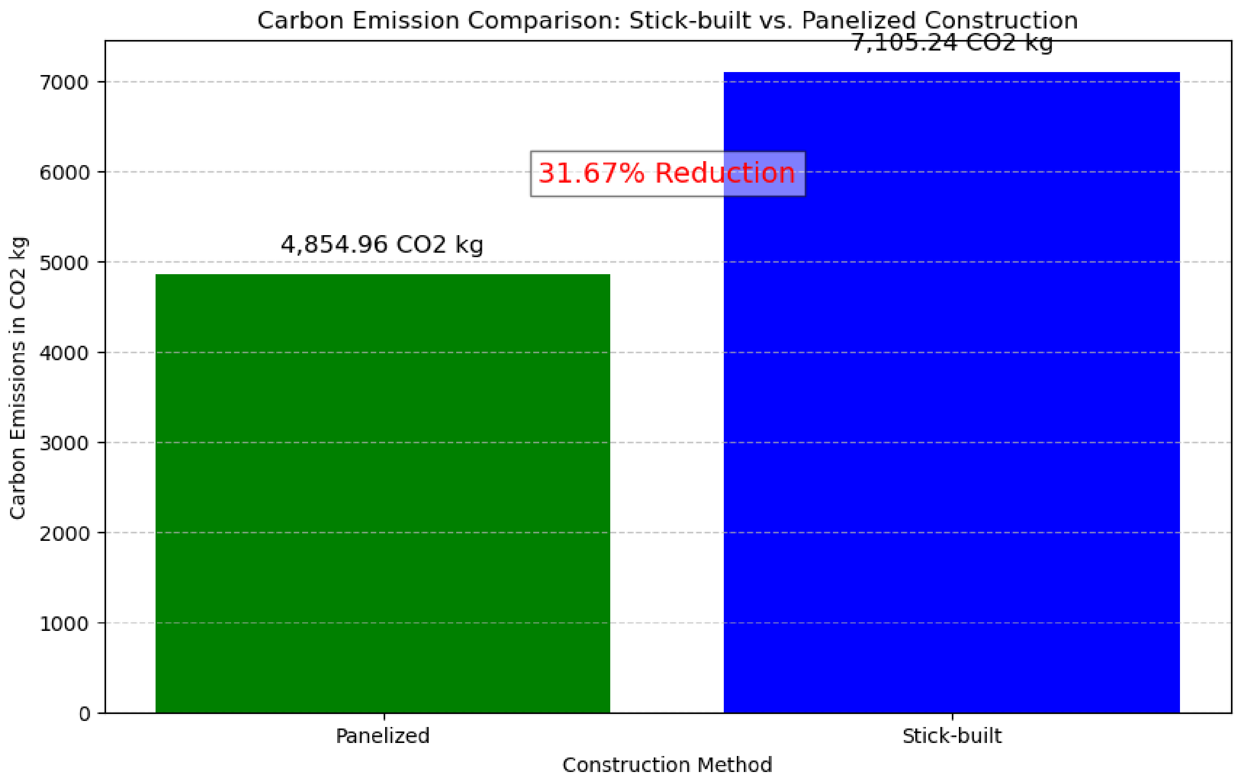


Figure 4.11. Panelized Construction Carbon Emission Reduction

CHAPTER FIVE

DISCUSSION

5.1 Findings and Recommendations

The primary objective of a construction project is to complete it within the designated timeframe and budget. However, numerous projects encounter unexpected challenges, such as weather disruptions, administrative issues, and errors leading to rework, resulting in project delays and budget overruns. In such circumstances, construction managers may accelerate the construction process by increasing the workforce and equipment to speed up activities. While this approach can reduce project duration, it invariably leads to higher direct costs encompassing labour, and equipment. An often-overlooked aspect of this acceleration is its environmental impact, specifically in terms of carbon emissions, as outlined in the scope of this study.

It is crucial to recognize that project objectives often conflict, including shortened duration, minimized costs, and reduced carbon emissions. Shortening project duration necessitates allocating more resources to increase work production rates, thus elevating costs and carbon emissions. Consequently, achieving an optimal solution where project duration is minimized within budgetary and environmental constraints requires careful consideration of the construction method adopted.

The onsite construction method, specifically the stick-built method in this study, can address time, cost, and carbon emission trade-offs by conducting a trade-off optimization between these objectives. This study employed a Non-dominated Sorting Genetic Algorithm (NSGA-II) to progressively shorten the project duration from 144 days to 94 days at minimal cost and carbon emissions. This was tested and compared with the manual approach of randomly crashing activities to achieve the same shortened project, but the manual approach proved to be expensive and environmentally unsustainable. The optimized approach allows for adjusting schedules and assigning resources to activities to shorten the project duration while being informed of the cost and carbon emissions outcomes, thereby avoiding overruns. This optimized approach also offers a technique for projects facing overruns, enabling them to meet predefined timelines and shorten project duration within the available budget and carbon emission constraints.

The panelized construction method involves transferring a portion of onsite activities, such as framing activities, to an offsite factory for prefabrication and transporting them to the construction site for installation. This method was tested by rescheduling onsite activities using Synchro Scheduler software so that while site preparation and foundation construction are ongoing, wall, floor, and roof elements are prefabricated and transported to the site once the site preparation and foundation construction are completed. This resulted in an 18% time reduction, leading to decreased costs and carbon emissions.

These two approaches, onsite trade-off optimization and offsite prefabrication can be considered to shorten project duration cost-efficiently and with less impact on carbon emissions. Offsite prefabrication, a solution to the labour shortage crisis in the on-site construction method, transfers a portion of the on-site workload to the factory, drastically reducing costs and carbon emissions. Additionally, offsite prefabrication ensures the predictability of schedules by avoiding uncertainties such as weather disruptions, site conditions, and administrative issues that can affect project timelines.

By adopting both the onsite trade-off optimization approach and the offsite prefabrication method, depending on the severity of the project in terms of time, cost, and carbon emissions, construction projects can be delivered more time and cost-efficiently, with less impact on carbon emissions, amidst the uncertainties and dynamism of construction projects. These practical solutions can significantly contribute to the field of construction project management.

5.2 Limitations and Future Works

The limitation of this study is that the data are not actual but rather a simulation and estimate of what a real construction project looks like based on previous studies. Another limitation is that it assumes time and cost are deterministic without accounting for uncertainties. To improve the model, future research should consider time and cost uncertainties. Additionally, trade-offs exist among various project objectives, such as time, cost, carbon emissions, quality, and safety, suggesting that future studies should focus on optimizing these trade-offs. Also, quantifying and monitoring the carbon emission impact of offsite construction is challenging due to the large-scale nature of project delivery. Thus, incorporating smart technologies to evaluate the environmental sustainability of offsite construction methods could be a valuable area for future research. BIM integrated with IoT technologies could automate the environmental impact assessment of offsite construction practices. Furthermore, future research could explore the use of BIM combined with Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). Integrating these with technologies such as RFID and GIS could enhance sustainability assessments for construction projects.

CHAPTER SIX

CONCLUSION

In conclusion, this research delved into the complexities of accelerating construction projects within constrained timelines while considering cost and environmental implications, using a single-family house construction project in Edmonton, Canada, as a case study. This study examines two strategies that can be considered to shorten project duration at a minimal cost and have less impact on carbon emissions. The first strategy uses a Non-dominated Sorting Genetic Algorithm (NSGA-II) to optimize the time, cost, and carbon emissions of a stick-built construction process. Input data consisting of a list of activities with their respective predecessors, cost, and carbon emissions at both normal and crash levels were fed into the model. The model generated an initial population from feasible solutions and evaluated their project duration, total cost, and carbon emissions. Solutions with minimum project duration, cost, and carbon emissions were classified as high fitness, while those with higher values were classified as low fitness. Through iterative selection, crossover, and mutation, the model produced optimal trade-off solutions for time, cost, and carbon emissions, consisting of a list of possible shortened project duration from the original project duration, which can be chosen based on project constraints such as budget and sustainability goals.

The second approach is a study on the offsite construction method, which involves transferring a portion of onsite construction activities to an offsite factory for prefabrication and then transporting the prefabricated panels or modules for installation. This approach provides greater schedule predictability by mitigating weather, site conditions, and crew availability issues. Offsite prefabrication also reduces build time, which can lower overhead supervision costs and utility expenses associated with extended construction periods. Additionally, it ensures higher quality control and less labour demand compared to traditional wood frame construction, enhancing operational efficiency. Based on the case study, adopting offsite construction will reduce the original project duration, cost, and carbon emission by 18%, 24.89%, and 31.67%, respectively.

Onsite trade-off optimization and offsite prefabrication are effective methods to shorten project duration more cost-efficiently and with less carbon impact. Offsite prefabrication addresses labour shortages by shifting part of the workload to a factory, significantly reducing costs and carbon emissions. By combining onsite trade-off optimization and offsite prefabrication, projects can be delivered more efficiently in terms of time, cost, and carbon emissions, even amidst construction uncertainties. These approaches can greatly enhance construction project management.

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