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Cradle to Gate Emissions Modeling for Scheduling of Construction Projects

Achintyamugdha Sharma, Ph.D. [1]*, Priyanka Deka, Ph.D. [2], Goutam Jois, Esq.[3], Umesh Jois[4], Pei Tang, Ph.D.[5]

[1] *JCMS, Inc., Mercerville, NJ 08619, USA,* E-mail address: asharma@jcms.com
[2] *JCMS, Inc., Mercerville, NJ 08619, USA,* E-mail address: pdeka@jcms.com
[3] *JCMS, Inc., Mercerville, NJ 08619, USA,* E-mail address: gjois@jcmsglobal.com
[4] *JCMS, Inc., Mercerville, NJ 08619, USA,* E-mail address: ukjois@jcms.com
[3] *JCMS, Inc., Mercerville, NJ 08619, USA,* E-mail address: ptang@jcms.com

Abstract: This paper presents an innovative way of integrating scheduling and project controls with the environmental impact of a construction project to track, monitor, and manage environmental emissions at the activity level. As a starting point, scheduling and project controls help monitor the status of a project to provide an assessment of the duration and sequence of activities. Additionally, project schedules can also reflect resource allocation and costs associated with various phases of a construction project. Owners, contractors and construction managers closely monitor tasks or activities on the critical path(s) and/or longest path(s) calculated through network based scheduling techniques. However, existing industry practices do not take into account environmental impact associated with each activity during the life cycle of a project. Although the environmental impact of a project may be tracked in various ways, that tracking is not tied to the project schedule and, as such, generally is not updated when schedules are revised. In this research, a Cradle to Gate approach is used to estimate environmental emissions associated with each activity of a sample project schedule. The research group has also investigated the potential determination of scenarios of lowest environmental emissions, just as project managers currently determine scenarios with lowest cost or time. This methodology can be scaled up for future work to develop a library of unit emissions associated with commonly used construction materials and equipment. This will be helpful for project owners, contractors, and construction managers to monitor, manage, and reduce the carbon footprint associated with various projects.

Key words: Scheduling, Project Controls, Life Cycle Analysis, Cradle to Gate

1. INTRODUCTION

The project schedule is a tool for monitoring of a construction project. According to PMBOK Fifth Edition by Project Management Institute, a Critical Path Method (CPM) based schedule model shows activities of the projects interlinked with appropriate relationships. As a result, planned dates, durations, key milestones and resources can be viewed and analyzed within the schedule model [1]. Through Control Schedule, the user is able to monitor the status of activities in the schedule, update forecast dates based on the dynamic changes in the project conditions and compare those changes to the baseline schedule [1]. As outlined in the Project Management Plan

(PMP) of a project, the project schedule determines when costs will be incurred [1, 2]. These costs are either directly loaded into the schedule model or monitored separately through key milestones in the schedule. Therefore, it is evident that a project schedule developed through the CPM technique and monitored throughout the life cycle of a project can provide the much-needed information about resources and costs associated with various activities and phases of the project. Through traditional waterfall-based methods, where the life cycle of a construction project is sequentially planned into various phases of design, construction, testing and commissioning and closeout, or through more dynamic and iterative agile techniques, a project schedule can paint an accurate picture of the status of activities of a project [3]. This enables agencies or owners, construction managers and contractors to make important decisions about resource allocation and cost control.

In addition to activity durations, resources and cost, there is also a need to monitor the emission of green-house gases (GHG) due to construction work that impact climate change. Prior studies have emphasized that concrete and steel are two major contributors of GHG [4]. Some studies have shown ways of monitoring GHG from construction projects, mostly emphasizing on the use of sustainable materials [4-7]. However, there is a lack of systematic monitoring of the impact of the construction industry towards climate change in the United States. After the United Nations Climate Change Conference (COP26) in 2021, the American Society of Civil Engineers (ASCE) released a communique urging government leaders to work with engineers, owners and other stakeholders of construction projects to create infrastructure to combat and adapt to climate change [8]. Therefore, there is a need to monitor and analyze GHG throughout the life cycle of construction projects. This will enable the stakeholders of a construction project to access vital information related to the environmental emissions responsible for climate change associated with each activity of the project schedule. The environmental emissions along with resources and cost associated with each project will be helpful for the stakeholders of a project to make responsible decisions. This is especially true for government funded projects for which the agencies are answerable to the taxpayers.

The primary goal of this study is to determine environmental emissions in Global Warming Potential (GWP) associated with each activity of the project schedule. Additionally, the study also aims to determine if changes in the sequence of activities result in different total emissions of the project. Finally, this study also aims to analyze temporal changes in GWP emissions throughout the life cycle of the project. In this paper, a methodology of tracking GWP emissions associated with each activity and phase of a construction project is presented. To the best of the authors' knowledge, this is the first time an integrated approach has been developed between project scheduling and GWP emissions at an activity level.

2. METHODS

2.1. CPM Schedule

In this paper, improvements to a fictitious train station is designed as the study project. The train station is shown in Figure 1. The scope of work includes the construction of platforms with overhead canopies on both the sides of the tracks, parking, inclined walkways on both platforms, and a skywalk connecting both the platforms with roof and handrails. Additionally, lights, electrical and communications components will also be installed. The existing station building will be retrofitted with the display and PA systems. Helical piles with depths of 30' are used as foundations for the platforms and inclined walkways R1 and R2. Three strip footings (6'x2'x2') each are used as foundations for the stairs S1, S2, S3, S4, S5, and S6. The skywalk is supported by two piers P1 and P2. These piers are supported by two piles each, consisting of $\frac{1}{2}$" thick steel rings with 24" outer diameter and a depth of 100’. A rebar cage of 6 #11 vertical bars supported by a spiral with #3 bar with a pitch of 3.5” is included in each pile, which is filled with concrete. The Skywalk is also equipped with Wheel-Chair Lift Enclosures (WCLE) W1 and W2 on both sides. Details of materials used in these structures can be found in Table 1 and Supplementary Information (SI).

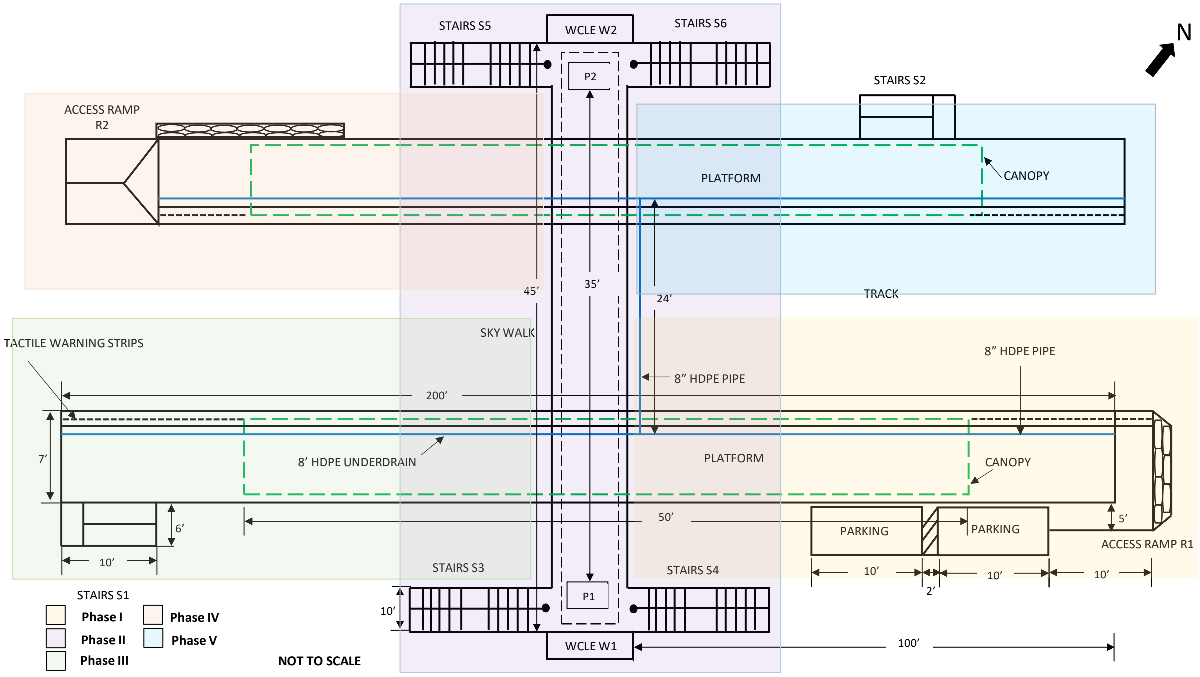

Figure 1. Fictitious train station project (Dimensions not to scale)

Table 1. Materials used in the Project

Code	Item	GWP CO2-eq / unit Material	Application
Steel Rebar	Steel reinforcement	6.28	Steel rebars in structural components
HG Steel	Hot-dipped Galvanized Steel	8.76	Helical piles, truss components in WCLE, deck girders for walkway
WP Steel	Welded Pipe Steel	8.87	Lighting, signage and canopy poles, handrail
TI-P	Concrete with Type I Cement (high C_3A+C_3S), no SCMs, smaller aggregate fraction	451.04	Strip footings, stairs
TI/II-P	Concrete with Type I/II Cement, no SCMs, smaller aggregate fraction	451.04	WCLE pad, piles
TI/II-FF	Concrete with Type I/II Cement, 20% replaced with Class F Fly Ash, smaller aggregate fraction	380.33	Pile caps for helical piles and Phase II, walkway deck
TI/II-FC	Concrete with Type I/II Cement, 30% replaced with Class C Fly Ash, smaller aggregate fraction	346.08	Parking and curb, foundation of lighting poles, signage poles, canopy poles

TI/II-P-2	Concrete with Type I/II Cement, no SCMs, larger aggregate fraction	444.92	Piers in Phase II
TI-FC-2	Concrete with Type I Cement (high C_3A+C_3S), 30% replaced with Class C Fly Ash, larger aggregate fraction	342.16	Pier caps
TIL-FC-2	Concrete with Type IL Portland Limestone Cement, 30% replaced with Class C Fly Ash, larger aggregate fraction	313.68	10" concrete slab on platform
HDPE	High Density Poly Ethylene	9.30	8" platform underdrain, 8" pipe connecting both sides, Tee connections, canopy hood, roof over walkway

Two scenarios of Critical Path Method (CPM) based schedule model are developed by using the commercial software Oracle Primavera P6 (SI). In Scenario 1, after start of construction, Phase I (SE Platform with Parking and Access Ramp will be completed. After Phase I is completed, Phase II (Skywalk and WCLE W1 and W2) and Phase III (SW Platform and Stairs) will be started simultaneously. After completion of Phase III, Phase IV (NW Platform and Stairs) will be executed, followed by Phase V (NE Platform and Stairs). The overall duration of Scenario 1 from Start of Construction to Substantial Completion is 18 months.

In case of Scenario 2, all the five phases will be completed in series with no overlap between any of them. The overall duration of Scenario 2 from Start of Construction to Substantial Completion is 28 months. In both the scenarios, Level of Effort (LOE) activities are added for site engineering, management and supervision, quality control and testing services, and the use of diesel generator (20 kW) to power the job site to last throughout the project.

2.2. Life Cycle Assessment (LCA)

The contribution of each activity in the schedule towards climate change is measured by Life Cycle Assessment (LCA). LCA is a tool to quantify the impact of a product or process on the environment [9]. In this study, a Cradle to Gate approach is adopted, which is an analysis from the acquisition of raw materials to the end of a process, which may not necessarily mark the end of life of the product [10]. The LCA methodology consists of four stages as outlined in ISO 14040: determination of scope and boundaries, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results [11]. *Materials:* For concrete, the functional unit is 1 m^3. The system boundary consists of production of cement, extraction of raw materials and production of aggregates and admixtures, transportation of materials, mixing at the batching plant, and unit volume of concrete being ready for delivery. Green Concrete LCA webtool is used for the concrete analysis [12]. For steel and HDPE, the functional unit is 1 kg. Default Global processes Open LCA commercial software program is used in this study for these materials [13]. *Fuel:* Environmental emissions leading to climate change due to gasoline use from passenger vehicles used by personnel in the project were calculated based on average fuel consumption, distance commuted, and emission factors defined by Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment. Similarly, the emissions due to diesel from backhoe, crane and concrete truck used in the project are calculated based on hourly diesel consumption and emission factors by IPCC [14].

3. RESULTS AND DISCUSSIONS

3.1. Emissions due to Materials and Fuel

In this study, a Cradle-to-Gate Life Cycle Assessment (LCA) approach is adopted to calculate environmental emissions associated with each activity of the project schedule. In Figure 2, a comparison is made between the emissions affecting climate change in terms of Global Warming Potential (GWP) for Scenarios 1 and 2. Compared to emissions due to fuel, GWP emissions due to the materials used in the project are higher (Figure 2a). This is also equal in case of both the scenarios. This is because of the same design, material quantities and types used in case of both the scenarios. Figure 2b shows that the GWP emissions for gas and diesel are higher in case of Scenario 2 compared to those of Scenario 1. In Scenario 1, the construction activities in Phase II consisting of the walkway bridge occur concurrently with those of Phase III (SW Platform and Stairs), Phase IV (NW Platform and ADA Ramp) and some activities of Phase V (NE Platform and Stairs). However, in case of Scenario 2, Phase III does not start until Phase II is completed. As a result, the overall project duration is increased from 546 calendar days to 843 calendar days. Additionally, the durations of the level of effort activities have also increased in case of Scenario 2 over those of Scenario 1 (Figure 3a). The role of the project management team for site engineering, management and supervision will not be completed until completion of the project. Additionally, testing and quality control services will be required throughout the completion of all the phases of construction. The personnel associated with these functions are required to commute to work longer in case of Scenario 2 compared to Scenario 1. As a result, gasoline consumption and resultant GWP emissions are higher in case of Scenario 2 compared to Scenario 1 (Figure 3b). Moreover, an increase in the overall duration of the project has also increased the hours of operation of generators required to power the job site. As a result, diesel consumption and resultant GWP emissions are higher in case of Scenario 2 compared to Scenario 1 (Figure 3b).

Out of the eight categories of items for which total emissions affecting climate change were calculated in terms of GWP, five (Concrete, Steel Rebars, HG Steel, WP Steel and HDPE) are due to materials used for construction, and three (Gas Commute, Diesel Equipment and Diesel Generator) due to fuel associated with construction. Among the materials used for construction, hot-dipped galvanized steel (HG Steel) has resulted in the highest GWP emissions (Figure 4a). This is mainly because of a high quantity of HG Steel materials used in this project (Figure 4b). As evident from Figure 4c, the bulk of the emissions in this category is due to HG Steel used in the helical piles used as foundations for the platform and helical walkways in Phases I, III, IV and V. Additionally, hot-dipped galvanized steel is also used in the bridge deck girders in Phase II.

In Figure 4b, it is seen that the quantity of HG Steel is 18.74% higher than that of steel rebars. However, in Figure 4d, it is seen that the GWP emissions of HG Steel is 65.55% higher than that of steel rebars. This effect is caused by a higher GWP CO_2-eq / unit material in case of hot-dipped galvanized steel (6.28) compared to that of steel reinforcement bars (8.76). Although both HG Steel and rebars are made of steel, the differences in their manufacturing techniques will influence their carbon footprint when used in construction projects. Therefore, this highlights a need to consider alternative materials by designers and government agencies to lower the GWP emissions from construction projects.

The different types of concrete used in this fictitious project is shown in Figure 5. Figure 5a shows the volume of each type of concrete used. Highest quantities are recorded for TI/II-FF and TIL-FF-2. The volume of concrete for TI/II-FF is 12.74% higher than that of TIL-FC-2. However, the resultant GWP emissions due to TI/II-FF concrete mixture is 36.70% higher than that of TIL-FC-2 concrete (Figure 5b). This is because of a lower GWP CO_2-eq/unit volume of TIL-FC-2 compared to TI/II-FF (Figure 5c). This is mainly because of a 30% replacement of portland cement with Class C fly ash in case of TIL-FC-2 [15]. Additionally, Type IL Portland Limestone Cement is created by grinding cement clinker with limestone. Overall, this cementitious combination and the resultant concrete are more environmentally sustainable compared to the others used in this project. This once again emphasizes the need to carefully consider the type of materials used for construction

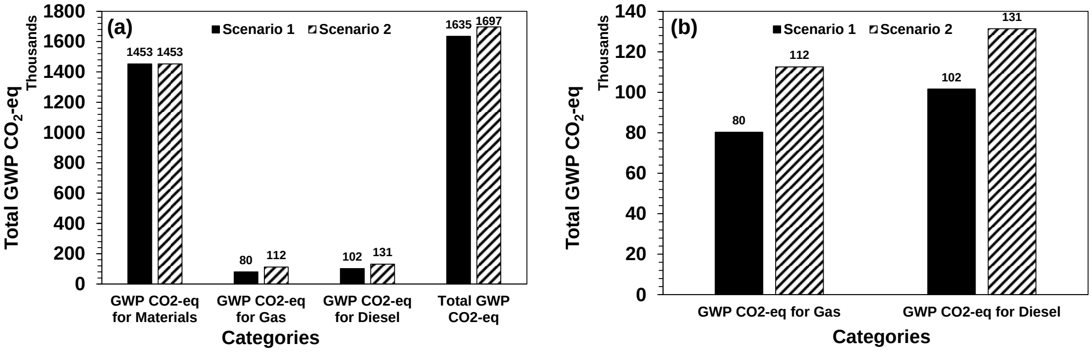

Figure 2. (a) GWP emissions due to materials and fuel, (b) GWP emissions due to fuel only

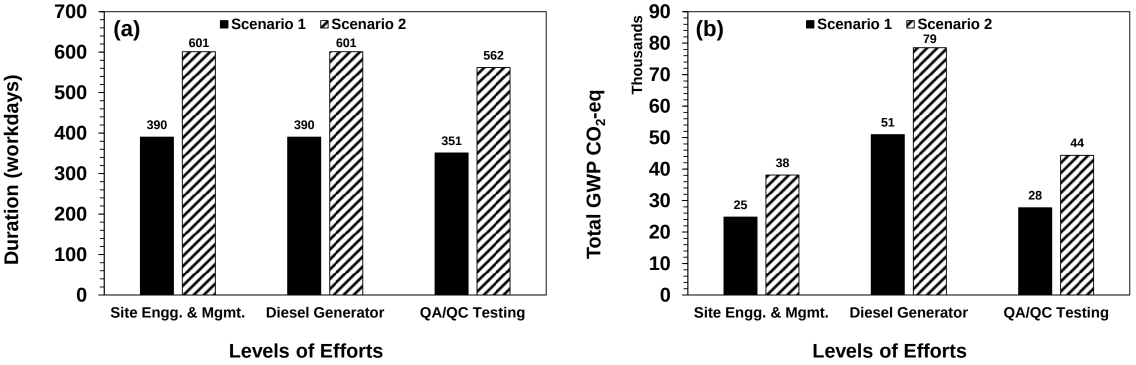

Figure 3. (a) Duration changes for LOE activities, (b) GWP emissions for LOE activities

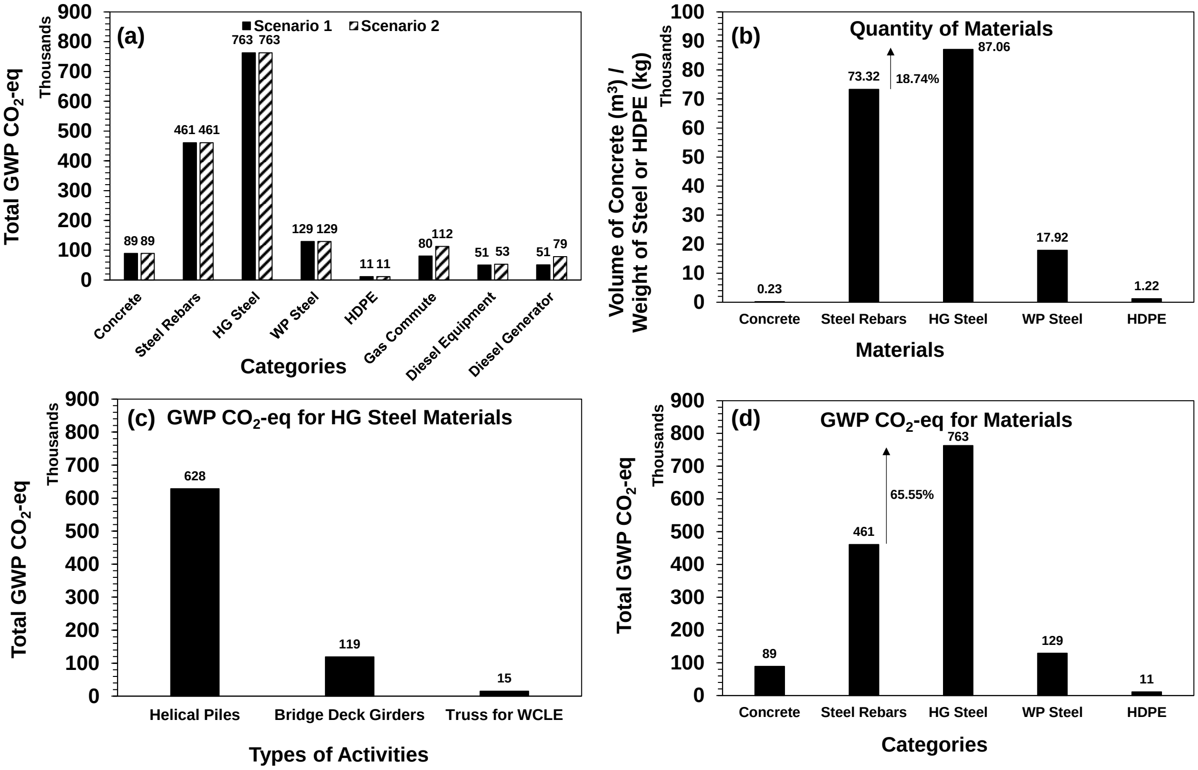

Figure 4. (a) GWP emissions due to different items (b) Quantity of different types of materials used, (c) GWP emissions due to different types of activities using HG Steel, (d) GWP emissions due to different types of materials used

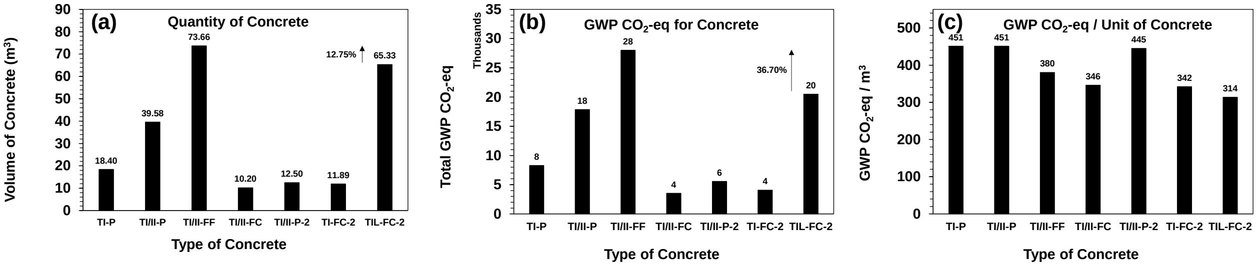

Figure 5. (a) Volume of different types of concrete used, (b) GWP emissions due to different types of concrete used, (c) GWP emissions per unit volume of concrete

3.2. Emissions Throughout Construction

Figure 6a and 6b show the monthly GWP emissions from start of construction to substantial completion of the project in Scenarios 1 and 2 respectively. In case of both the scenarios, highest emissions appear to be in June and July of 2022. Notably, the emission results in July 2022 in case of Scenario 1 are higher than that of Scenario 2. This is mainly because of an overlap between Phase II and Phase III in Scenario 1 (Figure 6c). The bulk of these emissions during summer of 2022 are due to materials used in Phases II and III. However, in case of Scenario 2, Phase III only starts after Phase II is complete (Figure 6d). Similarly, due to an overlap between the construction activities of walkway deck, handrails and roof in Phase II, and the construction activities in Phase IV, higher GWP emissions are observed in December 2022 in case of Scenario 1 compared to those of Scenario 2. However, this spike in GWP emissions in case of Scenario 1 is mostly from fuel. Prior researchers have determined that there is a relationship between the rate of GWP emissions and the impact on climate change in terms of global warming [16]. There may be some merit in investigating further if bulk environmental emissions within short periods of time pose a higher threat to climate change compared to similar emissions over longer periods of time. Therefore, the rate of environmental emissions due to construction activities should be taken into account.

4. CONCLUSIONS

This study uses a fictitious railway station project to estimate GWP in two different scenarios. Based on the assumptions about the project, the authors conclude that total GWP is higher in Scenario 2 over Scenario 1. Moreover, GWP emissions were analyzed temporally. In real-world situations, project owners, contractors, policy makers, and others, are regularly choosing between different scenarios based on the cost, resources, and duration. This study demonstrates that the effect of GWP can also be considered in the decision-making process. The following are the major conclusions of this study:

- The overall GWP emissions in Scenario 2 are higher than those of Scenario 1 due to fuel used during Level of Effort (LOE) activities like project management, quality control and site power. These LOE activities have higher durations in case of Scenario 2 compared to those in Scenario 1. As a result, the associated emissions are higher in case of Scenario 2 over those of Scenario 1.
- Different types of steel and concrete used in this study have different unit emissions, thereby emphasizing the need to consider alternative materials by the stakeholders.

- The rate of GWP emissions can impact climate change. Therefore, the project schedule should be carefully prepared keeping the rate of emissions in mind.
- Real-world decisions regarding various project scenarios often seek to minimize the cost, schedule, or duration of a project. This study demonstrates how GWP could be used as a consideration also.

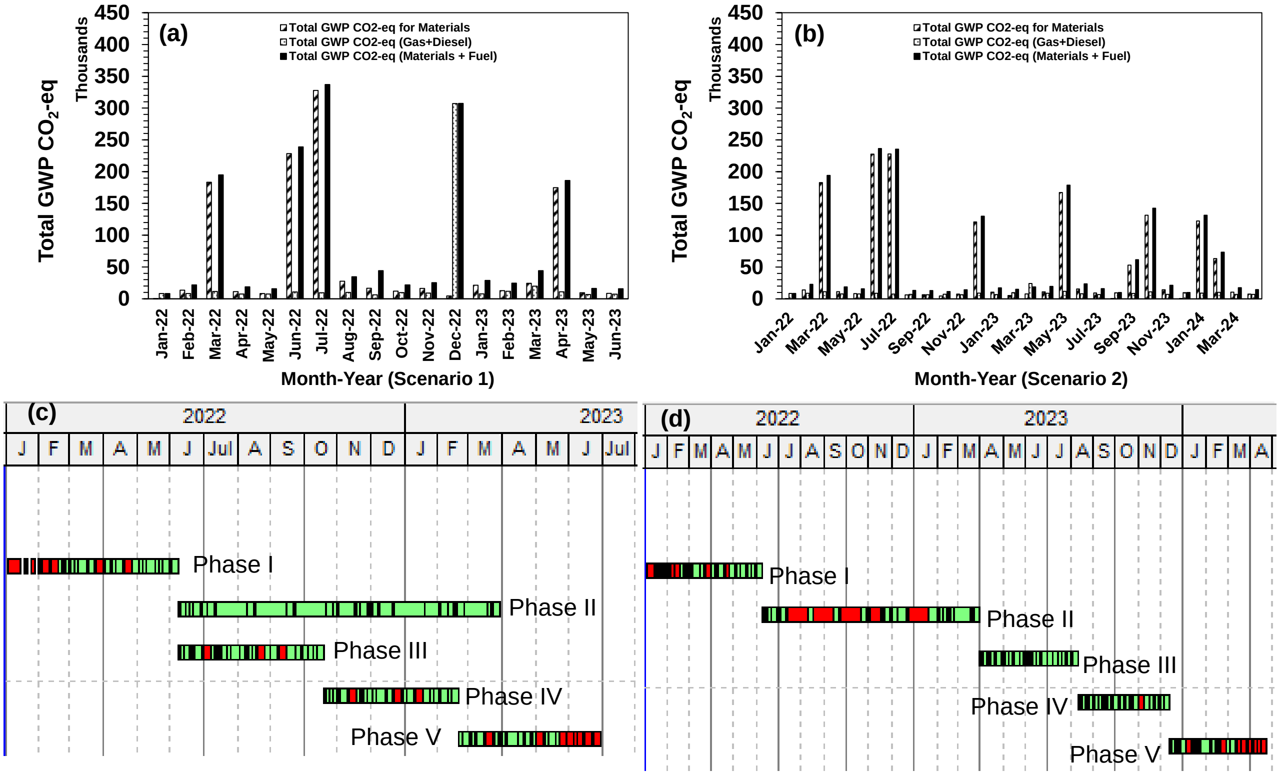

Figure 6. (a) GWP emissions throughout the life cycle of the project for Scenario 1, (b) GWP emissions throughout the life cycle of the project for Scenario 2; (c) Gantt Chart for Construction Phases for Scenario 1, (d) Gantt Chart for Construction Phases for Scenario 2

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