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USING SCHEDULE SIMULATION APPROACHES TO REDUCE GREENHOUSE GAS EMISSIONS IN HIGHWAY CONSTRUCTION PROJECT

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ABSTRACT

Scheduling approaches used in construction projects like Critical Path Method (CPM) and Linear Scheduling Method (LSM) are different ways of expressing resource, spatial and temporal constraints. Given the nature of the project, one or the other approaches may prove to be more suitable in representing project characteristics crucial to managing the schedule. This paper argues that different scheduling approaches have different impacts on project greenhouse gas (GHG) emissions regardless of the construction strategies used. The argument is investigated by applying two construction strategies to complete three as-planned highway construction schedules on a simulation platform. As-planned schedules are created from CPM, LSM, and an actual schedule. The quantities of GHG emissions were calculated and compared. The paper identified effective scheduling approaches in reducing GHG emissions. This research supports methods to reduce construction GHG emissions considering the trade-offs between cost, duration, and GHG emissions during the project planning and construction phase.

1 INTRODUCTION

The challenge posed by global climate change is motivating the investigation of strategies that reduce the life cycle GHG emissions (EPA 2006). According to U.S. Environmental Protection Agency, the construction sector accounts for 131 Million Metric Tons of CO2 Equivalent (MMTCO2Eq) of the U.S. industrial-related greenhouse gas emissions (EPA 2009). The GHG emissions from constructing and rehabilitating highway infrastructure make up 13.22% of the construction sector. While new construction material and technologies have received significant attention, there has been limited emphasis on studying the construction phase to understand how construction schedules and processes can be best managed to reduce carbon emissions.

Projects can produce different amount of GHG emissions when using various scheduling methods. At the process level, scheduling approaches like Critical Path Method (CPM) and Linear Scheduling Method (LSM) are different ways of expressing resource, spatial, temporal, and logical constraints that define the construction schedules. Given the nature of the project, one or the other approaches may prove to be more suitable in representing project characteristics crucial to managing the schedule. For example, in projects involving linear and continuous construction activities, LSM can more suitably express spatio-temporal sequencing relationships than the CPM approach. Previous research has shown that suitable scheduling approaches often lead to improved cost and duration performance (Tang, Mukherjee, and Onder 2010).

The objective of this paper is to investigate how construction schedule approaches can be managed to reduce project greenhouse gas (GHG) emissions. This paper argues that GHG emissions are directly affected by the scheduling approaches no matter what construction strategies are used. The argument can be investigated by analyzing historical onsite data. However, historical onsite data is usually unrepresentative because of the discrepancies in construction projects and construction environment. As an alternative,

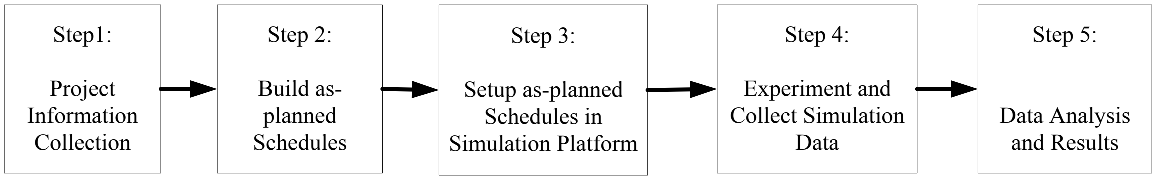

Figure 1: Methodology.

simulation experiment is used for more representative data collection. Specifically, two construction strategies are applied to complete a simulated highway construction project. The project as-planned schedules are created from CPM, LSM, and an actual onsite schedule. The quantities of GHG emissions, total cost, and completion duration in each schedule are recorded, calculated, and compared against that from other schedules. The significance of this research is that it investigates the impacts of alternative scheduling approaches on project GHG emissions. It seeds a conversation for considering trade-offs between cost and duration, and construction project emissions during the project planning and construction phase.

2 SCHEDULING TOOLS AND METHODOLOGY

Critical Path Method (CPM) and Linear Scheduling Method (LSM) are two commonly used scheduling tools in construction practice. They have different ways of expressing resource, spatial, temporal, and logical constraints that define the construction schedules. Linear Scheduling Method (LSM) is mainly used to schedule resources in highway, pipeline, high-rise building and rail construction projects, which are either repetitive and/or are linear in nature. LSM has the advantages in maintaining resource continuity over Critical Path Method (CPM) by scheduling the start date of an activity to ensure continuous flow of the resources. In contrast to CPM, this date is not necessarily the earliest possible start date of an activity. Researchers have found that LSM is more suitable than CPM in projects which have repetitive activities (Yamin and Harmelink 2001), while CPM is more suitable in representing discrete activities (Kallantzis, Soldatos, and Lambropoulos 2007). Kallantzis, Soldatos, and Lambropoulos (2007) found that LSM produces different controlling activity paths when compared to CPM. The differences in scheduling equipment usages, which in turn produce GHG emissions. Recent studies have shown that energy use and emissions of construction processes are primarily due to construction equipment usages, which can account for 50% of most types of emissions (Guggemos and Horvath 2006). It is therefore assumed that the differences in emissions due to alternative scheduling strategies are rooted in different equipment usages. This assumption is reasonable because alternative scheduling method does not impact material usage.

To explore the impacts of alternative scheduling approaches on GHG emissions, we need: (1) equipment usage data on the same or similar projects under different scheduling methods, and (2) a method to calculate the GHG emissions from the equipment usage data. This study proposes the use of a simulation to estimate equipment usage data (Figure 1). First, researchers collect project information, which includes uncertain events and associated possibilities, project activities and their estimated duration, usages of equipment, labor and material for each activity, unit cost of labor, equipment, and material, and unit space occupied by each material. The second step is to build as-planned schedules using different scheduling approaches. In the third step, the project information and as-planned schedules are input into the simulation platform. The simulation platform is called Interactive Construction Decision Making Aid (ICDMA), a general-purpose interactive simulation framework (Rojas and Mukherjee 2006). It simulates a construction project based on the as-planned schedule. During the simulation run, decision makers are presented with random external events thus allowing them to consider contingencies due to delay in schedule. The decision makers have to respond to those scenarios using different construction management strategies. ICDMA takes the response and updates the project. The consequences from the decisions result in new scenarios for subjects to respond. This process continues until the completion of the simulated construction project. At each simulation step, the data on project cost, duration, and equipment usage as well as the scheduling management decisions are

Table 1: Project activities and durations.

NO.	Activity Description	Duration
1	Strip Topsoil	8 days
2	Remove Concrete Pavement	15 days
3	Grade Subbase	19 days
4	Install Drainage	14 days
5	Place OGDC(Open Graded Drainage Course) Mainline	12 days
6	Pave East Bound (E.B.) Mainline	14 days
7	Place OGDC Ramps and Gaps	6 days
8	Pave E.B. Gaps and Ramps	8 days
9	Place Gravel Shoulder	4 days
10	Slope Grading and Restoration E.B.	17 days
11	Stripe to Open Pavement E.B.	3 days
12	Relocate Barrier Wall	10 days
13	Re-stripe West Bound	3 days
14	All Lanes Open	1 day

recorded. GHG emissions are calculated using equipment simulation data and equipment GHG emission rates developed in previous research (Cass and Mukherjee 2011).

3 CASE STUDY

The project is a 10.14 mile concrete pavement reconstruction project in Southeast Michigan. The project was planned to be completed in two years-the East Bound section in the first year and the West Bound section in the next year. This research studies the reconstruction of the East Bound section in the first year.

3.1 Project Information Collection

To simulate a construction project in ICMDA, the following project information is required: (1) a list of activities and the estimated duration for each activity; (2) material, labor, and equipment usages for each activity; (3) unit price of labor, equipment, and material along with unit space occupied by each material; (4) the uncertain events that might occur during the construction process; (5) as-planned schedule, which defines the constraints between activities.

(1) Activities and their durations. The East Bound section consisted of fourteen major activities as outlined in Table 3.1. The activities and duration were from the progress schedule, which was submitted to the Michigan Department of Transportation (MDOT) by the contractor before the project started (MDOT Form 1130). It should be noted that the scheduling approaches discussed in the next section used durations from this progress schedule.

(2) Labor, Equipment, and Material usages for each activity. The project proposal and construction management software called *FeildManager*^{TM} were used to determine the labor, equipment, and material usages for each activity. *FeildManager*^{TM} was construction management software required on all construction and rehabilitation projects by MDOT. Inspectors (on behalf of MDOT) record general site information, contractor personnel and equipment in use on site, and the material quantities used each day during the project in the Inspector's Daily Report (IDR). The IDR also contains equipment usage information. Researchers at Michigan Tech accessed the IDRs directly from the *FeildManager*^{TM} database. Pay-items in the project proposal were distributed into fourteen activities. One pay-item might consist of more than one type of material. Each pay-item is associated with several materials using information from *FeildManager*^{TM}. The labor crews needed to complete each pay-item were determined by estimating labor crews associated with the materials, using RS-Means 2009 cost data (Reed Construction Data. 2009). Once the labor crew on each pay-item was determined, the number of the labor crews and their contributions to each activity were determined by grouping similar labor crews.

Table 2: Uncertain events and probabilities.

NO.	Uncertain Events	Probability
1	Bad weather	0.20
2	Equipment failure or worker sick	0.12
3	Concrete testing failure	0.05

(3) Material unit price, equipment, and labor prices are obtained from the RS-Means, heavy construction cost data 2009. Because the pay-items contained one or more material, the unit price of pay-item was calculated by using the proportion of each material in the specific pay item. The information can be found in $FeildManager^{TM}$.

(4) Uncertain events. The frequencies of influential uncertain events were determined by investigating inspector comments in IDRs. Their probabilities were calculated by dividing frequencies by the duration. Bad weather and equipment failure were found to be the main causes responsible for interruptions because they had higher probabilities. Uncertain events are outlined in Table 3.1.

3.2 Project Scheduling

CPM, LSM, and an actual schedule used on site were investigated and their impacts on GHG emissions were estimated. Each scheduling approach determines an as-planned schedule for the highway construction project. The as-planned schedules are different from each other because each scheduling approach emphasizes different spatial and temporal constraints. Two types of constraints were used in the study, soft constraint and hard constraint. When soft constraints are violated, there is no immediate impact in the successive activities. When hard constraints are violated, the successive activities are impacted immediately because there is no free flow between them.

(1) Actual on site Schedule: Through correspondence with the primary contractor on this project, the activity constraints used in the construction process were identified. The constraints were originally measured in distances between activities. Because ICDMA uses temporal constraints, the space constraints, for example the length of highway that must separate equipment associated with any two activities, were converted to temporal constraints (Table 3.2). For example, the construction manager determined a distance of 1 mile to 3 miles distance between grading subbase and installing drainage, based on the frequency of drainage crossings. The maximum value was chosen in this case study. Since grading subbase had productivity of 0.53 mile/day ($= 10.14 miles/19 days$), it was decided that installing drainage activity should start six days($= 3 miles/0.53(mile/day)$) after the beginning of grading subbase. Based on the constraints identified in Table 3.2, the as-planned project duration was 47 working days.

(2) Critical Path Method: The application of Critical Path Method involved: (a) identifying all the activities in the project; (b) determining the constraints between activities; (c) estimating the duration for each activity; and (d) drawing critical path diagram, calculating the floats, and identifying the critical paths. Activities 2, 3, 4, 5, 6, 7, 8, and 9 were divided into three segments in order to better represent their logical and technique constraints. The minimum time required to finish this project was calculated in the critical path diagram (Figure 2). The as-planned duration was 66 working days. The critical activities were Activity 1, Activity 2-a, Activity 3-a, Activity 3-b, Activity 3-c, Activity 4-c, Activity 5-c, Activity 6-c, Activity 8-a, Activity 8-b, Activity 8-c, Activity 9-c, and Activity 11, Activity 12, Activity 13 and 14.

(3) Linear Scheduling Method: The application of linear scheduling involved the following steps: (a) identifying all the activities in the project; (b) estimating the production rate and completion time for each activity; (c) determining the technical and resource constraints between the activities; (d) determining the start and end date for each activity. To avoid two activities(assuming activity i precedes activity j) conflicting with each other in space, the minimum distance between them when the activity i starts was defined by equation 1.

$$D_{ij} \succcurlyeq \frac{1-P_j}{P_i} * L \tag{1}$$

Table 3: Constraints defined by actual onsite schedule.

Activity ID	Activity Description	Duration	Precedence	Constraints
1	Strip Topsoil	8 days	Begin	
2	Remove Concrete Pavement	15 days	1	1 day after the beginning of Activity 1 (soft)
3	Grade Subbase	19 days	2	2 days after the beginning of Activity 2
4	Install Drainage	14 days	2,3	6 days after the beginning of Activity 3
5	Place OGDC Mainline	12 days	2,3,4	2 days after the beginning of Activity 4
6	Pave E.B. Mainline	14 days	5	1 day after the beginning of Activity 5
7	Place OGDC Ramps and Gaps	6 days	4,5,6	7 days after the beginning of Activity 6(soft); after the completion of Activity 5
8	Pave E.B. Gaps and Ramps	8 days	7	0 days after the beginning of Activity 7
9	Place Gravel Shoulder	4 days	8	3 days after the beginning of Activity 8
10	Slope Grading and Restoration E.B.	17 days	9	1 day after the beginning of Activity 9(soft)
11	Stripe to Open Pavement E.B.	3 days	9	0 days after the completion of Activity 9
12	Relocate Barrier Wall	10 days	11	0 days after the completion of Activity 11
13	Re-stripe W.B.	3 days	12	0 days after the completion of Activity 12
14	All Lanes Open	1 day	12,13	0 days after the completion of Activity 1, Activity 13 and Activity 10

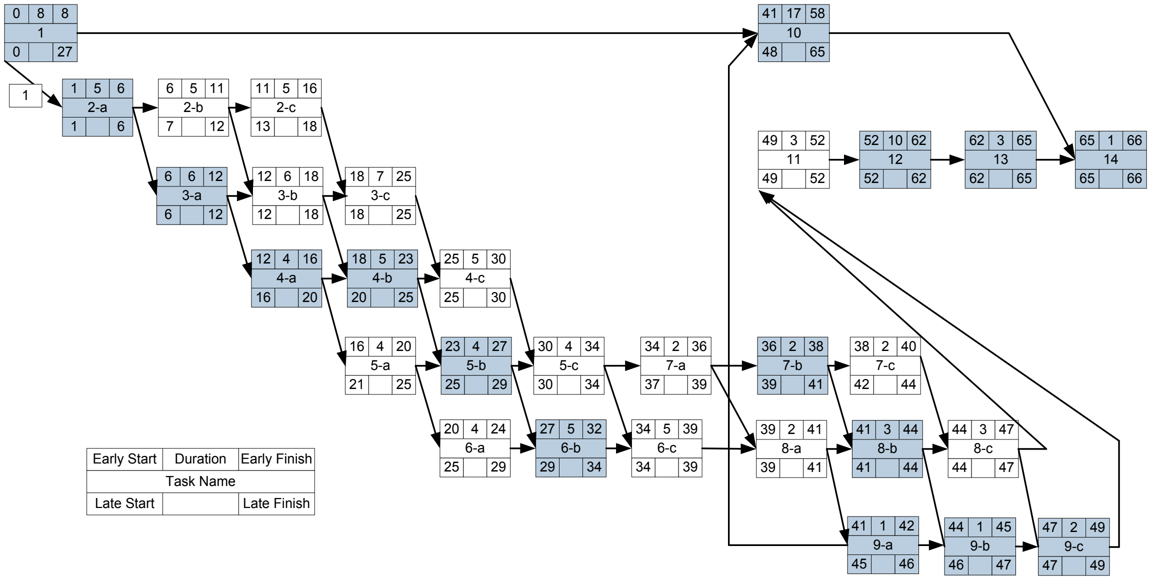

Figure 2: Critical path diagram.

Table 4: Constraints defined by linear scheduling method.

Activity ID	Activity Description	Duration	Precedence	Constraints
1	Strip Topsoil	8 days	Begin	
2	Remove Concrete Pavement	15 days	1	1 day after the beginning of Activity 1 (soft)
3	Grade Subbase	19 days	2	0 days after the beginning of Activity 2
4	Install Drainage	14 days	2,3	4 days after the beginning of Activity 3
5	Place OGDC Mainline	12 days	2,3,4	2 days after the beginning of Activity 4
6	Pave E.B. Mainline	14 days	5	0 days after the beginning of Activity 5
7	Place OGDC Ramps and Gaps	6 days	4,5,6	8 days after the beginning of Activity 6(soft); 0 days after the completion of Activity 5
8	Pave E.B. Gaps and Ramps	8 days	7	0 days after the beginning of Activity 7
9	Place Gravel Shoulder	4 days	8	0 days after the beginning of Activity 8
10	Slope Grading and Restoration E.B.	17 days	9	0 days after the beginning of Activity 9(soft)
11	Stripe to Open Pavement E.B.	3 days	9	0 days after the completion of Activity 9
12	Relocate Barrier Wall	10 days	11	0 days after the completion of Activity 11
13	Re-stripe W.B.	3 days	12	0 days after the completion of Activity 12
14	All Lanes Open	1 day	12,13	0 days after the completion of Activity 1, Activity 13 and Activity 10

L is the length of the project, which is 10.14 miles in this project. P_i and P_j represent the productivities of activity i and activity j. When activity j starts, D_{ij} is the minimum distance between them to avoid space confliction. For example, the distance between (Activity 4, Activity 2) was calculated in equation 2.

$$\frac{1-P(\text{Activity 3})}{P(\text{Activity 4})} * L \quad = \frac{1-0.53 \text{ mile/day})}{0.72 \text{ mile/day}} * 10.14 miles \quad = 2.67 miles \qquad (2)$$

It means activity 4 should start 2.67 miles after activity 3. This distance constraints are converted into temporal constrains as explained in the section of actual scheduling (Table 3.2). The as-planned completion duration is 44 working days.

3.3 Simulation Setup

To setup the project in ICDMA, a resource loaded as-planned schedule for the project is used as an input by the following steps:

- Input general information for material, labor and equipment. This includes material description, unit cost, whether it is perishable or not. For example, sand is not a perishable material but concrete is a perishable material. The daily price for using labor and equipment. The labor and equipment are assumed to work eight hours each day;
- Input material, labor and equipment usage information for each activity. This includes the set up of labor crews, involving the input of crew descriptions, the number and descriptions of labor and equipment, as well as the quantities of material for each activity;
- Set up as-planned schedules by inputting the constraints between the activities as identified in each scheduling approach;
- Setup risk environment by inputting uncertain events and associated probabilities.

Once the simulation is set up, multiple experiments are conducted. In each experiment, the simulated project is run by a decision maker (the author in this case) using a different schedule management strategy.

Table 5: Experiment design.

	Critical Path Method	Linear Scheduling	Actual onsite Schedule
Control Strategy	35 times	35 times	35 times
Crash Strategy	35 times	35 times	35 times

The goal of the experiment is to identify the role of the different schedule and schedule management strategies on project completion.

3.4 Experiment and Simulation Data Collection

A schedule management is a decision strategy defined as a guideline and direction that provides the basis for a family of decisions towards achieving a project outcome. Two strategies were created here to examine the impacts of different construction management scheduling approaches on GHG emissions regardless of the construction strategies. They are:

- Control Strategy: Control strategy manages the schedule by taking the minimum number of actions in dealing with interruptions. the situation that fewer actions are taken to deal with the interruptions. The implementation of Control Strategy is reflected from the following resource allocation policies: (a) labor crew policy: no extra worker is hired in case of illness; (b) equipment policy: no equipment is fixed on the same day it broke down; (c) space policy: space is firstly allocated to the critical activities; (d) no actions are taken when the schedule is falling behind.
- CatchUp Strategy: The objective of CatchUp Strategy is to manage the schedule to minimize the delay. The implementation of CatchUp Strategy is reflected from the following resource allocation policies: (a) labor policy: worker is hired and replaced in case of illness; (b) equipment policy: equipment is fixed by the mechanics immediately; (c) space policy: space is firstly allocated to the critical activities; (d) actions are taken to crash the schedule when the project is falling behind.

The experiment was designed as in Table 3.4. Two strategies were applied separately to each scheduling approach for 35 times. Because each simulation run is independent, it is assumed that when the number of experiments was very large, the results are normally distributed.

During each simulation run, the following data is collected: (a) total cost and duration to complete the project; (b) daily material, equipment, and labor usage. Once the equipment usage data is obtained, the GHG emission for each equipment was calculated by multiplying the equipment usage hours by the GHG emission rate of the equipment type. The method to determine GHG emission rates of the equipment can be found in previous work (Cass and Mukherjee 2011).

3.5 Data Analysis

Table 6 shows the average total cost, duration, and GHG emission in each scenario. In practice, the project was completed in 127 days and the cost was \$20,277,970.23. Different scheduling approaches did produce different average cost, duration, and GHG emissions regardless of the strategies. Now, the question is whether there is any statistical evidence to support the hypothesis that different scheduling approaches are producing significant different GHG emissions. If the answer is yes, it proves that there exist a appropriate scheduling method which can produce less project GHG emissions than other scheduling approaches. The one way analysis of variance (ANOVA) is an inferential statistical test to examine if any of several means are different from each other. ANOVA is a parametric test (Casella and Berger 2001) which assumes: (a) data is independent and normally distributed; (b) equality of the variances. In this simulation experiment, each run is independent and each group has 35 sets of data. Data in each group is assumed to be samples from normally distributed populations. However, the variances of the groups are unknown.

To perform ANOVA, the following steps are used:

Table 6: Average total cost, duration, and GHG emissions.

		Cost($)	Duration(Day)	GHG Emissions(kg CO2)
Control Strategy	CPM	27,377,124.30	81.89	103,603.40
	LSM	28,312,994.84	57.77	119,772.89
	Actual	28,294,098.93	62.06	118,252.41
CatchUp Strategy	CPM	26,921,849.80	66.69	102,872.20
	LSM	26,711,519.31	45.09	101,587.29
	Actual	26,988,490.67	47.66	107,914.46

- Determine null hypothesis: H0: μ(CPM)=μ(LSM)=μ(Actual), Where μ represents the mean GHG emissions;
- Determine alternative hypothesis: at least one of the means is different from the rest;
- Specify the significance level: α=0.05;
- Determine statistical test and calculate the appropriate statistic.

The test was carried out in SPSS 16.0 (Statistical Package for the Social Sciences). The inputs are GHG emissions calculated for each of the 35 runs for each strategy. The factors are three the scheduling methods. Homogeneity of Variance Test and Brown-Forsythe were used to test variance similarities. The homogeneity of variance is an important assumption in ANOVA. If this assumption turns out to be not applied, the Brown-Forsythe is used as an alternative version of the F statistic. The output of Test of Homogeneity of Variances (Table 7) indicated that the null hypothesis(equal variance exists) should be rejected in both strategies because the significance values are 0.000 and 0.001, which are less than the designated significance level of 0.05. Instead, Brown-Forsythe test is used, whose null hypothesis is that the groups have the same means. The results of Brown-Forsythe test indicated that the null hypothesis (the means are equal) should be rejected because the significance values are 0.000 and 0.030, both of which are less than the designated significance level of 0.05. This indicates that at least one of the scheduling methods is producing significant different amount of GHG emission during the construction phase.

Here, we can conclude that choosing an appropriate scheduling method can reduce the project GHG emissions. The next question was which scheduling approach should be chosen in this highway construction project? Post Hoc test is another statistical test that can be used to identify the differences between one group and the rest. The Games-Howell test was used because it does not assume equal population variances. The output of Games-Howell test (Table 8) showed that in control strategies, the significance values are 0.000 when comparing CPM against LSM and the actual schedule. Because the significance values are less than the designated significance level of 0.05, it indicated that CPM produced less GHG emissions than the other two scheduling approaches. In CatchUp strategy, the significance value is 0.619 when comparing LSM and CPM, which means LSM and CPM had similar performance in producing GHG emissions. When comparing actual schedule against LSM and CPM, differences are identified because the significance values are 0.009 and 0.049, which are less than the designated significance level of 0.05. The analysis showed LSM and CPM had better performance in reducing GHG emissions than actual scheduling.

4 DISCUSSION

Three scheduling approaches were used to investigate their impacts on project greenhouse gas (GHG) emissions. ANOVA tests show that alternative scheduling methods do have impacts on project greenhouse gas (GHG) emissions regardless of the construction strategies used. The data analysis identifies the most effective scheduling approach in reducing GHG emissions. For this highway construction project, CPM is a better strategy in reducing GHG emissions when using control strategy. When using CatchUp strategy, LSM and CPM had the best performance in reducing GHG emissions. CPM scheduling method tends to produces less GHG emissions regardless of the construction management strategies.

Table 7: Output of ANOVA.

Control Strategy	Test of Homogeneity of Variances: GHG Emissions	Levene Statistic	df1	df2	Sig.		
		14.970	2	102	0.000		
	ANOVA: GHG Emissions		Sum of Squares	df	Mean Square	F	Sig.
		Between Groups	5,580,836,349	2	2,790,418,175	31.546	0.000
		Within Groups	9,022,490,305	102	88,455,787		
		Total	14,603,326,654	104			
	Robust Tests of Equality of Means: GHG Emissions		Statistics	df1	df2	Sig.	
		Brown-Forsythe	31.546	2	73.221	0.000	
CatchUp Strategy	Test of Homogeneity of Variances: GHG Emissions	Levene Statistic	df1	df2	Levene Statistic		
		8.100	2	102	0.001		
	ANOVA: GHG Emissions		Sum of Squares	df	Mean Square	F	Sig.
		Between Groups	782,931,589	2	391,465,794	6.436	0.020
		Within Groups	6,203,665,272	102	60,820,248		
		Total	6,986,596,861	104			
	Robust Tests of Equality of Means : GHG Emissions		Statistics	df1	df2	Sig.	
		Brown-Forsythe	6.436	2	71.712	0.030	

Table 8: Output of Post Hoc test in ANOVA.

	(I) Scheduling Method	(J) Scheduling Method	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Control Strategy	CPM	LSM	-16,169.504*	2,199.51	0.000	-21,515.40	-10,823.57
		Actual	-14,649.004*	1,797.65	0.000	-19,003.53	-10,294.48
	LSM	CPM	16,169.48*	2,199.51	0.000	10,823.57	21,515.40
		Actual	1,520.48	2,663.54	0.836	-4,868.89	7,909.85
	Actual	CPM	14,649.00*	1,797.65	0.000	10,294.48	19,003.53
		LSM	-1,520.48	2,663.54	0.836	-7,909.85	4,868.89
CatchUp Strategy	CPM	LSM	1,284.91	1,371.22	0.619	-2,001.03	4,570.84
		Actual	-5,042.26*	2,083.37	0.049	-10,066.26	-18.26
	LSM	CPM	-1,284.91	1,371.22	0.619	-4,570.84	2,001.03
		Actual	-6,327.17*	2,050.77	0.009	-11,278.67	-1,375.66
	Actual	CPM	5,042.26*	2,083.37	0.049	18.26	10,066.26
		LSM	6,327.17*	2,050.77	0.009	1,375.66	11,278.67
*. The mean difference is significant at the 0.05 level. Dependent variable: GHG Emissions CPM represents critical path method; LSM represents linear scheduling method; Actual represents actual schedule.							

This study complements recent research that investigates ways of reducing GHG emissions using alternative materials and construction technologies. Though the results are project sensitive, the method proposed in this research is to help industry identify and develop better construction scheduling approaches to reduce GHG emission. In addition, this study identified the effective management strategies to reduce GHG emission regardless of the scheduling approaches. The data in Table 6 suggests that CatchUp Strategy is a better strategy over Control Strategy because of the decreases in average total cost, duration, and GHG emissions.

At the same time, the findings propose new challenges in construction management. Construction management strategy usually presents trade-offs between cost and duration. However, limited research has been done in incorporating GHG emissions management into construction management. Future work would address the relationships between the scheduling approaches, construction strategies, and the associated management objectives. In the long term, this research will support methods to reduce construction GHG emissions and enhance sustainability.

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