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Investigating the effect of construction management strategies on project greenhouse gas emissions using interactive simulation

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INVESTIGATING THE EFFECT OF CONSTRUCTION MANAGEMENT STRATEGIES ON PROJECT GREENHOUSE GAS EMISSIONS USING INTERACTIVE SIMULATION

By

Pei Tang

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

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This report, "Investigating the Effect of Construction Management Strategies on Project Greenhouse Gas Emissions Using Interactive Simulation," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN CIVIL ENGINEERING.

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To my loved,

Contents

List of Figures

List of Tables

Abstract

The challenges posed by global climate change are motivating the investigation of strategies that can reduce the life cycle greenhouse gas (GHG) emissions of products and processes. While new construction materials and technologies have received significant attention, there has been limited emphasis on understanding how construction processes can be best managed to reduce GHG emissions. Unexpected disruptive events tend to adversely impact construction costs and delay project completion. They also tend to increase project GHG emissions. The objective of this paper is to investigate ways in which project GHG emissions can be reduced by appropriate management of disruptive events. First, an empirical analysis of construction data from a specific highway construction project is used to illustrate the impact of unexpected schedule delays in increasing project GHG emissions. Next, a simulation based methodology is described to assess the effectiveness of alternative project management strategies in reducing GHG emissions. The contribution of this paper is that it explicitly considers projects emissions, in addition to cost and project duration, in developing project management strategies. Practical application of the method discussed in this paper will help construction firms reduce their project emissions through strategic project management, and without significant investment in new technology. In effect, this paper lays the foundation for best practices in construction management that will optimize project cost and duration, while minimizing GHG emissions.

Chapter 1

Introduction and Background

1.1 Introduction

According to the U.S. Environmental Protection Agency (EPA), the construction sector accounts for 131 Million Metric Tons of CO_2 Equivalent [1]. GHG emissions from construction and rehabilitation of highway infrastructure make up 13.22% of the emissions in construction sector [2]. The challenges posed by global climate change are motivating the investigation of strategies that reduce the life cycle GHG emissions of products, processes, and services. While novel construction materials and technologies have received significant attention [3, 4, 5, 6], there has been limited emphasis on studying the construction phase to understand if better management of construction processes can lead to reduction of project GHG emissions.

Close monitoring of a few highway construction projects shows that poor management during the construction phase is leading to significantly higher project GHG emissions. A detailed case study presented in this report illustrates the differences observed between the as-planned and the actual as-built project GHG emissions. Based on these observations, it is observed that unexpected interruptions and delays during the construction increase the total project GHG emissions. Often the underlying cause is the increased material and equipment use on site, as compared to the planned use. Recent research has shown that construction equipment usage accounts for 50% of most types of emissions and energy use of construction processes [7]. In addition, construction equipment was reported in 2005 to generate roughly 32% of all land-based non-road NO_X emissions and more than 37% of land-based Particulate Matter ($PM10$) [8]. In general, non-road equipment have higher emissions than heavy duty highway vehicles and automobiles [8]. In light of these observations and findings, this report aims to investigate the relationship between construction management strategies and increased project GHG emissions. The underlying assumption is that appropriately selected management strategies can better manage equipment usage. In turn, it is likely that such strategies can reduce project GHG emissions. However, as with cost and duration, there may be a trade-off involved between cost, duration and GHG emissions given different management strategies.

Therefore, this report introduces and implements a simulation based method that can be used to experimentally assess the relationships between project cost, duration, and GHG emissions for different management strategies. The first part of this report presents an empirical analysis of a highway construction project to illustrate the impacts of schedule delays on project GHG emissions. The second part of the report uses the same project in an experimental simulation platform to analyze the impact of different management strategies on project cost, duration and emissions. Project emissions for the planned project schedule (referred to as ‘as-planned emissions’) and each of the simulated outcomes (referred to as ‘as-simulated emissions’) are estimated and compared to the actual project emissions (referred to as ‘as-built emissions’). All emissions are estimated based on as-planned, as-simulated and as-built (observed) material and equipment use on the project site.

Traditionally, construction project planning considers trade-offs between project cost and duration. Project GHG emissions should become a third objective that needs to be explicitly considered, as well. The primary contribution of this report is that it introduces project GHG emissions as a third leg in the time-cost trade-off problem and investigates the relationships between project duration, cost, and GHG emissions. The proposed simulation method is expected to support project planning by identifying ways to optimize cost and schedule performance, while minimizing project GHG emissions.

1.2 Background

There are different ways of reducing GHG emissions of highway construction operations. The life cycle assessment (LCA) perspective supports the choice of products and processes that reduce GHG emissions during the different life cycle phases, namely raw materials mining, production and manufacturing, construction, service and end-of-life [9]. Current investigation of GHG emissions of the construction phase is limited to estimates of GHG emissions from transportation of materials to construction site and equipment use on construction sites [8, 7, 10]. A preliminary research has shown that there is a likely relationship between project delays and increased GHG emissions [11].

While decisions regarding use of alternative materials are made at the agency level, decisions to reduce GHG emissions during the construction phase are within the contractors' control. Sometimes such decisions place a financial burden on the contractors. For example, equipment larger than 175 HP made prior to 1996 tend to produce more GHG emissions than recent models [7]. This may require a contractor to consider a potentially expensive fleet update to achieve lower project emissions. In contrast, this study presents a method that advocates inexpensive improvements to planning and management to reduce emissions.

Methodologically speaking, the primary challenge of this research lies in directly observing the impact of different management strategies on project performance, for the same project and given the same conditions. Often the impacts of a particular strategy can be undermined by the occurrence of an unexpected external event - such as bad weather or a change order. The timing of unexpected external events - such as bad weather or equipment breaking down - plays a crucial role in deciding the ultimate fate of a strategy. This points to the application of statistical and simulation based methods that allow the assessment of alternative strategies. Discrete-event simulation has been used to predict GHG emissions at the pre-construction stage [12], allowing for a comparison of GHG emissions between alternative operations. However, the method did not consider the decision makers' responses to contingencies during the construction process. Therefore, this research uses a general purpose interactive simulation platform, the Interactive Construction Decision Making Aid (ICDMA) [13, 14]. It can be used as a test bed for multiple simulations, that are run under varying conditions and management strategies, for a given construction project. It allows decision makers to respond to project contingencies by (re)allocating resources during the simulation process. Previous research in ICDMA has established analytical techniques to assess strategies' performance in cost and schedule management [15, 16]. This report applies similar assessment techniques to assess the impact of alternative strategies on project GHG emissions.

The second methodological challenge is to validate the simulation outcomes. The as-built history is only a single instance of a project realization in reality. Comparing this single realization to the distribution of project histories generated from the simulated environment is not a true validation. However, it does provide a reality check on the reasonableness of the simulation outcomes and is a step in the right directions [17]. It is expected that the true validation of such methods lies in longitudinal simulations across multiple projects. In this research, this challenge is addressed by using the case study of a real highway construction project, that was closely observed and documented. This research compares the as-simulated outcomes to the actual as-built outcome observed from historical record for a real highway re-construction project. This provides a benchmark to compare the simulation outcomes. The next section describes the empirical study of the highway construction project in question.

Chapter 2

Empirical Analysis

The empirical analysis involved a ten-mile concrete pavement re-construction project in southeast Michigan. It studied the re-construction of the East Bound section in 2009. This section illustrates the gaps between as-planned and as-built project GHG emissions due to project delays. First, it provides how as-planned and as-built project data is collected. Second, it calculates as-planned and as-built project GHG emissions. Third, it identifies and analyzes the differences.

2.1 Data Collection

2.1.1 As-planned Data Collection

The as-planned project data was collected from the progress schedule (MDOT Form 1130) and the electronic proposal documents of the project. The progress schedule is a document submitted to the Michigan Department of Transportation (MDOT) by the contractor before the project starts. The form outlines construction activities (Table 2.1) along with proposed starting and end dates for each activity. When calculating the resource loaded as-planned schedule, the bid tab quantities were used. Activities defining the actual construction of the highway were identified. These activities were already associated with a division of work and section number as defined in the MDOT Standard Specifications for Construction [18]. Associated pay-items, which were in the electronic proposal of the project, were identified for each activity. The bid tab quantities, for each pay-item, represent the entire project, not just the mainline. Therefore, the ratio of as-built mainline quantities to that of the total quantities was applied to the bid tab quantities to calculate the as-planned quantities for each of the primary activities.

RS-Means 2009 cost data [19] was used to estimate the cost of the project so that a price could be ascribed to each activity. This was particularly true for estimating labor productivity, which was calculated by estimating labor crews associated with the materials assigned to each pay-item. The number of the labor crews and their contributions to each activity were determined by grouping similar labor crews. Though the unit price data could not be collected from the contractor, the expected activity durations, actual activity durations, and the quantity of work to be completed were available. Therefore, it is expected that the project price was reasonably estimated and, for the purpose of this analysis provides an useful benchmark to work with. The collected as-planned data supported the development of a resource loaded as-planned schedule.

2.1.2 As-built Data Collection

MDOT requires the use of software called $FieldManager^{TM}$ created by InfoTech Inc on all their construction and rehabilitation contracts. Inspectors (on behalf of MDOT) use the software to record general site information, contractor personnel and equipment, and postings of material quantities used on a daily basis. The software generates an Inspector’s Daily Report (IDR) that stores all this information. The following three fields of the IDRs were used to investigate the as built schedule.

1) General Site Information: This field defines the context within which the construction operations for the day were conducted. It includes the days and times work was performed, weather conditions on-site, general observations about site conditions, and site-specific location of the work being performed (including station information). Disruptive events, like bad weather, that adversely affected the project schedule were also reported.

2) Contractor Equipment: The contractor personnel and equipment inputs of the IDRs were critical to quantifying project GHG emissions. The types, hours of use, and make of construction equipment used on-site significantly impact a project's total GHG emissions. Equipment used throughout the project was recorded using this field. This information is very important as it is a crucial indicator of activity GHG emissions.

3) Material Posting: IDRs tracked progress on each pay-item as specified in the construction contract. It recorded the location, station information and quantities of materials associated with each activity. This data was used to develop an as-built record of procured and installed pay-items. Using as-built quantities in the calculation of life cycle impacts and GHG emissions is significantly more representative of project impacts compared to similar calculations done with estimated quantities.

The information in the IDRs was organized in a database and queried to extract as-built data associated with daily pay-item information. The material use for each activity on each day was established by associating pay-items with activities. The quantities of material installed, equipment used, station locations, and the inspectors' observations were queried for each day.

Besides investigating IDRs, the researchers visited on-site and corresponded with the contractor to ensure the accuracy of the data collected through $FieldManager^{TM}$. Equipment were checked to ensure that equipment posted in IDRs matched equipment actually being used on-site. The fuel usage and fleet data from the contractor was collected to identify equipment specifics. All these collected items validate and support the data collected through $FieldManager^{TM}$ and direct reports from contractors. Through correspondence with the primary contractor on this project, the as-planned schedule and the actual activity constraints in the construction process were obtained.

2.2 Project GHG Emission Estimation

Project GHG emissions are estimated for materials associated with the pay-items and the equipment used on construction sites. The co-authors present a detailed analysis and illustration of how GHG emissions are calculated for pavement construction using LCA tools [10]. The Economic Input Output-Life Cycle Assessment (EIO-LCA) and SimaPro (using the Eco Invent database) were used to estimate the impacts of materials through the life cycle stages of extraction/mining, transportation, and manufacturing. The data collected through $FieldManager^{TM}$ was used to develop material, and fuel inventories, which in turn were used as an input to the LCA tools. This method is not being described in this section to avoid repetition.

When assessing equipment GHG emissions, as-planned and as-built equipment usage per

Table 2.1
Activities' information and constraints between them

Activity ID	Activity description	Duration	Precedence activities	Spatial distance between activities
1	Strip topsoil	10 days		n/a
2	Remove concrete pavement	30 days	1	0.5 to 1 miles between stripping topsoil and concrete pavement removal
3	Grade subbase	26 days	2	n/a
4	Install drainage	18 days	2,3	0.5 to 1 miles between installing drainage and concrete pavement removal; 1 to 3 miles between installing drainage and grade subbase
5	Place open graded drainage course (OGDC) mainline	18 days	2,3,4	1 miles between grade subbase and placing OGDC mainline
6	Pave east bound mainline	32 days	5	1 miles between placing OGDC mainline and paving east bound mainline
7	Place OGDC ramps and gaps	8 days	4,5,6	3 to 5 miles between paving east bound mainline and placing OGDC ramps and gaps
8	Pave east bound gaps and ramps	9 days	7	n/a
9	Place gravel shoulder	4 days	4	2 to 3 miles between paving east bound gaps and ramps and placing gravel shoulder
10	Slope grading and restoration east bound	26 days	9	0.5 miles between placing gravel shoulder and slope grading and restoration east bound
11	Stripe to open pavement east bound	3 days	9	10 miles between placing gravel shoulder and striping to open pavement east bound
12	Relocate barrier wall	10 days	10	10 miles between striping to open pavement east bound and relocating barrier wall
13	Re-stripe west bound	3 days	12	n/a
14	All lanes open	1 days	12,13	n/a

working day is required. The make, model, type, and horsepower characteristics of each equipment type were identified in the fleet information provided by the contractor. Using Equation 2.1, the hourly GHG emissions were estimated for each equipment type.

$$\text{Hourly Equipment GHG Emission Rate} = O_t * L_f * HP * C_F * \varepsilon \tag{2.1}$$

Where O_t = Operating time factor, L_f=Average loader factor, HP =Average rated horsepower, C_F = Fuel consumption rate $(Gal/(HP*hr)$, and ε = GHG emission rate $(lbs\,CO_2/Gal)$. The following assumptions were made:

- † Operating time factor O_t = 45 minutes/hr (0.75)
- † Fuel consumption rate C_F = 0.04 $(Gal/(HP*hr)$ [20]
- † GHG emission rate ε = 22 $(lbs\,CO_2/Gal)$ [21]

Average loader factor and rated horsepower for equipment were obtained from Roadway Construction Emissions Model [22]. Table 2.2 shows the hourly GHG emission rate for each equipment type.

Table 2.2
Hourly GHG emissions rate for equipment

NO.	**Equipment**	**Load Factor**	**Avg. HP**	**GHG Emission Rate** $(lbs\, CO_2/hr)$
1	Aerial Lifts	0.46	60.49	9.50
2	Air Compressors	0.48	105.67	17.31
3	Bore/Drill Rigs	0.75	291.19	74.55
4	Cement and Mortar Mixers	0.56	10.32	1.97
5	Concrete/Industrial Saws	0.73	18.61	4.64
6	Cranes	0.43	399.10	58.58
7	Crawler Tractors	0.64	146.89	32.09
8	Crushing/Proc. Equip.	0.78	142.34	37.90
9	Excavators	0.57	168.08	32.70
10	Forklifts	0.30	144.59	14.81
11	Generator Sets	0.74	549.20	138.73
12	Graders	0.61	173.71	36.17
13	Off-Highway Tractors	0.65	266.98	59.24
14	Off-Highway Trucks	0.57	478.94	93.18
15	Other Construction Equip.	0.62	74.69	15.81
16	Other General Industrial Equip.	0.51	238.06	41.44
17	Other Material Handling Equip.	0.59	190.84	38.43
18	Pavers	0.62	100.23	21.21
19	Paving Equip.	0.53	103.70	18.76
20	Plate Compactors	0.43	8.00	1.17
21	Pressure Washers	0.60	0.91	0.19
22	Pumps	0.74	53.46	13.50
23	Rollers	0.56	95.40	18.24
24	Rough Terrain Forklifts	0.60	93.41	19.13
25	Rubber Tired Dozers	0.59	357.06	71.91
26	Rubber Tired Loaders	0.54	157.00	28.94
27	Scrapers	0.72	312.50	76.80
28	Signal Boards	0.78	20.16	5.37
29	Skid Steer Loaders	0.55	43.87	8.24
30	Surfacing Equip.	0.45	361.88	55.59
31	Sweepers/Scrubbers	0.68	91.14	21.15
32	Tractors/Loaders/Backhoes	0.55	107.98	20.27
33	Trenchers	0.75	62.76	16.07
34	Welders	0.45	45.43	6.98
35	Work Trucks, Haul Trucks Semis	0.75	250.00	64.00
36	Generator	0.75	20.00	5.12

2.3 Description of As-built Progress and Uncertainties

The scope of this analysis is to investigate project GHG emissions associated with the highway re-construction process, so activities are chosen that are representative of typical highway construction projects. These activities are referred to as primary activities. Traffic control activities were excluded because they may vary significantly from project to project, and are not strictly part of the highway construction processes. Pavement removal, earthwork and paving operations are considered as primary activities because they are common to all highway projects. For each primary activity, a controlling pay-item was identified to represent the activity. They were:

- † Primary Activity: Remove Concrete Pavement, Controlling Item: Pavement Removal
- † Primary Activity: Grade Subbase, Controlling Item: Station Grading
- † Primary Activity: Install Drainage, Controlling Item: Underdrain Pipe
- † Primary Activity: Place Base Material, Controlling Item: Geotextile Separator
- † Primary Activity: Pave Mainline, Controlling Item: Non-reinforced Concrete

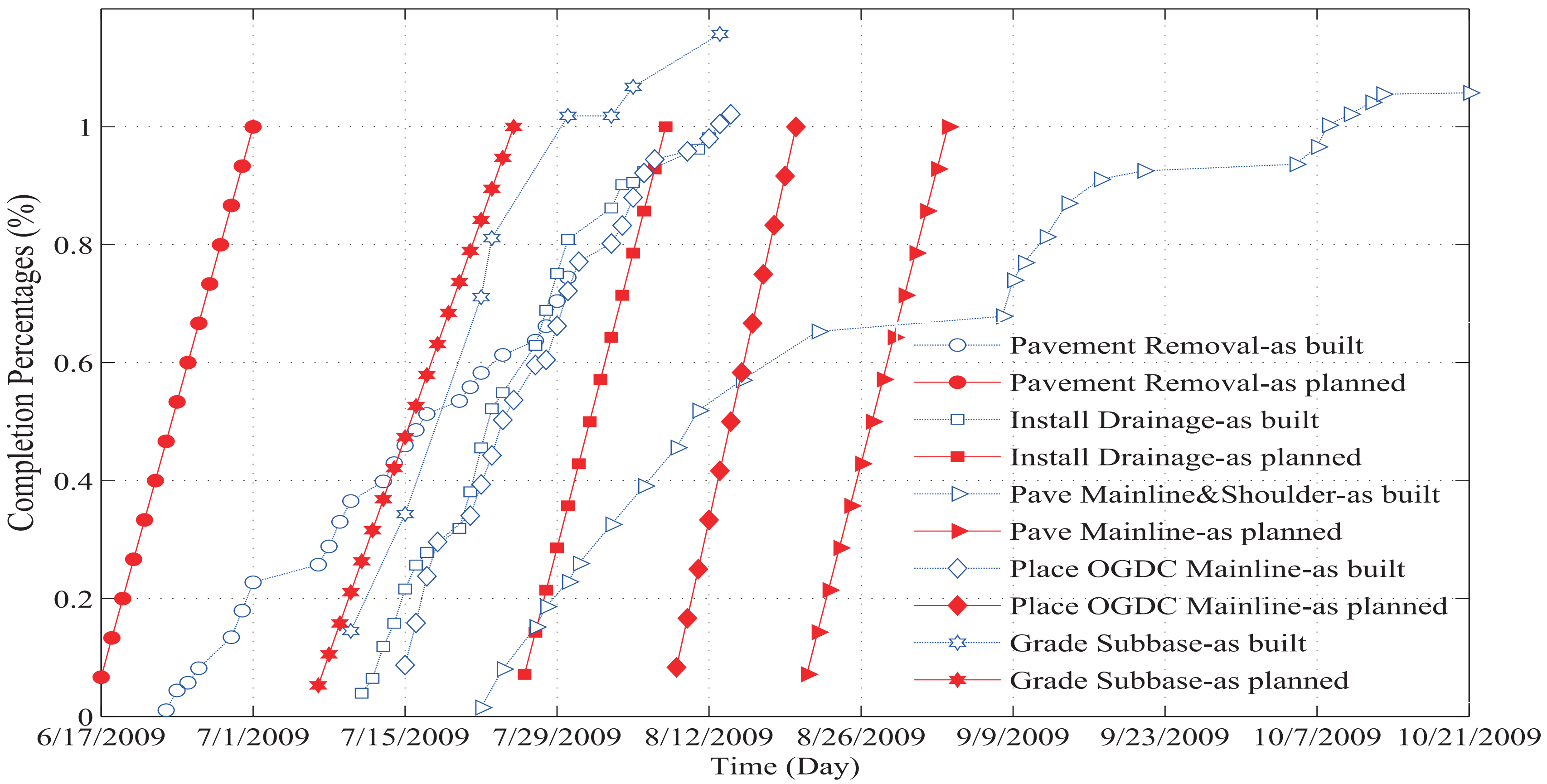

Figure 2.1: As-planned v.s. as-built progress schedule

Each activity was assigned controlling equipment, as follows:

- † Remove Concrete Pavement: Pavement Breaker
- † Grade Subbase: Grader
- † Install Drainage: Trencher
- † Place Base Material: No equipment was required by the controlling item
- † Pave Mainline: Concrete Paver

Figure 2.1 shows the as-planned and as-built completion rates for each activity. The X-axis represents the time and the Y-axis represents the cumulative completion percentages. Project activities turned out to be performed differently from the as-planned schedule. Pavement removal activity started later than as planned. Delays in pavement removal activity did not affect the grade subbase activity starting on time. The rest activities started earlier than planned, but mainline paving activity took five times longer than the as-planned to complete the job. IDRs from $FieldManager^{TM}$ showed that the activities were interrupted by: (1) seasonal rains, which added to the flooding on site and brought all operations to a stand still, (2) equipment break down, worker illness or accidents, which decreased activities' productivity, (3) the concrete test failure, which interrupted the progress because an extra test was required, (4) traffic accidents on the construction site, (5) rework in pavement removal between the fifth and the sixth mile points, caused by the ground water flooding due to agitation of the soil during the pavement removal and

Table 2.3
Controlling pay-item quantity comparison

Consumption based on Controlling Item (Quantities)					
Primary Activity	**Controlling Item**	**Unit**	**AsPlanned Qty**	**AsBuilt Qty**	**% Change**
Remove Concrete Pavement	Pavement Removal	Syd	249065.99	185431.46	-25.55
Grade Subbase	Station Grading	Syd	448.67	519.32	15.75
Install Drainage	Underdrain Pipe	Ft	110007.45	107945	-1.87
Place Base Material	Geotextile Separator	Syd	213236.10	217750.15	2.12
Pave Mainline & Shoulder	Non-reinforced Concrete	Syd	217358.96	229876.19	5.76

the presence of heavy equipment on site. Besides the disruptive events, the discontinuous gaps along the project also increased the duration. For example, as shown in Figure 2.1, the mainline paving activity was halted for two weeks on August 20, 2009 and September 23, 2009.

2.4 Gaps between As-planned and Actual As-built GHG Emissions

Compared to the as-planned quantities of controlling pay-item (Table 2.3), grading subbase activity, placing base material activity, and paving mainline and shoulder activity actually consumed respectively 15.75%, 2.12%, and 5.76% more pay-items. Removing existing concrete pavement activity and installing drainage activity used 25.56% and 1.87% fewer pay-items than planned. Paving the mainline and shoulder activity produced 800 mt of

Table 2.4
Controlling pay-item GHG emissions comparison

Production of GHG Emissions from Controlling Pay-item				
Primary Activity	**Controlling Item**	**AsPlanned**	**AsBuilt**	**% Change**
		GHG Emissions ($mtCO_2eq$)	**GHG Emissions** ($mtCO_2eq$)	
Remove Concrete Pavement	Pavement Removal	NA^1		
Grade Subbase	Station Grading	NA^1		
Install Drainage	Underdrain Pipe	45	44.1	-2
Place Base Material	Geotextile Separator	379	387	2.11
Pave Mainline & Shoulder	Non-reinforced Concrete	13600	14400	5.88
NA^1: No consumption of virgin materials				

extra emissions (Table 2.4), which is 5.88% more than planned. Installing drainage activity produced 2% fewer emissions than planned and placing base material activity produced 2.11% more than planned. Material that can not be stored indefinitely should partly account for the extra material usage. For example, concrete was disposed if it was not used on the day it was produced.

Except the grading subbase activity, high exceedance percentages were found when comparing the as-built equipment emissions to the as-planned (Table 2.5). Pavement breaker produced 60% extra emissions due to rework and non-rework disruptions. The trencher and the concrete paver respectively produced 57.14%, and 85.71% more emissions mainly because of non-rework disruptions identified as bad weather, equipment break down, worker sickness, on-site accidents, and concrete test failure.

Rework has weaker influences than non-rework related disruptive events in this project

Table 2.5

Controlling equipment GHG emissions comparison

Production of GHG Emissions from Controlling Equipment Operations							
Primary Activity	**Contr. Equip.**	**Contr. Item**	**AsPlanned**	**AsBuilt**	**AsPlanned**	**AsBuilt**	**% Change**
			# of working days	**# of working days**	**GHG emissions** $(mtCO_2eq)$	**GHG emissions** $(mtCO_2eq)$	
Remove Concrete Pavement	Pavement Breaker	Pavement Removal	15	24	5.66	9.06	60.00
Grade Subbase	Grader	Station Grading	19	8	14.87	6.26	-57.89
Install Drainage	Trencher	Underdrain Pipe	14	22	5.29	8.31	57.14
Place Base Material	NA^1	Geotextile Separator	NA^1				
Pave Mainline &Shoulder	Concrete Paver	Non-reinforced Concrete	14	26	11.63	21.60	85.71
NA^1:Geotextile Separator placed by manual labor (4-person crew)							

because it only influenced the pavement removal activity. Non-rework related disruptive events assumed more responsibilities for the project delays and extra GHG emissions. When considering the as-built GHG emissions from all the equipment and material instead of the controlling ones, a larger amount of project emissions were found due to the non-rework related disruptive events. Therefore, the pertinent questions raised are: (1) is it possible to reduce project GHG emissions through better construction management strategies, and (2) what is the relationships between project total cost, completion date, and GHG emissions? To answer these questions, the next section introduces an interactive simulation experiment, from which decision makers can explore and compare the performance of alternative construction management strategies.

Chapter 3

Simulation Experiment

The experiment is carried out on the interactive simulation platform of ICDMA [14]. ICDMA simulates a construction project based on its resource loaded as-planned schedule and project environment. The resource loaded as-planned schedule provides a baseline to complete the project, and the project environment is defined by the possible disruptive events that deviate the project from the as-planned schedule. During the simulation run, decision makers are presented with random external events, thus allowing them to respond to disruptions. The decision makers apply a specific strategy to manage the contingencies by (re)allocating resources. ICDMA takes the response and updates the project. The consequences from the decisions result in new scenarios for decision makers to respond to. This process continues until the completion of the simulated project. The simulation experiment is expected to identify appropriate management strategies to reduce project

GHG emissions.

3.1 Simulation Project Setup

To set up the highway reconstruction project in ICDMA, a resource loaded as-planned schedule and construction environment are required. The following process is used.

† Input general information for material, labor and equipment. This includes material description, unit cost, and material information such as - whether the material can be stored indefinitely not.

† 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 quantities and types of labor and equipment, and the quantities of material for each activity.

† Input the constraints between the activities. This includes precedence relationships and activity/resource constraints driving the schedule.

† Set up risk environment by defining disruptive events, associated probabilities, and their consequences on the project (Table 3.1). The disruptive events were recorded in IDRs and their probabilities were defined based on occurrence frequencies. Bad weather, equipment failure, worker illness, and concrete test failure were found to be

the three most influential events that should be responsible for project delays.

Spatial constraints between activities, such as the length of highway that must separate equipment associated with any two activities, were measured in distances by the primary contractor (Table 2.1). They were converted to temporal equivalents because ICDMA uses temporal constraints. For example, the construction manager required a distance of three miles between the sub-base grading activity and the drainage installation activity, depending on the frequency of drainage crossings along the mainline. Sub-base grading operation has a productivity of 0.53 mile/day ($= 10.14\ miles/19\ days$). Therefore, it was decided that the drainage installation activity would start six days($= 3\ miles/0.53\ (mile/day)$) after the beginning of the sub-base grading activity. Activities of removing concrete pavement, grading the sub-base, installing the drainage, placing OGDC along the mainline, and paving the east bound mainline were divided into three segments to better represent the constraints [23]. The total as-planned duration was estimated to be 106 working days and the critical activities are marked in the shaded boxes (Figure 3.1) .

The general information for material, labor and equipment, and their usage for each activity were obtained in the as-planned data. The disruptive events, associated probabilities, their consequences, and activity constraints were acquired from the as-built data.

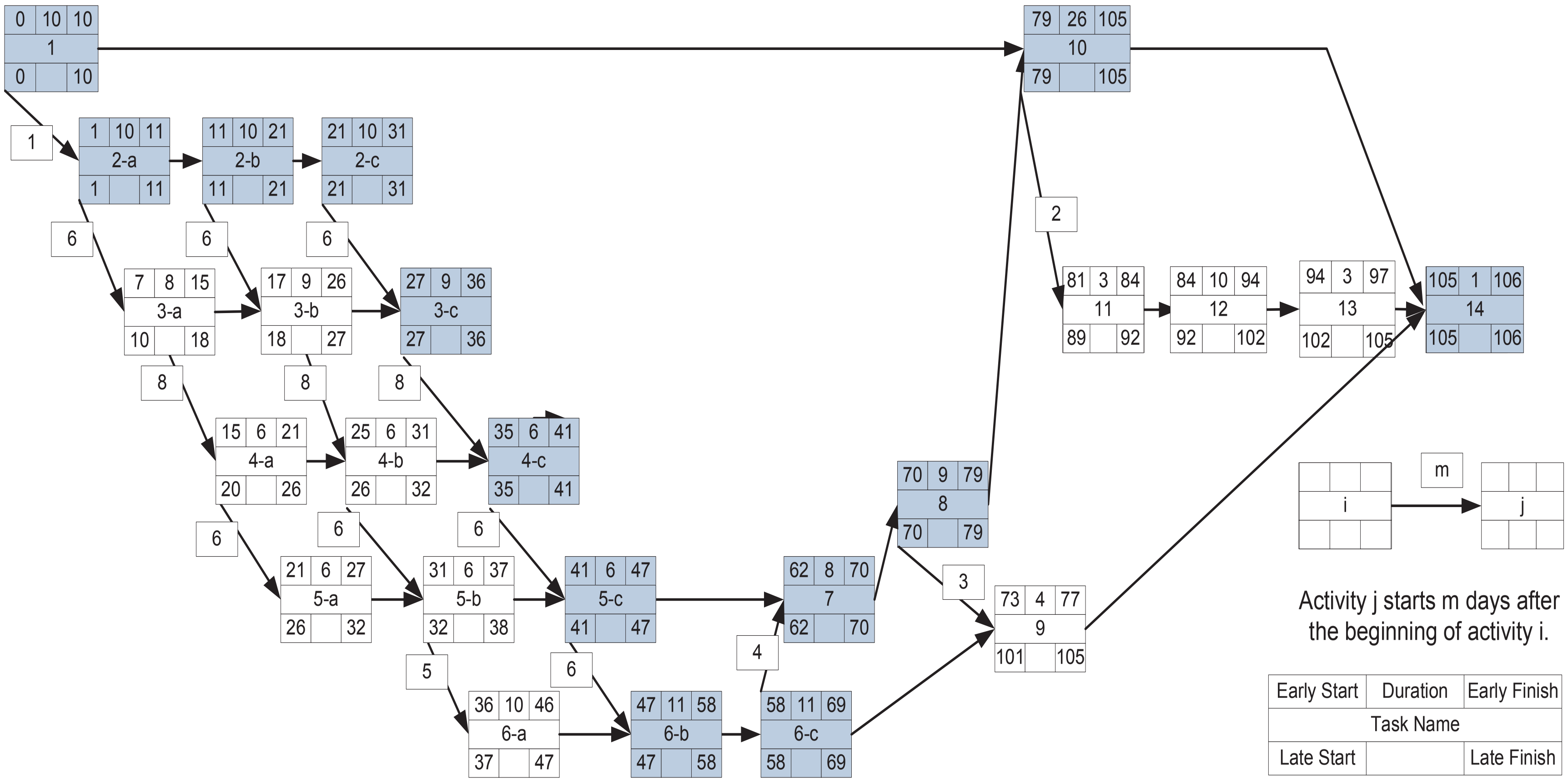

Figure 3.1: Activity diagram

Table 3.1
Project environment

NO.	Disruptive Event	Precondition	Postcondition	Probability
1	Bad weather	N/A	Productivity reduces to 50% for each activity on the bad weather day.	0.20
2	Equipment failure or worker sick	N/A	Random labor(s) is(are) sick or equipment break(s) down when the event occurs. The labor crew's productivity reduces according to the weight of labor or equipment in the labor crew.	0.12
3	Concrete testing failure	Paving east bound mainline or paving east bound gaps and ramps is in operation.	Productivity of paving activity reduces to zero for one day waiting for clearance of new test.	0.05

3.2 Construction Management Strategy Development

Once the simulation was set up, multiple experiments were conducted to test and compare the performance of different strategies. In each experiment, a decision maker ran the simulated project using a specific management strategy. Each strategy reflects a set of priorities governing project cost and duration. For illustration purposes, this research considers three strategies, a control strategy, a passive management strategy, and an aggressive management strategy. Passive management is based on ad-hoc response to unexpected events. Aggressive management aims to anticipate the future and prepare contingency plans that minimize adverse consequences from unexpected disruption to the project schedule. Strictly speaking, the control strategy is a special case of passive strategies. It manages the schedule by taking the minimum number of actions in dealing with interruptions and is used as a *baseline* strategy to contrast the impacts of other strategies. Each decision strategy consists of policies that determine the ordering, and (re)allocation of material, labor and equipment resources. To understand how ICDMA functions and deals with events such as disruptions and decisions, please refer to co-author's previous work [24, 25, 26, 27, 14]. The strategies considered are as follows.

† Control Strategy: No actions are taken when the project is falling behind. Resource allocation policies: (a) labor crew policy: no extra workers are replaced in cases of illnesses; (b) equipment policy: equipment is fixed the next day if it breaks down; (c) space policy: critical activities are prioritized when allocating space on site.

† Passive strategy: It is named as the Catch Up Strategy. Resource allocation policies are applied to catch up to the schedule every time the project is three days behind the as-planned schedule. When approaching the end of the project, the Catch Up Strategy reduces the tolerance of schedule delay to one day for timely completion. Resource allocation policies: (a) labor policy: extra workers are hired and replaced in cases of illnesses and project delay; (b) equipment policy: equipment is fixed by the mechanics immediately and extra equipment is used in case of schedule delay; (c) space policy: critical activities are prioritized when allocating space on site.

- † Aggressive strategy: It is named as the Crash Strategy. The decision maker assesses future risks and applies resource allocation policies to stay three days ahead of the as-planned schedule. When approaching the end of the project, the Crash Strategy reduces the desire of staying three days ahead of the as-planned schedule to one day for timely completion. Resource allocation policies: (a) labor policy: extra workers are hired and replaced in cases of illnesses or to expedite the schedule; (b) equipment policy: equipment is fixed by the mechanics immediately and extra equipment is used to expedite the schedule; (c) space policy: critical activities are prioritized when allocating space on site.

3.3 Simulation Experiment and Data Collection

Each of the three strategies was implemented to complete the construction for thirty five runs in order to meet the minimum requirement of statistical analysis. For the sake of uniformity and given the experimental nature of this research, a single decision maker (one of the authors, in this case) ran all the simulations. Because each simulation run is independent, it is assumed that the results are normally distributed for each strategy, when the number of experiments was large.

During each simulation run, the following data was collected: (1) total cost and duration at the completion of the project, and (2) daily material, equipment, and labor usage. The

Table 3.2
Average project total cost, duration, and GHG emissions

	Esimated As-planned	**As-Simulated**			**As-built**
		Control Strategy	**Catch Up Strategy**	**Crash Strategy**	
Total Cost ($):	28,111,603	29,993,662	29,334,228	29,298,617	20,277,970
Duration (Days):	106.00	127.91	106.46	105.57	129.00
Equipment GHG Emission $(mt\ CO_2)$**:**	1,167.56	1,414.58	1,427.38	1,450.78	1,683.75

GHG emissions from equipment were calculated by multiplying the equipment usage hours by their hourly GHG emission rates in Table 2.2.

3.4 Comparing Alternative Management Strategies

In all, there were three data sets used for the analysis. First, a single instance of the *as-planned* project schedule and the cost estimated from project documents and RS Means respectively, as described in a previous section. This was the same *as-planned* schedule used to set up the simulation. Second, a single instance of the *as-built* project schedule and final cost data collected from $FieldManager^{TM}$ and other construction site records, as described in a previous section. Finally, the third data set was collected from the simulation. For each of the three strategies tested in the simulation, 35 instances of the project realization were collected - a total of 105 instances with a final *as-simulated* project cost, schedule, and GHG emissions. In the empirical analysis, differences between the *as-planned* and *as-built* GHG emissions were identified. This section compares the instances of the three strategies to test the sensitivity of the project performance to each strategy. A comparison between the *as-built* and the *as-simulated* is provided as a reality check for the simulation.

Table 3.2 summarizes the *as-built* and *as-simulated* total costs, durations, and GHG emissions. The *as-planned* data showed that it took 129 working days to complete the project, with a production of 1,683.75 mt of CO_2 at total cost of $20,277,970. In the simulation experiment, the Control Strategy took an average 127.91 days to complete the project, which was comparable to the *as-built* duration (129 days). In addition, simulation results showed that the Control Strategy, Catch Up Strategy, and Crash Strategy respectively produced 1,768.22, 1,784.22, and 1,813.48 mt CO_2. The quantities were comparable (within <8% of the as-built amount) to the emission produced in the actual construction process (1,683.75 mt CO_2). While this comparison does not provide a true validation of the simulation, it establishes credibility for the simulation platform. In addition, ICDMA has shown a similar application to a real steel construction project [14].

The two sample t-test was used to examine if the project GHG emission means are different between two strategies. The Control Strategy is the reference group for the Crash Strategy and Catch Up Strategy to compare against. The null hypothesis and alternative hypothesis are:

† Null hypothesis H_0: μ(Strategy i)=μ(Control Strategy), where i represents Crash Strategy or Catch Up Strategy, and μ represents the average project GHG emissions;

- † Alternative hypothesis H_a: The means of two strategies' GHG emissions are different;
- † The significance level: α=0.05;

The test was implemented in SPSS 16.0 (Statistical Package for the Social Sciences) [28]. The test variables were *as-simulated* emissions from each of the strategies. Because the variances of the groups were unknown, the two sample t-test was performed assuming both equal variances and unequal variances. Levene's Test was used to test the equal variances between the data. When comparing the Crash Strategy against the Control Strategy, the significance value in Levene's Test was 0.001 (<0.05). It indicated that the variances of project GHG emissions from the two strategies are statistically unequal, so the results of the t-test, which assumed unequal variances, were used. The significance value of the t-test was 0.020 (<0.05), thus providing evidence to reject the null hypothesis that the Control Strategy and Crash Strategy produced the same project GHG emissions. When comparing the Catch Up Strategy against the Control Strategy, there was not enough evidence (0.297 >0.05) to reject the null hypothesis, indicating that the Catch Up Strategy and Control Strategy produced a comparable amount of project GHG emissions. Therefore, the t-test results showed different management strategies did produce different project GHG emissions.

Similarly, the abilities of alternative strategies to control project cost and duration were evaluated and compared. First, the one way analysis of variance (ANOVA) was used to examine if three strategies had the same *as-simulated* cost and duration. Next, the Post Hoc test identified which strategy had different mean cost or duration from other strategies. Results from ANOVA showed that strategies had different project costs and durations (significance values were 0.000, which were less than 0.05). The Tukey HSD Post Hoc test showed that the Control Strategy had different project costs and durations from the Crash Strategy and Catch Up Strategy (both significance values were 0.000, which were less than 0.05). In addition, the Crash Strategy and the Catch Up Strategy had comparable project cost and duration (significance values were 0.164 and 0.890, which were greater than 0.05).

The statistical analysis of how the strategies performed can be summarized as follows:

- † Cost: Strategies did have an effect on the project costs. The Crash Strategy and Catch Up Strategy statistically had the same cost. The Control Strategy had a higher cost than the Crash Strategy and Catch Up Strategy.

- † Duration: Strategies did have an effect on the project duration. The Crash Strategy and Catch Up Strategy statistically had the same duration. The Control Strategy had a longer duration than the Crash Strategy and Catch Up Strategy.

- † GHG emissions: Strategies did have an effect on the project GHG emissions. The Control Strategy and Catch Up Strategy statistically produced the same amount of project GHG emissions. The Crash Strategy produced more emissions than the Control Strategy and Catch Up Strategy.

Compared to the Control Strategy, the Crash Strategy and Catch Up Strategy completed the project with a shorter duration and lower cost. However, the Catch Up Strategy produced less project GHG emissions than Crash Strategy. In addition, there is no significant differences between the emissions of the Catch Up Strategy and the Control Strategy. Hence, the Catch Up Strategy was identified among the three as the most preferred strategy in managing project cost, duration, and GHG emission.

Chapter 4

Discussion and Conclusion

4.1 Discussion

The empirical analysis revealed that unexpected delays and interruptions increased the total project GHG emissions during the construction. Extra usage of equipment and materials were the underlying causes for the increased *as-built* emissions. This motivated the investigation of the relationship between project GHG emissions and construction practices. In the simulation experiment, construction management strategies were tested to compare their performance on project cost, duration, and GHG emissions. Statistical analysis showed that strategies had significantly different influences on project cost, duration, and GHG emissions. Possible recommendations of this research are as follows:

† There exist strategies that are both cost and duration efficient. Compared to the Control Strategy, the Crash Strategy and Catch Up Strategy averagely spent \$75,228.42 more direct cost but \$752,468.41 less indirect cost. This is why the Crash Strategy and Catch Up Strategy had a shorter duration than Control Strategy while still maintaining lower cost at the same time (Table 3.2). The prerequisite of developing cost and duration efficient strategies is that the savings in indirect cost for reducing the schedule should be higher than the increase in direct cost.

† Cost and duration efficient strategies are not always going to be emission efficient strategies. The Crash Strategy, which was a cost and duration efficient strategy, produced 36,203.50 mt CO_2 more GHG emissions than the Control Strategy. This implies that improvement in cost and duration management did not automatically increase emission efficiencies.

† Including GHG emissions as a third leg in the traditional project cost and duration problem, net daily emission of the activity resource being impacted should be considered as equally important as the cost incurred per day when crashing project schedule. Given the project environment and the connections between activities, the Catch Up Strategy was found to use lower emission rate equipment more frequently than the Crash Strategy. This accounts for why the Crash Strategy and Catch Up Strategy had comparable average project cost but different project GHG emissions. It pointed out that the construction multi-objective management problem should consider resources associated strategies when making decisions. Investigating other

strategies which prioritized crashing critical activities with lower daily project GHG emissions might provide further evidence to improve strategies in reducing project GHG emissions [15].

- Appropriately selected strategies can reduce project GHG emissions without increasing contractor's financial burden or causing project schedule delays, such as the Catch Up Strategy for this project.
- Project is vulnerable to schedule delays, cost and GHG emission increases because of disruptive events like severe weather and on site accidents. This report suggested that the differences between total cost in Control Strategy and the as-planned total cost could be used as an estimate of possible contingency budget. The amount is \$1,882,059 (\$29,993,662 - \$28,111,603=\$1,882,059) for this project.
- Interactive simulation is an important method for developing optimal management strategies at the pre-construction phase. The disruptive events can occur at any time in the construction and the critical activities tend to change. Evaluation of management strategies should be based on the statistical analysis of a large number of complete project realizations by each of the strategies. Performing simulation experiments can help identify favorable strategies before a project starts.

Although different projects may have different strategy recommendations, the proposed method in this report is general and can be applied to any project. It is expected that this research can help identify the best strategies in managing project cost, duration, and GHG emissions before a project starts.

Having said that, there are various limitations to this research at this time point. The empirical analysis and simulation experiment of one project does not provide statistical evidence. More projects should be investigated to better understand the relationship between project management strategies and GHG emissions. In addition, the definition of strategies and the strategy evaluation system need to be significantly more robust. A simulation based optimization method must be developed to optimize strategies.

4.2 Conclusion

This report investigated the relationships between project cost, duration and GHG emissions, and established a method for exploring best construction management practices at the pre-planning stage. It is recommended that appropriately selected strategies can reduce project GHG emissions without increasing contractor's financial burden or causing project schedule delays. In the short term, the report advises the best practices involved in reducing project GHG emissions for a specific project. In the long run, it is expected that longitudinal simulation studies using such methods will help identify the best construction management practices that apply across different construction projects. Revealing the relationships between project cost, duration, and GHG emissions can expand the theory of construction management as well.

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