KICEM Journal of Construction Engineering and Project Management
Online ISSN 2233-9582

www.jcepm.org
http://dx.doi.org/10.6106/JCEPM.2014.4.4.033

Time-Profit Trade-Off of Construction Projects Under Extreme Weather Conditions

Ahmed Senouci [1] and Saleh Mubarak [2]

Abstract: ***Maximizing the profitability and minimizing the duration of construction projects in extreme weather regions is a challenging objective that is essential for project success. An optimization model is presented herein for the time-profit trade-off analysis of construction projects under extreme weather conditions. The model generates optimal/near optimal schedules that maximize profit and minimize the duration of construction projects in extreme weather regions. The computations in the model are organized into: (1) a scheduling module that develops practical schedules for construction projects, (2) a profit module that computes project costs (direct, indirect, and total) and project profit, and (3) a multi-objective module that determines optimal/near optimal trade-offs between project duration and profit. One example is used to show the impact of extreme weather on construction time and profit. Another example is used to show the model's ability to generate optimal trade-offs between the time and profit of construction projects under extreme weather conditions.***

Keywords: genetic algorithms; multi-objective optimization; construction profit, construction total cost; construction duration, extreme weather conditions.

I. INTRODUCTION

Extreme weather conditions have significant impacts on project schedules, costs, and profits. During extreme weather conditions, workers' productivity may significantly decrease. Moreover, workers have reduced working hours due to government regulation such as the one imposed by the State of Qatar, which forbids outdoor work from 11 am to 3 pm in the summer when the weather is extremely hot and humid. The reduction in labor productivity and working hours may be a source for construction delays, additional costs, and reduced profits.

The impact of weather conditions on project schedules has been addressed by several researchers. The National Cooperative Highway Research Program [1] studied the impact of different types of weather on different highway construction operations. According to the study, 45% of all construction activities are affected to some degree by weather, resulting in significant additional costs that can run into billions of dollars annually. Thomas and Yiakoumis [2] developed a factor model for evaluating the productivity of labor intensive construction activities. Moselhi et.al. [3] presented an automated support system for estimating the combined effect of reduced labor productivity and work stoppage caused by adverse weather conditions on construction sites. South Dakota DOT [4] used available construction and weather records to determine the expected number of working days due to extreme weather conditions. McDonald [5] examined weather-related delay claims for construction projects and how they can be resolved. El-Rayes and Moselhi [6] developed a decision support system for quantifying the impact of rainfall on the productivity and duration of highway construction operations. Moselhi and Zafar [7] identified, analyzed, and ranked the parameters that affect job-site daily labor productivity to help job-site staff in planning and comparing their daily targets and to fine-tune their resource allocations according to the daily situation. Apipattanavis et.al. [8] proposed an integrated framework to identify the weather attributes that cause construction delays and to quantify weather's threshold values.

Significant research work has been done in the optimization of construction schedules. A number of models have been developed using a variety of approaches, including linear programming, integer programming, dynamic programming, neural networks, genetic algorithms, ant colony, and particle swarm optimization. They can be classified according to their optimization objectives into models that attempted to: 1) minimize cost and duration of construction projects using time-cost trade-off analysis [9, 10, 11, 12, 13, 14, 15], 2) minimize cost and duration and maximize quality of construction projects using time-cost-quality trade-off analysis [16, 17, 18], 3) minimize the duration and profit of construction projects using time-profit trade-off analysis [19, 20, 21, 22]. Senouci and Mubarak [23] presented a time-cost trade-off analysis method of construction projects in extreme weather regions. While the above research studies have provided significant contributions to this research area, there has been little or no reported research focusing on the time-profit analysis of construction projects in extreme weather regions.

This paper presents a multi-objective optimization model for the scheduling of construction projects in extreme weather conditions. The model enables construction planners to generate scheduling plans that establish optimal trade-offs between the duration and profit of construction projects in extreme weather regions. Each scheduling plan identifies a start date for the project

[1] Associate Professor, Qatar University, P.O. Box 2713, Doha, Qatar, a.senouci@qu.edu.qa (*Corresponding Author)
[2] Associate Professor, Qatar University, P.O. Box 2713, Doha, Qatar, saleh.mubarak@qu.edu.qa

and an optimal crew formation for each project activity. To accomplish this, the model incorporates: (1) a scheduling module that computes the project duration; (2) a profit module that computes the project profit; and (3) an optimization module that identifies optimal construction plans.

II. MODEL FORMULATION

2.1 Decision Variables

The current model is designed to consider all relevant decision variables that have an impact on the scheduling of construction projects in extreme weather regions. These decision variables includes: (1) construction methods representing the availability of different types of utilized materials and/or methods, (2) crew configurations and sizes representing the possibility of utilizing single or multiple crews on each activity; (3) crew overtime policy representing available overtime hours and night time shifts; and (4) project start date. In order to control the complexity of the optimization model, the current model combines the first three decision variables into a single variable called crew formation while another variable called project start date variable represents the last decision variable. Each crew formation option has an expected daily productivity and cost rates. The starting date variable takes integer values from 0 to 364, which cover all calendar days of the year. A value of “0” of the project start date variable corresponds to the first day of January while a value of “364” corresponds to the thirty first of December.

2.2 Search Space

The main challenge of this problem is to select an optimal project start date (Ndays = 0, 2, … 364) for the project and an optimal crew formation option from the available set of feasible alternatives (Cn = 1, 2, …, NCrew(n)) for each project activity (n = 1, 2, …, NAct). The current model is designed to search large solution spaces in order to identify project start dates and activity crew formations that maximize profit and minimize the duration of construction projects.

III. MODEL IMPLEMENTATION

The model computations are organized into: (1) a scheduling module that develops practical schedules for construction projects; (2) a profit estimating module that computes the costs (direct, indirect, and total) and profit of construction projects; and (3) a multi-objective genetic algorithm module that determines optimal trade-offs between project duration and profit. The following sections present a detailed description of the three modules.

3.1 Scheduling Module

(1) Weather-Adjusted Activity Durations: The project start date defines the time frames when all activities are executed. Starting the project close to or during the extreme weather will result in increased activity durations because of the loss of productivity due to extreme weather conditions. In order to account for the impact of the extreme weather on the durations of project activities, the calendar year is divided into time segments (months for simplicity herein). Productivity and cost multipliers are assigned for each activity at each time segment in respect to the base numbers.

The duration of activity n using crew formation Cn during time ***segment*** i is adjusted for extreme weather conditions using the following equation:

$$AD(n,C_n,i)=\frac{BD(n,C_n)}{PM(n,i)} \tag{1}$$

Where: AD(n, C_n, i) = weather-adjusted duration of activity n using crew formation C_n during time segment i, BD(n, C_n) = base duration of activity n using crew formation C_n, PM(n, i) = productivity multiplier for activity n during time segment i, NAct = number of activities; and NCrew(n) = number of crew formations for activity n.

When an activity is executed during two or more time segments, the productivity multiplier is computed as the average value of all the productivity multipliers during the duration of that activity.

(2) Activity Start and Finish Times: CPM computations are used to determine the start time STime(n, C_n) and the finish time FTime(n, C_n) of activity n using crew formation C_n. The precedence relationships between succeeding activities, namely, finish-start, start-start, finish-finish, and start-finish are used herein to compute activity start times.

CPM computations are used to determine the activity start and finish times. The early start time STime(n, C_n) is defined as the earliest start time of activity n using crew formation C_n. Similarly, the early finish FTime(n, C_n) time is defined as the earliest finish time of activity n using crew formation C_n. The model compute the early start time STime(n, C_n) of an activity n using crew formation C_n using one or more of the following precedence relationships equations:

For finish-start precedence relationship:

$$STime(n,C_n)= FTime(m,C_m)+Lag(n,m) \tag{2}$$

For start-finish precedence relationship:

$$STime(n,C_n)= STime(m,C_m)+Lag(n,m) - AD(n,C_n,i) \tag{3}$$

For finish-finish precedence relationship:

$$STime(n,C_n)= FTime(m,C_m)+Lag(n,m) - AD(n,C_n,i) \tag{4}$$

For start-start precedence relationship:

$$STime(n,C_n)= STime(m,C_m)+Lag(n,m) \tag{5}$$

Lag(n, m) = lag/lead times between activity n and its predecessor m; and

AD(n, C_n, i) = duration of activity n during segment i when crew formation C_n is used

The finish time FTime(n, C_n) of an activity n using crew formation C_n is computed using the following equation:

$$FTime(n,C_n) = STime(n,C_n) + AD(n,C_n,i) \quad (6)$$

3.2 Profit Estimating Module

1) Weather-Adjusted Activity Direct Cost: Cost multipliers are assigned for each activity at each time segment to account for the impact of the extreme weather on labor productivity. Changes in labor productivity due to extreme weather conditions will affect both activity duration and direct cost. To explain, let us consider an excavation activity. The crew assigned to the activity has a base productivity of 500 m^3/day, a base direct cost of $1,200/day, and a base unit direct cost of $2.40/$m^3$ (i.e., 2.40= 1,2000/500). Let us now assume that the labor productivity of the activity has decreased due to the extreme weather to a value of 400 m^3/day. Now, if the crew is still paid the same amount, say, $1,200/day, the unit direct cost becomes $3.00/$m^3$ (i.e., 3.00 = 1,200/400). The increase (or decrease) in the direct cost is due to labor productivity.

The direct cost for activity n using crew formation C_n during time segment i is adjusted for weather conditions using the following equation:

$$AC(n,C_n,i) = CM(n,i) * BC(n,C_n) \quad (7)$$

Where AC(n, C_n, i) = weather-adjusted direct cost of activity n using crew formation C_n during time segment i, BC(n, C_n) = base cost of activity n using crew formation C_n, and CM(n, i) = cost multiplier for activity n during time segment i.

2) Project Direct, Indirect, and Total Costs: The project total cost is the sum of project direct and indirect costs. The indirect cost, which represents the overhead costs, is assumed to be a linear function of the project duration. The project direct cost is equal to the sum of the weather-adjusted direct cost of all project activities.

3)Project Profit: Figure 1 shows a typical contractor cash flow profile of expenses and incomes. The contractor expenses are represented by a piecewise continuous curve while the progress payments from the owner are represented by a step *function*. The owner's payments for the work completed are assumed to lag one period behind the expenses while the total retainage withheld is paid back to the contractor at the end of the construction project.

The profit computation steps consist of the following computational steps [24, 19]

- **a.** Compute the contractor’s monthly expenditures.
- **b.** Compute the sub-contractors’ monthly expenditures.
- **c.** Estimate the contractor’s monthly indirect expenditures.
- **d.** Compute the contractor’s monthly total expenditures.
- **e.** Compute the contractor’s monthly total worth.
- **f.** Compute the owner's monthly payments to the contractor.
- **g.** Calculate the contractor's monthly payments to sub-contractors.
- **h.** Compute the contractor's monthly cash out flows.
- **i.** Compute the contractor's cumulative cash out flows.
- **j.** Compute the contractor’s cumulative Incomes.
- **k.** Compute the contractor’s overdraft before receiving owner’s payments.
- **l.** Compute the interest paid every month.
- **m.** Compute the contractor cumulative interest payments.
- **n.** Compute the contractor’s overdrafts after receiving owner’s payments.
- **o.** Compute the contractor’s total profit.

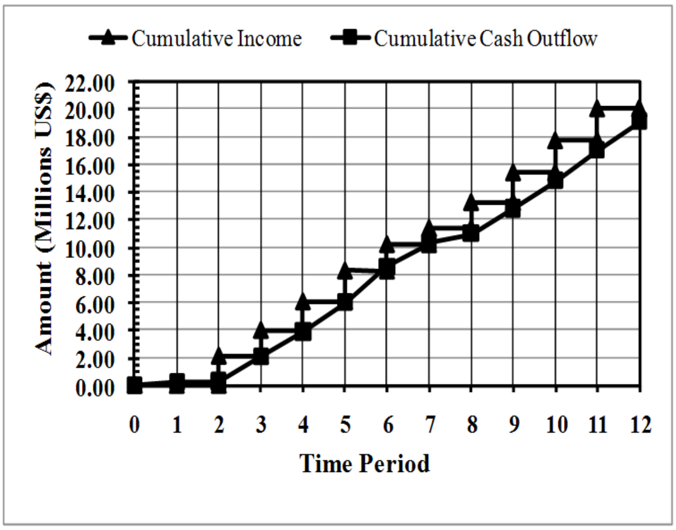

FIGURE I
CONTRACTOR EXPENDITURES AND OWNER PAYMENTS

An example is used herein to describe the computation procedure of project profit. The project, which has a contracted price of $750,000, is scheduled to be completed in 48 workdays (i.e., Two months and 4 workdays). The contractor’s indirect expenditures are estimated at $1,200/day. The percent retainage is estimated at 10% for both the owner payments to the contractor and the contractor payments to subcontractors. The percent interest charged by the financial institution on overdrafts is estimated at 1% per month. Table 1 summarizes the profit computations. The monthly expenditures of the contractor CE(t) and subcontractors SE(t) are summarized in rows 1 and 2 of Table 1, respectively. The profit computation procedure also includes the following steps:

- **a.** Compute the contractor’s indirect expenditures IE(t) using Eq. 8 (see row 3 of Table 1).

$$IE(1) = IE(2) = 1200 * 22 = 26400 \qquad (8)$$
$$IE(3) = 1200 * 4 = 4800$$

b. Compute the contractor's monthly total expenditures TE(t) using Eq. 9 (see row 4 of Table 1).

$$TE(t) = CE(t) + SE(t) + IE(t) \qquad t = 1,..,4 \qquad (9)$$

c. Compute the contractor's monthly total income TW(t) using Eq. 10 (see row 5 of Table 1). These monthly incomes are determined based on the project contracted price using the following equation:

$$TW(t) = \frac{Project\ Contracted\ Price}{Number\ of\ Workdays\ per\ month} * Project\ Duration \qquad (10)$$
$$TW(1) = TW(2) = \frac{750000}{22} * 48 = 343750$$
$$TW(3) = \frac{750000}{22} * 4 = 62500$$

d. Compute the owner's monthly payments to the contractor CP(t) using Eq. 11 (see row 6 of Table 1).

$$CP(t) = TW(t) * (1 - O\_Retainage) \qquad (11)$$

Where O_Retainage = percent retainage withheld by the owner from the payments to the contractor. The total amount of retainage will be returned to the contractor with the last payment. The percent retainage selected herein is 10%.
The owner's payments to the contractor CP(t) are usually delayed one period (1 month herein).

e. Calculate the contractor's monthly payments to sub-contractors SP(t) using Eq. 12 (see row 7 of Table 1).

$$SP(t) = SE(t) * (1 - C\_Retainage) \qquad (12)$$

Where C_Retainage=percent retainage withheld by the contractor from payments to subcontractors. The total amount of retainage will be returned to subcontractors with the last payment. The selected percent retainage is 10 (%).

f. Determine the contractor's monthly cash out flows CF(t) using Eq. 13 (see row 8 of Table 1).

$$CF(t) = TE(t) - SE(t) + SP(t) \qquad (13)$$

g. Determine the contractor's monthly cumulative cash out flow CCF(t) using Eq. 14 (row 9 of Table 1).

$$CCF(t) = \sum_{n=1}^{t} CF(n) \qquad n = 1,....,t \qquad (14)$$

h. Determine the contractor's monthly cumulative Income CI(t) using Eq. 15 (see row 10 of Table 1)

$$CI(t) = \sum_{n=1}^{t} CP(n) \qquad n = 1,....,t \qquad (15)$$

i. Determine the contractor's overdraft before receiving owner's payment ODBP(t) at the end of period t using Eq. 16 (see row 11 of Table 1) :

$$ODBP(t) = CI(t-1) - CCF(t) + CInt(t-1) \qquad (16)$$

Where CInt(t-1) = cumulative interest paid at period t-1.

j. Determine the interest Int (t) paid at period t using Eq. 17 (see row 12 in Table 1)

$$Int(t) = ODBP(t) * InterestRate \qquad (17)$$

Where InterestRate =overdraft interest rate per time period (1% per month herein).

k. Determine the contractor cumulative interest payment CInt(t) at the end of period t using Eq. 18 (see row 13 of Table 1):

$$CInt(t) = \sum_{n=1}^{t} Int(n) \qquad n = 1,....,t \qquad (18)$$

l. Determine the contractor's overdraft after receiving owner's payment ODAP[t] at period t using Eq. 19 (see row 14 of Table 1)

$$ODAP(t) = ODBP(t) + SP(t) \qquad (19)$$

m. Determine the contractor's total profit at the end of the project (t = 6) using Eq. 20 (Profit = $163272).

$$Profit = ODAP(6) \qquad (20)$$

The above calculations are based on the assumption that the contractor pays the interest charges at the end of the period.

TABLE I
PROJECT PROFIT COMPUTATION

Computation Steps	Project Time Periods *t* (Months)					
	1	2	3	4	5	6
Contractor's Expenditures **CE(t)**	237758	237758	43229	0	0	
Subcontractor's Expenditures **SE(t)**	0	0	0	0	0	
Contractor's Indirect Expenditures **IE(t)**	26400	26400	4800	0	0	
Contractor's Total Expenditures **TE(t)**	264158	264158	48029	0	0	
Contractor's Total Worth **TW(t)**	343750	343750	62500	0	0	
Owner's Payment to Contractor **CP(t)**	309375	309375	56250	0	0	
Owner's Payment to Contractor with delay ***CP(t)***	0	0	309375	309375	131250	0
Contractor's Cash Out Flow **CF(t)**	264158	264158	48029	0	0	0
Contractor's Cumulative Cash Out Flow **CCF(t)**	0	264158	528316	576345	576345	576345
Contractor's Cumulative Income **CI(t)**	0	0	309375	618750	750000	750000
Contractor's OverDraft Before Payment **ODBP(t)**	0	-264158	-530958	-274921	31705	163272
Interest **IC(t)**	0	-2642	-5310	-2749	317	1633
Cumulative Interest **CIC(t)**	0	-2642	-7951	-10700	-10383	-8751
Contractor's OverDraft After Payment **ODAP(t)**	0	-264158	-221583	34454	162955	163272

3.3 Multi-Objective Genetic Algorithm Module

This module searches for optimal/near-optimal trade-offs between project duration and profit using a multi-objective genetic algorithm model. Genetic algorithms are search and optimization tools for problems with large search spaces. They adopt the survival of the fittest and the mechanism of genetic evolution [25]. The present model is implemented in three main phases: (1) Initialization phase that generates an initial set of S possible solutions for the problem; (2) Fitness evaluation phase that calculates the time and total cost for each possible solution; and (3) Population generation phase to improve the fitness of solutions over successive generations [12, 19] .

Phase 1: Initialization

This phase generates an initial set of S possible solutions that will evolve in subsequent generations to a set of optimal/near optimal solutions. It consists of the following tasks:

1. Read project and genetic algorithm parameters.

2. Generate a set of random solutions (s= 1 to S) for the initial population P1 in the first generation (g=1). These solutions represent an initial set of activity crew formations and project starting date variables. This set of possible solutions evolves in the following two phases to yield a set of optimal crew formations and project starting date variables that establish an optimal trade-off between project duration and profit.

Phase 2: Fitness Function Evaluation

The main purpose is to evaluate the two identified fitness functions for each solution using the following two steps:

1. Calculate the duration of the project for solution s in generation g using the procedure described in the scheduling module.

2. Calculate the profit of the project for solution s in generation g using the procedure described in the profit estimating module.

Phase 3: Population Generation

This phase creates three population types in each of the considered generations: parent, child, and combined. For each generation g, a parent population Pg is used to generate a child population Cg in a manner similar to that used in traditional genetic algorithms (Goldberg 1989). The purpose of generating this child population is to introduce a new set of solutions by rearranging and randomly changing parts of the solutions of the parent population. The child and parent populations are combined to form the population Ng for generation g. This combined population Ng is used to facilitate the comparison among the initial solutions in the parent population and those generated in the child population. The best solutions in this combined population regardless of their origin are retained and passed to the following generation as a parent population [26, 27, 28].

IV. ILLUSTRATIVE EXAMPLES

4.1 Example#1

An example consisting of one excavation activity is used herein to illustrate the impact of extreme weather conditions on project profit. The activity consists of excavating 30,000 m3 of the earth at a contracted price of $750,000 (i.e., $25/m3). The activity is executed by a crew that has a base productivity rate of 600 m3/day. The crew base direct cost is $11,400/day (i.e., $19/m3). The indirect cost is $1,200/day. The percentage retainage in this project is 10% while the percentage interest rate paid on overdrafts is 1% per month.

A study was conducted to investigate the impact of the start date on the project profit. The study consisted of computing the project profit by moving forward the project start date from January 1, 2012 to December 31, 2012 using two-week increments. Figure 2 and Table 2 summarize the results of the case study. The results show that the variation between profit and start date of the project follows a cyclic trend (i.e., increasing, decreasing, and then increasing trends along the year). The obtained results allow construction planners to pick an optimum project starting date that yields the maximum profit for the construction project while satisfying the requirements of total duration and finish time.

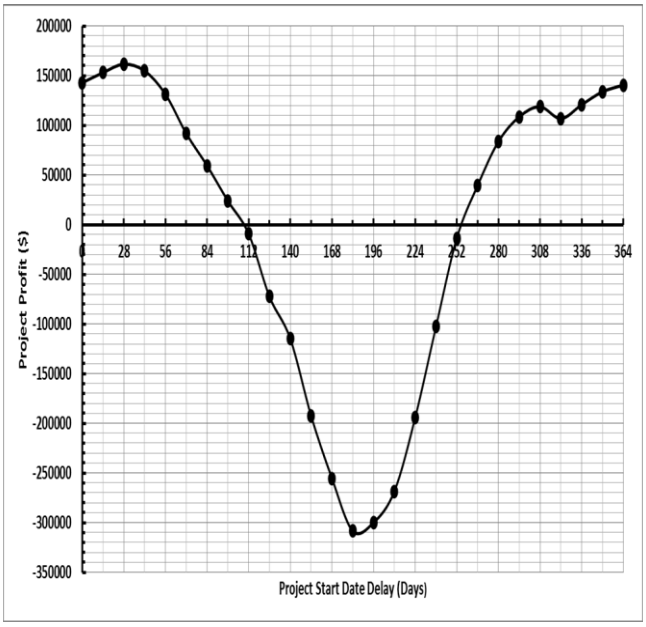

FIGURE II
PROJECT PROFIT VS. PROJECT START DATE DELAY

TABLE II
PROJECT PROFIT RESULTS.

Project Start Date Delay (Days)	Project Start Date	Project Finish Date	Project Duration (Work Days)	Project Project Profit ($)
0	2012-01-03	2012-03-12	48	142899
14	2012-01-16	2012-03-23	48	153085
28	2012-01-30	2012-04-06	48	161573
42	2012-02-13	2012-04-20	49	154875
56	2012-02-27	2012-05-04	51	131385
70	2012-03-12	2012-05-18	53	91789
84	2012-03-26	2012-06-01	54	59504
98	2012-04-09	2012-06-15	55	23915
112	2012-04-23	2012-06-29	56	-9189
126	2012-05-07	2012-07-13	59	-72415
140	2012-05-21	2012-07-27	61	-114828
154	2012-06-04	2012-08-10	65	-192473
168	2012-06-18	2012-08-24	68	-255296
182	2012-07-02	2012-09-07	71	-308336
196	2012-07-16	2012-09-21	71	-299925
210	2012-07-30	2012-10-05	70	-268464
224	2012-08-13	2012-10-19	67	-194321
238	2012-08-27	2012-11-02	63	-102631
252	2012-09-10	2012-11-16	59	-13441
266	2012-09-24	2012-11-30	57	39494
280	2012-10-08	2012-12-14	54	83660
294	2012-10-22	2012-12-28	52	108661
308	2012-11-05	2013-01-11	51	118768
322	2012-11-19	2013-01-25	51	106752
336	2012-12-03	2013-02-08	49	120801
350	2012-12-17	2013-02-22	48	133844
364	2012-12-31	2013-03-08	48	140635

4.2 Example#2

A second project is analyzed herein to demonstrate the capabilities of the developed model in generating optimal tradeoffs between the time and profit of construction projects in extreme weather regions. The example project includes 12 outdoor activities as shown in Figure 3.

The project is assumed to be in the State of Qatar, where the weather is extremely hot and humid during the summer months. The precedence relationship between succeeding activities is finish-to-start with zero lag time. Each activity can be constructed using five alternative crew formations as shown in Table 3.

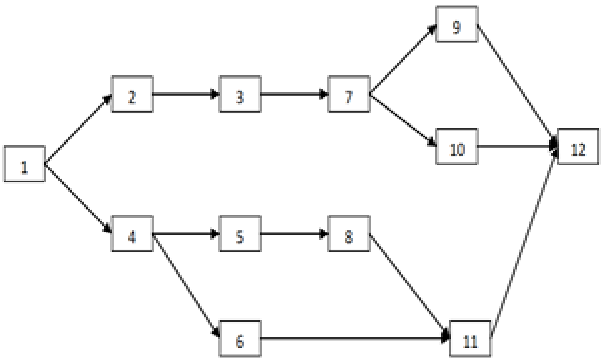

FIGURE III
PROJECT PLANNING NETWORK

TABLE III
ACTIVITY BASE DURATIONS AND DIRECT COSTS

Activity No.	Crew Formation	Duration (Days)	Direct Cost ($)	Activity No.	Crew Formation	Duration (Days)	Direct Cost ($)
1	1	5	190000	7	1	10	160000
	2	6	170000		2	11	140000
	3	7	150000		3	12	120000
	4	8	130000		4	13	100000
	5	9	110000		5	14	80000
2	1	6	180000	8	1	9	170000
	2	7	160000		2	10	150000
	3	8	140000		3	11	130000
	4	9	120000		4	12	110000
	5	10	100000		5	13	90000
3	1	7	170000	9	1	8	180000
	2	8	150000		2	9	160000
	3	9	130000		3	10	140000
	4	10	110000		4	11	120000
	5	11	900000		5	12	100000
4	1	8	160000	10	1	7	190000
	2	9	140000		2	8	170000
	3	10	120000		3	9	150000
	4	11	100000		4	10	130000
	5	12	800000		5	11	110000
5	1	9	150000	11	1	6	200000
	2	10	130000		2	7	180000
	3	11	110000		3	8	160000
	4	12	90000		4	9	140000
	5	13	70000		5	10	120000
6	1	10	150000	12	1	5	220000
	2	11	130000		2	6	200000
	3	12	110000		3	7	180000
	4	13	90000		4	8	160000
	5	14	70000		5	9	140000

Table 4 shows the estimates of the monthly productivity and cost multipliers for a typical outdoor activity in an extreme hot and humid weather region. The productivity and cost multipliers are assumed constant for all activities. The daily indirect cost of the project is estimated at $8,000 per day with an initial indirect cost of $20,000. The percentage retainage is specified to be 10% while the percentage interest rate paid on overdrafts is set equal to 1% per month. The project contract price is set equal to $2,300,000.

TABLE IV
ROUGH ESTIMATES OF PRODUCTIVITY AND COST MULTIPLIERS IN QATAR

Month	Productivity Multiplier (PM)	Cost Multiplier (CM)
January	1.00	1.00
February	1.00	1.00
March	1.10	0.90
April	1.05	0.90
May	0.95	0.95
June	0.85	1.05
July	0.75	1.10
August	0.70	1.20
September	0.85	1.10
October	1.00	1.00
November	1.10	0.90
December	1.00	0.95

The present optimization model was used to search the space of possible solutions. The rate of crossover and mutation were set equal to their most commonly used values (i.e., 0.8 and 0.005, respectively). After a number of trial-and-error adjustments, a population size equal to 125 individuals and a number of generations equal to 5000 were found to meet the accuracy requirements of the example.

The model was able to reduce the search space by precluding dominated solutions in the successive generations of the genetic algorithm, using the Pareto optimality principles. This led to the selection of 17 Pareto optimal (i.e., non-dominated) solutions for this example. Each of these solutions identifies an optimal trade-off among project duration and profit. Table 5 summarizes these optimal solutions and their impact on project profit. Figure 4 shows the time-profit trade-off curve of the project, where the horizontal axis represents project durations and the vertical axis project profits in US Dollars.

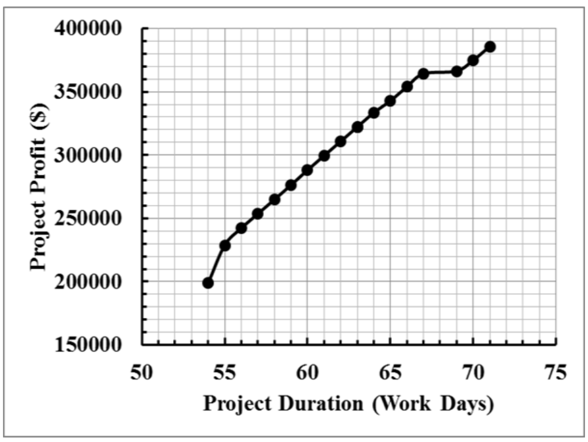

FIGURE IV.
PROJECT TIME-PROFIT TRADE-OFF CURVE

TABLE V.
PARETO OPTIMAL/NEAR OPTIMAL SOLUTIONS

Project Duration (Days)	Project Profit ($)	Project Start Date	Activity Crew Formations											
			Act#1	Act#2	Act#3	Act#4	Act#5	Act#6	Act#7	Act#8	Act#9	Act#10	Act#11	Act#12
54	198914	2013-02-14	3	1	1	5	5	4	5	1	1	4	1	2
55	228843	2013-02-14	3	1	1	5	5	4	5	1	1	5	1	3
56	242251	2013-02-12	5	1	1	4	5	4	5	1	1	5	1	1
57	253595	2013-02-12	5	1	1	4	5	4	5	1	1	5	1	2
58	264942	2013-02-12	5	1	1	4	5	4	5	1	1	5	1	3
59	276289	2013-02-12	5	1	1	4	5	4	5	1	1	5	1	4
60	288210	2013-02-05	5	5	1	4	5	4	5	1	1	5	1	1
61	299538	2013-02-05	5	5	1	4	5	4	5	1	1	5	1	2
62	310866	2013-02-05	5	5	1	4	5	4	5	1	1	5	1	3
63	322196	2013-02-05	5	5	1	4	5	4	5	1	1	5	1	4
63	322196	2013-02-05	5	5	1	4	5	4	5	1	1	5	1	4
64	333527	2013-02-05	5	5	1	4	5	4	5	1	1	5	1	5
65	342896	2013-02-05	5	5	1	4	5	4	5	1	1	5	2	5
66	353985	2013-02-05	5	5	1	4	5	4	5	1	1	5	3	5
67	364261	2013-02-05	5	5	1	4	5	4	5	1	1	5	4	5
69	366426	2013-02-05	5	5	1	4	5	4	5	1	1	5	5	5
70	374986	2013-02-05	5	5	3	4	5	4	5	1	1	5	4	5
71	385849	2013-02-05	5	5	3	4	5	4	5	1	1	5	5	5

TABLE VI
PROJECT SHORTEST AND LONGEST SCHEDULES

Project Duration (Work Days)	Project Profit ($)	Activity Number	Project Sart Time (Days)	Project Finish Time (Days)
54	198914	1	0	7
		2	7	12
		3	12	18
		4	12	22
		5	18	29
		6	18	29
		7	22	34
		8	29	37
		9	37	44
		10	34	43
		11	44	49
		12	49	54
71	385849	1	0	9
		2	9	18
		3	18	26
		4	18	28
		5	26	37
		6	26	37
		7	28	40
		8	37	45
		9	45	52
		10	40	50
		11	52	62
		12	62	71

As shown in Table 5 and Figure 4, the project duration varies from 54 to 71 working days with varying levels of profits. For example, the shortest project duration of 54 days, which yields a total profit of $ 198,914, is based on the project start date and the activity crew formations shown in Table 5. Similarly, the longest project duration of 71 days, which leads to a total profit of $ 385,849, is based on the project start date and the activity crew formations shown in Table 5. The shortest and longest project schedules are summarized in Table 6. The obtained results show that the project start date has a significant impact on the project duration and profit. Table 7 shows the project durations and profits obtained when the project is started on January 3, 2013 as well as those obtained when the project is delayed as determined by the proposed program. Starting the project on February 14, 2013 instead of January 3, 2013, resulted in a 5.6% decrease in the project duration and a 44.4% increase in the project profit. On the other hand, starting the project on February 5, 2013 instead of January 3, 2013, resulted in a 5.0% decrease in the project duration and a 23.4% increase in the project profit.

TABLE VII
PROJECT START DATE ON PROJECT DURATION AND PROFIT

Initial Project Start Date	Project Duration (Days)	Project Profit ($)	Delayed Project Start Date	Project Duration (Days)	Project Profit ($)	Duration Decrease (%)	Profit Increase (%)
2013-01-03	57	110585	2013-02-14	54	198914	5.6	44.4
2013-01-03	58	140383	2013-02-14	55	228843	5.5	38.7
2013-01-03	59	160836	2013-02-12	56	242251	5.4	33.6
2013-01-03	60	171138	2013-02-12	57	253595	5.3	32.5
2013-01-03	61	181440	2013-02-12	58	264942	5.2	31.5
2013-01-03	62	191744	2013-02-12	59	276289	5.1	30.6
2013-01-03	63	220896	2013-02-05	60	288210	5.0	23.4
2013-01-03	64	231182	2013-02-05	61	299538	4.9	22.8
2013-01-03	65	241470	2013-02-05	62	310866	4.8	22.3
2013-01-03	66	251976	2013-02-05	63	322196	4.8	21.8
2013-01-03	67	262364	2013-02-05	64	333527	4.7	21.3
2013-01-03	68	272751	2013-02-05	65	342896	4.6	20.5
2013-01-03	69	283136	2013-02-05	66	353985	4.5	20.0
2013-01-03	70	293519	2013-02-05	67	364261	4.5	19.4
2013-01-03	71	303901	2013-02-05	69	366426	2.9	17.1
2013-01-03	72	322310	2013-02-05	70	374986	2.9	14.0
2013-01-03	73	332682	2013-02-05	71	385849	2.8	13.8

V. CONCLUSIONS

A robust multi-objective optimization model was developed to support the scheduling of construction projects in extreme weather regions. The model enables construction planners to generate scheduling plans that establish optimal trade-offs between project duration and profit for construction projects in extreme weather regions. Each scheduling plan identifies a start date for the project and an optimal crew formation for each activity in the project. To accomplish this, the model incorporates (1) a scheduling module that calculate the project duration; (2) a profit module that computes the project total profit; and (3) an optimization module that identifies optimal construction plans. An application example was analyzed to illustrate the impact of extreme weather on construction time and profit. Another example was analyzed to illustrate the capabilities of the developed model in generating optimal trade-off solutions between project duration and profit in a single run, where each provides the maximum project profit that can be achieved for a given project duration. The new tool is expected to be particularly useful to construction professionals for the scheduling of construction projects in extreme weather regions.

REFERENCES

[1] NCHRP, "Effect of weather on highway construction", *National Cooperative Highway Construction (NCHRP) Synthesis 47*,

Transportation Research Board, National Research Council, Washington, D.C, 1978.

[2] H. Thomas, I. Yiakoumis, "Factor Model of Construction Productivity", *Journal of Construction Engineering and Management, ASCE*, vol.113, no.4, pp. 623-639, 1987.

[3] O. Moselhi, D. Gong, K. El-Rayes, "Estimating weather impact on the duration of construction activities", *Canadian Journal of Civil Engineering*, vol.24, no.3, pp.359-366, 1997.

[4] South Dakota DOT (SDDOT), "Development of working day weather charts for transportation construction in South Dakota", Final Report Study SD97-07, Rapid City, S.D., 1997.

[5] F. McDonald, "Weather delays and impacts." *Cost Engineering*, vol.42, no.5, pp.34-39, 2000.

[6] K. El-Rayes, O. Moselhi, "Impact of rainfall on the productivity of highway construction", *Journal of Construction Engineering and Management*, ASCE, 127(2), 125-131, 2001.

[7] O. Moselhi, Z. Khan, "Significance ranking of parameters impacting construction labour productivity", *Construction Innovation: Information, Process, Management*, vol.12, no.3, pp. 272-296, 2012.

[8] S. Apipattanavis, K. Sabol, K. R. Molenaar, B. Rahagopolan, Y. Xi, B. Blackard, S. Patil, "Integrated framework for quantifying and predicting weather-related highway construction delays", *Journal of Construction Engineering and Management*, ASCE, vol.136, no.11, pp. 1160-1168, 2012.

[9] S. S. Leu, C. H. Yang, "GA-Based Multicriteria Optimal Model for Construction Scheduling", *Journal of Construction Engineering and Management*, ASCE, vol.125, no.3, pp.420-427, 1999.

[10] A.B. Senouci, H. Adeli, "Resource scheduling using Neural Dynamics model of Adeli and Park", *Journal of Construction Engineering and Management*, ASCE, vol.127, no.1, pp. 28-34, 2001.

[11] A.B. Senouci, N.N. Eldin, "Use of genetic algorithms in resource scheduling of construction projects", *Journal of Construction Engineering and Management*, ASCE, vol.130, no.6, pp.869-877, 2004.

[12] A.B. Senouci, H.R. Al-Derham, "Genetic algorithm-based multi-objective model for scheduling of linear construction projects", *Advances in Engineering Software*, 39(12), 1023-1028, 2008.

[13] T. Blaszczyk, M. Nowak, "The time-cost trade-off analysis in construction project using computer simulation and interactive procedure", *Technological and Economic Development of Economy*, vol.15, no.4, pp.523-539, 2009.

[14] E. Kalhor, M. Khanzadi, E. Eshtehardian, A. Afshar, "Stochastic time-cost optimization using non-dominated archiving ant colony approach", *Automation in Construction*, vol.20, no.8, pp.1193-1203, 2011.

[15] P. Jaskowski, A. Sobotka, "Using soft precedence relations for reduction of the construction project duration", *Technological and Economic Development of Economy*, vol.18, no.2, pp. 262-279, 2012.

[16] K. El-Rayes, A. Kandil, "Time-Cost-Quality Trade-Off Analysis for Highway Construction", *Journal of Construction Engineering and Management, ASCE*, vol.131, no.4, pp.477–486, 2005.

[17] A. Afshar, A. Kaveh, A., O. R. Shoghli, "Multi-objective optimization of time-cost-quality using multi-colony ant algorithm", *Asian Journal of Civil Engineering (Building and Housing)*, vol.8, no.2, pp. 113-124, 2007.

[18] X. Diao, H. Li, H., S. Zeng, V. W. Y. Tam, H. Guo, "A Pareto multi-objective optimization approach for solving time-cost-quality trade-off problems", *Technological and Economic Development of Economy*, 17(1), 22-41, 2011.

[19] A. B. Senouci, K. El-Rayes, "Time-profit trade-off analysis for construction projects", *Journal of Construction Engineering and Management*, ASCE, vol.135, no.8, pp. 718-725, 2009.

[20] H. Fathi, A. Afshar, "GA-based multi-objective optimization of finance-based construction project scheduling", *KSCE Journal of Civil Engineering*, vol.14, no.5, pp. 627-638, 2010.

[21] A. M. Elazouni, M. Abido, "Multi-objective evolutionary finance-based scheduling: individual projects within a portfolio", *Journal of Automation in Construction*, vol.20, no.7, pp.755-766, 2011.

[22] A. Jiang, R. R. A. Issa, M. Malek, "Construction Project Cash Flow Planning Using the Pareto Optimality Efficiency Network Model", *Journal of Civil Engineering and Management*, vol.17, no.4, pp.510-519, 2011.

[23] A. Senouci, S. Mubarak, "Multi-Objective Optimization Model For Scheduling of Construction Projects Under Extreme Weather Conditions", *Journal of Civil Engineering and Management*, accepted for publication.

[24] C. Hendrickson, T. Au, "Project Management for Construction", Prentice Hall, Englewood Cliffs, New Jersey, USA, 1986.

[25] D. E. Goldgerg, "Genetic Algorithms in search, optimization, and machine learning", Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, USA, 1