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A Multi Objective Scheduling Model for Minimization of Construction Project Duration, Total Cost and Environmental Impact

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Abstract

The performance of construction projects has traditionally been measured based on cost, time, and quality. Recently, the environment impact has been introduced as a fourth criterion for the assessment of project performance. Significant research advancements have been made in the area of optimizing resource utilization to minimize the total cost, duration, and quality for construction projects. A number of models have been developed using a variety of methods, including heuristics methods, mathematical programming, genetic algorithms, ant colony, and particle swarm optimization. However, there has been little or no reported research focusing on studying and optimizing the collective impact of resource utilization decisions on construction cost, duration, and environmental impact. The objective of this paper is to present the development of a multi-objective optimization model for optimizing resource utilization and scheduling of projects. The model provides construction planners and decision makers with new and important capabilities, including: (1) evaluating the combined impact of multiple resource utilization decisions on construction cost, duration, and environmental impact and (2) generating and visualizing optimal/near-optimal resource utilization and scheduling plans that provide optimal trade-offs between the project cost, duration, and environmental impact. The model is developed in two stages: (1) model formulation to identify the decision variables and optimization objectives for the construction optimization problem and (2) model implementation to perform the optimization computations using three modules that compute project duration, total cost, and environmental impact, respectively.

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Keywords: Multi objective optimization, Environmental impact, ;

1. Introduction

The construction industry, which has a major share in consuming natural resources and energy, will continue to impact the physical environment as long as the industry demands natural resources. The construction and demolition processes cause several direct and indirect environmental impacts. These impacts are serious and need to be controlled. Current construction methods involve consumption of a large amount of energy that directly impacts environmental impacts through both fuel extraction and supply. Moreover, the emissions generated to produce this energy produce hazardous gases as well as dust and noise pollution. Thus, the impact of construction projects on the environment requires the assessment of the contribution by each activity. Therefore, it has propelled many construction professionals to consider

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environmental impact as a performance assessment of construction projects [1]. Environmental impact was considered as a performance assessment factor for construction projects. Various studies have addressed environmental impact model for building during the phases of design, operations, construction etc. Assessing contractors environmental performance through calculating an environmental performance score [2], qualitative analysis and quantitative assessments through measuring the construction pollution index [3]. Environmental impact by life cycle assessment approach [4].

The performance of construction project has traditionally been measured based on cost, time and quality. Recently, the environment impact has been introduced as a fourth criteria for the assessment of project performance. Significant research advancements have been made in the area of optimizing resource utilization to minimize the total cost, duration, and quality for construction projects. A number of models have been developed using a variety of methods, including heuristics methods, mathematical programming, genetic algorithms, ant colony, and particle swarm optimization. While these research studies have provided significant contributions to this important research area, there has been little or no reported research focusing on studying and optimizing the collective impact of resource utilization decisions on construction cost, duration, and environmental impact. The objective of this paper is to present the development of a multi-objective optimization model for optimizing resource utilization and scheduling of projects. The model provides construction planners and decision makers with new and important capabilities, including: (1) evaluating the combined impact of multiple resource utilization decisions on construction cost, duration, and environmental impact and (2) generating and visualizing optimal/near-optimal resource utilization and scheduling plans that provide optimal trade-offs between the project cost, duration, and environmental impact. The model is developed in two stages: (1) model formulation to identify the decision variables and optimization objectives for the construction optimization problem and (2) model implementation to perform the optimization computations using three modules that compute project duration, total cost, and environmental impact, respectively.

This paper creates an automated way to choose optimum durations for the individual activities to maximize the benefits in time, cost, and effect on the environment. The research aims at achieving this in a user-friendly way that allows the owner to set his priorities. Sometimes time is the number one priority. For example, if you are building a structure or facility to be ready by a strict deadline like a stadium for World Cup or an exhibition hall for an international event. In this case, we need to focus on finishing the project on time no matter what the cost may be. In other projects, a residential compound or office building for example; while finishing on time is important but staying within budget may be the number one criterion. Minimizing the pollution may be more important than both time and money in other cases. The user has to rank his priorities to achieve minimum project time, least cost, or least Pollution; although the program would help in all three criteria.

However, there are limited studies on collective impact considering the multi objective nature of a construction project. This paper provides construction professionals with a model to evaluate the collective impact and generate optimal resource utilization and scheduling plans.

2. Environmental pollution impact measures and metrics

This task will focus on estimating and quantifying the environmental pollution impacts on the scheduling of construction projects. The pollution hazards such as noise, solid and liquid wastes, dust and harmful gases that are generated from construction sites represents serious environmental issues, in the present and future where the construction activities are increasing at very high speed. The awareness of these environmental issues should be addressed by all the government, construction companies and general public. There should be general consensus as to reduce the level of environmental pollution and hazard in construction projects especially in heavily populated urban areas.

The pollution generated by construction projects can be quantified by using two parameters, namely the Activity Pollution Index (API) and the Hazard Magnitude Index (HMI) [5]. The activity pollution Index (API) for activity n using crew formation C_n can be computed using the following equation:

$$\boldsymbol{AEI(n, C_n) = \sum_{i=1}^{M_n} h(i, C_n) * D(i, C_n)} \quad (1)$$

Where ***AEI(n,Cn)*** = Environmental Index for activity ***n*** using crew formation $\mathbf{C_n}$, ***h(i, Cn)*** = construction hazard magnitude per unit time generated by a specific construction operation ***i*** for activity ***n*** using crew formation $\boldsymbol{C_n}$, ***D(i,Cn)*** = duration of construction operation ***i*** for activity ***n*** using crew formation $\boldsymbol{C_n}$ that generates hazard ***h(i,Cn)***, and $\boldsymbol{M_n}$ = number of construction operations for activity ***n***. The value of ***h(i,Cn)*** lies between zero and one indicating the seriousness of the hazard. For example, if a construction operation ***i*** for activity ***n*** using crew formation $\boldsymbol{C_n}$ generates noise that exceeds the threshold of pain, which is 140 db [6], then the value of ***h(i,Cn)*** is one. A value of zero is an indication that no hazard is generated by the construction operation.

3. Decision variables

The primary purpose of this development stage is to formulate a robust optimization model that supports both time and environmental index minimization. To this end, the present model is formulated to determine the main decision variables in this optimization problem and model the three important objectives of optimizing construction time, total cost, and environmental pollution impact in a robust optimization model.

For each construction activity in the project, the present model is designed to consider all relevant decision variables that may have an impact on project time and environmental index, including: 1) subcontracting option, which indicates whether the construction activity is performed using the contractor's own force or subcontracted; 2) construction methods, which represents the availability of different types of materials and/or methods that can be used; 3) crew configurations and sizes that represents the possibility of using single or multiple crews on each activity as well as the size of the used crew and/or equipment; and 4) crew overtime policy, which represents available overtime hours and night time shifts. To control the complexity of the optimization model, the present model combines these four major decision variables into a single variable called crew formation.

The major challenge confronting construction planners in this problem is to select an optimal crew formation option, from the available set of feasible alternatives (n=1…N), for each activity (i=1…l) in the project. The possible combinations of these alternatives create a large search space, where each solution in this space represents a possible resource utilization option for delivering the project. For example, a small-size project that includes 20 activities and five possible crew formations for each activity creates a search space of approximately 95 trillion (i.e., 5^{20}) possible solutions and this search space increases exponentially with the increase in the number of activities in the project. The present model is designed to help planners in this challenging task of searching large solution spaces to identify optimal crew formation plans that achieve multiple project objectives. The two main objectives in the present model are to 1) minimize the project overall time T; 2) minimize the project total cost, and 3) minimize environmental pollution impact.

4. Model formulation

The model will enable decision- makers to study the impact of various crew formation options on the project objectives in order to identify an optimal/near-optimal crew formation for each project activity. The impact of various crew formation decisions on activity cost, duration, and environmental pollution index need to be quantified and measured in order to minimize the overall project duration, total cost, and environmental pollution impact.

The project overall time T is computed using the following equation:

$$T = \sum_{n \in S_n} AD(n, C_n) \quad (2)$$

Where, ***AD(n,Cn)*** = duration of activity n using crew formation $\boldsymbol{C_n}$ and $\boldsymbol{S_n}$= set of critical activities. On the other hand, the project total cost ***TCost*** is computed using the following equation:

$$TCost = DirectCost + IndirectCost = \sum_{n=1}^{NA} AC(n, C_n) + a_0 + a_1.T \quad (3)$$

Where N = number of project activities, $AC(n,C_n)$ = direct cost of activity n using crew formation C_n, a_0 = initial indirect (mobilization) cost, and a_1 = indirect cost slope.

The project environmental index ***PEI*** is computed using the following equation:

$$PEI = \sum_{n=1}^{NA} AEI(n, C_n) \quad (4)$$

Where: $AEI(n,C_n)$ = environmental index for activity n using crew formation C_n.

5. Optimization module

The objective of this module is to search for optimal/near-optimal trade-offs between project time, total cost, and environmental pollution index using a multi-objective genetic algorithm model. Genetic algorithms are search and optimization tools that assist decision makers in identifying optimal or near-optimal solutions for problems with large search spaces. They are inspired by the mechanics of evolution and they adopt the survival of the fittest and the structured exchange of genetic materials among population members over successive generations as a basic mechanism for the search process (Goldberg 1989). The present model is implemented in three major phases: 1) initialization phase that generates an initial set of S possible solutions for the problem; 2) fitness evaluation phase that calculates the time, total cost, and environmental pollution index of each generated solution; and 3) population generation phase that seeks to improve the fitness of solutions over successive generations. The detailed computation procedure in these three phases is explained in the following sections.

5.1. Initialization

This step generates the random set of possible solutions. Parameters such as population size, generations, mutation rate and crossover mutation rate are read by the module. The project parameters are the number of activities, the number of crew formations for each activity, the duration and cost for each crew formation, and the predecessor activities. The initial population of binary strings is created randomly.

5.2. Fitness evaluation

The solution strings and each candidate solution are tested in its environment. The main purpose of this is to evaluate the time, cost and environmental index for each possible solution s in generation G to determine the fitness of the solution. This phase is carried out in two stages. All the solutions are assigned an identical dummy fitness. The lonely solutions are emphasized in the crow by sharing function strategy proposed by Deb 2001. Later all solutions are assigned fitness equal to the population size. This results in a fitness that any solution can have in any population. Therefore it calculates the project time, cost and environmental index for solution s in generation G.

5.3. Population generation

The purpose of this phase is to reproduce population according to the dummy fitness values. Three types of population are created parents, child and combined. A parent population is used to generate a child population. The child population is combined with the parent population to create the combined population. A new child population is created using genetic algorithm operation of selection, crossover and mutation. Selection operation which selects the solutions that can go through the process of reproduction, one with the higher shared fitness are favoured. Crossover operation which selected solutions are crossed at a randomly determined point and swap the variables in the strings at this point resulting in two new solutions. Mutation operation, in this operation the value of one of the variables in the string randomly changes to induce innovation and to prevent premature convergence to local optimal solution.
These all steps are continued until the number of generations is completed.

6. APPLICATION OF AN EXAMPLE

This study analyzes a construction project case to demonstrate the module to find an optimal scheduling solution for the project. The case project adopts the previously studied example of an actual tunnel construction project [9]. It comprises set of activities which have various possible crew formations. Each alternative is associated with a certain duration, cost, and pollution index. The activities considered in the example have several crew formations. Table 1 lists the duration, cost and environmental index for each activity crew formation.

Table 1. List of activities.

ID	Activity	Crew	ID	Activity	Crew
1	Excavation (1st part)	1	20	40 000	0.8
		2	18	50 400	0.9
		3	15	54 000	0.9
		4	14	58 800	1.0
2	Excavation (2nd part)	1	15	30 000	0.8
		2	12	34 000	0.8
		3	10	36 000	0.9
3	Sheet piles (1st part)	1	7	25 400	0.7
		2	5	29 000	0.9
		3	4	31 000	0.9
4	Sheet piles (2nd part)	1	5	19 000	0.7
		2	3	24 000	0.9
5	Dewatering	1	14	15 000	0.2
6	Water tightness (1st part)	1	3	20 000	0.2
		2	1	20 800	0.2
7	Water tightness (2nd part)	1	2	16 000	0.2
		2	1	16 400	0.2
8	Reinforcement for raft (1st part)	1	3	38 000	0.2
		2	2	39 000	0.2
		3	1	39 400	0.2
9	Reinforcement for raft (2nd part)	1	2	35 400	0.2
		2	1	36 000	0.2
10	RC for raft (2nd part)	1	1	24 000	0.8
11	RC for raft (1st part)	1	1	28 000	0.8
12	Formwork for walls (1st part)	1	5	8000	0.2
		2	3	9000	0.2
		3	2	10 000	0.2
13	Formwork for walls (2nd part)	1	3	7000	0.2
		2	2	8000	0.2
14	Reinforcement for walls (2nd part)	1	5	70 000	0.2
		2	3	72 000	0.2

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		3	2	75 000	0.2
15	Reinforcement for walls (1st part)	1	7	76 000	0.2
		2	5	77 200	0.2
		3	3	77 600	0.2
		4	2	78 000	0.2
16	RC for walls (1st part)	1	4	50 000	0.8
		2	3	55 000	0.8
		3	2	60 000	0.8
17	RC for walls (2nd part)	1	3	40 000	0.8
		2	2	45 000	0.8
18	Formwork for slab (2nd part)	1	8	6000	0.2
		2	5	6800	0.2
19	Formwork for slab (1st part)	1	10	6000	0.2
		2	8	6800	0.2
		3	5	8000	0.2
20	Reinforcement for slab (1st part)	1	3	26 000	0.2
		2	2	26 500	0.2
		3	1	27 000	0.2
21	Reinforcement for slab (2nd part)	1	3	24 000	0.2
		2	2	24 800	0.2
22	RC for slab (2nd part)	1	1	18 000	0.8
23	RC for slab (1st part)	1	1	20 000	0.8
24	Backfilling	1	8	16 000	0.7
		2	5	20 000	1.0

The example of 24 activities is analyzed to illustrate the model capabilities in generating and evaluating optimal solution for time, cost and environmental index for construction projects. In this example, each activity can be constructed using alternative crew formations. The precedence relationships between successive activities are finish to start with zero lag time. The indirect cost a1 is estimated at $20,000 per day with an initial cost a1 of $8000.

Table 2. Optimal solutions for the example.

Project time	Total cost	EI	Crew formation option for project activities																							
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
70	2085000	11.1	1	1	1	1	1	2	1	1	2	1	1	2	2	3	4	1	2	1	3	3	2	1	1	1
67	2089400	11.1	1	1	1	1	1	2	1	3	2	1	1	3	2	3	4	1	2	2	3	3	2	1	1	1
62	1948600	11.4	3	2	3	1	1	2	1	1	2	1	1	2	2	3	4	1	2	1	3	3	2	1	1	1

Table 3. Start and finish time for the activities with the lowest duration.

Activity	Direct cost	EI	Duration	start time	finish time

1	58000	1	14	0	14
2	34000	0.8	12	0	12
3	31000	0.9	4	14	18
4	19000	0.7	5	12	17
5	15000	0.2	14	18	32
6	20800	0.2	1	32	33
7	16400	0.2	1	32	33
8	39400	0.2	1	33	34
9	36000	0.2	1	33	34
10	24000	0.8	1	34	35
11	28000	0.8	1	34	35
12	10000	0.2	2	35	37
13	8000	0.2	5	35	40
14	75000	0.2	2	40	42
15	78000	0.2	2	37	39
16	55000	0.8	3	39	42
17	45000	0.8	2	42	44
18	6800	0.2	8	44	52
19	8000	0.2	5	42	47
20	27000	0.2	1	47	48
21	24800	0.2	2	47	49
22	18000	0.8	1	48	49
23	20000	0.8	1	49	50
24	20000	1	5	49	54

The analysis of the example illustrate the capability of the present model in generating a set of optimal resource utilization and scheduling plans that establish optimal trade-offs between project time, project cost and environmental impact helping contractors/decision makers in construction projects to select an optimal plan that satisfies the specific requirements of the project being considered. The Duration-Cost-Environmental impact trade-off Curve also illustrated in the Fig. 1.

Table 4. Start and finish time for activities with lowest environmental impact.

Activity	Direct cost	EI	Duration	start time	finish time
1	40000	0.8	20	0	20
2	30000	0.8	15	0	20
3	25400	0.7	7	20	27
4	19000	0.7	5	20	25
5	15000	0.2	14	27	41
6	20800	0.2	1	41	42
7	16000	0.2	2	41	42
8	38000	0.2	3	42	45
9	36000	0.2	1	42	44
10	24000	0.8	1	44	45
11	28000	0.8	1	45	46
12	9000	0.2	2	46	49

13	8000	0.2	5	45	50
14	75000	0.2	2	50	52
15	78000	0.2	2	49	51
16	50000	0.8	4	51	55
17	45000	0.8	2	52	54
18	6000	0.2	8	54	62
19	8000	0.2	5	55	60
20	27000	0.2	1	60	61
21	24800	0.2	2	60	62
22	18000	0.8	1	61	62
23	20000	0.8	1	62	63
24	16000	0.7	8	62	70

Table 5. Start and finish time for the activities with lowest direct cost.

Activity	Direct cost	EI	Duration	start time	finish time
1	40000	0.8	20	0	20
2	30000	0.8	15	0	20
3	25400	0.7	7	20	27
4	19000	0.7	5	20	25
5	15000	0.2	14	27	41
6	20800	0.2	1	41	42
7	16000	0.2	2	41	42
8	38000	0.2	3	42	45
9	36000	0.2	1	42	44
10	24000	0.8	1	44	45
11	28000	0.8	1	45	46
12	9000	0.2	2	46	49
13	8000	0.2	5	45	50
14	75000	0.2	2	50	52
15	78000	0.2	2	49	51
16	50000	0.8	4	51	55
17	45000	0.8	2	52	54
18	6000	0.2	8	54	62
19	8000	0.2	5	55	60
20	27000	0.2	1	60	61
21	24800	0.2	2	60	62
22	18000	0.8	1	61	62
23	20000	0.8	1	62	63
24	16000	0.7	8	62	70

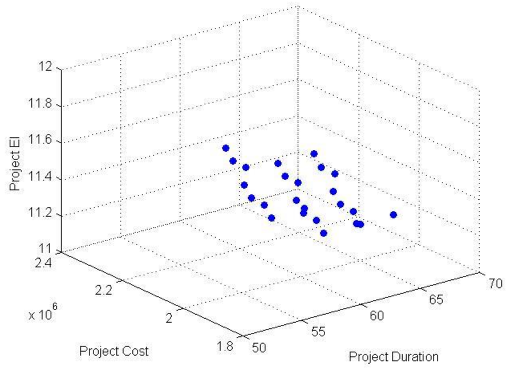

Fig. 1. Duration-Cost-Environmental Impact Trade-off Curve.

7. CONCLUSIONS

A multi objective optimization model was developed that manages the construction pollution hazards. This model utilizes evolutionary genetic algorithm to consider three objective functions project duration, project total cost and environmental index. The model helps construction professionals to generate and evaluate optimal scheduling plans that establish tradeoffs between project time, project total cost and environmental index. It can be utilized by construction authorities and environmental bodies to ensure that the total pollution of construction projects is within the permissible threshold.

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