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BRIDGE_SIM: FRAMEWORK FOR PLANNING AND OPTIMIZING BRIDGE DECK CONSTRUCTION USING COMPUTER SIMULATION

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ABSTRACT

This paper presents a framework (named *Bridge_Sim*) that aids contractors in planning bridge deck construction using computer simulation. The proposed framework estimates the time and cost required for construction of bridges' decks. Seven construction methods are included in the proposed framework. These are: cast-in-place on falsework, steel bridge construction, cantilever carriage, pre-cast balanced cantilever, deck pushing, stepping formwork, and launching girder method. The framework estimates total duration and cost for each zone along with its sub-zones, taking into account uncertainties inherited in tasks duration by allowing utilization probability density functions. It allows defining different options and ranges of parameters that influence the duration and total cost associated with launching girder construction method to carry out optimization analysis utilizing Ant Colony optimization. A numerical example is presented to demonstrate the practical features of *Bridge_Sim*.

1 INTRODUCTION

Infrastructure projects are characterized by long duration, large budget, and complexity. They encompass bridges tunnels, airports, dams, highways projects. Construction of bridge projects is a complex process that inherits uncertainty since the construction is executed in different job conditions. These conditions includes unusual or complex works, equipments breakdown, unfavorable weather conditions, and unexpected site conditions. When such production rates are altered within large-scale projects, like bridge construction projects, this might lead to deviation from original work plan. Traditional planning techniques do not account for uncertainties. New construction methods have been developed to improve constructability of bridges decks, such as "Segmental" construction which eliminates falsework system (Podolny and Muller 1982). Segmental construction is executed in a cyclic manner which nominates computer simulation as a best modeling technique. This paper presents a framework, named *Bridge_Sim*, for planning and optimizing bridge deck construction utilizing computer simulation. The paper provides an overview of the developed framework and its designated components. A numerical example is worked out to illustrate the practical use of the proposed framework.

2 PROPOSED FRAMEWORK

The developed framework (*Bridge_Sim*) helps contractors in planning bridge deck construction. It performs two main functions; deck construction planning and optimizing deck construction using launching girder. These two functions are performed by four main components; Bridge Analyzer Module, Simulation Module, Optimization Module, and Reporting Module. Figure 1 depicts a schematic diagram for the proposed framework that shows the interaction between its components. The planning function of the framework is performed by Bridge Analyzer, Simulation, and Reporting modules (solid arrows in Figure 1). Meanwhile, the optimization function is performed by Optimization, Simulation, and Reporting modules (dashed arrows in Figure 1). The following sections describe the four components of *Bridge_Sim*.

2.1 Bridge Analyzer Module

Bridge Analyzer Module is used to carry out planning function inherited in *Bridge_Sim*. It analyzes the project and breaks it down into construction zones and sub-zones. Seven construction methods are provided by *Bridge_Sim*: 1) cast-in-place on falsework, 2) steel girder construction, 3) cantilever carriage, 4) pre-cast balanced cantilever, 5) deck pushing, 6) stepping formwork, and 7) launching girder. The number of construction zones is determined based on the following criteria:

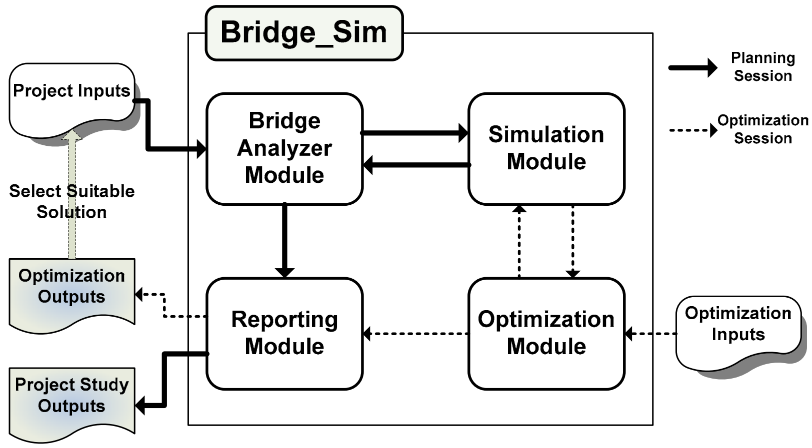

Figure 1: *Bridge_Sim*: main components

1. The construction method that is used in execution; i.e., a separate zone should be assigned for each utilized construction method.
2. The resources that are assigned in each construction method. For a given construction method, resources can be assigned differently in two different construction locations, these two locations are defined as two separate zones, however, they are using the same construction method.
3. The sequence of construction. If two parts are constructed using the same construction method and the same set of resources but it is required to be executed simultaneously or successively. In this case, these two parts are defined as two separate zones.

On the other hand, zones are divided into sub-zones to model the existing segments' types (e.g, typical, closing, and shoring segments) that lie thought and between piers. The procedure followed by the Bridge Analyzer Module to perform a planning session of deck construction is depicted in Figure 2.

2.2 Simulation Module

Simulation Module is utilized for estimating the total duration and total cost of bridge deck construction. The proposed Simulation Module utilizes STROBOSCOPE (Martinez 1996), as a simulation engine. The module has been designed to adopt discrete event simulation (DEVS) technique. The simulation module is implemented in Microsoft Visual Basic 6.0 to activate STROBOSCOPE program. There are fourteen models that are built-in the developed Simulation Module as listed in Table 1. These simulation models are built based on the seven construction methods and their respective construction techniques. According to the method of construction, the simulation module selects the model that represents the case under consideration. Then, it modifies the selected model to account for the in-

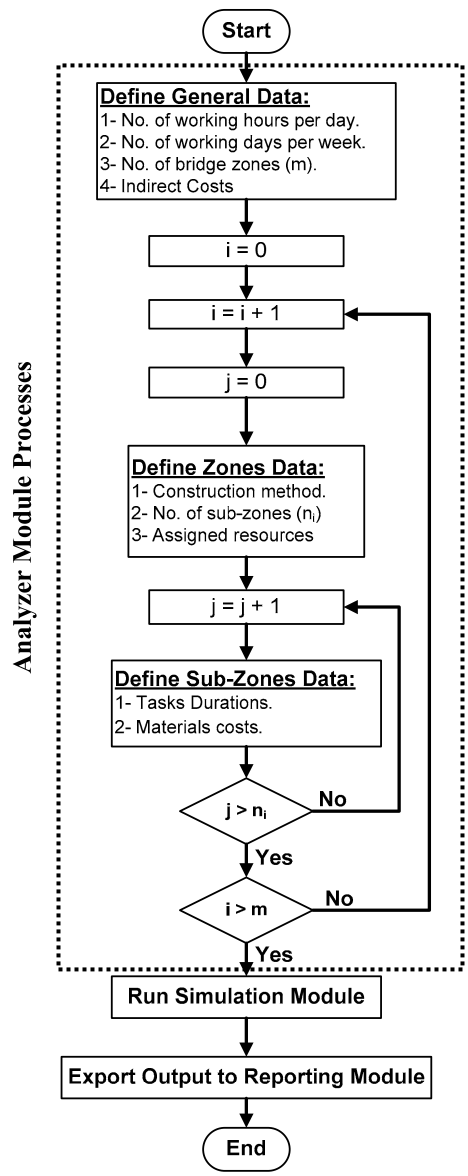

Figure 2: Bridge analyzer module procedure

put data (see Figure 3). These input data include; the scope of work (i.e. number of segments), numbers of the assigned resources, number of replications, number of working hours per day, and estimated durations for construction tasks. Once the modification is carried out, the simulation module launches STROBOSCOPE to run the model that has the case parameters. STROBOSCOPE estimates the durations which is exported to a text file in order to perform cost calculations. Table 2 lists the involved tasks of stepping formwork erection; considered in *SteppingFormwork* model, whereas, its simulation network is depicted in Figure 4. Detailed description of the fourteen models, coded in Simulation Module, can be found elsewhere (Zein 2006).

2.3 Optimization Module

The proposed framework is capable to carry out time-cost trade-off analysis in order to optimize the construction of bridges' decks using launching girder method. It searches for the near-optimum solution by minimizing the time and cost of construction. The construction of bridges' deck using launching girder technique is influenced by several parameters that impact construction time and associated totalcost. These parameters are: 1) location of casting yard, 2) time lag between pre-casting yard and construction zone tasks, 3) number of casting forms, 4) number of preparation platforms, 5) curing method, 6) number of reinforcement crews in the casting yard, and 7) number of stressing crews.

The proposed framework provides construction contractors with a set of optimal solutions that form a Pareto face. *Bridge_Sim* performs the optimization analysis through three components; 1) Optimization Module, 2) Simulation Module, and 3) Reporting Module (see Figure 5). The optimization session starts by defining the available options of the optimization variables. Then, a random set of solutions is generated and fed to the Simulation Module to estimate the duration and total cost of generated solutions. The Optimization Module receives the duration and cost values to carry out the multi-objective optimiza tion. The interaction between Simulation and Optimization Modules occurs in a cyclic manner, producing a number of iterations. The number of iterations is a problem-dependent and is determined by conducting several pilot trials. When all iterations are generated, the Optimization Module exports its outputs to the Reporting Module as depicted in Figure 5.

Table 1: Models of simulation module

Method	Model	Description
Cast-in-place on falsework	*CastinSitu*	Cast-in-place on falsework method.
Steel girder construction	*Steel*	Steel span construction
Cantilever carriage	*Carriage(1)*	Cantilever carriage method using pump line technique for typical segments only
	TotalCarriage(1)	Cantilever carriage method using pump line technique for typical and stump segments
	Carriage(2)	Cantilever carriage method using truck mixers technique for typical segments only
	TotalCarriage(2)	Cantilever carriage method using truck mixers technique for typical and stump segments
	ClosingSegment	Cantilever carriage method for closing segment construction
Pre-cast balanced cantilever	*Precast(1)*	Pre-cast balanced cantilever method using mobile cranes technique
	Precast(2)	Pre-cast balanced cantilever method using Beam-Winch technique
Deck pushing	*DeckPushing(1)*	Segments fabrication operation (Deck pushing method) using single form technique
	DeckPushing(2)	Segments fabrication operation (Deck pushing method) using multi-forms technique
	DeckPushingTotal	Deck pushing method including all operations
Stepping formwork	*SteppingFormwork*	Stepping formwork method
Launching girder	*LaunchingGirder*	Launching girder method

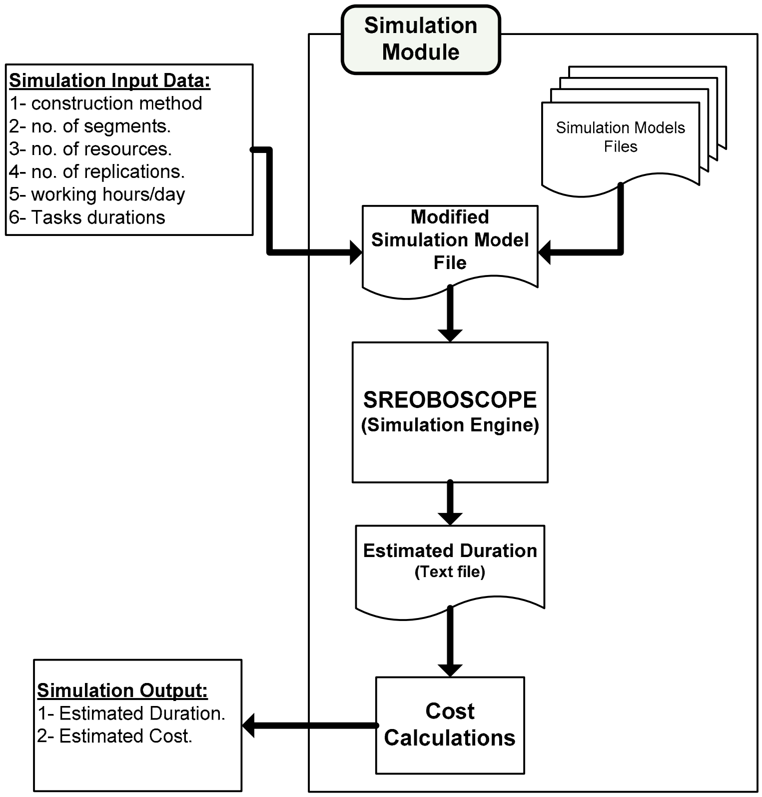

Figure 3: Simulation module procedure

Table 2: Processes and tasks of *SteppingFormwork* model

Operation	Process	Task Code	Task Description
System Erection		St0	Erection of stepping formwork system on existing deck.
Segments Construction	Construction of Bottom Flange	St1	Prepare stepping formwork for advancing phase.
		St2	Advance the stepping formwork into new position.
		St3	Regroup bottom slab forms.
		St4	Placement of first layer of the reinforcement for bottom flange.
		St5	Placement of ducts for bottom flange.
		St6	Finish reinforcement work for bottom flange.
		St7	Casting of bottom flange.
		St8	Curing of bottom flange.
	Construction of Webs and Top Flange	St9	Erection of formwork for webs and top flange.
		St10	Placement of first layer of the reinforcement for webs and top flange.
		St11	Placement of ducts for webs and top flange.
		St12	Finish reinforcement work for webs and top flange.
		St13	Casting of webs and top flange.
		St14	Curing of webs and top flange.
		St15	Placement and pre-stressing of cables of webs and top flange.

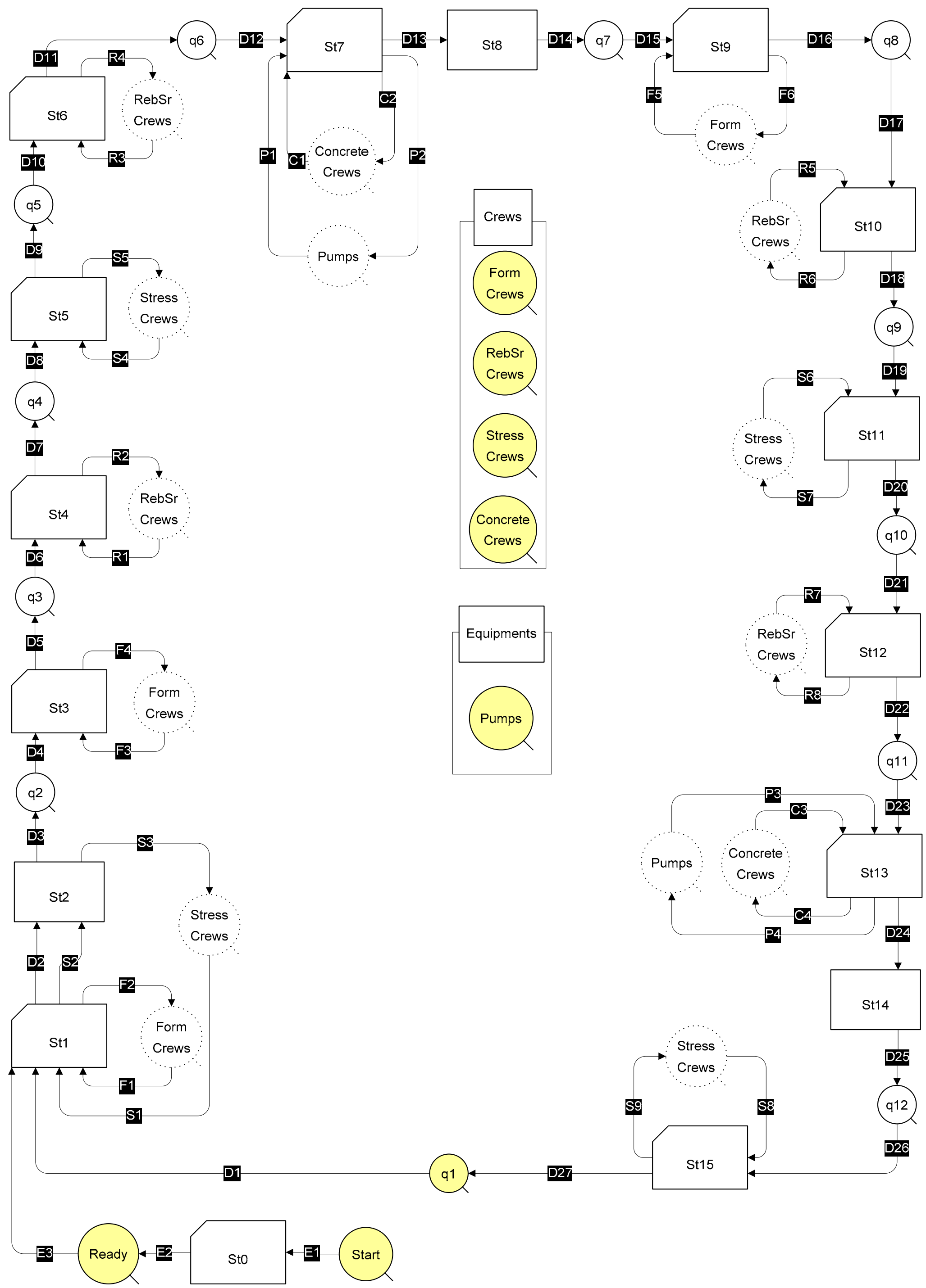

Figure 4: Simulation network of *SteppingFormwork* model

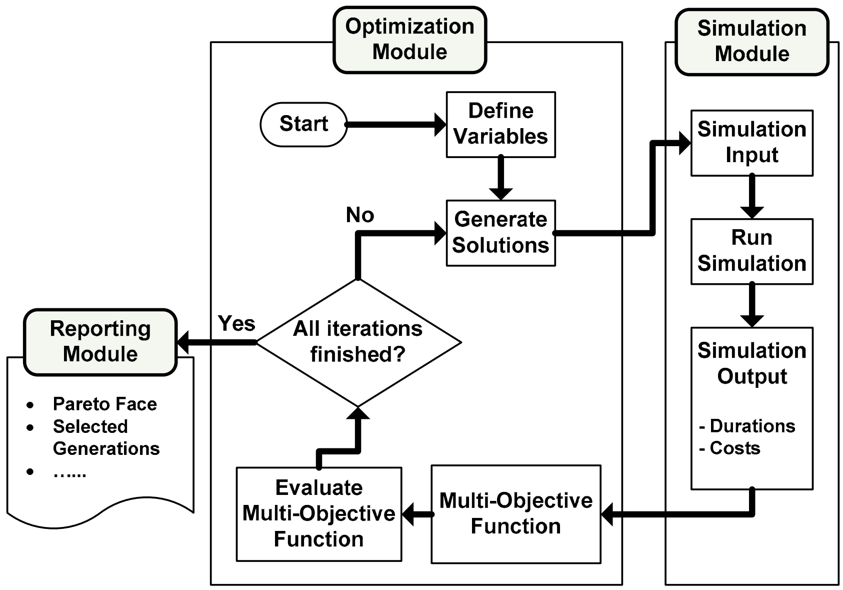

Figure 5: Interaction between optimization, simulation, and reporting modules

The developed Optimization Module utilizes a modified Ant Colony Optimization (ACO) to perform multi-objective optimization method (Zein et al. 2006). Ant Colony Optimization is one of the evolutionary algorithms which are used to solve optimization problems depicting nature evolution and species behavior living in it. ACO mimics ants' behavior to find shortest path (optimum path) between their nest and the food using what is named as pheromone trails (see Figure 6). These trails are chemical compounds left behind each ant whenever and wherever it moves as indirect communication between ants (Dorigo 1996).

Two multi-optimization methods are utilized to combine total duration and cost into one single fitness function to be evaluated by ACO. These methods are modified distance (Osyczka and Kundu 1996) and function-transformation (Marler and Arora 2005). The modified distance method depends on expressing each solution with any generation with fitness value according to its location to the existing Pareto face. Meanwhile, function-transformation method combines the cost and duration in a dimensionless function as per Equation 1. Detailed description of the fourteen models, coded in Simulation Module, can be found elsewhere (Zein 2006).

$$Fitness(k,t) = \left(\frac{Cost(k,t) - MinCost}{MinCost}\right) + \left(\frac{Duration(k,t) - MinDuration}{MinDuration}\right) \quad (1)$$

Where; $Fitness(k,t)$ is a combined fitness for ant k at iteration t; *Cost(k,t)* and Duration(k,t) are the total cost and duration of ant k at iteration t; *MinCost* is the minimum value of total cost within iteration t, and *MinDuration* is the minimum value of durations within iteration t.

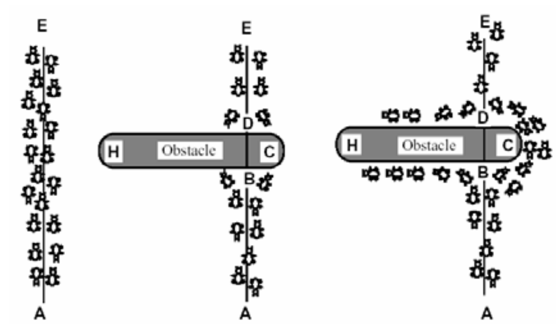

Figure 6: Ants' movement behavior (Dorigo 1996)

2.4 Reporting Module

The Reporting Module is triggered in both planning and optimization operations provided by *Bridge_Sim*. It generates reports in text and graphical formats. Simulation Module provides Reporting Module with the duration and cost for each sub-zone. Reporting Module calculates minimum, mean, and maximum values of direct cost for each zone by summing up the corresponding values of its respective sub-zones. Similarly, it calculates minimum, mean, and maximum values of zones' durations. The total duration of bridge deck construction is calculated utilizing central limit theorem, taking into account the defined relationships and lags amongst zones. The minimum and maximum values of total duration of deck construction are obtained by calculating the summation of minimum and maximum values of zones on the critical path. Subsequently, the total cost (direct and indirect) is calculated using the following equations:

$$TC_{min} = \sum_{i=1}^{m} DC_i + TIIC + (TDIC \times TD_{min}) \quad (2)$$

$$TC_{mean} = \sum_{i=1}^{m} DC_i + TIIC + (TDIC \times TD_{mean}) \quad (3)$$

$$TC_{max} = \sum_{i=1}^{m} DC_i + TIIC + (TDIC \times TD_{max}) \quad (4)$$

where:

TC_{min}, TC_{mesn}, and TC_{max} are the minimum, mean, maximum value of total cost of bridge deck construction respectively.
TD_{min}, TD_{mesn}, and TD_{max} are the minimum, mean, maximum value of total duration of bridge deck construction respectively.
DC_i is the direct cost of zone i, where i = 1, 2, 3, …, m. and m is the number of zones
TIIC is the time in-dependent indirect cost.
TDIC is the time dependent indirect cost.

3 NUMERICAL EXAMPLE

This numerical example considers El-Warrak Bridge, constructed using traditional cast-in-place on falsework and cantilever carriage methods. El-Warral Bridge is part of the Ring Road, around Greatest Cairo, crossing the River Nile (see Figure 7). It consists of five zones: i) eastern shore, ii) eastern Nile branch, iii) El-Warrak Island, iv) western Nile branch, and v) western shore. El-Warrak Bridge is executed in two stages. The first phase started in November 1996 and finished in October 1999. The second phase started immediately after the first phase and finished in October 2001. This case models the first phase construction. Table 3 lists the information pertaining to El-Warrak bridge zones and sub-zones. The data of the case are included in Zein (2006). Once the data are fed and the simulation experiments are conducted, *Bridge_Sim* estimates the direct cost and duration for El-Warrak Bridge zones as listed in Table 4.

Figure 7: El-Warrak bridge after construction

Table 3: Bridge zones vs. number of spans

ID	Zone	No. of spans	Construction Method	No. of Sub-Zones	Total Length (m)
I	Eastern Shore	13	Cast-in-Place on Falsework	4	400
II	Eastern Nile Branch	6	Cantilever Carriage	7	600
III	El-Warrak Island	6	Cast-in-Place on Falsework	3	230
IV	Western Nile Branch	4	Cantilever Carriage	7	360
V	Western Shore	22	Cast-in-Place on Falsework	11	670

Table 4: Simulation outputs

ID	Zone	Expected Duration (Days)	Direct Cost (L.E.)
I	Eastern Shore	122.75	6,460,190
II	Eastern Nile Branch	381.33	12,884,271
III	El-Warrak Island	90.61	4,064,869
IV	Western Nile Branch	375.41	12,566,617
V	Western Shore	405.93	21,815,761

The expected total duration is estimated to be 544 working days (equals to 635 calendar days). The associated total cost of the deck is 66,875,526 L.E which consists of 57,791,708 and 9,083,818 L.E. as direct and indirect costs, respectively. The cost of cantilever carriage zones represents 44% of the total cost of the deck. The cost of casting concrete is 1,277 L.E/m^3 in cantilever carriage zones, compared to 1,045 L.E/m^3 in falsework zones.

4 CONCLUSIONS

Construction of bridge projects is a complex process that inherits uncertainty and variety of demands. Construction contractors have to select the construction method that suits project constraints including: project conditions, technical, financial, and time constraints. This paper presented a framework (*Bridge_Sim*) that can be used in planning and optimizing of bridges decks. It estimates the time and cost required for construction of bridges' decks. Seven construction methods can be modeled in the proposed framework. *Bridge_Sim* consists of four components: Bridge Analyzer Module, Simulation Module, Optimization Module, and Reporting Module. Bridge Analyzer module aids in dividing bridge deck into zones and subzones, according to the utilized construction method. Whereas, simulation module estimates total duration and cost for each defined sub-zones, taking into account uncertainties inherited in tasks duration by allowing utilization probability density functions. Optimization Module allows defining different options and ranges of parameters that influence the duration and total cost associated with launching girder construction method. It utilizes a modified Ant Colony optimization to model time-cost trade-off analysis. The multi-objective problem is treated using the modified distance method and function-transformation. Reporting Module provides the time and cost of bridges decks construction in text and graphical formats. A numerical example was presented to demonstrate the use of the proposed framework.

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