A COMPUTER MODEL FOR TIME AND COST OPTIMISATION DURING PRE-TENDER STAGE

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ABSTRACT

An integrated computer model for the evaluation of different project duration/cost solutions during pre-tender and pre-contract stages has been developed for multi-storey reinforced concrete office buildings. The model performs two processes; simulation and optimisation. The optimisation part, which is the subject of this paper, uses data provided by the simulation part to determine sets of time vs. cost solutions. The model takes account of the precedence relationships, the lag values, and the normal and crash values of time and cost for activities. Linear programming is used to solve the optimisation problem. Minimum increase in the project direct cost when the project duration is accelerated is achieved by the minimisation of the objective function. The model has been validated by checking the optimisation process and the validity of the theoretical basis using a hypothetical six storey reinforced concrete office building. In addition the model has been reviewed by construction practitioners using the same hypothetical building to check the validity of the results.

Keywords: Computer modelling, optimisation, time/cost curves, linear programming, Simplex Algorithm

Introduction

In competitive bidding, the project completion time is usually dictated by the requirements of the client and the successful tender is usually the lowest priced one. However for the sensible contractor a successful tender is the basis from which the successfully finished project (i.e. on time and within budget) is achieved. Thus, it is vital for a contractor to arrive at a realistically achievable minimum tender price in terms of which the contract can be completed within the period required by the client. To be able to arrive at realistic cost estimates which satisfy the required project completion time, the contractor has to consider a range of alternative solutions. However, the pressure on the contractor due to time restrictions may result in him/her not undertaking the required analysis of the large amount of data and information associated with the bid and in basing the decisions on intuition and experience only. Thus, contractors can benefit from the use of computer-based time and cost models which support the analysis of large amounts of data.

Various computer based time and cost models have been developed since the 1980s. Simulation, generation and optimisation methods have been used to develop these models (Bennett and Ferry, 1987; Newton, 1991; Laptali et al., 1995). Laptali et al. (1995) state that each method has its limitations in providing a realistic solution to the practical problems of estimating time and cost and one approach to improve effectiveness may be to combine two or more of the methods. Thus, an integrated computer-based time and cost model which can be used during pre-tender and pre-contract stages for reinforced concrete multi-storey office buildings has been developed by combining simulation and optimisation methods. The model enables rapid comparison of the effect of possible alternative solutions (i.e. different choices for manpower, materials and plant) on project time and cost, simulates the relationship between construction activities, models cost/duration relationships for activities, and determines different project duration and cost values including the minimum cost corresponding to the optimum duration. The simulation part of the model deals with the structure of the time/cost estimation problem. Structure refers to how time/cost estimation is conceptualised in terms of the problem boundaries, the variables considered and the inter-relationship between variables. The duration and cost of a multi-storey reinforced concrete office building is calculated through the simulation part. A set of choices for the selection of materials and plant and possible methods of work are provided by the model. User input is required for quantities of work, gang sizes, quantity of plant, lag values between activities, output rates, unit costs of plant and labour, and indirect costs. Also required is productivity loss due to project acceleration in order to determine the project duration and cost values for normal and crash conditions (Laptali et al., 1995). The optimisation part then evaluates a series of time/cost solutions and searches for the best solution for the given variables.

In the current paper, the authors discuss cost/duration relationships, the formulation of a model, the programming technique used, and the validation procedures followed during the development of the optimisation part.

Methodology Of The Research

During the development of the integrated model, a total number of fourteen, two to three hour interviews were conducted with the construction practitioners (planners, estimators and in-house researchers) from two large (in terms of turnover) construction companies. The interviews were in structured and semi-structured forms and undertaken during different stages of the model. In general the aims of the interviews were to;

(1) obtain information/data that could be used for the development of the model,
(2) elicit the opinions of the practitioners related to the model and its potential application areas,
(3) validate the results from the model.

Time And Cost Relationships

The total cost of completing a project consists of both direct and indirect costs which change if the project completion time is shortened or extended, resulting in different total cost values for different project completion times.

Antill (1990) states that a multi-linear relationship between duration and direct cost of an activity is the most frequent condition encountered in practice. However, for the sake of simplicity when developing computer models, the multi-linear activity cost curves can be approximated to a linear form. Linear activity cost/duration relationships have been utilised within the integrated model described in this paper. This minimises the amount of input data required from the user to accelerate the activities but, when the multi-linear relationship is approximated, greater direct cost values are obtained. However, reports in the literature suggest that for a high percentage of activities only minimum cost/duration data will require analysis and that a high percentage (90%) of the activities in a construction project have multi-linear time/cost curves with a maximum of only three sections (Cusack, 1981). Additionally, when the activity is accelerated by overtime work, the cost/duration relationship is linear without any approximations. Thus, although it may seem to be in the contractor's interest to use models that utilise multi-linear relationships between activity cost and duration to arrive at a more accurate minimum project cost, the additional effort for modelling may not be justified when the two results are compared.

Optimisation Programming Techniques

Dynamic programming, heuristic modelling, integer linear programming and linear programming are techniques used to formulate time and cost relationships and determine minimum project cost corresponding to optimum project duration. All of these techniques have their advantages and disadvantages, and these have been discussed by various authors (Jelen, 1970; Lutz et al., 1993; Taha, 1989; Atkin, 1987; Cusack, 1984; Cusack, 1985; Sebestyen, 1993; Skibiniewski et al., 1994). For the development of the optimisation model in the current project, linear programming has been chosen and the other techniques have been rejected due to the following reasons.

Dynamic Programming

Jelen (1970) states that “dynamic programming is an optimisation technique that is especially applicable to the solution of multistage problems”. Computations are carried out in stages which reduce their total amount. As each stage of the problem is considered independently, these stages must be linked in a manner that guarantees a feasible solution both for each stage and for entire problem (Taha, 1989). The output needs to be converted into a graphical format to be easily interpreted by the end user (Taha, 1989; Lutz and Hijazi, 1993). While not being limited to the linear assumption is a strength of the technique in general programming, it is a weakness in solving general linear programming problems (Taha, 1989).

Heuristic Methods

Heuristic methods are stated to be alternative solutions to the mathematical methods of dynamic, integer linear, linear and non-linear programming in order to handle large networks directly. The heuristic approach provides a less complicated mathematical procedure than the mathematical methods. However, the results obtained by utilising heuristic methods have proved to be less mathematically accurate when compared with the results from the mathematical methods (Cusack, 1981). Additionally, application of heuristic methods would require more computational effort for the development of the simulation part of the integrated model to enable ‘what if’ analysis to provide a range of alternative solutions.

Integer Linear Programming Techniques

Integer linear programming techniques can deal with problems in which some or all of the variables can only have non negative integer values. It could have been used in this research by rounding up the time, cost and lag values to the nearest integer. As the rounding up these values is a common practice by the construction planners, that would not affect the results substantially. However, it is stated by Taha (1989) that the performance of models based on integer programming has not been as successful as the linear programs, especially when the size of the problem increases. This is because although several finite algorithms have been developed for the integer linear problem, none of them are uniformly efficient from the computational standpoint especially due to the effect of round off error.

Linear Programming Formulation

To be able to evaluate different project duration/cost values using a linear programming technique, the problem has to be presented in a certain format, namely:

(1) There has to be an objective function to be maximised or minimised.
(2) The objective function has to have linear relationships with the decision variables.
(3) There have to be constraints on the decision variables and these should be in the form of linear inequalities or equalities.
(4) All the decision variables have to be non-negative.

The Objective Function

To be able to set up an objective function for determining the minimum total project cost, firstly the total project (construction) cost (TPC) for normal conditions is defined (formula (1), below). The changes in direct and indirect costs are also formalised. As stated by CIOB (1991) while accelerating the project by overtime work or by employing more resources, the direct cost of each accelerated activity increases mainly due to the reduction in labour productivity. The increase in activity direct cost due to acceleration is represented by the formulae (2) and (3) .

$$TPC = IPC_n + \sum_{i=1}^{i=n} DC_n(i) \qquad \text{........(1)}$$

$$DC_a(i) = DC_n(i) + U(i) \times T(i) \qquad \text{......(2)}$$

and

$$U(i) = (DC_c(i) - DC_n(i)) / (D_n(i) - D_c(i)) \qquad \text{......(3)}$$

where TPC = total project cost, IPC_n = indirect project cost under normal conditions, $Dc_n(i)$ = direct cost of activity i under normal conditions, and n = number of activities, $Dc_a(i)$ = direct cost of activity i due to the accelerated duration, U(i) = increase in direct cost per one unit duration time (days) of an activity, i.e. cost slope, T(i) = number of days in which the activity i should be compressed, $DC_c(i)$ = direct cost of the activity i under all crash conditions, $D_n(i)$ = duration of the activity i under normal conditions, and $D_c(i)$ = Duration of the activity i under all crash conditions.

As the project duration is accelerated, the indirect cost of the project decreases linearly and can be expressed as:

$$IPC_c = IPC_n \times Dur_a / Dur_n \qquad \text{.......(4)}$$

where IPC_c = indirect project cost at the accelerated duration, IPC_n = indirect project cost at the normal duration, Dur_n = normal duration of the project, and Dur_a = accelerated duration of the project.

Consequently, the objective function Z can be expressed as:

$$Z = \underbrace{Min((\sum_{I=1}^{i=n} DC_n(i))}_{\text{Part (1)}} + \underbrace{(IPC_c)}_{\text{Part (2)}} + \underbrace{(\sum_{i=1}^{i=n} U(i) \times T(i)))}_{\text{Part (3)}} \quad .....(5)$$

For a particular project, the first part (1) of equation (5) will be a constant value which is calculated in the simulation part of the model from the user's input. The second part (2) (i.e. indirect project cost at an accelerated duration) is directly proportional to the project duration and can be calculated using equation (4). Thus only part (3) of the equation requires to be minimised with only the T(i) values being unknown. Thus, the objective function effectively minimises the direct cost increase while accelerating the project.

Constraints

The following constraints, which are based on the discussion by Stark and Mayer (1983), have been formulated to operate the data input by the user into the simulation part of the model. However, while the aim of Stark and Mayer's formulation is to minimise the cost of completing the project within a given period and provide one project duration/cost solution, the aim in the current model is to determine sets of project duration/cost solutions.

$$X_p \leq A \quad ......(6)$$
$$X(pi) - X(i) + T(i) \geq L(i) \quad ......(7)$$
$$T(i) \leq Ts(i) \quad ....(8)$$
$$Ts(i) = D_n(i) - D_c(i) \quad ....(9)$$

where X_p = project duration, X(i) = earliest start time of the activity i, X(pi) = earliest start time of the activity pi which is following activity i, T(i) = number of days in which the activity i should be compressed, L(i) = lag value between activity i and the following activity pi, T_s (i) = maximum amount of time by which each activity can be shortened, $D_n(i)$ = duration of the activity i under normal conditions, $D_c(i)$ = duration of the activity i under crash conditions, and A = project duration under normal conditions.

According to constraint (6), project duration/cost solutions are determined for the project durations which are not longer than the project duration under normal conditions (calculated by the simulation part). While constraints (8) and (9) show that the activities can not be accelerated more than the difference between their crash and normal durations as calculated by the simulation part, constraint (7) states that the acceleration of two successive activities should not affect the lag value and the start to start precedence relationship between them (Laptali et al., 1995).

The Optimisation Model 'OPTIMA'

Based on the above discussion the principal elements of 'OPTIMA' are shown below in Fig. 1.

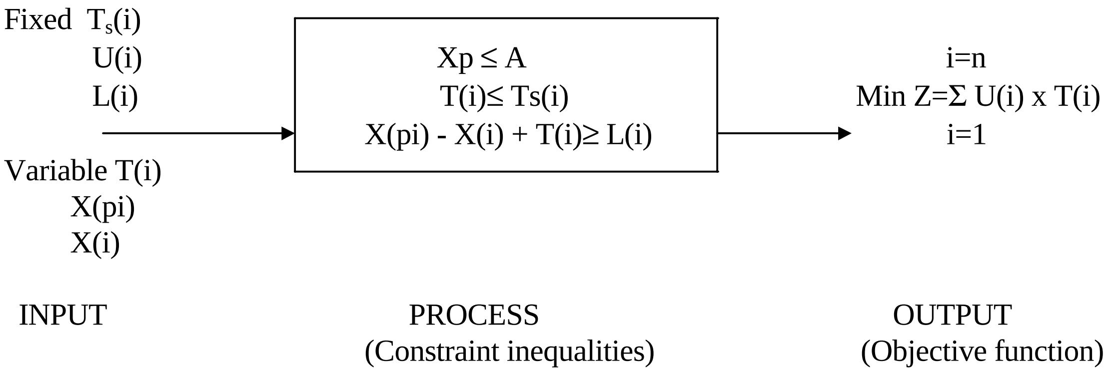

FIG. 1 Flow Chart of the Linear Programming Method

The principle used in the optimisation procedure is to crash the activities on the Critical Path with the lowest cost slope or cheapest fist and repeat the process until the optimum time and cost are obtained.

Both the activity and the project duration and cost values for normal and crash conditions are determined by the simulation part utilising the user input for quantities of work, gang sizes and the quantity of plant, lag values between activities, output rates, unit costs of plant and labour, indirect costs and productivity loss due to project acceleration. Thus, the fixed input shown in Fig. 1 is determined either from the output of the simulation part (T_s(i) and U(i) values) or input by the user (L(i) values). These are then used by a Simplex Algorithm to obtain the objective function which minimises the direct project cost increase. However, as stated previously, the aim of the development of OPTIMA is not only to obtain the minimum direct project cost increase but also to evaluate sets of project duration vs. cost solutions including the minimum total project cost corresponding to the optimum project duration. Thus, when the value of the objective function (i.e. the minimum direct cost increase and the corresponding project duration) has been determined, the duration of the project is accelerated by one day intervals from the minimum direct cost duration, and the project costs (direct, indirect and total) are calculated. The process is then repeated until the minimum duration below which the project cannot be completed is reached. During this process, while the values of fixed input (Fig. 1) do not change, the values of the variable input change for each project duration time. However, the integration of simulation and optimisation enables changing the values of the fixed input if required and enables the rapid observation of the effect of changes in quantities of materials, output rates, gang sizes, unit costs and lag values, on the project cost/duration values during project acceleration. At the end of the execution of the programme the following information can be obtained by the user for every one day acceleration of the project duration between all normal and all crash durations:

(a) The change in direct and indirect costs of the project,
(b) new direct, indirect and total project costs,

(c) the names of the activities to be accelerated.

Validation Of 'OPTIMA'

Methodology

A hypothetical six storey reinforced concrete office building has been taken as a case study for the validation of OPTIMA. Use of a hypothetical building and data may not be found to be enough for the acceptance of the model by some of the end users. However it should be noted that it is very difficult to obtain what may be sensitive commercial information/data related to tendering processes (especially estimating) from the construction practitioners. The interviewed practitioners for this research have only agreed to use a hypothetical case for the validation of this model. Also it should be stressed that validation is concerned with testing the validity of a model's theoretical basis and its ability to reproduce observed performance (Bowman and Lomas, 1985; Laptali et al., 1996), and a model is valid if it can give a reasonable prediction of the system's performance in spite of its inexactness in presenting the system (Taha, 1989). Additionally, another approach is to have the overall model reviewed by people who are most familiar with the operation of the real system (Anderson et al. (1985). Thus, for the validation of OPTIMA, it is found to be enough to include the hypothetical case study and opinions of the construction practitioners related with the performance and the acceptability of the model.

Requirements For The Validation Of The Model's Theoretical Basis

The duration of a project can only be decreased if the activities on the critical path of the project are accelerated. Additionally, when an activity is accelerated by employing either more labour or overtime work or both at the same time, an increase in the direct cost of the project occurs. Thus, the validation of the results has been based on the principle that the activity with the lowest cost slope (i.e. U(i) values from the objective function expression) on the critical path should be accelerated first. The acceleration will continue with the second lowest and so on until crashing any activity will not result in acceleration of the project duration. Additionally, the constraints on the objective function should be considered during the validation process. According to the constraints discussed above, the project duration cannot be less than the duration calculated within the Simulation Model under normal conditions i.e. an activity cannot be compressed more than the difference between its normal and crash duration (both of which are calculated within the Simulation Model). Moreover the lag values between two preceding activities cannot be less than the lag input value to the Simulation Model. Neither can they be less than the difference between the duration of the preceding activity and the lag value, if the following activity starts after the finish date of the preceding activity.

Input Data

The normal and accelerated cost and duration values for the activities of the hypothetical building project were calculated by the Simulation Model. The results from the Simulation Model were validated by comparing them with the duration and cost results obtained by the interviewed planners and by using spreadsheet (Laptali et al., 1995). As discussed by Laptali (1996) the comparison of the results obtained by the planners with the results obtained from the Simulation Model showed that the procedures applied within the model are exactly the same as the procedures applied in practice when calculating the cost and duration of activities during pre-tender planning stage. Meanwhile, it also showed some discrepancies in the results of the activity cost calculations between those of the model and those of the spreadsheet (which do not exceed 0.4%). However, these differences can be ignored as firstly the degree of precision of results is influenced by the fact that the model makes calculations only to the first place of decimals and during pre-tender planning process values are usually rounded to the nearest whole number.

The input data for OPTIMA, obtained from the Simulation Model and the cost slope values (U(i)) are summarised in Table 1. In addition to the normal and crash values, the total indirect cost for normal conditions and the lag values between activities are also provided through the Simulation Model (see Fig. 2) (Laptali et al., 1995).

Description	Normal	Crash	Normal	Crash	Cost Slope
	Direct Cost	Direct Cost	Duration	Duration	U(i)
	(£)	(£)	(days)	(days)	
SUBSTRUCTURE					
Excavate topsoil	324.0	385.7	2	1	61.7
Reduce levels	428.4	510.0	3	2	81.6
Excavate foundations	283.5	337.5	2	1	54.0
CONCRETE FOR:					
Blinding Foundations	803.7	808.0	3	2	4.3
Foundations	27128.0	27802.1	8	4	168.53
REINFORCEMENT					
Foundations	7946.1	8185.1	9	7	119.5
FORMWORK	1236.2	1332.3	3	2	96.1
SUPERSTRUCTURE					
COLUMNS/WALLS:					
Formwork	1099.8	1160.8	2	1	61.0
Reinforcement	814.5	816.2	3	1	1.7
Concrete	1317.8	1329.6	3	2	11.8
SLABS/BEAMS:					
Formwork	29100.0	29766.1	13	7	111.02
Reinforcement	15264.0	15272.0	12	9	2.0
Concrete	26002.8	26262.0	4	2	129.6
STAIRCASES					
Formwork	300.2	312.3	1	1	0.0
Reinforcement	157.5	157.2	1	1	0.0
Concrete	267.7	269.2	1	1	0.0
BRICK/BLOCKWORK					
EXTERNAL					
Brickwork	20380.0	20622.0	8	5	80.6
Blockwork	6031.2	6321.1	6	4	145.0
INTERNAL					
Blockwork	2983.7	3255.3	7	4	90.5
ROOF					
Asphalt	15120.0	16387.6	30	15	84.5

TABLE 1. Normal and Crash Cost and Duration Values Provided By the Simulation Model

Lag Values (days)(start to start relationship)

Excavate Topsoil
2.0
Excavate to reduce levels
3.0
Excavate & Compact Foundations
1.0
Blinding Foundations
0 .0
Formwork to Foundations
2.0
Reinforcement to Foundations
3.0
Concrete to Foundations
5.0
Frc Ground Floor Slab
11.0
Frc Cols/Walls Gr to 1st
6.0
1st Floor Frc Slab/Beams
19.0
Frc Staircases

Explanation:
Floor no 1 = Ground to 1st
Floor no 2 = 1st to 2nd
Floor no 3 = 2nd to 3rd

Floor 1 Frc Stairc.
3.0
Internal Cladding

Floor 3 Frc Slab/Beam
20.0
External Cladding

Roof Slab/Beam (concrete) 4.0 Roof Asphalt

(a) The First Screen Displayed for the Input of Lag Values

Please input the lag values (days) between the following activities for reinforced concrete floors.

COLUMNS & WALLS	SLABS & BEAMS	STAIRCASES
Reinforcement	Formwork	Formwork
4.0	10.0	2.0
Formwork	Reinforcement	Reinforcement
8.0	10.0	6.0
Concrete	Concrete	Concrete

(b) The Second Screen Displayed for the Input of Lag Values

FIG. 2 Screens For the Input of Lag Values (Within the Simulation Mode

Output Data And Discussion Of Results

Table 2 shows the output from the optimisation programme using the input from the Simulation Model. The data in Table 2 is plotted in Figs. 3(a), 3(b), 3(c). Fig. 3(a) shows the change in project direct cost with duration. At long project duration times, only minor increases in cost occur with decreases in project time but for short project times costs accelerate more rapidly with decrease in time. While Fig. 3(b) shows the indirect costs decrease linearly by accelerated project duration, Fig. 3(c) shows the total project cost curve with the minimum cost value of £ 691604.8 at 143 days.

The results in Table 2 show that indirect costs is only £16900.0 (these are input into the simulation model). This value is equal to about 3% of the direct costs and may be unrealistically low. However, input of a higher value for the indirect costs for this case study would not result in an optimum point as the decrease in indirect costs would always be more than the increase in direct costs until the end of the acceleration procedure (i.e. 137 days). For the aim of the validation such a low value for the indirect costs is found to be acceptable as the aim is only to find out if the model has the ability to reproduce an observed performance. However, these results show the significant effect of the value of the indirect cost decrease on project cost while accelerating the project duration and the importance that should be given to what is included in the estimation of indirect costs. They also raise a question as to the accuracy of the results when a linear relationship is assumed between indirect costs and duration.

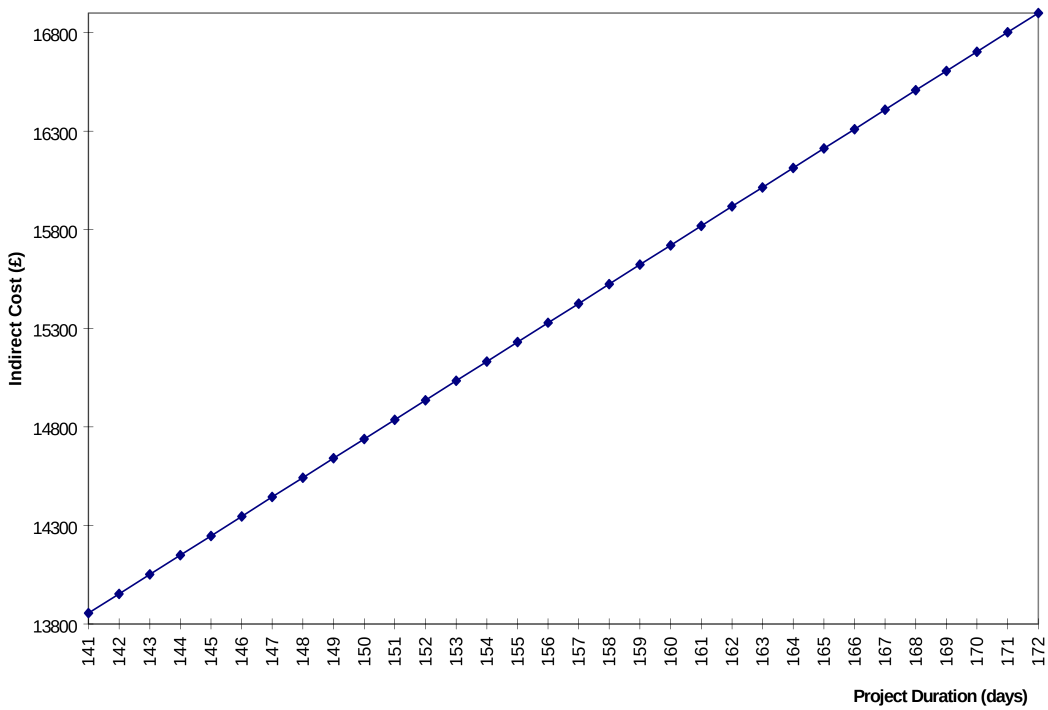

FIG. 3(a) Project Direct Cost-Duration Curve

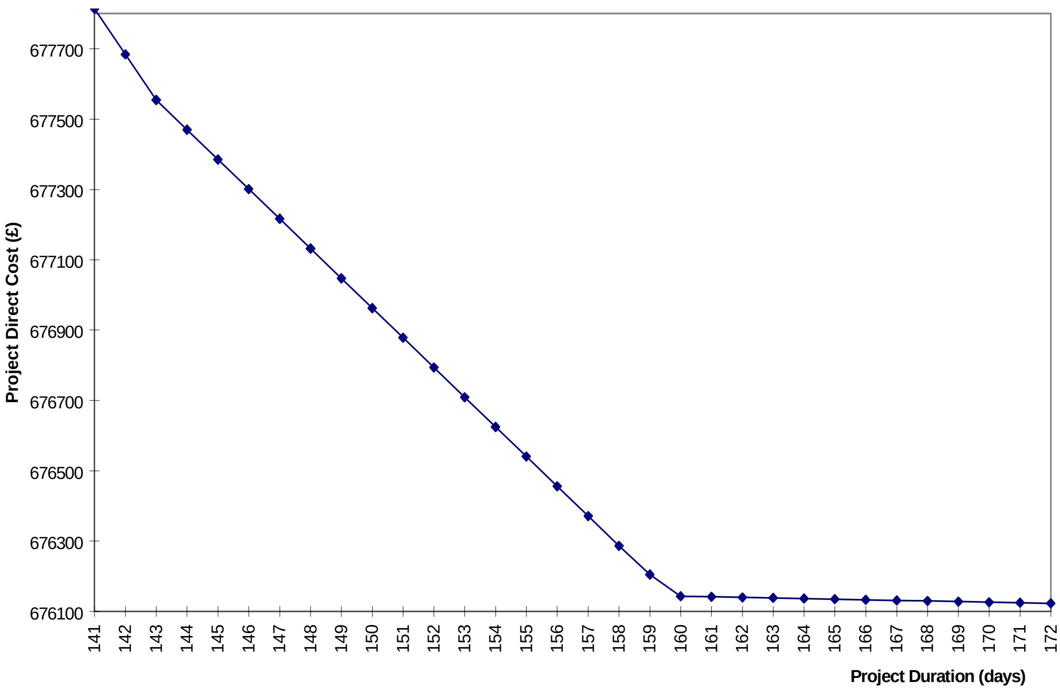

FIG. 3 (b) Indirect Cost-Project Duration Curve

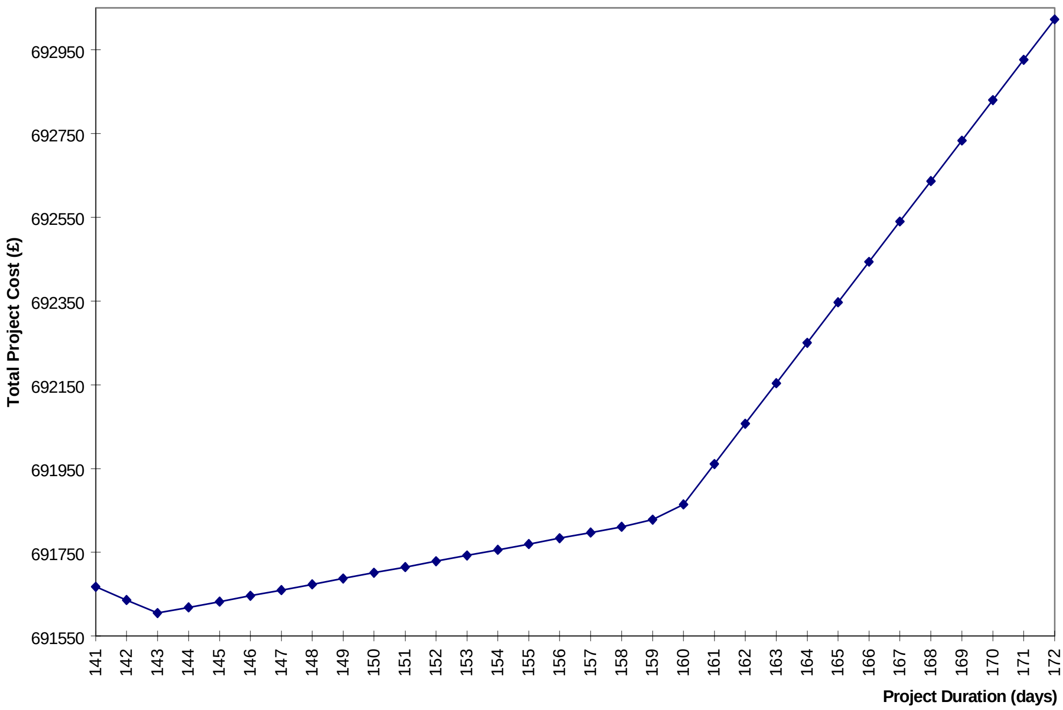

FIG. 3(c) Total Project Cost-Duration Curve

TABLE 2. Duration-Cost Results While Accelerating The Hypothetical Project For All Normal to All Crash Duration

Duration (days)	Direct Cost Increase	Indirect Cost Decrease	Total Cost Increase	New Direct Cost	New Indirect Cost	New Total Cost	Crashed Activity
172	0	0	0	676122.9	16900.0	693022.9	
171	1.7	98.3	-96.6	676124.6	16801.7	692926.3	1
170	3.4	196.5	-193.1	676126.3	16703.5	692829.8	1
169	5.1	294.8	-289.7	676128.0	16605.2	692733.2	2
168	6.8	393.0	-386.2	676129.7	16507.0	692636.7	2
167	8.5	491.3	-482.8	676131.4	16408.7	692540.1	3
166	10.2	589.5	-579.4	676133.1	16310.5	692443.6	3
165	11.9	687.8	-675.9	676134.8	16212.2	692347.0	4
164	13.6	786.1	-772.5	676136.5	16114.0	692250.5	4
163	15.3	884.3	-869.0	676138.2	16015.7	692153.9	5
162	17.0	982.6	-965.6	676139.9	15917.4	692057.3	5
161	18.7	1080.8	-1062.1	676141.6	15819.2	691960.8	6
160	20.4	1179.1	-1158.7	676143.3	15720.9	691864.2	6
159	82.1	1277.3	-1195.2	676205.0	15622.7	691827.7	7
158	163.7	1375.6	-1211.9	676286.6	15524.4	691811.0	8
157	248.2	1473.8	-1225.6	676371.1	15426.2	691797.3	9
156	332.7	1572.1	-1239.4	676455.6	15327.9	691783.5	9
155	417.2	1670.4	-1253.1	676540.1	15229.7	691769.8	9
154	501.7	1768.6	-1266.9	676624.6	15131.4	691756.0	9
153	586.3	1866.9	-1280.6	676709.2	15033.1	691742.3	9
152	670.8	1965.1	-1294.4	676793.7	14934.9	691728.5	9
151	755.3	2063.4	-1308.1	676878.2	14836.6	691714.8	9
150	839.8	2161.6	-1321.9	676962.7	14738.4	691701.1	9
149	924.3	2259.9	-1335.6	677047.2	14640.1	691687.3	9
148	1008.8	2358.1	-1349.3	677131.7	14541.9	691673.6	9
147	1093.3	2456.4	-1363.1	677216.2	14443.6	691659.8	9
146	1177.8	2554.7	-1376.8	677300.7	14345.4	691646.1	9
145	1262.3	2652.9	-1390.6	677385.2	14247.1	691632.3	9
144	1346.8	2751.2	-1404.3	677469.7	14148.8	691618.6	9
143	1431.4	2849.4	-1418.1	677554.3	14050.6	**691604.8**	9
142	1561.0	2947.7	-1386.7	677683.9	13952.3	691636.2	10
141	1690.6	3045.9	-1355.4	677813.5	13854.1	691667.5	10
140	1825.4	3144.2	-1318.8	677948.3	13755.8	691704.1	11
139	1960.2	3242.5	-1282.3	678083.1	13657.5	691740.6	11
138	2095.0	3340.8	-1245.8	678217.9	13559.2	691777.1	11
137	2229.8	3439.1	-1209.3	678352.7	13460.9	691813.6	11

activity numbers: 1 to 6 = ‘reinforcement for columns/walls', from ground/1st floor to 5th/roof,
7 = ‘excavate topsoil’, 8 = ‘reduce levels’, 9 = ‘roof asphalt’, 10 = ‘concrete for roof slabs/beams’, 11= ‘concrete for foundations’.

Table 1 shows that, according to the cost slope priority, 'reinforcement for columns/walls' should be crashed first as this has the minimum cost slope.

Fig. 4 shows that the activities 'reinforcement for columns/walls' and 'formwork for columns/walls' are both on the critical path. This is due to the fact that the activity 'formwork for slabs/beams', which is the starting activity of another critical activity starts after the finish date of both (i.e. both the activities 'reinforcement for columns/walls' and 'formwork for columns/walls' have total floats equal to 0). Thus, crashing 'reinforcement for columns/walls' would affect the project duration. It can be seen from Table 1 that this activity can be crashed for 2 days for each floor. This brings the project duration down to 160 days. Fig. 5 shows that, due to the 2 day acceleration of 'reinforcement for columns/walls', formwork for slabs/beams ' starts 2 days earlier than it would in normal conditions (as shown in Fig. 4).

Although activity 'reinforcement for slabs/beams' has the second lowest cost slope, when Fig. 6 is examined it can be seen that crashing this activity would have no effect on the critical path. This is because activity 'reinforcement for columns/walls' starts 1 day after the start of activity 'reinforcement for columns/walls', making activity 'reinforcement for columns/walls' partially critical. The case of partially critical activities is discussed later.

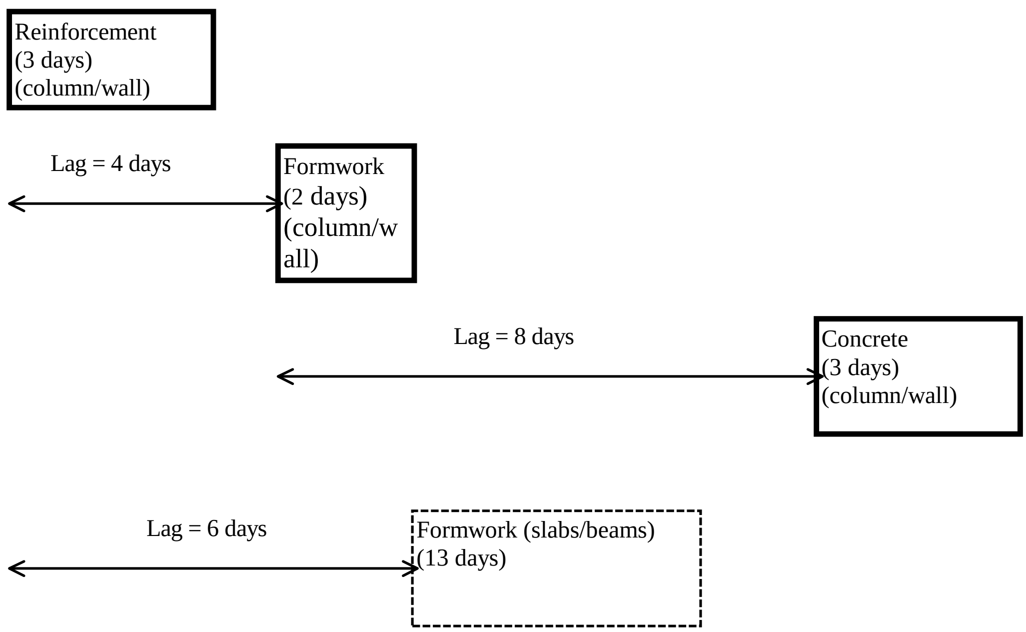

FIG. 4 Detailed Presentation of FRC for Columns/Walls

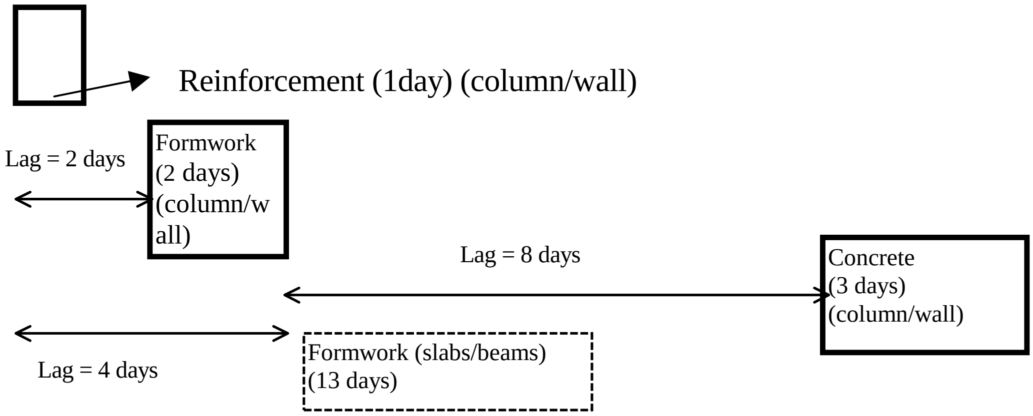

FIG. 5 Detailed Presentation of FRC for Clumns/Walls After Crashing Reinforcement for Clumns/walls

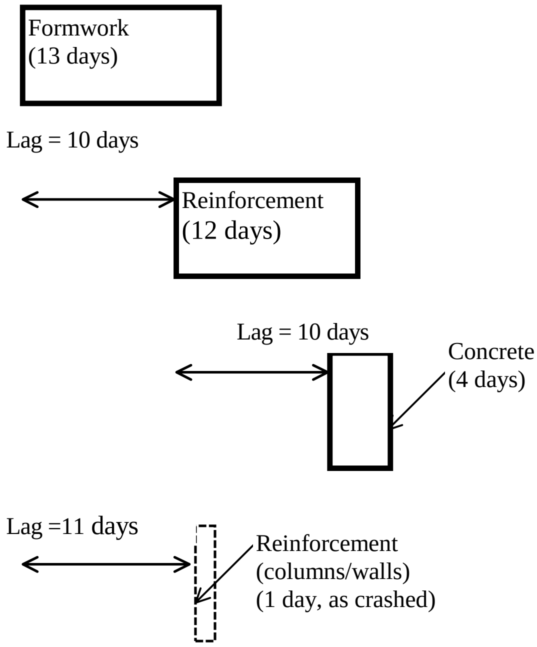

FIG. 6 Detailed Presentation of FRC for Slabs/Beams With Reinforcement for Clumns/Walls

'Blinding concrete for foundations' has the third lowest cost slope. However, as this activity starts at the same time as its following activity 'formwork for foundations', crashing it would therefore not have any effect on the project duration. This is also the case for the activity 'concrete for columns/walls' in Fig. 4 which has no effect on the critical path and is by ignored by the model.

The above logic is applied during the crashing of all the activities. Thus, while activity 'excavate foundations' is not crashed as crashing this would not affect the project duration, ‘formwork for columns/walls’ is not crashed due to the constraints on lag values as discussed previously. However, activity ‘excavate topsoil’ which is on the critical path is crashed for 1 day. The activity ‘reduce levels’ is crashed for 1 day and ‘roof asphalt’ is crashed for 15 days resulting in 143 days project duration with total project cost of £ 691064.8 (which is the minimum cost corresponding to the optimum duration). After ‘roof asphalt’, ‘concrete for roof slabs/beams’ is crashed for 2 days.

It should be pointed out that during the interviews undertaken with the construction planners for the development of the integrated model, the planners stated that when crashing the activity durations some of the lag values may also change. However, within the integrated model only one lag value between two activities is considered. Thus, for the activities with end floats (i.e. being partially critical, in that the critical duration is equal to the lag value with the preceding activity), a shorter lag value would require the difference between the normal and the crash lag values to be taken into account while crashing the activities. However, such an approach would mean splitting each activity into different activities and constructing the constraints accordingly. It is the authors’ opinion that to apply such an approach would be impracticable as it would increase the number of constraints to at least double, and dealing with a large number of constraints was found to be a particular disadvantage of the linear optimisation method.

Conclusions

The optimisation part of an integrated computer model (OPTIMA) for the evaluation of different project duration/cost solutions during pre-tender and pre-contract stages for multi-storey reinforced concrete office buildings has been described.

A linear relationship has been assumed between the direct cost and the duration of an activity which leads to an assumption of a multi-linear relationship between project direct cost and duration. Indirect costs of the project are taken to be directly proportional to the project duration.

The strengths and weaknesses of utilising various programming techniques for optimisation problems have been established and linear programming has been found to be the most suitable one for this particular research project. A Simplex Algorithm has been used to solve the linear programming formulation with an objective function being the minimisation of the direct cost increase when accelerating the project. The constraints are formulated using the data provided by the Simulation Model and by taking into account of the precedence relationships, lag values and normal and crash durations.

The results from OPTIMA have been validated by checking that the project is accelerated with the lowest possible cost increase. This was achieved by plotting the project cost curves and checking that they maintain the correct form and by checking that the accelerated activities are on the critical path . The validation results demonstrate that, despite its inexactness in representing the system, OPTIMA can give a reasonable prediction of the system’s performance. Additionally, the model’s most important strength is its integration with a simulation model which enables human interaction to take place in a user friendly environment.

Future developments are required for the model to undertake the cash flow aspects during pre-tender stage. A more detailed research for the relationship between indirect cost -

project duration is recommended for any future developments of time/cost optimisation models.

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