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Toward Reducing Construction Project Delivery Time under Limited Resources

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Abstract: One of the most vital construction project aspects is to complete a project in minimum time restricted to the time–cost trade-off. Overlapping activities' planning and their impact on the project under limited resource constraints should be considered. This study aims to develop a model for optimizing the project schedule and cost regarding overlap activities and their impacts. This study reviews previous studies on changes in past activities likely to produce additional reworking of subsequent activities. In addition, an AHP model is developed to assess the reworking time of subsequent activities based on possible changes in previous activities. In addition, five realistic construction projects are applied. Finally, an optimizing model is developed for optimizing project time and cost using overlapping techniques by using the Java program. The results indicate that the proposed model can be used by project managers easily for solving time and cost optimization problems. In addition, it can be updated to continuously improve its functionality. Finally, it can be updated later to support AI for finding better solutions.

Keywords: fast-tracking; AHP; rework time; Java; construction schedule

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1. Introduction

Rework in construction projects is a widespread problem that affects project performance negatively. First, it is necessary to clarify the definition of reworking, because how it is defined helps to find solutions and reduce risks [1]. Love et al. [2] defined rework as the unnecessary effort to re-implement a process or activity incorrectly carried out the first time regardless of any changes in project scope or design that might lead to additional work. Enshassi et al. [3] defined rework as a serious problem in construction projects in the Gaza Strip, which was one of the main reasons for the delays in schedule and increased construction costs, besides customer dissatisfaction. There are various definitions of rework in the construction management literature, which mainly include quality deviations, quality failures, defects, and non-conformance. Martins et al. [4] introduced a model using cluster analysis to classify risks. Risks are classified according to different risk categories, activity development, sensitivity, production reliability, and constraints on construction projects. The delay in the schedule was defined as completing the construction project after the specified date. This delay is often accompanied by cost overruns. Delays in the schedule include location conditions, slow approval of work permits, design errors, delays in funding and progress payments, owner intervention, improper planning, inadequate subcontractors, and source change orders [5]. Cheng and Darsa [6] developed an ANN model to predict the time delay in a project. Identifying the most important factors affecting a project could reduce delays in the construction schedule.

2. Literature Review

Chaos and complexity dominate construction sites, imposing difficult conditions for the establishment of reliable, robust, and easily controlled schedules [7]. For the past few decades, both the critical path method (CPM) and the program evaluation and review technique (PERT) are the main methods for planning and scheduling construction projects [8]. However, one of the biggest drawbacks of both the CPM and PERT is that they usually assume unlimited resources [9] In addition, the CPM assumes that unlimited resources will be available at any time, when necessary, for implementing project activities; this assumption is unrealistic because activities require quantification of resources and are limited in terms of resources (resources are limited in scheduling). Often, the demand for resources exceeds the maximum number of resources available for a project. To reduce the supply and demand problem, scheduling techniques (RCS) based on priority rules are used. The start date for some activities for which the required resources are not available is postponed [10–12]. Construction projects often face a challenge to complete them in the minimum time. Overlapping between construction activities with early information from precedent activities shortens project completion with the expense of rework in downstream activities. However, the expected amount of rework must be properly quantified to decide on the overlapping method. Ballesteros-Pérez et al. [13] stated that the sensitivity of activities measures the importance of the activities in the project schedule. Based on this, highly sensitive activities are those that are likely to increase the volatility of project duration and/or cause project duration extensions. Hossain and Chua [14] stated that reconstruction would lead to physical rework, such as adding more concrete to the foundation or even replacing the existing one with a new one. This rework is costly and may take a long time, delaying the completion of the project. Wasfy [15] indicated that rework results in a cost increase in commercial residential towers from 2% to 30%. It also results in delays in the duration of implementation from the original 10% to 77%. In addition, the rework causes dissatisfaction among clients and contractors. Love et al. [2] introduced a conceptual framework of causality from reworking that focused on errors and violations visually, besides improving the outcomes of safety. Rework negatively affects construction projects and causes risks, such as losses in productivity, stress and fatigue, reputational damage, loss of profit, project delays, disputes, and an increase in the cost of insurance [16]. Lindhard et al. [17] studied the impact of some different sequences of activities on the production gap, crew waiting time, and production delay by simulating work items where the sequence of items was arranged from line to parallel. Pena-Mora and Li [18] proposed a framework for overlap between two parallel activities to reduce the risk of reworking downstream activity using the concept of the upstream evolution rate and the sensitivity of the downstream activity. Hamdi et al. [19] mentioned that traditional project-scheduling methods are widely used as tools to support projects but cannot exploit direct and indirect forms of information flow between activities in projects. Han et al. [20] and Hwang et al. [21] reported that the design error causes up to 79% of the cost of reworking. In addition, reworking contributes to cost overruns of 5% of total construction costs. Wandahl et al. [22] identified the key factors causing time overruns in on-site construction. These factors were construction design, connecting works, external conditions, workforce, components and materials, space, equipment, and machinery. Starting a downstream activity based on unfinished information introduces the risk of rework in the downstream work should there be a change in upstream information. The information exchanged is also associated with a level of uncertainty, depending on this upstream activity. Future upstream information modifications require to rework in the downstream activity to address the changes in the initial information based on which the downstream activity has started. The resulting rework usually consumes resources (e.g., time and money) and disrupts the flow of downstream work. Kyunghwan [23] proposed a general approach to the critical path to limited resources method (RCPM) that helps implement the RCPM regardless of the resource-constrained scheduling (RCS) method applied under multiple resource constraints. Ammar [24] modeled the problems of leveling and allocating resources under the LOB scheme. Considering the maintenance of the continuity of resources and the logical dependency of activities, in addition, a steady rate of progress in the activity has been imposed. Figure 1 shows that the mechanism of overlapping of two dependent activities in the case of rework is probable to take place. Figure 1 was created using the Microsoft Excel program. The probability of rework depends on several factors, such as the type and complexity of overlapped activities, their relation with other activities in the project schedule, and the value of overlapping. The mechanism of activity overlapped is shown in two cases, (A) where there is no overlapping between activities and case (B) where there is overlapping between activities and rework time. Hossam et al. [25] identified the most significant changes and risks that may have occurred in previous activities. These changes lead to the rework of subsequent and dependent activities. The study was conducted through a 100-item questionnaire in Egyptian companies. The top eight important variables were lack of coordination and poor communication, the contractor's instructions to modify a design, non-compliance with the specification, the owner's instructions to modify a design, incomplete design at the time of the tender, poor planning and coordination of resources, errors made in the contract documentation, and lack of experience and knowledge of the design and construction process. These variables are used in this study to assess the value of reworking construction projects using the AHP model.

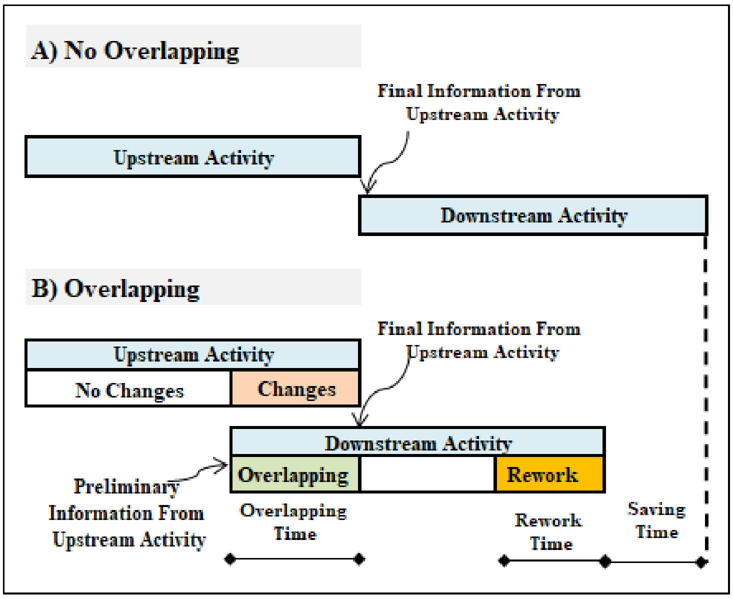


Figure 1. Mechanism of activity overlapping in case (**A**) and Case (**B**).

3. Research Objectives

The main objectives of this research are shown in these steps: (1) To develop an analytical hierarchy to predict the value of reworking on subsequent activities based on possible changes in past activities, considering the overlap between dependent activities; (2) To develop a model for optimizing the project schedule and cost under project constraints, such as the overlap of activities, the amount of reworking time because of applying the overlap method, and loss of productivity due to application of the overtime method; and (3) assess the impact of these changes, the time of emergency reworking, the loss of productivity on the project schedule, and the cost by applying the model to a real project.

4. Research Methodology

This paper introduces a four-step process for generating a fast-track mathematical model in Figure 2. The first step is to quantify the category and level of the potential changes in upstream activities. These potential changes caused reworks in downstream activities due to activity overlapping. The second step is to predict the number of reworks in downstream activities. This was developed by using the AHP model depending on the overlapping period and the potential changes in upstream activities. The third step consists of formulating a Java program to derive the minimum duration and cost of the construction project. This was generated by several trials conducted due to overlapping between the critical paths. Then, in each trial, the net benefit of the project was computed by considering the number of overlapping periods, extra costs due to overlapping, indirect costs, and time saving. The fourth and last is the presentation of the conclusion. These assumptions were made to ensure proper implementation of the Java mathematical model:

1) The resource requirements of each activity during the execution process remain unchanged.
2) The overlapping period is an integer and time reworks added to successor activities in a fraction.
3) Work on an activity starts as soon as some information is received from the other dependent activities (the relationship between activities is early to start).
4) The study is concerned only with the eight most critical changes in upstream activities.

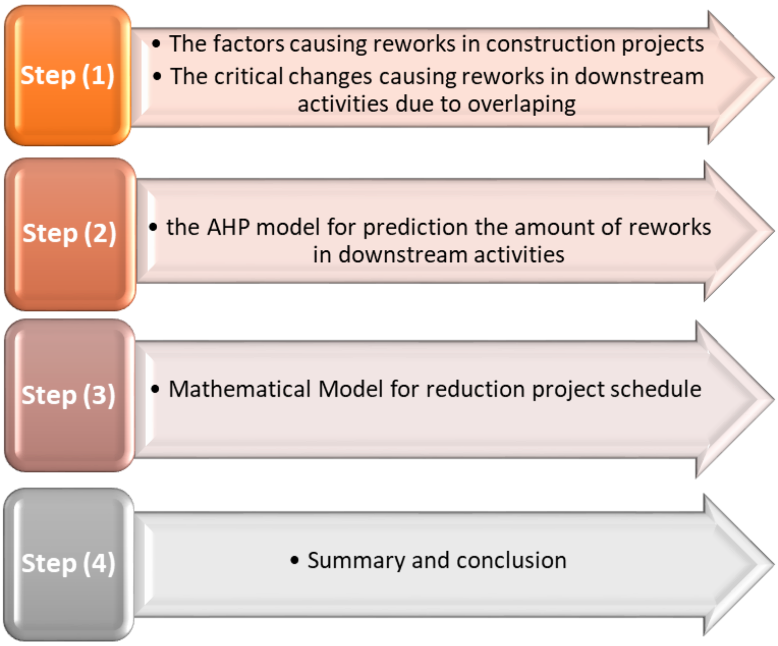


Figure 2. Research methodology.

5. Analytical Hierarchy Model

A questionnaire survey was used to evaluate and predict the amount of rework in downstream activities, depending on activity overlapping and the changes in upstream activities.

5.1. Sample Size

To compute the specified sample size for an infinite population, we used Equation (1) of Bartlett et al. [26]:

$$N = K2 \times P\,(1 - P)/E2 \tag{1}$$

where N is the required sample size for an infinite population, K is equal to 1.645 when the confidence level is 90%, P is the population proportion (the critical value of P is 0.5), and E is an appropriate margin of error, at 10% for a confidence level of 90%.

By substituting these parameters into Equation (1), the sample size for the infinite population in the specified study was 68, which was the minimum value.

5.2. Survey Analysis

In total 125 questionnaires were administered to professionals and experts in different construction projects, and 100 questionnaires representing 80% of the 125 questionnaires administered were returned. The respondents' job titles were classified into three categories in construction projects. The first category from a designer viewpoint represented 71%, the second category from a contractor viewpoint represented 89%, and the third category from an owner viewpoint represented 80% of all categories. The respondents to the questionnaire were classified according to their experience, which showed that about 14% of the respondents had an experience of less than 10 years, around 48% had an experience of greater than or equal to 10 years and less than 20 years, around 30% had an experience of greater than or equal 20 years and less than 30 years, and, finally, 8% had an experience of greater than or equal to 30 years.

6. The Analytic Hierarchy Process (AHP) Model

The analytic hierarchy process (AHP) developed by Saaty [27] is a powerful multi-criteria decision-making tool used in numerous applications in various fields of economics, politics, and engineering. This method allows determining the weights of hierarchically non-structured or particular hierarchical-level criteria regarding those belonging to a higher level. The hierarchy of the top important changes causing reworks in downstream activities is shown in Figure 3. The analytic hierarchy process (AHP) steps are shown in Figure 4 by using the Microsoft Excel program. The data were gathered from experts in construction projects in Egypt via Microsoft forms and physical and telephone interviews with senior managers of several construction management teams. The experts performed pairwise comparisons, and then we analyzed the results.

The priority weights of rework time contingency criteria from the AHP model are shown in Table 1.

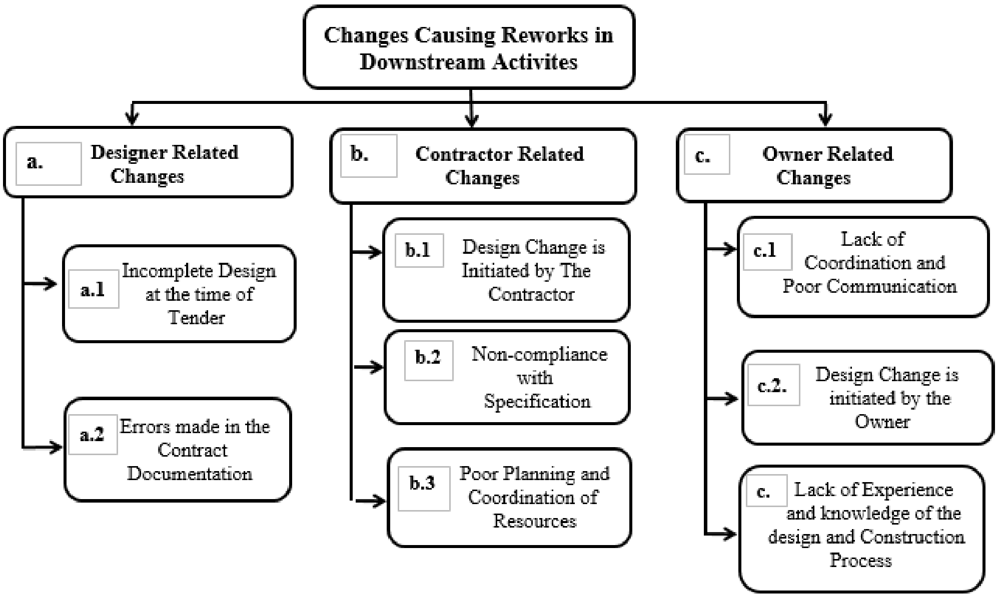


Figure 3. Hierarchy of the top important changes affecting time rework contingency due to overlapping.

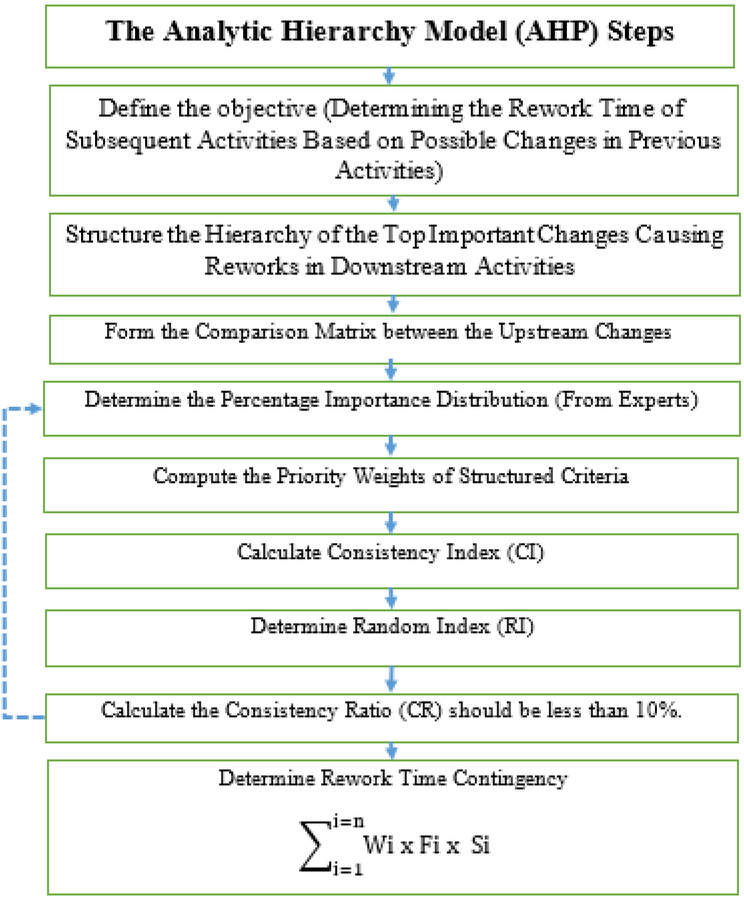


Figure 4. The analytic hierarchy model process (AHP) steps.

Table 1. Priority weights of rework time contingency criteria from the AHP model.

Criteria	Criteria Weight	Sub-Criteria	Sub-Criteria Weight	Relative Weight (Wi)	Frequency (Fi)	Severity (Si)	Rework Time Contingency (R_{tc})
Designer	0.14240	Incomplete design at the time of the tender	0.4177	0.0595	0.444	0.486	0.0128
		Errors made in the contract documentation	0.5680	0.0809	0.405	0.517	0.0169
Contractor	0.46657	Design change initiated by the contractor	0.2296	0.1071	0.345	0.442	0.0163
		Non-compliance with specification	0.3763	0.1756	0.463	0.515	0.0419
		Poor planning and coordination of resources	0.3798	0.1772	0.368	0.576	0.0376
Owner	0.37674	Lack of coordination and poor communication	0.2131	0.0803	0.514	0.659	0.0272
		Design change initiated by the owner	0.3808	0.1435	0.419	0.517	0.0311
		Lack of experience and knowledge of the design and construction process	0.3918	0.1476	0.417	0.497	0.0306
		Rework time contingency (C) = $\sum Wi \times Fi \times Si$.					0.2144

In addition, the ranking of the main changes and sub-changes is shown in Table 2. The average relative weights of the main changes and sub-changes are shown in Figures 5 and 6, respectively, by using the Microsoft Excel program.

Table 2. Ranking of the main changes and sub-changes.

	Changes Category	Total Weight	Priority Victor	Rank
a	Designer-related changes	9.9682	0.1424	3
b	Contractor-related changes	32.6599	0.4666	1
c	Owner-related changes	26.3719	0.3767	2
a	Designer-Related Changes			
a.1	Incomplete design at the time of the tender	29.2407	0.4177	2
a.2	Errors made in the contract documentation	39.7593	0.5680	1
b	Contractor-Related Changes			
b.1	Design change initiated by the contractor	16.0730	0.2296	3
b.2	Non-compliance with specifications	26.3432	0.3763	2
b.3	Poor planning and coordination of resources	26.5837	0.3798	1
c	Owner-Related Changes			
c.1	Lack of coordination and poor communication	14.9159	0.2131	3
c.2	Design change initiated by the owner	26.6591	0.3808	2
c.3	Lack of experience and knowledge of the design and construction process	27.4250	0.3918	1

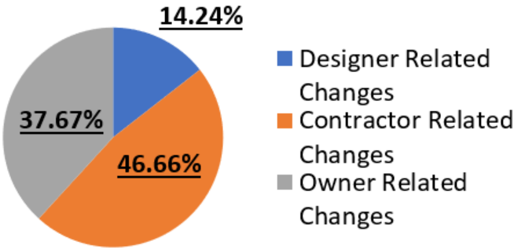


Figure 5. Relative weights of main changes.

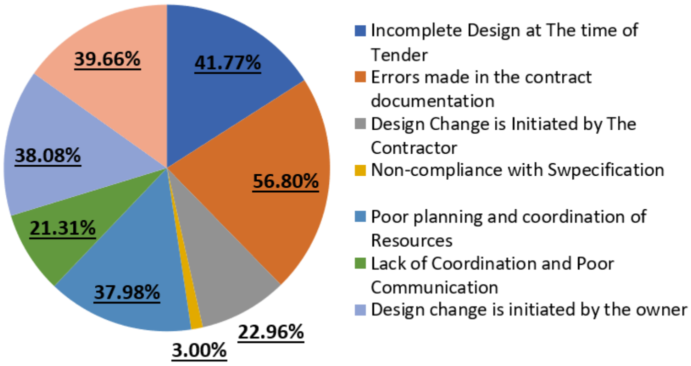


Figure 6. Relative weights of sub-changes.

7. AHP Model Verification

To check the accuracy of the estimated time rework contingency (21.44%) that came from the AHP model, data were collected from experts from their previous projects. Table 3 includes the collected data and their analysis for five projects. It was noted that the actual time rework contingency ranged from 0.11 to 0.40 out of the project duration. Thus, the average actual rework time contingency of the five projects was 24.79% close to the value obtained from the developed model (22.44%). From the five real projects, the actual time rework consistency = (original total time (without overlapping) − actual total time (after overlapping))/(original total time (without overlapping)) × 100. Based on Zayed and Halpin [28], two equations were used to verify the developed time contingency model in Equations (6) and (7) as follows:

$$\%\ \text{Error (Average Invalidity Percent)} = (\text{E} - \text{A})/\text{A} \times 100 \quad (2)$$

$$\%\text{Average Validity Percent} = 100 - \%\ \text{Error} \quad (3)$$

where E: estimated time rework contingency (output value from the model), A: actual time rework contingency (%)

% Error (average invalidity percentage = (21.44−24.79)/(21.44) × 100 = 15.63%)
Average validity percentage = 100 − 15.63 = 84.37%

The values of percentage error and average validity percentage showed that the developed model is robust in predicting the values of time rework contingency.

Table 3. Actual time rework contingency analysis for the five actual construction projects.

Project No.	Project Description	Changes in Upstream Activities	Target Total Time (Days)	Actual Total Time (Days)	Actual Time Rework Contingency (Time Saving/Target Time)
1	Primary school (Aswan)	Removal of damaged items, installation of new items, and maintenance of some damaged items	300	210	0.30
2	A multi-story building (Suez)	Modifications from the owner at the Hall of Conferences; several design changes introduced by the owner in a lot of items	480	400	0.17
3	Construction of building in 10th Ramadan City	Low experience for certain activities to be constructed and teamwork not qualified	900	540	0.400
4	Construction of building in 10th Ramadan City	Lack of coordination, poor communication, and design change initiated by the contractor	135	120	0.11
5	Construction of governmental garage in Cairo	Change in the area of the garage by the owner from 200 × 100 m^2 to 200 × 150 m^2 and addition of inspection rooms	420	310	0.26
		Average actual time rework consistency			0.247936508

8. AHP Model Validation (Application in Actual Case Studies)

The expected time rework contingency for five case studies of real projects was calculated with the relative weight (Wi) from the AHP model by these steps:

1. Insert the frequency and severity number for each factor to reflect its significance, where 0 indicates the lack of the factor's effect and 10 indicate the high factor's effect.
2. Put the relative weight (Wi) = weight of main criteria × weight of sub-criteria, as determined in Table 3 from the AHP model.
3. Calculated the rework time contingency = $\sum$Wi × Fi × Si.

The expected time rework contingency for project 1 is shown in Table 4. The expected time rework contingency for the other case studies was computed as project 1. Table 5 presents the actual and estimated time rework contingencies calculated by using the model. It shows that the absolute difference in cost contingency ranged from 9% to 14.04%, which is less than the mentioned mean absolute percentage (15.63%). Therefore, the model testing passed successfully.

Table 4. Estimated time rework contingency analysis for project 1.

Factor No.	Changes in Upstream Activities That Caused Time Rework in Downstream Activities	Relative Weight (Wi)	Project 1		
			Frequency (Fi) %	Severity (Si) %	Estimated Rework Time Contingency
F1	Incomplete design at the time of the tender	0.059484936	0.7	0.4	0.0167
F2	Errors made in the contract documentation	0.080883328	0.8	0.5	0.0324
F3	Design change initiated by the contractor	0.107131275	0.5	0.7	0.0375
F4	Non-compliance with specifications	0.17558497	0.4	0.5	0.0351
F5	Poor planning and coordination of resources	0.177188089	0.55	0.3	0.0292
F6	Lack of coordination and poor communication	0.080277663	0.4	0.4	0.0128
F7	Design change initiated by the owner	0.143480008	0.8	0.5	0.0574
F8	Lack of experience and knowledge of the design and construction process	0.147602383	0.5	0.7	0.0517
Estimated rework time contingency for project 1 = ∑Wi × Fi × Si					0.2728

Table 5. Actual and estimated time rework contingency analysis for the five actual construction projects.

No.	Project Description	Changes in Upstream Activities	Target Total Time (Days)	Actual Total Time (Days)	Actual Time Rework Contingency (Time Saving/Target Time)	Estimated Time Rework Contingency (from Model)	% Error (E-A)/A	% Absolute
1	Primary school (Aswan)	Removal of damaged items, installation of new items, and maintenance of some damaged items	300	210	0.300	0.2728	−0.091	9.082
2	Residential building (Suez)	Modifications from the owner at the Hall of Conferences; several design changes introduced by the owner in a lot of items	480	400	0.167	0.1870	0.1222	12.2211
3	Construction of building in 10th Ramadan City	Low experience for certain activities to be constructed and teamwork not qualified	900	540	0.400	0.4475	0.119	11.863
4	Construction of building in 10th Ramadan City	Lack of coordination, poor communication, and design change initiated by the contractor	135	120	0.111	0.0955	−0.14	14.04
5	Construction of governmental garage in Cairo	Change in the area of the garage from 200 × 100 m^2 to 200 × 150 m^2 and addition of inspection rooms	420	310	0.262	0.2855	0.09	9.00

9. Model Formulation for Applying the Overlapping Method

In this research, an optimizing model was developed for optimizing project time and cost using overlapping techniques by using the Java program.

4. The objective function was to minimize the total time and optimize the costs.
5. Decision variables were indexes to choose among different overlapping periods between upstream and downstream activities.
6. Constraints defined the availability of overlapping time for each activity in integer time, limiting the total time of the project to a deadline, and the resource limit was 10 labor/day. In addition, the predecessor's logical relationship was a constraint.

The mathematical model was developed using a Java program depending on the following equations. The impact of overlapping time on the project duration, the time saving, indirect saving cost, and net benefit of overlapping are shown in the following Equations (4)–(10):

$$\text{CI (Downstream activity)} = \text{Wi} \times \text{Fi} \times \text{Si} \quad (4)$$

$$\text{Rt (due to overlapping)} = \text{CI} \times \text{OT} \quad (5)$$

$$\text{Rt (Critical activities)} = \sum \text{CI} * \text{OT (Critical activities)} \quad (6)$$

$$\text{Time-Saving of the Project (due to overlapping)} = \sum \text{(OT) Critical Activities} - \text{(Rt (Critical activities))} \tag{7}$$

$$\text{Cost Saving (due to overlapping)} = \text{[Time Saving (due to overlapping)]} * \text{[Early Completion Cost]} \tag{8}$$

$$\text{Rc (due to overlapping)} = \text{C Successor/unit} * \text{Rt (due to overlapping)} \tag{9}$$

$$\text{Net Benefit of Overlapping} = \text{[Cost Saving (due to overlapping)]} - \text{Rc (due to overlapping)} \tag{10}$$

where:

CI: time rework contingency index in the downstream activity, Wi: relative weight of each problem in an upstream activity and equal to weight of main criteria × weight of sub-criteria, Fi: frequency of each problem (probability of occurrence of rework), Si: severity of each problem causing rework in the downstream activity due to overlapping (impact), OT: overlapping period between the downstream and upstream activities, Rt (due to overlapping): predicted rework time value in the downstream activity, Rc (due to overlapping): cost of rework of the successor activity due to overlapping (overlapping costs), C Successor: total cost of the downstream activity and C Successor/unit: cost of the downstream activity per unit

10. Application Model for Case Study 4 with Limited Resources

The project was assigned to one main contractor and included these works: removal of damaged items, installation of new items, and maintenance of damaged items. A project with seven activities with their description and the technical relationship is shown in Table 6 by using the Microsoft Excel program. The project indirectly cost EGP 500/day; the penalty costs were EGP 400/day. The main objective of the study was to resolve the resource overallocation and meeting the project deadline with minimum cost. The planner's target was to meet the 135-day deadline, and the resource limit was 10 labor/day.

Table 6. Initial project data.

ID	Activity Name	Activity Description	Predecessors	Duration (Days)	Lag	Cost (EGP)
1	A	Mobilization works	. . . . . .	15		22,000
2	B	Supply of materials	A	15		32,000
3	C	Supply of carpentry and electrical works	A	20	30 with A	10,000
4	D	Excavation works	A	20		22,000
5	E	Placing the concrete footing	B, D	30	10 with D	36,000
6	F	Placing the concrete columns	E	30		30,000
7	G	Wall works	C, F	30		20,000

The initial schedule is shown below in Figure 7 by using the Microsoft Excel program and shows that the total time equaled 135 days. The total cost was equal to the total cost of all activities and early completion cost per day multiplied by the total cost. The total cost was equal to 172,000 + (500 × 135) = EGP 239,500. In addition, the resource over-allocated is shown in Figure 8 by using the Microsoft Office Project program. The resource over-allocation was solved by delaying the task; the simplest way to correct that over-allocation is to delay one task, ideally a task with lower priority than the others. This done using Microsoft Office Project in Figures 9 and 10. We noted that the total time of the project increased from 135 days to 160 days, and the total cost was EGP 252,000. All resources were allocated.

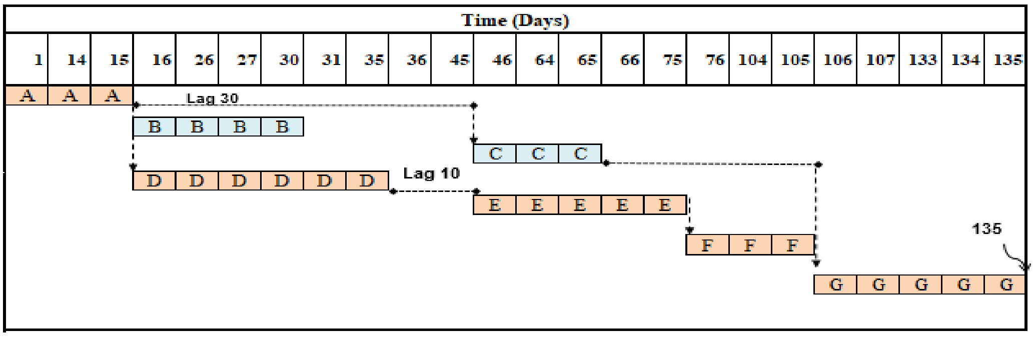


Figure 7. Snapshot of the initial project schedule using the Microsoft Excel program.

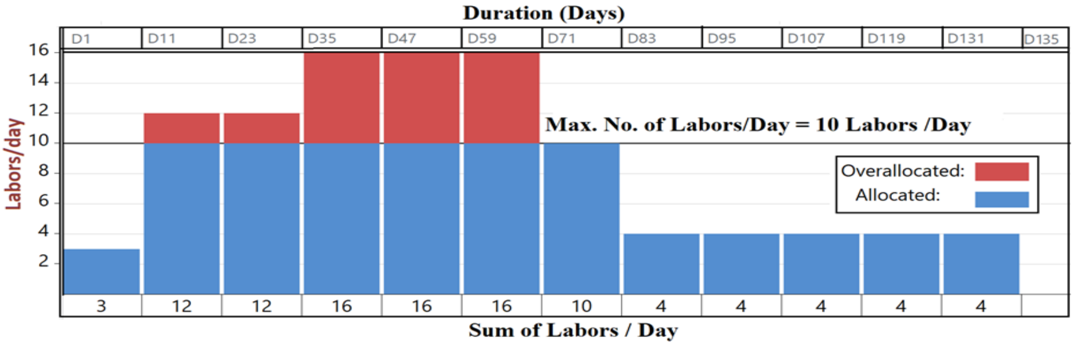
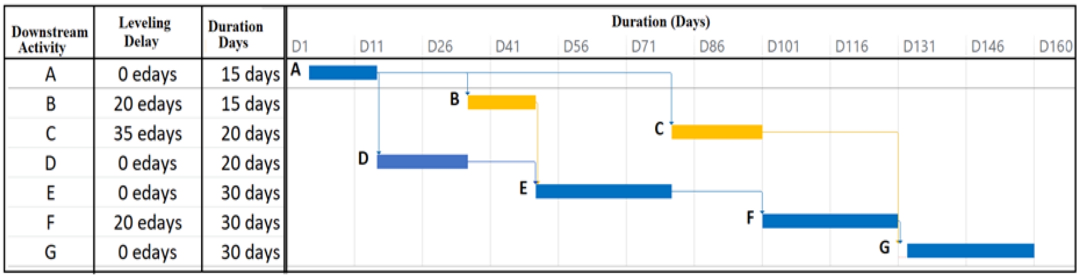


Figure 8. Resource usage of resources by Microsoft Office Project.



Downstream Activity	Leveling Delay	Duration Days
A	0 edays	15 days
B	20 edays	15 days
C	35 edays	20 days
D	0 edays	20 days
E	0 edays	30 days
F	20 edays	30 days
G	0 edays	30 days

Figure 9. Project schedule after leveling resources of the activities.

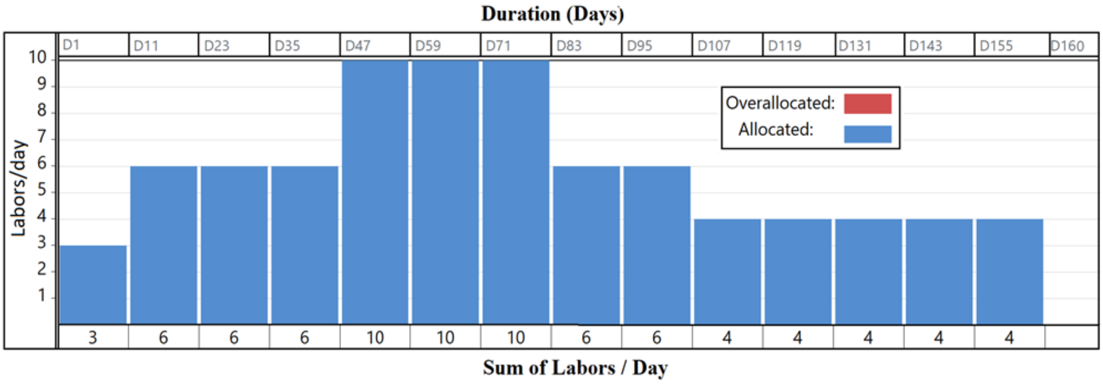


Figure 10. Activities' resources after delaying the activities by Microsoft Office Project.

11. Applying the Overlapping Method

The overlapping method can be applied by these steps in Figure 11 using the Microsoft Word program. The activity data after resolving resource constraints using Microsoft Office

Project are shown in Figure 10. The steps in applying the mathematical model are shown below.

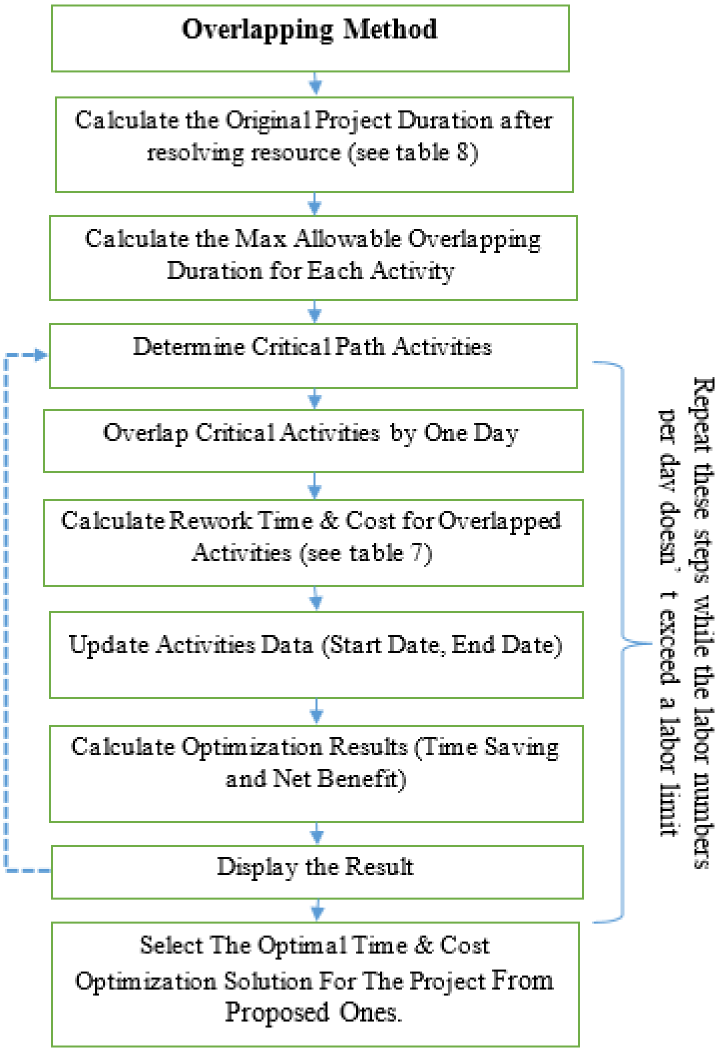


Figure 11. Overlapping method.

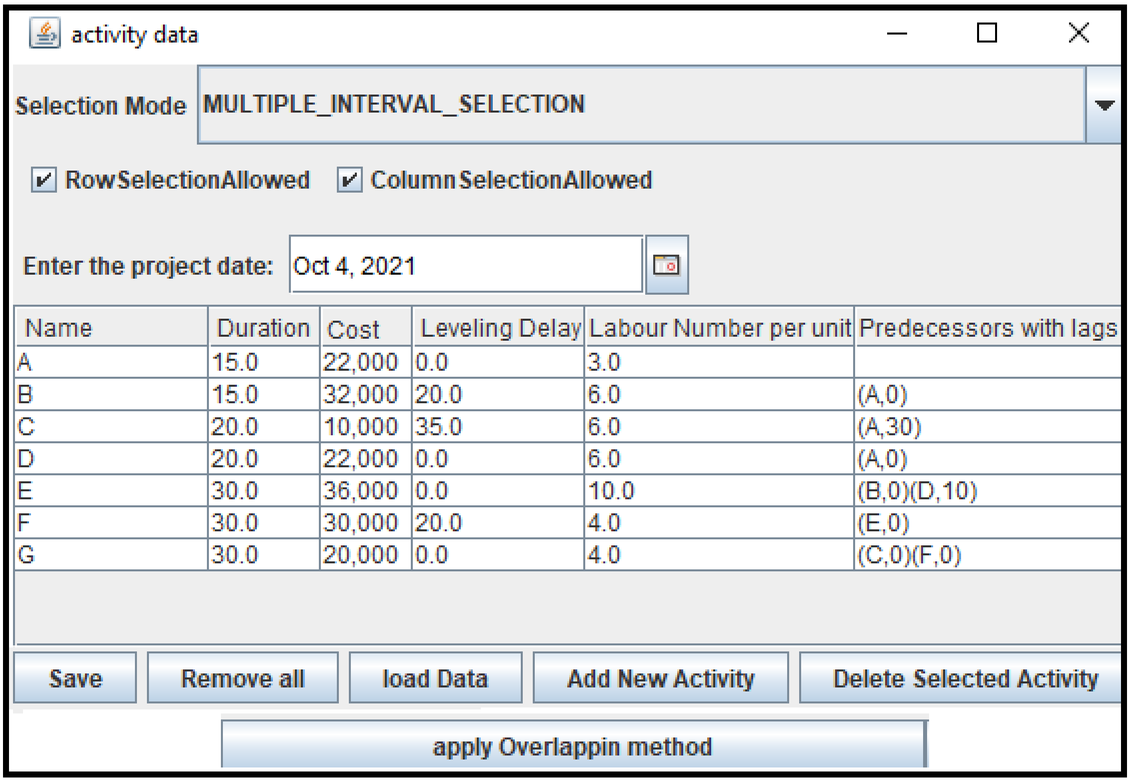
First, the rework time and cost slope for the overlapping activities were calculated by data from the AHP model in Table 7. If each of the subsequent activities was exposed to all possible changes in the previous activities, then its rework time value was the maximum value of all activities and was equal to 0.2144.

Second, the activity data that included activity name, description, duration, cost, leveling delays, labor number, and precedence were inserted, as shown in Figure 12.

Third, the indirect cost per day, early completion cost per day, and resource limit per day were inserted, finally applying the overlapping method, as shown in Figure 13.

Table 7. Rework time and cost slope for the overlapping activities by data from the AHP model.

ID	Downstream Activity	Upstream Activities	Overlapping Activities	Max. Overlapping Downstream	Effect of the Upstream Changes on the Upstream Activity Due to 1-Day Overlapping	
					Time Rework	Cost Slope (Rework Cost)
1	A	… …	… … …	… ….	… ….	… ….
2	B	A	OL (A, B)	15	0.2144	686.0714
3	C	A	OL (A, C)	15	0.2144	214.3973
4	D	A	OL (A, D)	15	0.2144	471.6741
5	E	B	OL (E, B)	15	0.2144	771.8303
		D	OL (E, D)	20	0.2144	771.8303
6	F	E	OL (E, F)	30	0.2144	643.1919
7	G	C	OL (G, C)	20	0.2144	428.7946
		F	OL (G, F)	30	0.2144	428.7946



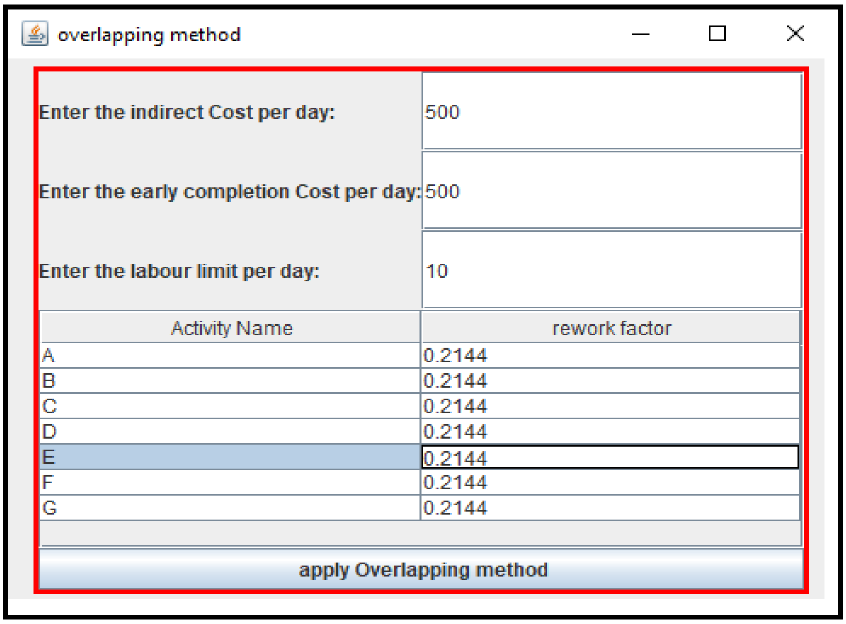
Selection Mode MULTIPLE_INTERVAL_SELECTION

☑ RowSelectionAllowed ☑ ColumnSelectionAllowed

Enter the project date: Oct 4, 2021

Name	Duration	Cost	Leveling Delay	Labour Number per unit	Predecessors with lags
A	15.0	22,000	0.0	3.0	
B	15.0	32,000	20.0	6.0	(A,0)
C	20.0	10,000	35.0	6.0	(A,30)
D	20.0	22,000	0.0	6.0	(A,0)
E	30.0	36,000	0.0	10.0	(B,0)(D,10)
F	30.0	30,000	20.0	4.0	(E,0)
G	30.0	20,000	0.0	4.0	(C,0)(F,0)

Figure 12. Activity data after resolving resource constraints using the Java program.



Enter the indirect Cost per day: 500

Enter the early completion Cost per day: 500

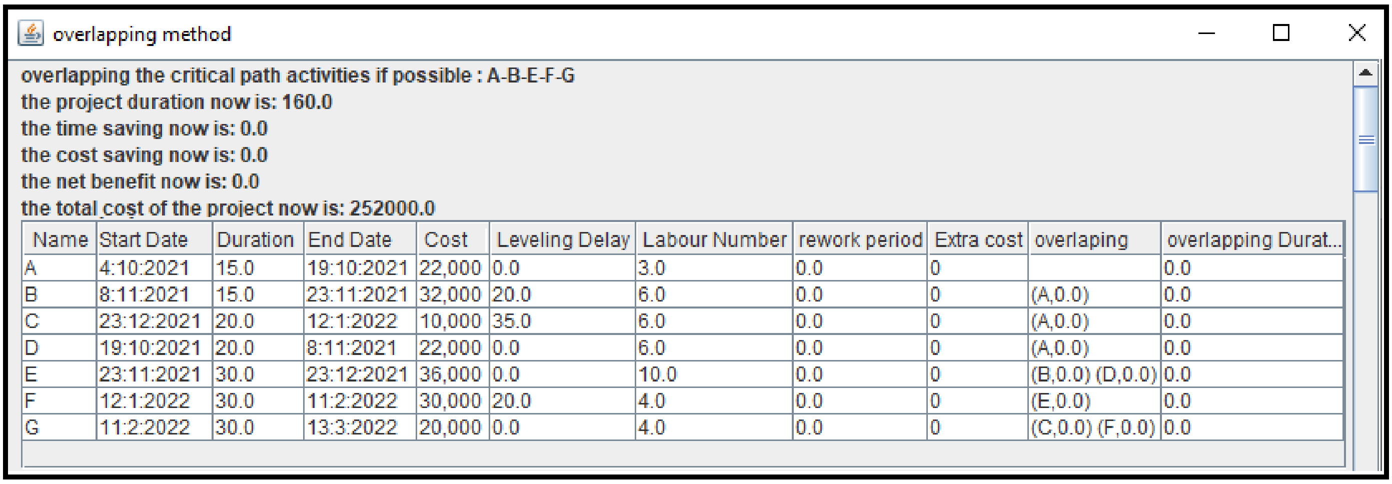
Enter the labour limit per day: 10

Activity Name	rework factor
A	0.2144
B	0.2144
C	0.2144
D	0.2144
E	0.2144
F	0.2144
G	0.2144

Figure 13. Applying the overlapping method.

12. Results of Applying the Overlapping Method

From the optimization model, in the first case without applying the overlapping method, the total time was equal to 160 days, the total cost was equal to EGP 252,000, and overlapping costs were equal to zero, as shown in Figure 14.

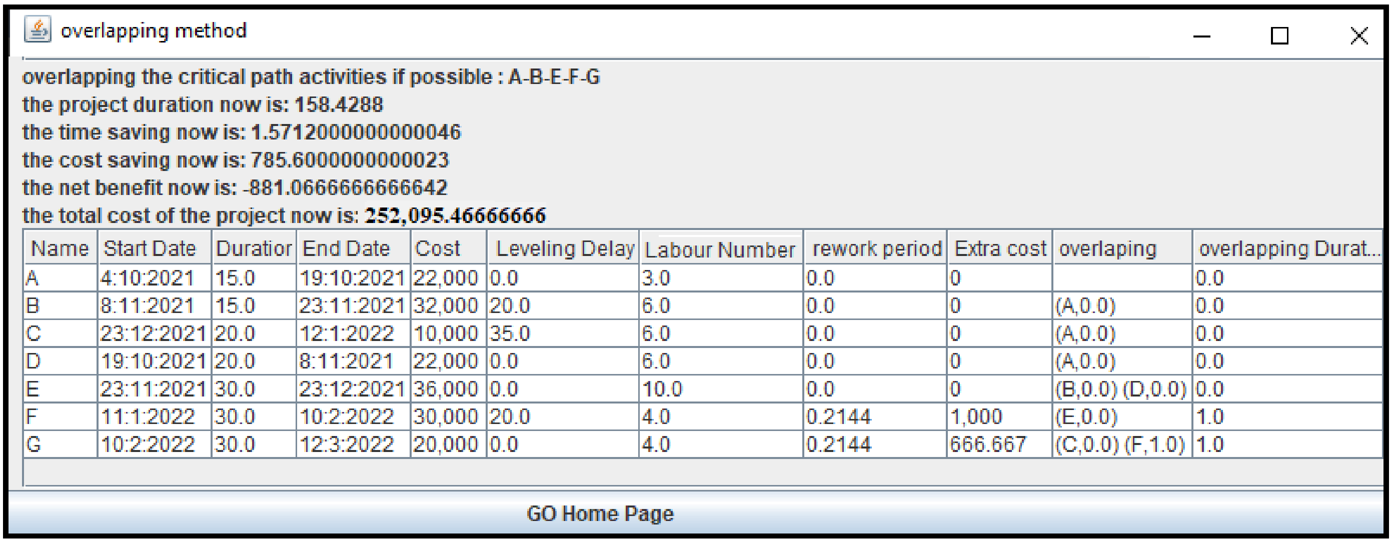


```
overlapping the critical path activities if possible : A-B-E-F-G
the project duration now is: 160.0
the time saving now is: 0.0
the cost saving now is: 0.0
the net benefit now is: 0.0
the total cost of the project now is: 252000.0
```

Name	Start Date	Duration	End Date	Cost	Leveling Delay	Labour Number	rework period	Extra cost	overlaping	overlapping Durat...
A	4:10:2021	15.0	19:10:2021	22,000	0.0	3.0	0.0	0		0.0
B	8:11:2021	15.0	23:11:2021	32,000	20.0	6.0	0.0	0	(A,0.0)	0.0
C	23:12:2021	20.0	12:1:2022	10,000	35.0	6.0	0.0	0	(A,0.0)	0.0
D	19:10:2021	20.0	8:11:2021	22,000	0.0	6.0	0.0	0	(A,0.0)	0.0
E	23:11:2021	30.0	23:12:2021	36,000	0.0	10.0	0.0	0	(B,0.0) (D,0.0)	0.0
F	12:1:2022	30.0	11:2:2022	30,000	20.0	4.0	0.0	0	(E,0.0)	0.0
G	11:2:2022	30.0	13:3:2022	20,000	0.0	4.0	0.0	0	(C,0.0) (F,0.0)	0.0

Figure 14. Output calculations in the first case without applying the overlapping method.

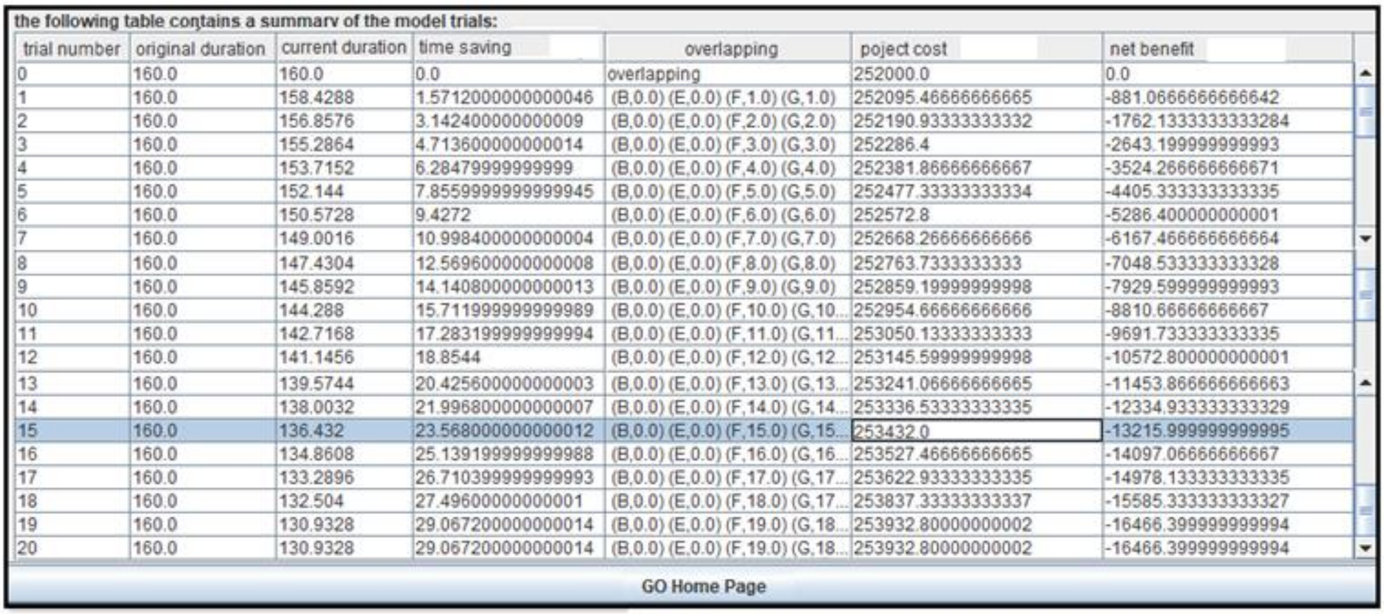
The second case was of selecting activities that can overlap with dependent activities, considering the lower-cost activity priority and critical activities. One-day overlapping from activity G and 1-day overlapping from activity F. The extra cost equal to EGP 1666.667, the saving time equal to 1.5712 day, a total cost of EGP 252,095.4666, and a net benefit of EGP −881.06666 L.E after computing indirect costs as shown in Figure 15. The next step was repeated for all critical activities, and the number of all tries equaled 20 trials in Figure 16. In each trial, the overlapping activities were selected, the overlapping duration determined, and the extra cost and net benefit determined. The minimum time was 130.9328 days, with a time saving of 29.0672 days.



overlapping the critical path activities if possible : A-B-E-F-G
the project duration now is: 158.4288
the time saving now is: 1.5712000000000046
the cost saving now is: 785.6000000000023
the net benefit now is: -881.0666666666642
the total cost of the project now is: 252,095.46666666

Name	Start Date	Duratior	End Date	Cost	Leveling Delay	Labour Number	rework period	Extra cost	overlaping	overlapping Durat...
A	4:10:2021	15.0	19:10:2021	22,000	0.0	3.0	0.0	0		0.0
B	8:11:2021	15.0	23:11:2021	32,000	20.0	6.0	0.0	0	(A,0.0)	0.0
C	23:12:2021	20.0	12:1:2022	10,000	35.0	6.0	0.0	0	(A,0.0)	0.0
D	19:10:2021	20.0	8:11:2021	22,000	0.0	6.0	0.0	0	(A,0.0)	0.0
E	23:11:2021	30.0	23:12:2021	36,000	0.0	10.0	0.0	0	(B,0.0) (D,0.0)	0.0
F	11:1:2022	30.0	10:2:2022	30,000	20.0	4.0	0.2144	1,000	(E,0.0)	1.0
G	10:2:2022	30.0	12:3:2022	20,000	0.0	4.0	0.2144	666.667	(C,0.0) (F,1.0)	1.0

Figure 15. Output calculations of the second case after applying the overlapping method (1-day overlapping from activity G and 1-day overlapping from activity F).



the following table contains a summary of the model trials:

trial number	original duration	current duration	time saving	overlapping	poject cost	net benefit
0	160.0	160.0	0.0	overlapping	252000.0	0.0
1	160.0	158.4288	1.5712000000000046	(B,0.0) (E,0.0) (F,1.0) (G,1.0)	252095.46666666665	-881.0666666666642
2	160.0	156.8576	3.142400000000009	(B,0.0) (E,0.0) (F,2.0) (G,2.0)	252190.93333333332	-1762.1333333333284
3	160.0	155.2864	4.713600000000014	(B,0.0) (E,0.0) (F,3.0) (G,3.0)	252286.4	-2643.199999999993
4	160.0	153.7152	6.28479999999999	(B,0.0) (E,0.0) (F,4.0) (G,4.0)	252381.86666666667	-3524.266666666671
5	160.0	152.144	7.8559999999999945	(B,0.0) (E,0.0) (F,5.0) (G,5.0)	252477.33333333334	-4405.333333333335
6	160.0	150.5728	9.4272	(B,0.0) (E,0.0) (F,6.0) (G,6.0)	252572.8	-5286.400000000001
7	160.0	149.0016	10.998400000000004	(B,0.0) (E,0.0) (F,7.0) (G,7.0)	252668.26666666666	-6167.466666666664
8	160.0	147.4304	12.569600000000008	(B,0.0) (E,0.0) (F,8.0) (G,8.0)	252763.7333333333	-7048.533333333328
9	160.0	145.8592	14.140800000000013	(B,0.0) (E,0.0) (F,9.0) (G,9.0)	252859.19999999998	-7929.599999999993
10	160.0	144.288	15.711999999999989	(B,0.0) (E,0.0) (F,10.0) (G,10...	252954.66666666666	-8810.66666666667
11	160.0	142.7168	17.283199999999994	(B,0.0) (E,0.0) (F,11.0) (G,11...	253050.13333333333	-9691.733333333335
12	160.0	141.1456	18.8544	(B,0.0) (E,0.0) (F,12.0) (G,12...	253145.59999999998	-10572.800000000001
13	160.0	139.5744	20.425600000000003	(B,0.0) (E,0.0) (F,13.0) (G,13...	253241.06666666665	-11453.866666666663
14	160.0	138.0032	21.996800000000007	(B,0.0) (E,0.0) (F,14.0) (G,14...	253336.53333333335	-12334.933333333329
15	160.0	136.432	23.568000000000012	(B,0.0) (E,0.0) (F,15.0) (G,15...	253432.0	-13215.999999999995
16	160.0	134.8608	25.139199999999988	(B,0.0) (E,0.0) (F,16.0) (G,16...	253527.46666666665	-14097.0666666667
17	160.0	133.2896	26.710399999999993	(B,0.0) (E,0.0) (F,17.0) (G,17...	253622.93333333335	-14978.133333333335
18	160.0	132.504	27.49600000000001	(B,0.0) (E,0.0) (F,18.0) (G,17...	253837.33333333337	-15585.333333333327
19	160.0	130.9328	29.067200000000014	(B,0.0) (E,0.0) (F,19.0) (G,18...	253932.80000000002	-16466.399999999994
20	160.0	130.9328	29.067200000000014	(B,0.0) (E,0.0) (F,19.0) (G,18...	253932.80000000002	-16466.399999999994

Figure 16. Summary of results of the overlapping method.

The results show that the method first determined critical paths that overlapped between downstream activities, depending on upstream potential changes. The rework factor is determined to always depend on the activity. Here, the rework factor was the maximum value for each activity (0.2144) from the AHP model. The rework time amount was determined by the multiplied rework factor and overlapping duration. Then the rework time for each factor was added to its duration. In each trial, the model calculated overlapping costs, total time, time saving, cost saving, and net benefit. Activity G overlapped 19 days with activity F and 18 days with activity E. The minimum reduction time was 130.9328 days, time saving was 29.0672 days, and total cost was EGP 253932.80.

13. Conclusions

The results show that the average rework time contingency of five real projects was 24.79% close to that (22.44%) obtained from the model. The value of percentage error was 15.63%, and the average validity percentage was 84.37%. This study is the first to consider the time rework value. Previous studies have assumed or neglected these values. In this study, overlapping rework values were added to the duration of the downstream activity and to the required hours for the successor task. The calculated hours and cost for each activity were next added to calculate the overall cost of schedule compression. In addition, a new model based on the AHP technique was developed to guide time rework planners in estimating time rework contingencies. A time rework contingency model was developed to predict an appropriate contingency percentage based on the anticipated project's level of changes occurring in upstream activities. The time rework contingency value resulted from the model (21.44%), not being constant for projects, will change for every project, depending on the value of the frequency and impact of factors affecting cost contingency. The research methodology was performed using a deterministic approach. In the deterministic approach, the average impact and likelihood for each factor were obtained from the survey results. Future research work can improve the model by using stochastic data inputs. In addition, the overlapping method is cheaper than the overtime method; the duration in the calculation is used in hours to increase the accuracy of the model. The model is easy to update, and it is easy to improve its functionality with no limits using the Java programming capabilities. In addition, it is easy to use by project managers for solving time and cost optimization problems.

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