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Optimization Techniques in Civil Works and Electrical Contracting

Basel Alsayyed Ahmad, Amani Alkhodari, Khaled ElSayed, Mansoor Al Jabri, and Rashed Al Dhaheri
Department of Mechanical Engineering
United Arab Emirates University (UAEU)
Al Ain, United Arab Emirates
balsayyed@uaeu.ac.ae

Abstract

This paper presents the research undertaken in studying two Operations Research (OR) problems that commonly arise in the field of civil works and electrical contracting. As the complexity in organizations increases, it becomes demanding to handle activities in an optimal way. In this regard, OR tools have been applied extensively in areas as public services, health care, manufacturing, and the military. However, there has not been found in the literature as many applications in civil works and electrical contracting. This paper demonstrates how OR tools have been utilized in minimizing the costs in this area while reaching goals effectively. Problems illustrated here are of a real-life project in the field whose scope covers the installation of underground cable circuits between two grid stations. This paper shows the mathematical models and optimal solutions of the problems of scheduling integer programming and transportation linear programming, which are very common to this field.

Keywords
Civil work, optimal costs, cable installation, scheduling and transportation; linear and integer programming

1. Introduction

Operations Research (OR) is applied to problems that are concerned with conducting and coordinating the operations within an organization [1]. In any OR study, the main stages usually include defining the problem of interest, formulating a relevant mathematical model to represent it, and then following the procedures and algorithms to solve the model and obtain optimal solutions. The same applies for this undertaken project of installing underground cable circuits between two grid stations[7].

The first stage of work, as in almost every excavation activity, is testing the land of interest in order to make sure it is compatible with the specifications of cable installation (Task 1). This usually begins with route surveying that initially checks which routes on the land are the best for installation. To validate the surveying results, trial pits are excavated as shown in Figure 2 below (Task 2). The soil is then investigated in order to check the type of ground: normal, sand, or rocky (Task 3). Each type of soil has excavation requirements different from the others; that is why it is important to identify every region on the land of interest in terms of its soil type. Last but not least, thermal resistivity tests are conducted so as to check how resistant the soil is to the flow of heat by determining the variations and characteristics of thermal dissipation that exist in soil (Task 4). This in turn is extremely valuable for determining the correct cabling requirements, cable alignments, and suitable cable backfill material [2]. This phase should be completed in a month, and its daily time span is from 7:00 a.m. to 5:00 p.m except Fridays. The problem here is to determine how many workers should be assigned to the four different tasks each day in order to minimize their total labor cost over a month, subject to the restrictions imposed by the minimum number of workers needed at different times of the day to complete the work on time.

Figure 1. Excavation of trial pits

Next steps of work include trough installation, cable laying, and Cement Bound Sand (CBS) filling. A cable trough is a deep solid enclosure inside which cables are laid, and it can be seen as a support system for the installed cables. After laying the cables inside troughs, a thermally-stable backfill of cement bound sand is used to ensure a known thermal conductivity around the cables in order to maintain the cable rating, which is the capacity of a cable to carry current. Figure 2 below shows the three tasks of trough installation, cable laying, and CBS filling. Cable troughs are usually shipped from three different suppliers: Supplier 1, Supplier 2, and Supplier 3. They are collected at four different locations at the site: Sec1, Sec2, Sec3, and Sec4. The problem is to figure out which plan for assigning the shipments would minimize the total shipping cost, subject to the restrictions imposed by the fixed output from each supplier and the fixed allocation in each location at the site.

Figure 2. From up to down: trough installation, cable laying, and CBS filling

The next section of the paper shows the mathematical models formulated for both problems as well as their optimal solutions. The following software packages have been used in obtaining optimal results: Excel Solver, MPL/CPLEX, and LINGO/LINDO. It is worthwhile to mention that the data needed to formulate and solve each model is acquired from the company from which this real-life project has been taken. However, number values presented in this paper are encrypted for the sake of confidentiality.

2. Mathematical Models and Optimal Results

This section illustrates the mathematical models of the problems of scheduling integer programming and transportation linear programming. It also discusses the solution procedures followed and the software packages utilized to obtain optimal results for each problem.

2.1 Scheduling Integer Programming

The data that needed to be gathered included three categories: the time periods of the day for each of the four tasks in this stage of work, the daily cost per worker for each task (In AED), and the minimum number of workers that need to be on duty at different times of the day to complete the work of this phase on time. Obtaining reasonable estimates of these quantities required enlisting the help of key personnel in various units of the company. Engineers supervising the work of each task in this phase provided the data in the first category above. Developing estimates for the second category of data required analyzing cost data from the payroll along with the finance and accounting department. By thinking ahead and establishing the number and skills of the workforce required by the project as a whole, the technical department along with the human resources department developed estimates for the third category. Table 1 below summarizes the data gathered.

Table 1. Data for the scheduling problem

Time Period	**Land / Route Surveying (x1)**	**Trial Pits (x2)**	**Soil Identification (x3)**	**Thermal Resistivity Tests (x4)**	**Minimum Number of Workers Needed**
7:00 a.m. to 8:00 a.m.	X				15
8:00 a.m. to 9:00 a.m.	X	X			25
9:00 a.m. to 10:00 a.m.	X	X			25
10:00 a.m. to 11:00 a.m.	X	X	X		35
11:00 a.m. to 12:00 p.m.	X	X	X		38
12:00 p.m. to 1:00 p.m.			X	X	12
1:00 p.m. to 2:00 p.m.	X	X	X	X	45
2:00 p.m. to 3:00 p.m.	X	X	X	X	45
3:00 p.m. to 4:00 p.m.				X	2
4:00 p.m. to 5:00 p.m.				X	2
Daily Cost per Worker (AED)	280	200	280	600	

After gathering the needed data, it was immediately recognized that this was an integer programming problem of the scheduling type, and the formulation of the corresponding mathematical model that needed to be solved was then undertaken. Where the objective function **Z** represents the minimum total labor cost per day and the values of **x** are the numbers of workers assigned to each task every day, the relevant mathematical model is illustrated in Figure 3 below. Each of the parameter values in **Z** is the daily cost per worker for each of the four tasks.

$$
\text{Minimise } Z = 280x1 + 200x2 + 280x3 + 600x4
$$

Subject to

Functional constraints:

$x1 \geq 15$	(7-8 a.m.)
$x1 + x2 \geq 25$	(8-9 a.m.)
$x1 + x2 \geq 25$	(9-10 a.m.)
$x1 + x2 + x3 \geq 35$	(10-11 a.m.)
$x1 + x2 + x3 \geq 38$	(11-12 a.m.)
$x3 + x4 \geq 12$	(12-1 p.m.)
$x1 + x2 + x3 + x4 \geq 45$	(1-2 p.m.)
$x1 + x2 + x3 + x4 \geq 45$	(2-3 p.m.)
$x4 \geq 2$	(3-4 p.m.)
$x4 \geq 2$	(4-5 p.m.)

and

xj is integer, for j = 1, 2, 3, 4

Positivity constraint:

$xj > 0$, for j = 1, 2, 3, 4

Figure 3. Mathematical model of the scheduling problem

Solving the system of equations above by hand is tedious, time-consuming, and almost impossible. Therefore, Excel Spreadsheet was utilized to solve the model of this problem and find the number of workers assigned to each task everyday in a combination that reduces the total labor cost as much as possible. Figure 4 below is a snapshot from the relevant Excel sheet illustrating the data, the constraints, and the final solution. The 1's and 0's in the constraints table indicate respectively whether the task is on progress or not during each time period. Values of the decision variables are highlighted in yellow while the optimal result of the objective function is highlighted in orange.

To minimize the total labor cost per day, it was found from the solver that a daily total of 15 workers should be assigned to the first task of land/route surveying (x1=15), 18 workers to the second task of trial pits excavation (x2=18), 10 workers to the third task of soil investigation (x3=10), and only 2 workers to the last task of thermal resistivity tests (x4=2). This returned an optimal result of AED 11800 as a minimal total labor cost per day (Z=11800). In a month, excluding Fridays, the minimal total labor cost was found to be AED 306800. It is also worth to mention that the total number of workers available at the site for all tasks during each time period satisfies the constraints of the minimum number needed.

Scheduling Integer Programming Problem of Phase 1: Testing the Land

B	C	D	E	F	G	H	I
	7 a.m. - 12 p.m.	8 a.m. - 12 p.m.					
	1 p.m. - 3 p.m.	1 p.m. - 3 p.m.	10 a.m. - 3 p.m.	12 p.m. - 5 p.m.			
	Task 1	Task 2	Task 3	Task 4			
Daily Cost per Worker (DHS)	280	200	280	600			
Time Period	Task on Progress during Time Period? (1 = Yes, 0 = No)				Total Number of Workers		Minimum Needed
7 a.m. - 8 a.m.	1	0	0	0	15	>=	15
8 a.m. - 9 a.m.	1	1	0	0	33	>=	25
9 a.m. - 10 a.m.	1	1	0	0	33	>=	25
10 a.m. - 11 a.m.	1	1	1	0	43	>=	35
11 a.m. - 12 p.m.	1	1	1	0	43	>=	38
12 p.m. - 1 p.m.	0	0	1	1	12	>=	12
1 p.m. - 2 p.m.	1	1	1	1	45	>=	45
2 p.m. - 3 p.m.	1	1	1	1	45	>=	45
3 p.m. - 4 p.m.	0	0	0	1	2	>=	2
4 p.m. - 5 p.m.	0	0	0	1	2	>=	2
	7 a.m. - 12 p.m.	8 a.m. - 12 p.m.					
	1 p.m. - 3 p.m.	1 p.m. - 3 p.m.	10 a.m. - 3 p.m.	12 p.m. - 5 p.m.			
	Task 1	Task 2	Task 3	Task 4	Total Number of Workers per Day		Total Labour Cost per Day (DHS)
Number of Workers in Task	15	18	10	2	45		11800
							Total Labour Cost per Month (DHS)
Per Month (Excluding Fridays)	390	468	260	52			306800

Figure 4. Excel sheet snapshot of the scheduling problem solution

As expected, the same results were obtained using MPL and LINGO software tools. In MPL, Index parameters were listed, Data values were stated, and decision variables were defined in the Variables section. Then, the model with its constraints was written and the solution file was generated using CPLEX 300 solver. LINGO, on the other hand, used the same solution algorithm but with a slightly different syntax. Figure 5 below shows a caption from MPL status window and solution file where the word "Activity" means the value of the decision variable. MPL graph of objective function indicating the number of iterations gone through is illustrated in Figure 6 below. Figure 7 below shows a caption from LINGO solver status and solution report whereas Figure 8 is its generated bar graph of the values of the decision variables.

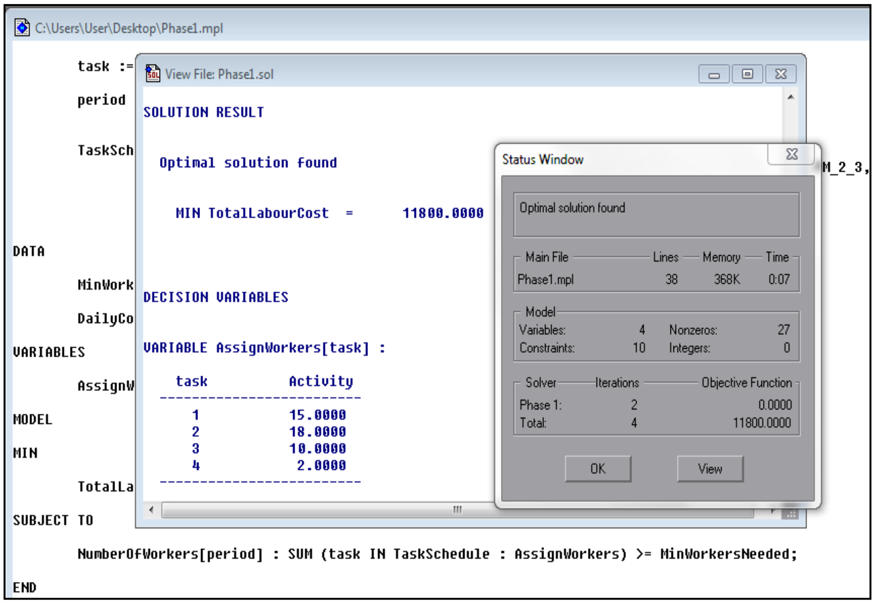

Figure 5. MPL status window and solution file of the scheduling problem

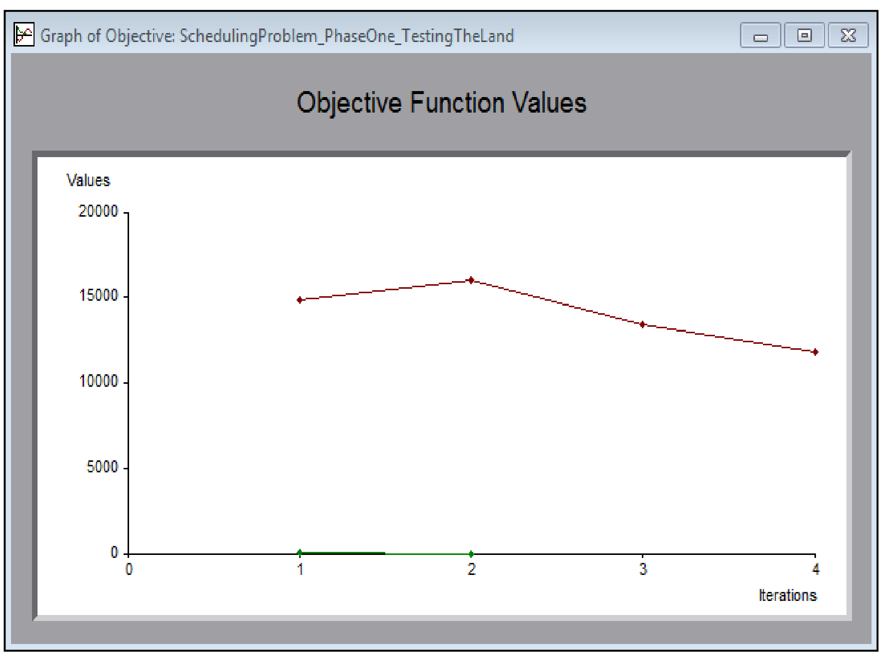

Figure 6. MPL graph of objective function values of the scheduling problem

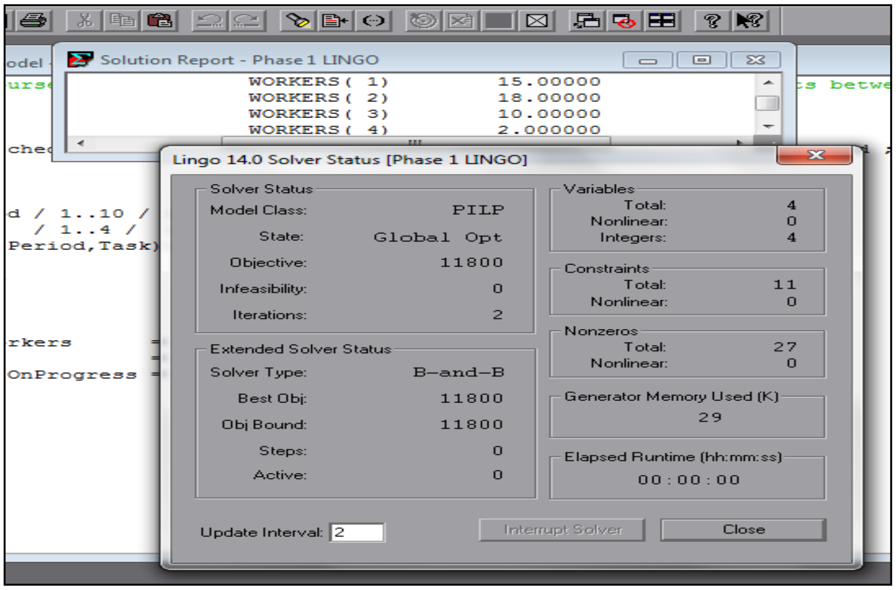

Figure 7. LINGO solver status and solution report of the scheduling problem

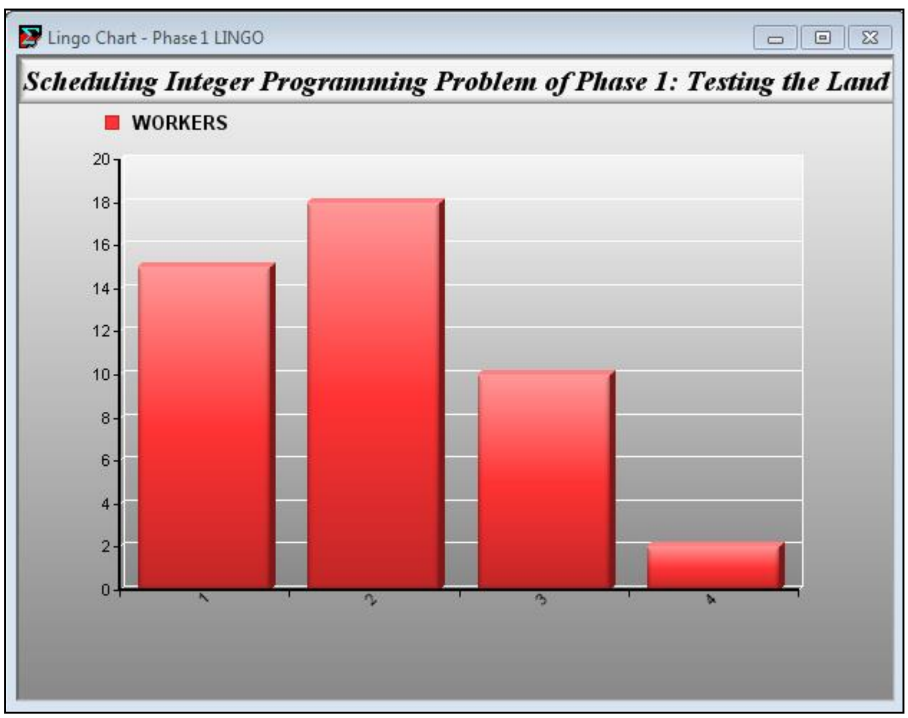

Figure 8. LINGO graph of decision variables values of the scheduling problem

2.2 Transportation Linear Programming

For this problem, the data that needed to be gathered included three categories: the output from each source (Supply), the allocation at each destination (Demand), the cost per unit shipped from each source to each destination (In AED). The procurement department at the company provided the data needed for the first and third categories above. Engineers supervising the work in each of the four locations at the site provided data of the second category. The cost from each supplier to each location depends on the distance, the type of road whether Asphalt or Gatch, and the time of shipment whether day or night. Usually, the cost of the night shipping is higher than that during the day because it needs proper lightning to ensure clear visibility and hence safe conditions. However, this case was excluded from the model formulation.

Since each trip can load four troughs, the shipping cost per trough can be found by dividing the shipping cost per trip by 4. This information of supply and demand (in units of cable troughs) along with the shipping cost per cable trough for each supplier-location combination is given in Table 2 below. A network representation of this problem is also provided in Figure 9 below, where all the sources are lined up in one column on the left and all the destinations in one column on the right. The arrows show the possible routes for the cable troughs shipments, where the number next to each arrow is the shipping cost per cable trough for that route. A square bracket next to each supplier gives the number of cable troughs to be shipped out of that supplier (so that the allocation in each location at the site is given as a negative number).

Table 2. Shipping data for the transportation problem

	Shipping Cost (AED) per Cable Trough				
	Location at the Site				
	Sec1	**Sec2**	**Sec3**	**Sec4**	**Output**
Al Meraikhy	175	250	325	225	600
UPC	225	300	375	275	2516
EPC	500	550	625	525	2220
Allocation	2068	2168	788	312	

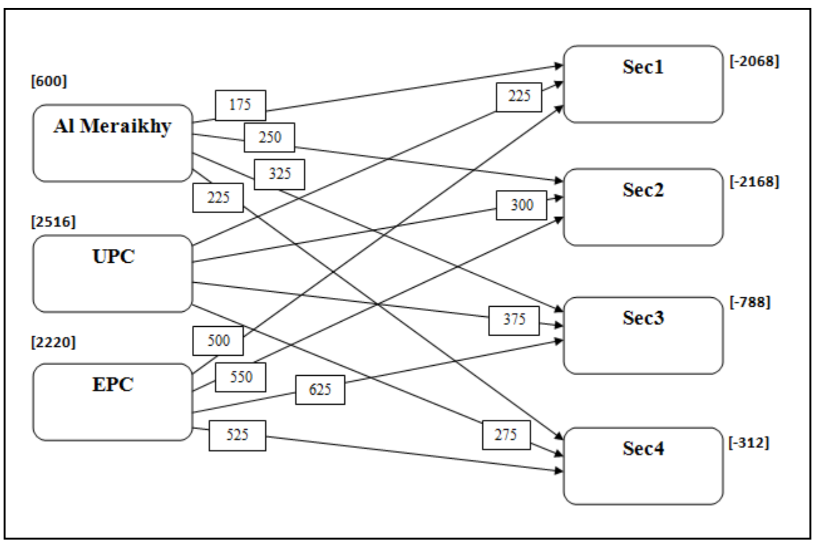

Figure 9. Network representation of the transportation problem

The problem of this phase of work is actually a linear programming problem of the transportation type. To formulate the mathematical model, let **Z** denote the total shipping cost, and let $\mathbf{x_{ij}}$ (i = 1, 2, 3; j = 1, 2, 3, 4) be the number of cable troughs to be shipped from supplier i to location j at the site. Thus, the objective is to choose the values of these 12 decision variables (the $\mathbf{x_{ij}}$) so as to minimize **Z**. The relevant mathematical model of this problem is shown in Figure 10 below.

Minimise $Z = 175x11 + 250x12 + 325x13 + 225x14 + 225x21 + 300x22 + 375x23 + 275x24 + 500x31 + 550x32 + 625x33 + 525x34$

Subject to

Supply constraints:

$$x11 + x12 + x13 + x14 = 600$$
$$x21 + x22 + x23 + x24 = 2516$$
$$x31 + x32 + x33 + x34 = 2220$$

Demand constraints:

$$x11 + x21 + x31 = 2068$$
$$x12 + x22 + x32 = 2168$$
$$x13 + x23 + x33 = 788$$
$$x14 + x24 + x34 = 312$$

and

Non-negativity constraint:

$$xij \geq 0 \ (i = 1, 2, 3; j = 1, 2, 3, 4)$$

Figure 10. Mathematical model of the transportation problem

In finding the transportation plan that minimizes the total shipping cost, an initial feasible solution can be found using the Northwest Corner method, the Minimum Cell Cost method, or Vogel's Approximation method. Then, the Stepping-stone or the Modified Distribution methods are used to solve the problem itself [1]. It is worth to mention here that different modeling tools may turn out different shipment allocations but with the same optimal shipping cost, and this is referred to the fact that they may not use the same method for solving the problem. Figure 11 is a snapshot from the Excel sheet used to solve this problem, and it shows one possible shipment quantity plan with an optimal total shipping cost of AED 2022000.

Transportation Problem of Phase 4: Shipment of Cable Troughs to the Site

B	C	D	E	F	G	H	I	J
		Shipping Cost (DHS) per Cable Trough						
		Destination: Location at the Site						
		Sec1	Sec2	Sec3	Sec4			
	Supplier 1	175	250	325	225			
Source: Supplier	Supplier 2	225	300	375	275			
	Supplier 3	500	550	625	525			
		Shipment Quantity Plan (Cable Troughs)						
		Destination: Location at the Site						
		Sec1	Sec2	Sec3	Sec4	Total Shipped		Supply
	Supplier 1	600	0	0	0	600	=	600
Source: Supplier	Supplier 2	1468	1048	0	0	2516	=	2516
	Supplier 3	0	1120	788	312	2220	=	2220
	Total Received	2068	2168	788	312			
		=	=	=	=			Total Shipping Cost (DHS)
	Demand	2068	2168	788	312			2022000

Figure 11. Excel sheet snapshot of the transportation problem solution

MPL also gives the same optimal value of total shipping cost but with a different quantity allocation plan, because it probably followed a solution approach different from the Excel solver. Figure 12 below shows the status window and part of the solution file of MPL to this phase. MPL graph of objective function indicating the number of iterations gone through is illustrated in Figure 13 below. LINGO also provides the same optimal value of total shipping cost with different values of decision variables. Figure 14 below shows a caption from LINGO solver status and solution report while Figure 15 is its generated bar graph of the values of the decision variables.

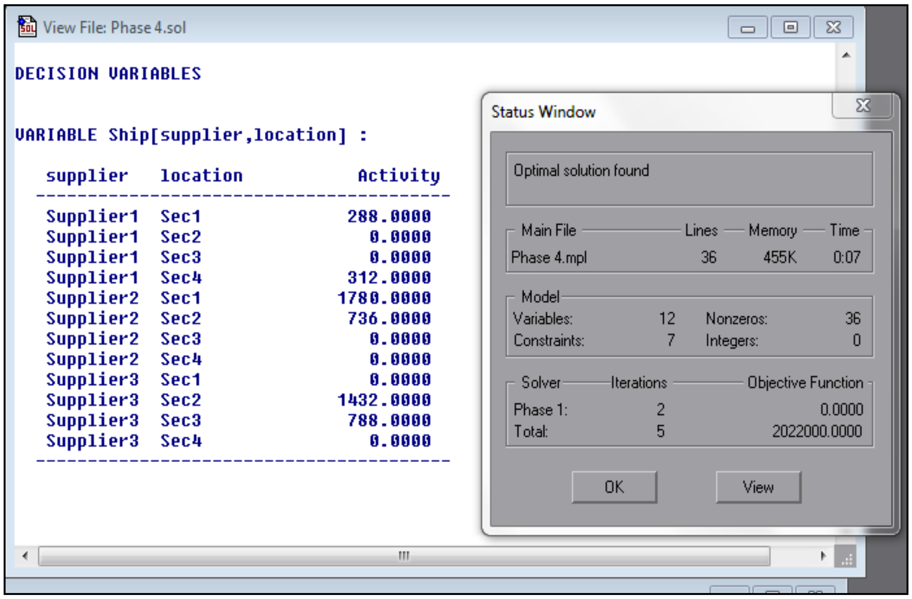

Figure 12. MPL status window and solution file of the transportation problem

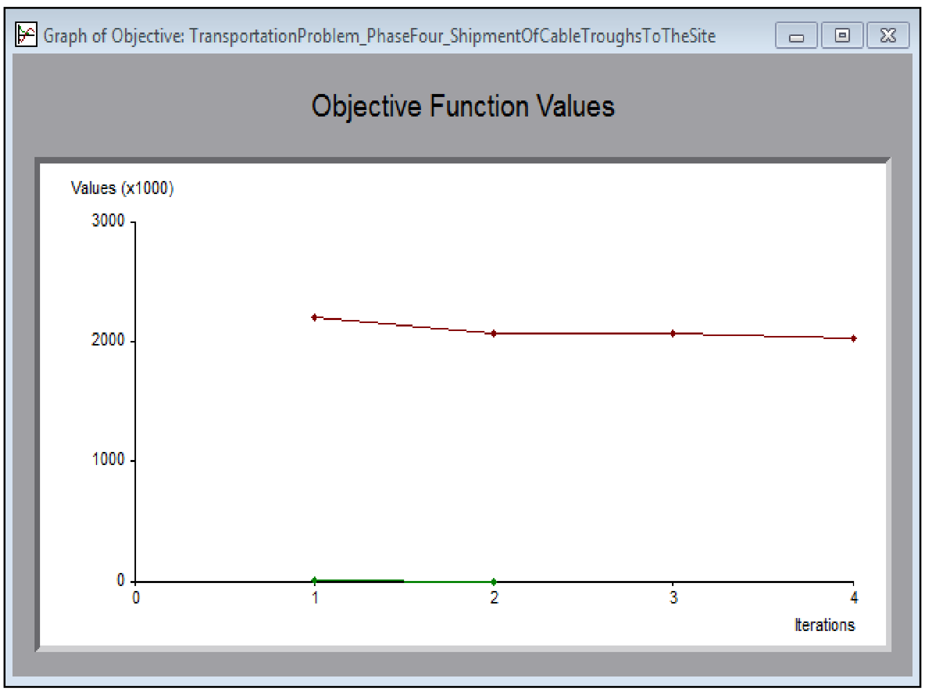

Figure 13. MPL graph of objective function values of the transportation problem

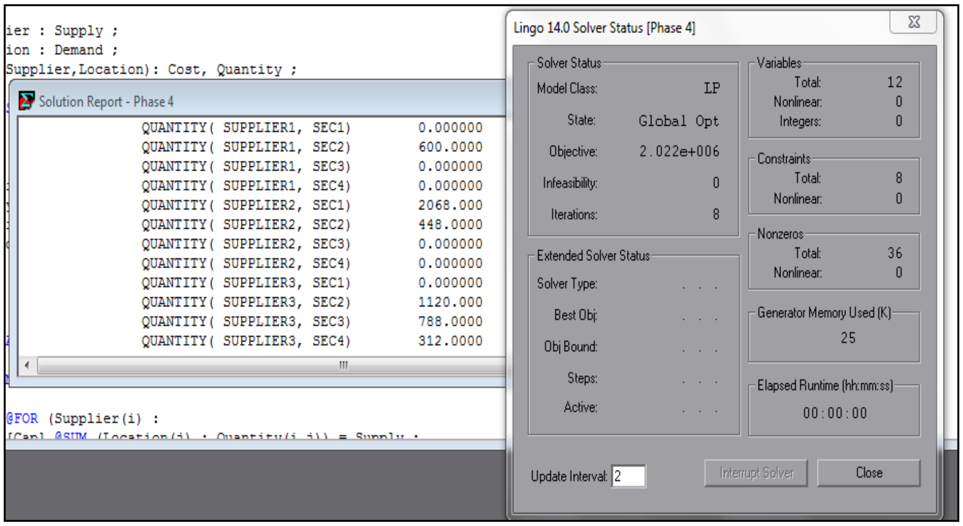

Figure 14. LINGO solver status and solution report of the transportation problem

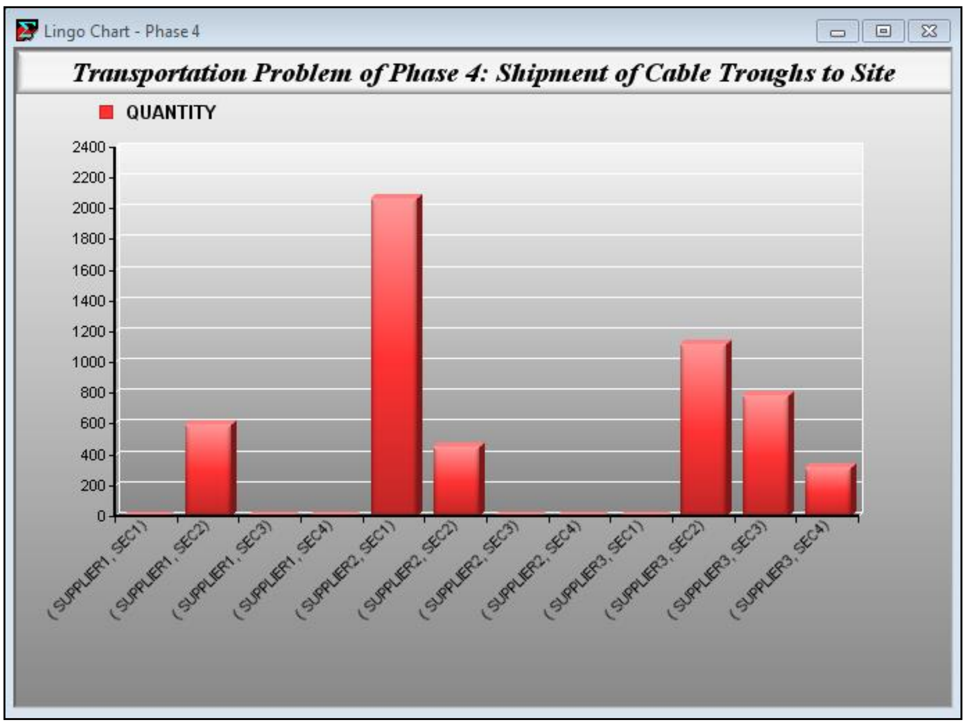

Figure 15. LINGO graph of decision variables values of the transportation problem

3. Conclusions and Recommendations

In this paper, two different operations research problems were explored with regard to a project in the field of civil works and electrical contracting: the problem of scheduling workers in shifts of tasks, and the transportation problem. The objective was to find the most optimal solution of each problem through minimizing the total associated costs. For the scheduling integer programming problem, a daily reduction of about AED 4500 was incurred using the proposed optimization model. It is recommended to consider two different scheduling plans; one for the summer and another for the rest of the year. Regarding the transportation costs, a reduction of approximately AED 80000 resulted from the optimization model presented in the paper. It would be beneficial here, and perhaps more accurate, to re-study this transportation problem after incorporating the costs of the night shipping.

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Biography

Basel Alsayyed Ahmad is an assistant professor at the department of mechanical engineering in the United Arab Emirates University. With over 16 years of experience in academia in many colleges and universities, and over 12 years of industrial experience, most of which are in the American automotive industry, Dr. Alsayyed has a passion for education in general and teaching in particular. Teaching is an art, a trust, a valuable transformation of students using certain methods and tools, and it is holy, are all part of his belief. He practices it in all aspects of his life, and to Dr. Alsayyed, students are the most valuable element in the education process; their needs have to be addressed in any continuous improvement discussion of the education process. Integration of academia and industry goals and activities are paramount. Sensing the industry needs and prepare future engineers to meet the challenges is an important dimension of Dr. Alsayyed's activities. Dr. Alsayyed research interests are in the areas of advanced manufacturing, quality & reliability, renewable energy, engineering education and knowledge management.