A linear mathematical programming model for optimization of the energy consumption in construction projects

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In this study, a linear mathematical programming model is formulated to manage the consumption of electrical energy and fossil fuels in the construction projects simultaneously. The aim is to determine at what time period and for how long each electric machine is employed in the whole project, the optimal number of periodic services for the machines with fossil fuels and optimal service time so that the total objective function value is minimized. The objective function of the proposed problem is the sum of electricity consumption costs, service costs and fossil fuel consumption costs in the whole project. In the proposed model, different intervals are considered for electrical energy consumption and the effects of the average speed of each machine with fossil fuel consumption and the time required to these machines in each day are also applied in decisions-making. For solving the mathematical model, the LINGO optimization software package is employed. For a better understanding of the behavior of the proposed problem, sample problems with different sizes are investigated and the results are interpreted graphically. The results show that the objective function value of the proposed problem increases with an increment in the project completion time and number of machines, the consumption cost of the fossil fuels machines accounts for a significant portion of the objective function value in all samples and also, the contribution of service costs is more than that of the electric machines. Also, the proposed model is implemented for a sample problem and its sensitivity to some parameters are tested. The results of sensitivity analysis show that by increasing the project completion time, the number of intervals selected for the daily use of electric machines, number of service times required for the fossil fuel machinery and consequently the amount of objective function are increased. Also, the model solving time increases logarithmically with an increment in the project completion time.

keywords: *Linear mathematical programming model, energy consumption management, electric machines, fossil fuel machines, LINGO optimization software.*

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NOMENCLATURE

Acronyms

t	Project day number index,
j	Machine number index,
l	Energy consumption interval index,
n	Number of service time (repair and maintenance).
TC	Project completion time,
NM	Number of machines,
AV_j	Average speed of the jth machine during the activity (km/hour),
KS_j	Number of kilometers after which the jth machine needs to be serviced,
KM_{tjn}	Kilometer number of the jth machine on tth day for the nth time,
RT_{tj}	Time duration of need for the jth machine on tth day (hour),
D_{tj}	Distance traveled by the jth machine on tth day (km),
C_l^E	The consumption cost of each electrical energy unit during the lth consumption interval,
C^F	The consumption cost of each fossil fuel unit which is a fixed value,

FC_j Fixed service cost of the jth machine,

Q_j^E The amount of electrical energy consumption by the jth machine (kw/hour),

Q_j^F The amount of fossil fuel consumption by the jth machine (lit/hour),

α_j Fuel consumption increasing coefficient of the jth machine,

M Large positive value.

X_{jtn}^F Equal to 1 if the jth fossil machine is serviced on the nth day for the nth time, otherwise 0,

Y_{jtn}^F Equal to 1 if the cumulative kilometer number of the jth fossil machine on the tth day is greater than or equal to n.KSj for the nth time, otherwise 0,

NX_{jtl}^E Duration of using jth electric machine on the tth day within the lth interval (hour),

NS_j Number of service time (repair and maintenance) for the jth machine.

1. INTRODUCTION

Energy is one of the most important resources and the basic force of human life. Human civilization has been formed on the basis of innovations and discoveries in order to convert different types of energy into each other. Energy consumption has drastically increased in recent decades. After the 1974 energy crisis which was accompanied by rising crude oil and energy prices, the energy consumption trend generally was less changed and countries without oil resources acted more systematically in terms of its consumption [1]. Optimization of energy consumption means selecting patterns and applying methods and policies towards the proper use of energy which are economically desirable and ensure the sustainability and durability of the energy as well as continuation of life and movement. Nowadays, useful measures have been taken to optimize the energy consumption. Despite what has been conducted before, there is still a great potential for optimizing the energy consumption, which through the use of appropriate approaches, leads to many results such as decreasing energy demand and limited increasing rate of power plant capacity building, improved consumption patterns and utilization rate of the existing systems as well as the supply capacities release for a more active attendance at the international energy markets [2].

Today, energy is recognized as one of the main factors in the formation and development of industrial societies so that the access level of countries to various energy resources indicates their progress and political-economic power. In Iran, the energy consumption has been estimated to be 50, 25 and 25% in the construction, industry and transportation sectors, respectively. In this country, the construction-civil projects, both during and after construction, account for a large share of energy consumption so that the cost due to the improper energy consumption in the country is estimated to be more than five billion dollars a year, from which the residential and commercial sectors account for the major energy consumers [3]. In the coming decades, in addition to the environmental issues and global warming, the cost of different types of energy for different uses will undoubtedly increase significantly, and in the meantime electricity as a secondary energy resource will always maintain its increasing contribution. The aim of the presents study is to present a mathematical model for managing the electricity and fossil fuels consumptions in a simultaneous manner in construction projects.

The rest of study is organized as follows. In the next section, the research background is presented. Section 3 defines the original problem, the hypotheses, the indices, the parameters and the decision variables. Also, the proposed mathematical model is presented in this section. In section 4, the numerical results are presented for problems of various sizes. A sample problem is also examined in this section. Section 5 gives the conclusions and suggestions for future studies.

2. RESEARCH BACKGROUND

2. Research background Today, due to the growth of the energy and economic crises, it is necessary to optimize energy consumption in the design and building construction [4]. The construction industry includes enormous activities with the different consumption of energy and resources [5, 6]. Studies show that the embodied energy, the energy used to construct the building (extraction, processing and manufacture, transportation and assembly), includes a major percentage of the life cycle energy of the building [7–9]. Generally, the problem under consideration is based on the literature in the following investigation categories: (1) optimization of the embodied energy consumption in construction projects, (2) optimization of the operation energy consumption in construction projects. In following, the related literature are provided.

Reference [10] presented an energy estimation system for estimation of energy consumption during construction of buildings. They showed that the energy applied in extraction, manufacturing, transportation, and installation of building elements have a vital role in construction of energy efficient buildings. The proposed system permits contractors to specify energy intensive activities during construction and employ energy effective means and techniques to decrease energy consumption of a certain project. The authors used an example of a repair garage to test the performance of the proposed system. Reference [11] provided a structure for evaluation of embodied energy consumption for building construction engineering. The authors compared nine sub-projects using the building construction engineering. Also, a cluster of landmark commercial buildings in E-town, Beijing was studied. Reference [12] analyzed the different models and variables to identify some main findings and some limitations of the existing models and then, developed an integrated mathematical model for measuring embodied energy, greenhouse gases, waste, time-cost parameters of building projects. Also, the authors studied the relationships between them to simplify the quantification process and the engagement into low carbon building design by construction experts. Reference [13] provided a method for evaluating energy used for onsite construction activities. The proposed method catch and analyze data to investigate the quantification of the onsite energy consumptions. The author found three linear positive correlations among electricity consumption on a construction site and three project features (construction period, gross floor area and gross building volume). The proposed method was conducted on a sample of residential building projects. Reference [14] incorporated a multi-objective optimization algorithm with building information modeling and life cycle assessment to balance embodied and operation energy. The authors concentrated on renewable energy use and applied a parametric simulation in Grasshopper to estimate operation energy. Also, a Hypervolume estimation algorithm was employed for Multi-objective Optimization. The authors found that there is an optimal domain through maximizing embodied energy to decrease the operation energy and also, a decrease of 65% in the total life cycle energy of the building was achieved.

Reference [15] employed the bi-level models in order to optimize the design of energy supply network for the distributed energy system (DES). Based on the price fluctuations and heat demand of consumers in a region, this study presented a bi-level programming model for a regional DES. The aim of the model was to minimize the overall cost of the regional DES and can be used to cope with the programming problems including the number, capacity and optimal location of energy suppliers along with the optimal heat distribution network. A hybrid algorithm was presented for solving this bi-level programming problem. Also, the authors conducted a case study. Reference [16] employed a bi-level model for the electricity retailers' participation in a demand response market environment. The authors proposed a game theory model accounting for the Stackelberg relationship between the retailers (leaders) and the consumers (followers) in a dynamic price environment. The model allows the dynamic price signals to provide maximum profit to the seller and optimal load pattern for the consumers under this pricing. The authors found that this dynamic pricing scheme is very useful in achieving load shifting and thus reduces the retail costs for energy procurement and regulation in the wholesale markets. Reference [17] investigated the relationship between economic development and energy consumption in order to reduce the greenhouse gases emission. This work mainly focused on comparing the approximate energy consumption thresholds in the form of the minimum energy required to achieve higher development levels with the representation of the final energy supply per capita, from a group of the integrated evaluation models. The authors pointed out to the role of infrastructures, such as steel and cement to emphasize the importance of basic energy needs in the future. Reference [18] introduced an energy-based target cost modeling framework. The proposed model led to a balance between the project cost and the performance criteria through combining the target costing principles and energy analysis techniques. The authors developed energy-based mathematical models by introducing the standard energy factors, using energy simulations and performing statistical analysis. Furthermore, they were able to effectively evaluate the construction system options. Then, they used the rule-based analysis system to automatically select the building system (s) which lead to the optimized energy consumption according to the target cost and set of performance criteria. Reference [19] presented the mathematical modeling and control system of nearly zero energy building. The authors examined three different kinds of mathematical models of nearly zero energy building, including: (1) the model for optimizing the structure and definition of the key parameters of energy efficient building, (2) model for designing passive houses with renewable energy resources, and (3) model for monitoring and controlling the energy supply system of nearly zero energy building on an hourly basis throughout the year. Reference [20] provided a complete review of energy consumption optimization techniques in smart building environments based on the internet of things. The authors examined various factors which contribute to the thermal comfort, visual acuity and indoor air quality, as well as fog and edge calculation techniques used in smart homes. A framework for reducing dust emissions and energy consumption on construction locations was provided by [21]. The proposed framework is an intelligent system that can automatically manage dust emissions and energy consumption from construction locations. Also, real-time monitoring, assessment, the minimization of dust emissions and energy consumption of a construction location and reduction of other different environmental issues such as noise and vibration and economic issues such as cost of litigation, additional construction, can be conducted by the presented framework. Reference [22] used a combination of the occupancy data in the building equipment programming. First, they formulated the proposed problem as a binary optimization model. In the proposed model, the actual occupancy patterns of different building sections as well as equipment interdependence were considered to regularly determine the optimal schedule for each equipment and at the same time the minimum service level required to meet the demands of the occupants. The authors then integrated the proposed model with a simulation optimization framework in order to determine the optimal frequency of scheduling updates and the best design option for new buildings or retrofitting projects. The authors implemented their proposed model on a university building. Reference [23] designed a consumption-based multi-objective optimization model in which minimization of the energy consumption and maximization of the economic growth were considered simultaneously. The authors conducted a case study in China and found that there are key parts and economic relations amongst parts that played vital roles for optimizing the industrial framework. Reference [24] presented a bi-objective optimization model to choose passive energy alternatives in retrofit projects in which the uncertainties that may occur in cost assessments were considered. An analytic network process technique was used for determination of the relative importance of these alternatives considering their non-monetary benefits and subjects. The authors studied a case study of a typical building to investigate the applicability of the proposed model. Reference [25] developed a Manta-Ray Foraging Optimization algorithm to minimize the energy consumption in residential buildings by optimizing their shapes. The authors employed RIUSKA to simulate whole-building energy and investigated various forms of the building. To the best of our knowledge, there is no mathematical programming model for optimization of the consumption of electrical energy and fossil fuels simultaneously in the construction projects. The aim is to provide an optimal schedule for the electrical energy consumption of electric machines (at what time period and for how long to use it each day), to determine the optimal number of periodic services for the machines with fossil fuels and optimal service time so that the total objective function is minimized.

3. PROBLEM DEFINITION

Consider a construction project in which there is a certain number of equipment and energy consuming machinery. In this study, two categories of machinery and equipment have been considered in terms of the energy consumption, including: (1) machinery with electrical energy consumption and (2) machinery with fossil fuels consumption. Fig. 1 shows some electric and fossil fuel machines which are widely used in the construction projects. As shown in this Fig. 1, the size and dimensions of these machines are different. As a result, the hourly consumption rate varies for different sizes of these machines. For electrical energy consuming machines, three consumption intervals are considered per day with different and certain energy consumption costs, including: (1) low-load, (2) medium-load, and (3) high-load intervals. The duration of each interval is assumed to be 3 hours. Machines which use fossil fuels are expected to have useful activity with the least useless hours during the day. Therefore, the activity schedule of these machines during the day and their maintenance plan should be determined in such a way to achieve the maximum efficiency. The maintenance program is used to create the best performance in equipment and machinery. These programs include servicing of engines, axles and worn parts. In general, the machinery maintenance goals in the construction projects are as follows: (1) prevent the development of defects, (2) fix defects and shortcomings before the need for general repair that leads to economic savings, (3) prevent unforeseen interruptions in the project which causes additional costs due to delays in execution, (4) reducing the consumption of spare parts, (5) increasing the machinery life, and (6) increasing the working efficiency of machines.

Since the energy consumption plays an important role in the construction projects and accounts for a large portion of the project costs, in this paper, a mathematical programming model is formulated in order to minimize the total energy consumption of the project through optimally scheduling the machinery activities and their timely servicing. This mathematical model helps the project manager determine in what period of time and for how long can use each machine on each day of the project, as well as the number and frequency of the machine maintenance operations so that the time and quality of the project proceed according to the plan and also the total energy consumption cost of the project is minimized.

(a) Excavator (b) Roller (c) Grader

(d) Welding machine (e) Electric concrete mixer (f) Lifting machine

Fig. 1. The electric and fossil fuel machines being widely used in the construction projects.

A. Assumptions

The assumptions of the proposed model are given as follows:

- There is no prerequisite relationship between the machines on a day.
- The machines are available during all working hours of the day.
- The activity interruption is possible for the machines every day.
- Energy consuming machines are divided into two categories, including the electric and fossil.
- For electric machines, three consumption periods have been considered per day, including: (1) low-load, (2) medium-load, and (3) high-load periods.
- The project is limited in time.
- The number of machines is limited.
- At the beginning, the machine odometer was set to zero.
- The machines servicing (maintenance and repair) is possible after the end of working hours.
- Working hours are from 8 am to 5 pm for 9 hours a day.

In nomenclature section, the indices, the parameters and the decision variables required to formulate the proposed problem are presented. It should be noted that the index l in the nomenclature may have three values, representing the energy consumption interval in terms of the electricity consumption of the customers per day. In Table 1, an interpretation of each of these values are provided. Since in construction projects, fossil fuel machines require regular maintenance and account for a large portion of maintenance and repair costs, therefore, the service schedule and costs are determined only for these machines in the proposed model. Also, in the proposed problem, the value of parameter Q_j^E for the fossil fuel machines and those of AV_j, KS_j, D_{tj}, FC_j, Q_j^F and α_j for the electric ones are zero. The servicing costs of fossil fuel machines includes two categories: (1) fixed service cost, which can be different for each machine and (2) variable service cost, which is a factor of the total consumption cost of the corresponding machine in the service day. Since it is not possible to service the machine during the operation time, it is assumed here that the maintenance and repair processes associated with each one be performed at the end of the selected day, not during its operation. It is clear that the lack of timely service can affect the fuel consumption of fossil fuel machinery and the cost as a consequence. Therefore, in this study, a cost called variable service cost is applied due to the possible delay in servicing. This cost is represented using coefficient α_j, which is defined as the fuel consumption increasing coefficient of the jth machine. This means that a delay in servicing the jth machine leads to an increased fuel consumption per hour to the extent of $\alpha_j \times Q_j^F$.

Table 1. Interpretation of index l value

Index value	*l=1*	*l=2*	*l=3*
Description	Low-load interval	High-load interval	Medium-load interval
Time interval	8-11	11-14	14-17

B. Proposed mathematical model

In the following, using the indices, the parameters and the decision variables defined in the previous section, the mathematical programming model of the proposed problem is provided.

$$\min \sum_{t=1}^{TC} \sum_{j=1}^{NM} \sum_{l=1}^{3} C_l^E.Q_j^E.NX_{jtl}^E + \sum_{t=1}^{TC} \sum_{j=1}^{NM} \sum_{n=1}^{NS_j} X_{jtn}^F. \left(FC_j + \alpha_j.Q_j^F.RT_{tj}.C^F\right) + \sum_{j=1}^{NM} C^F.Q_j^F. \sum_{t=1}^{TC} RT_{tj} \tag{1}$$

$$D_{tj} = RT_{tj}.AV_j, \forall t, j, \tag{2}$$

$$KM_{tjn} = \sum_{i=1}^{i \leq t} D_{ij}, \forall t, j, n, \tag{3}$$

$$KM_{tjn} - n.KS_j \geq \left(Y_{jtn}^F - 1\right).M, \forall t, j, n, \tag{4}$$

$$KM_{tjn} - n.KS_j < Y_{jtn}^F.M, \forall t, j, n, \tag{5}$$

$$KM_{tjn}.Y_{jtn}^F - KM_{t-1,j,n}.Y_{j,t-1,n}^F - KS_j \geq \left(X_{jtn}^F - 1\right).M, \forall t > 1, j, n, \tag{6}$$

$$KM_{tjn}.Y^{F}_{jtn} - KM_{t-1,j,n}.Y^{F}_{j,t-1,n} - KS_j < X^{F}_{jtn}.M, \forall t > 1, j, n, \tag{7}$$

$$\sum_{l=1}^{3} NX^{E}_{jtl} = RT_{tj}, \forall t, j, \tag{8}$$

$$NX^{E}_{jtl} \leq 3, \forall t, j, l, \tag{9}$$

$$NS_j = \sum_{t=1}^{TC} \sum_{n=1}^{NS_j} X^{F}_{jtn}, \forall j, \tag{10}$$

$$X^{F}_{jtn} \; and \; Y^{F}_{jtn} \in \{0, 1\}, \forall t, j, n, \tag{11}$$

$$NX^{E}_{jtl} \geq 0, \forall t, j, l, \tag{12}$$

$$NS_j \geq 0, \; integer, \forall j. \tag{13}$$

Eq. (1) estimates the total value of the proposed model's objective function. In the first part of the objective function, the total electricity consumption cost of the corresponding project has been calculated. In this section, using the variable NX^{E}_{jtl}, the daily duration and interval of using jth electric machine are determined in such a way to optimize the total electricity consumption cost of the project. However, in the second part of the objective function, the total maintenance and repair cost of the machinery has been calculated for the whole project. In this section, the variable denotes the X^{F}_{jtn} best time to service the jth fossil fuel type machine. Failure to provide timely service will both increase the energy consumption and the project cost and may delay the project. The total cost associated with the fossil fuel consumption by the relevant machines in the whole project has been also calculated in the third part of the objective function. The sum of the last two sections estimates the total cost of the fossil fuel machinery. Eq. (2) determines the amount of distance traveled by each machine per day (km) with respect to the duration of operation and speed. The cumulative amount of distance traveled by each machine from the beginning of the project to different days is given by Eq. (3). Besides, constraints (4) and (5) are given in order to define the variable Y^{F}_{jtn}. In these constraints, the variable Y^{F}_{jtn} becomes 1 when the cumulative distance traveled by the jth machine in the nth iteration is greater than n.KS_j, and otherwise 0. Constraints (6) and (7) calculate the kilometer number difference between two consecutive service times of each machine to determine the appropriate service day according to the values of the binary variables Y^{F}_{jtn} and X^{F}_{jtn}. Further to these, constraint (8) ensures that the sum of NX^{E}_{jtl} values associated with different intervals in a day for a machine does not exceed its working hours in the same day. Constraint (9) also ensures that the duration of using the jth electric machine during the lth interval on the tth day does not exceed the time of each consumption interval (3 hours). Moreover, constraint (10) calculates the number of service (maintenance and repair) times of the jth machine. Finally, constraints (11)-(13) describe the binary, non-negative and non-negative integer variables of the proposed model, respectively.

4. COMPUTATIONAL RESULTS

In this section, various examples are presented and solved in order to better understand the behavior of the proposed problem. The examples vary based on the numbers of project days, machines, electric and fossil fuel machines. In general, 9 different values have been considered for the number of project days and for each case, a different number of machines, electric and fossil fuel machines are considered. In all cases, it is assumed that the number of electric machines is greater than or equal to that of the fossil fuel counterparts. The values of the parameters associated with the sample problems have been randomly selected from the certain intervals. Table 2 presents the intervals corresponding to each of the parameters AV_j, Q^{E}_{j}, Q^{F}_{j}, FC_j, KS_j and RT_{tj} . The fuel consumption increasing coefficient is considered to be 0.1 for all fossil fuel machines. Also, the values of the parameters C^{F} and M are considered to be 600 and 1000000, respectively. All problems are resolved on a PC with an Intel Pentium (R) Dual Core 2.27 GHz processor and 4 GB of RAM. The proposed model has been coded in LINGO 9 optimization software and solved using Global solver. It should be noted that the results for each problem are reported with two decimal places.

Table 2. Intervals associated with the parameters KS_j,AV_j,RT_{tj},Q^{E}_{j}, Q^{F}_{j} and FC_j

Index value	*l=1*	*l=2*	*l=3*
Description	Low-load interval	High-load interval	Medium-load interval
Time interval	8-11	11-14	14-17

Table 3 lists the results for these sample problems. In the columns of this table, in addition to the amount of the objective function, the total cost values of each part of the objective function (total costs of the electric machines, servicing operations and fossil fuel machines) are also reported. The zero values in the column associated with the total servicing cost indicate that for the corresponding samples, the kilometer number required for servicing has not been obtained due to the short completion time of the project and therefore there is no need to service the machines in these sample problems. In the last column, the CPU times required to achieve the optimal solution via LINGO optimization software are reported in seconds. Also, Fig. 2 displays the curves related to each of the costs. As shown in Table 3 and Fig. 2, for each project completion time, the amount of each cost and consequently objective function value increase as the number of machines increases. It can also be observed in Fig. 2 (b) that the amount of service costs is zero for samples 1-8. This means that in these examples, the distance traveled by the machines is less than the amount set for servicing, thus there was no need to service these machines.

Fig. 3 illustrates the simultaneous effects of the project completion time and number of machines on the objective function value as a three-dimensional curve. It is observed that the objective function value of the proposed problem increases with an increment in the project completion time and number of machines. This is due to the fact that by increasing these two parameters, in addition to consuming more fossil fuels, the number of service times required for each fossil fuel machine as well as that the electricity consumption intervals selected for each electric machine during the project are increased.

For each sample problem, the contributions of the total costs associated with the electric machines, service and fossil fuel

Table 3. Results obtained for various sample problems.

Number	TC	NM	Number of electrical machines	Number of fossil fuel machines	The total cost			Objective function value	Elapsed time (s)
					electrical machines	Service	fossil fuel machines		
1	5	3	2	1	24080.00	0.00	432000.00	456080.00	1
2		5	3	2	33274.25	0.00	751395.52	784669.77	1
3		7	4	3	44834.71	0.00	1315726.43	1360561.14	2
4	10	4	3	1	74619.84	0.00	1025863.40	1100483.24	3
5		6	4	2	82864.46	0.00	1811631.53	1894495.99	3
6		8	5	3	97136.77	0.00	2257475.28	2354612.05	5
7		10	7	3	123228.93	0.00	2687475.88	2810704.81	11
8	20	4	3	1	134617.27	0.00	1478824.94	1613442.21	4
9		6	4	2	143646.23	401116.91	3332284.84	3877047.98	7
10		8	5	3	156324.82	586222.92	5294950.72	6037498.46	21
11		10	7	3	175671.54	644845.21	5080550.77	5901067.52	27
12	40	4	3	1	251734.29	384287.05	2733955.12	3369976.46	16
13		7	5	2	337661.61	734043.95	6544428.83	7616134.39	24
14		9	6	3	371926.58	896921.06	11513182.59	12782030.23	78
15		10	6	4	319856.87	957817.49	14089786.40	15367460.76	112
16	70	4	2	2	369088.09	1196491.63	8774430.82	10340010.54	73
17		6	4	2	528397.18	1254175.88	13974676.54	15757249.60	145
18		9	6	3	688064.43	1542704.23	21727738.43	23958507.09	279
19		11	7	4	737892.48	1599555.21	26927985.75	29265433.44	366
20	100	4	3	1	584023.55	1026046.43	6892743.48	8502813.46	567
21		7	4	3	697484.28	2425702.92	27124080.69	30247267.89	642
22		10	6	4	1038977.29	2653154.45	38061823.83	41753955.57	727
23		12	8	4	1244651.08	2882662.49	40350023.77	44477337.33	809
24	150	4	3	1	940277.92	1754539.39	11692176.28	14386993.59	739
25		7	4	3	962528.31	4390522.28	43838556.43	49191607.02	781
26		10	6	4	1329890.93	3767479.32	55764286.71	60861656.96	844
27		12	8	4	1929209.17	4756393.10	54005138.59	60690740.86	983
28	200	5	3	2	1363402.98	2568982.14	32272263.46	36204648.58	867
29		10	6	4	2141124.40	4855272.65	74727492.58	81723889.63	1137
30		14	8	6	2488679.83	6693814.47	108090674.44	117273168.74	1583
31	250	5	3	2	1867862.08	2907949.82	41839252.16	46615064.06	1288
32		10	6	4	2526537.79	5729221.72	90164278.36	98420037.87	1761
33		14	8	6	3509038.56	7497072.21	138319873.08	149325983.85	2647

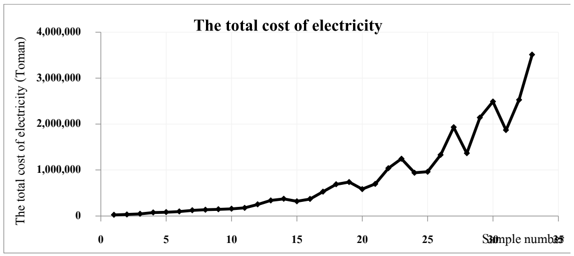
machines to the objective function of the proposed problem are depicted in Fig. 4 in percentage. It can be seen that the consumption cost of the fossil fuels machines accounts for a significant portion of the objective function value in all samples. Also, the contribution of service costs is more than that of the electric machines.

In Fig. 5, the impacts of number of electrical and fossil fuel machines on their corresponding costs in the proposed problem are shown, separately. In Fig. 5 (a), it can be seen that when a project with a certain completion time occurs, depending on number of electrical machines, the cost of electrical machines will be different and by growing their number, the differences between the values of the cost of electrical machines for different numbers increase. This is due to the fact that when the number of electrical machines change, the number of electricity consumption intervals involved will also change. So, the values of the cost of electrical machines also change. Similarly, in Fig. 5 (b), it can be seen that depending on number of fossil fuel machines, the sum of service costs and fossil fuel machines costs will be different and by growing their number, the differences between the sum of these costs for different numbers increase. This is due to the fact that when the number of fossil fuel machines change, the amount of fossil fuel consumed and the number of service times needed for the fossil fuel machines also change.

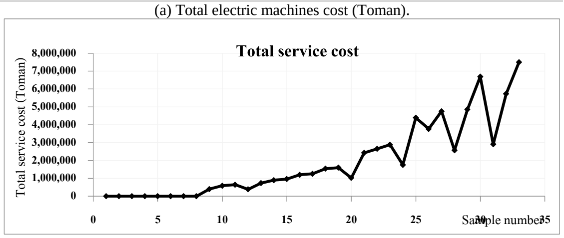
Fig. 6 shows the CPU times required to achieve the optimal solution by LINGO optimization software for each of the sample problems. The results indicate that the solution time increases with increasing the problem size. This is due to the fact that by increasing the values of each of the problem parameters, the number of service times required for each fossil machine and also the number of intervals selected for the electrical energy consumption of each electric machine during the project increase. Therefore, the problem becomes more complex and the number of computational attempts to find the optimal solution is increased. It can be seen from this Fig. 6 that the problem solving time significantly increases for samples larger than 28.

Here, in order to better understand the behavior of the proposed problem and to validate it, a sample problem is presented and described as well. The proposed sample problem includes a project with 120 working days and 8 machines (5 electric and 3 fossil machines). In order to simplify the sample problem, the working hours of the machines are considered to be the same in 14-day intervals. Therefore, the results obtained from solving the proposed model are also displayed in 14-day intervals to avoid content redundancy. Tables 4-6 lists the values of the problem parameters.

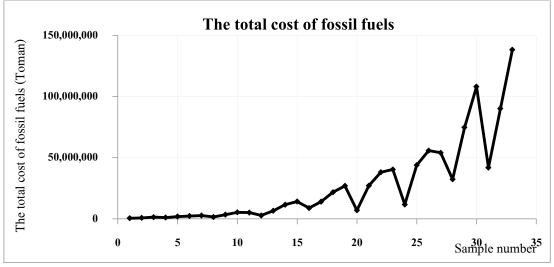
Solving the sample problem using LINGO optimization software, the total cost values associated with the electric machines,



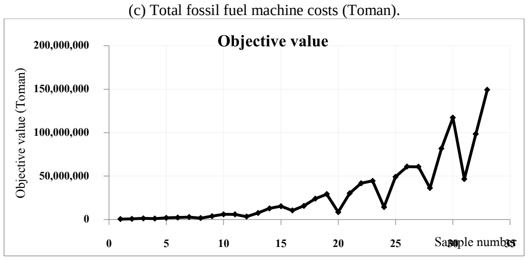
(a) Total electric machines cost (Toman).



(b) Total service cost (Toman).



(c) Total fossil fuel machine costs (Toman).



(d) Total cost of the proposed problem (Toman).

Fig. 2. The total cost associated with each part of the objective function in the sample problems.

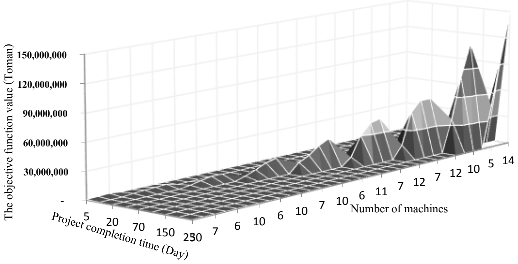


Fig. 3. The three-dimensional representation of the simultaneous effects of project completion time and number of machines on the objective function value.

servicing and fossil fuel machines and finally the amount of objective function have been achieved as 932180, 2767440, 39326400 and 43026000, respectively. Table 7 reports the selected intervals for the daily use of electric machines and duration of using each machine in each interval along with the number of required service times and selected days for servicing the fossil fuels machinery. It is observed that during 120 days, fossil machines 6, 7 and 8 need to be serviced once on the 79th day, three times on the 33rd, 66th and 99th days and once on the 67th day, respectively. The reason for these differences is the average speed of the machines, time required for each machine per day and kilometer number corresponding to each machine servicing. Fig.

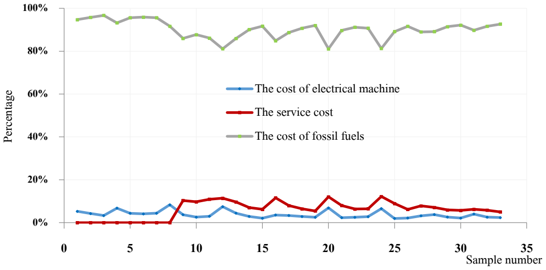
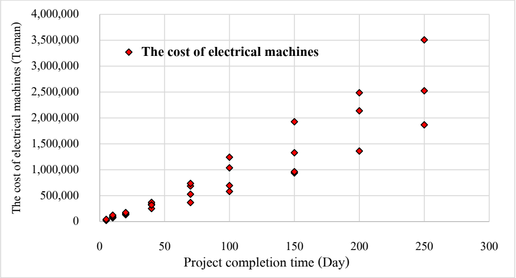
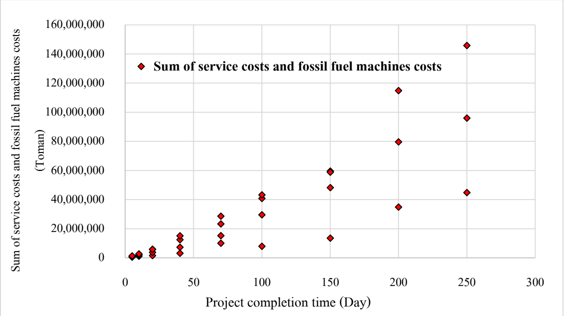


Fig. 4. The contributions of the total electric machine, service and fossil fuels machine costs to the objective function of the proposed problem.



(a) The impact of number of electrical machines on the cost of electrical machines.



(b) The impact of number fossil fuel machines on the sum of service costs and fossil fuel machines costs.

Fig. 5. The impact of number of electrical and fossil fuel machines on their corresponding costs.

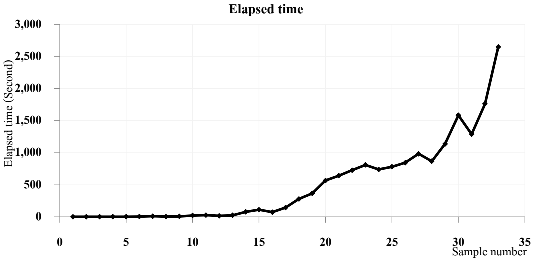


Fig. 6. Time elapsed to solve each of the sample problems using LINGO optimization software.

Table 4. The values of the parameters AV_j, ^E_j, Q^F_j, FC_j and KS_j

	j1	2	3	4	5	6	7	8
Parameter								
AV_j (km/hour)	0	0	0	0	0	20	40	30
Q^E_j (kw/hour)	4	10	6	8	5	0	0	0
Q^F_j (lit/hour)	0	0	0	0	0	26	30	16
FC_j	0	0	0	0	0	400000	600000	500000
KS_j (km)	0	0	0	0	0	12000	10000	15000

Table 5. The values of C^E_l

l	1	2	3
Parameter			
C^E_l	40	80	60

Table 6. The values of RTtj (hour)

j	1	2	3	4	5	6	7	8
t								
1	5	3	3	1	7	9	9	9
2	7	5	8	2	7	9	9	9
3	2	4	6	3	6	9	9	9
4	9	2	2	9	3	9	9	9
5	8	7	9	4	1	9	9	9
6	5	8	7	6	9	9	9	9
7	0	0	0	0	0	0	0	0
8	8	6	4	7	7	9	9	9
9	3	5	4	8	3	9	9	9
10	4	2	3	8	2	9	9	9
11	7	8	6	5	9	8	7	5
12	5	5	5	5	5	9	9	9
13	7	8	4	6	3	9	9	9
14	0	0	0	0	0	0	0	0

7 illustrates the service day and time for each fossil fuel machine graphically.

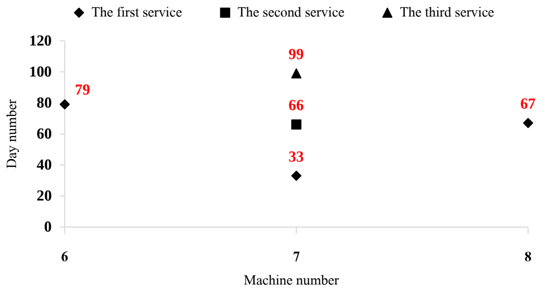


Fig. 7. Graphical representation of the service day and time for the fossil fuel machines in the sample problem.

In the following, for further analysis of the proposed model behavior, the sensitivity of the model to changing some parameters of the problem is investigated. Here, the effect of changes in project completion time on the value of the objective function and the solution time of the mathematical model and also, the effect of changes and KSj on the value of the objective function of the sample problem are investigated. Fig. 8 shows the results for each of these scenarios. Fig. 8 (a) shows that, as expected, by increasing the project completion time, the number of intervals selected for the daily use of electric machines, number of service times required for the fossil fuel machinery and consequently the amount of objective function will be increased. Also, as shown in the Fig. 8 , although the curve slope is mostly constant, a sudden increase is observable in the slope at some points. This is due to the costs associated with the service operations performed at that time period. The effect of project completion time on the solving time of the sample problem using LINGO optimization software is investigated in Fig. 8 (b). The results indicate that the model solving time increases logarithmically with an increment in the project completion time. It can also be seen that in the studied problem, for times longer than 50 days, the solution time of the proposed model is significantly increased.

To show the effect of changes in the parameter in the sample problem, different values from 0 to 1 are tested and the values of the objective function obtained are shown in Fig. 8 (c). As can be seen, although the objective function value increases with an increment in , the difference between these values corresponding to the minimum and maximum values of this parameter is about 600000. In Fig. 8 (d), the sensitivity of the studied problem to the parameter KS_j is investigated. For this purpose, the effect of changes km of this parameter on the value of the objective function is investigated. The results show that by increasing the number of service kilometers, the value of the objective function decreases and also with decreasing the number, this value increases. This is due to the fact that by reducing the value of this parameter, the number of times required for service and consequently the total service cost is increased.

5. CONCLUSIONS AND SUGGESTION FOR FUTURE RESEARCHES

In this study, the electrical energy and fossil fuels consumption managements were simultaneously considered in the construction projects. The aim was to provide an optimal schedule for the electrical energy consumption of the electric machines (in what period of time and for how long a day each machine can be used), to determine the optimal number of periodic services for the machines with fossil fuels consumption as well as the optimal service times so that the objective function value is minimized. For this reason, a linear mathematical programming model was formulated in which all costs corresponding to the electricity consumption, service costs and fossil fuel consumption costs were considered throughout the project. In the proposed model, different intervals were considered for the electrical energy consumption and the effects of the average speed of each fossil fuel machine and the time required to these machines in each day were applied in the decision making process. To solve the proposed mathematical model, LINGO optimization software with Global solver was employed. For a better understanding of the behavior of the proposed problem, several sample problems with different sizes were examined. The obtained results showed that the objective function value of the proposed problem increases with an increment in the project completion time and number of machines. This is due to the fact that by increasing these two parameters, in addition to consuming more fossil fuels, the number of service times required for each fossil

Table 7. The values of RTtj (hour).

	NX^E_{jtl}															X^F_{jtn}		
Machine	1			2			3			4			5			6	7	8
Consumption Interval Day	l=1	l=2	l=3	l=1	l=2	l=3	l=1	l=2	l=3	l=1	l=2	l=3	l=1	l=2	l=3			
1	3	1	3	0	0	1	0	0	3	0	0	3	2	0	3			
2	3	1	3	0	0	2	3	2	3	2	0	3	3	1	3			
3	3	0	3	0	0	3	3	0	3	1	0	3	0	0	2			
4	0	0	3	3	3	3	0	0	2	0	0	2	3	3	3			
5	0	0	1	1	0	3	3	3	3	3	1	3	3	2	3			
6	3	3	3	3	0	3	3	1	3	3	2	3	2	0	3			
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
8	3	1	3	3	1	3	1	0	3	3	0	3	3	2	3			
9	0	0	3	3	2	3	1	0	3	2	0	3	0	0	3			
10	0	0	2	3	2	3	0	0	3	0	0	2	1	0	3			
11	3	3	3	2	0	3	3	0	3	3	2	3	3	1	3			
12	2	0	3	2	0	3	2	0	3	2	0	3	2	0	3			
13	0	0	3	3	0	3	1	0	3	3	2	3	3	1	3			
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
The number of servings required																1	3	1
Selected day for service																79	33 66 99	67

fuel machine as well as that the electricity consumption intervals selected for each electric machine during the project were increased. Also, the results of the investigations showed that the consumption cost of the fossil fuels machines accounts for a significant portion of the objective function value in all samples. Also, the contribution of service costs is more than that of the electric machines. In terms of solution time, the results indicated that by increasing the problem size, it becomes more complex and the number of computational attempts to find the optimal solution is increased. Therefore, the solution time of the proposed model will be increased significantly. In the following, a sample problem was studied in detail and its sensitivity to some of the problem parameters were investigated as well. The results of sensitivity analysis showed that by increasing the project completion time, the number of intervals selected for the daily use of electric machines, number of service times required for the fossil fuel machinery and consequently the amount of objective function were increased. Also, the model solving time increased logarithmically with an increment in the project completion time. The obtained results indicated that the proposed model is capable to minimize the energy consumption costs in the construction projects by providing an optimal planning for the electric and fossil fuel machines.

In the future, the proposed model can be applied in any construction project that deals with fossil and electrical machines. Using this model, an optimal schedule for the electrical energy consumption of electric machines can be determined (at what time period and for how long to use it each day). Also, the optimal number of periodic services for the machines with fossil fuels and optimal service time can be determined. As the limitations of the proposed model, we can mention three main limitations: (1) by increasing the amount of problem parameters such as the number of machines and the project completion time, optimal solution of the proposed model with LINGO is not possible, (2) the proposed model can only be solved for motionless electrical machines and (3) the proposed model uses fossil fuel machines only for transportation. Since solving the proposed mathematical model is time consuming for very large problems, the introduction of heuristic or metaheuristic algorithms to solve these problems seems to be useful for future relevant researches.

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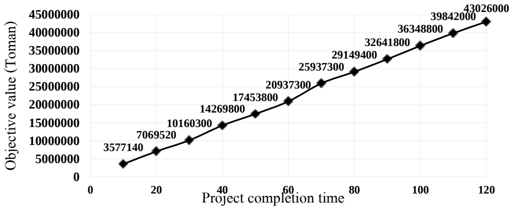
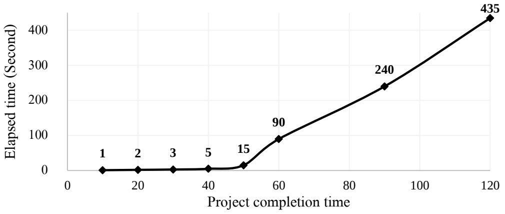
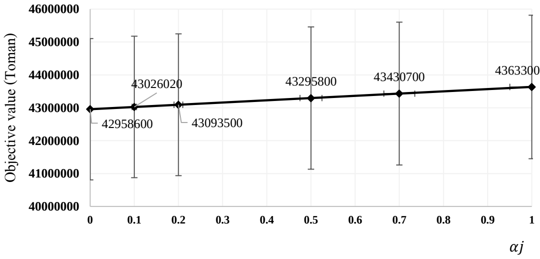


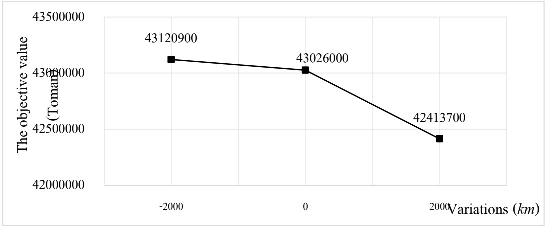
(a) Sensitivity of the objective value to variations of the project completion time.



(b) Sensitivity of the problem solving time to variations of the project completion time.



(c) Sensitivity of the objective value to variations of α_j .



(d) Sensitivity of the objective value to variations of KS_j.

Fig. 8. Sensitivity of the model to some parameters of the problem.

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