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Multi-objective Optimization for a Complex Intersection Using Design of Experiments and Simulation

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ABSTRACT

Considering the importance of time in today's world and the rising traffic congestion in urban areas, using methods to reduce wait times and air pollution can have a significant impact on promoting urban management. Given the uncertainty in the number of vehicles and the emission rate of vehicles, a complex T intersection with three traffic lights was simulated in this study. Three objective functions were defined for the mean of wait time, average queue length, and aggregate pollutant emission of the vehicles in queue. First, regression equations for each of the variables were obtained by a full factorial design and analysis of variance, and the optimal period for each traffic light was then computed with a utility function approach. Finally, the results were compared to the results obtained from the optimization of each response variable OptQuest for Arena software.

1. INTRODUCTION

In the twentieth century, a large number of vehicles and population increase has led to a decrease in the effectiveness of urban passageways. The improvement of transport networks is largely limited by the boundary of the existing networks [1]. Nowadays, cities have to deal with traffic congestion caused by an increase in the number of vehicles and the need for transportation [2]. Solving problems such as traffic congestion, air pollution, and fuel waste, which are caused by traffic, are of great importance [3]. Fuel consumption is also a significant parameter; for example, in the United States drivers spend 40 hours per year stuck in traffic. The cost of the fuel that is used in these 40 hours is about 87 billion dollars per year [4]. Pollution is also one of the permanent problems in today's world [5]. A study has been conducted on bus drivers to detect the probable damages to DNA. Traffic congestion has adverse effects on human health, especially in big cities [6]. In industrialized countries, and especially in major cities, air pollution is one of the factors that affect the population and is associated with many diseases such as cancer [7, 8]. Another issue is the time people waste in traffic. An origin and destination study were conducted to investigate this wasted time [9]. Simulation is one of the most common methods for analyzing and solving problems in a complex transport network [10]. Bieker et al. [11] presented a scenario for Bologna's traffic that could be used as a source for more research. The semantic language of the Web is studied as well [12]. The amount of deviation from molecules' mechanical force is also examined to simulate the structure [13]. Five software programs were used to evaluate the simulation of several models [14]. A multi-agent simulation environment that could be generalized for Java programming is presented [15]. Balci [16] presented a large-scale model to determine the quality of the application of modeling and simulation. Simulation is also of importance in health and medicine. Simulating a Glucose-insulin system, which was

done by Dalla et al. [17], can greatly help diabetic patients. Analysis of different approaches and evaluation of their effects in a clear and comprehensible way is also possible through simulation. Selecting the right software is an important issue as well. Among various software programs, a great number of researchers have used Arena; for instance, this software was used to simulate the design and analysis of a coastal town [18]. Bush et al. presented a technique that utilizes both optimization and simulation [19]. An automated driving system for vehicles is simulated with regard to JIT philosophy by Kesen et al. [20]. Arena Software is used for reliability and simulation in health systems [21]. One of the most common uses of Arena is in modeling different types of transportation. Almaz et al. have provided a model for Vessel Traffic [22]. The simulation of the transportation of cargo in Sevia, a port city, is also noteworthy [23]. Arena has been used for the simulation of the Newcastle railway network and to show the efficiency of railways [24]. Through simulation modeling in Arena, the amount of use of various parts of the railway was computed [25]. Due to time change, fuzziness, and non-linearity, artificial intelligence is used in traffic control [26]. D'Ambrogio et al. have presented a method to help designers simulate traffic systems [27]. The traffic flow in a T-shaped intersection is simulated using Monte Carlo techniques [28]. Arena software is also used to simulate a T-shaped intersection [10], the intersection is then studied in two different situations: with and without traffic lights. The results were encouraging; thus, Arena can be used as a tool to model various transportation issues and find a solution for the problems. Arena is used to model a traffic signal system [29]. As mentioned before, simulation is done to model many types of traffic and analyze the solutions. Since Arena is easily available for researchers, the present study has selected this software for simulation. The comprehensiveness of Arena also lends to its use for purposes other than production, which was another reason that we decided to use this software.

The literature review reveals that most articles only study

queues at intersections and are not concerned with issues such as pollution. They also merely use mathematical models and as a result, uncertainty factors are investigated less. Therefore, the present study attempts to use these two methods simultaneously. Thus, parameters such as entry rate for each of intersection entrances and the amount of emission per vehicle are regarded as probable variables. The amount of emission for various vehicle types is also separately considered. Figure 1 shows a schematic abstract of the problem.

In this study, we have simulated a T-shaped intersection in the city of Bojnourd, using Arena software. Intersections are one of the most common areas in which traffic congestion happens. As mentioned, many solutions to reduce traffic at crossroads and intersections have been proposed, but simulation and the analysis of simulated conditions can provide very useful information with minimal cost and trial and error. These two features of simulation distinguish it and make it very important in transportation issues, as these issues are quite complex and costly. The simulation gives us a systematic view, which can help provide new solutions.

This paper is organized as follows. We present a description of the Proposed Approach, Selected methods, and evaluation metrics used to compare the algorithms in Section 2. Section 3 presents three mathematical models. Section 4 concludes the simulation model and results. Section 4 presents the design of experiment (DOE) and regression Equations for optimization. Section 6 concludes the Optimization approach for desirability function as well as discussing the advantages and

disadvantages of the selected methods. The main contribution is the optimization of three objectives function average wait time, the average number of vehicles in the queue, and total Pollutant emission simultaneous by using experiment design and simulation-based on desirability functions.

Figure 1. Schematic abstract

2. THE PROPOSED APPROACH

The present study attempts to provide an optimal approach for finding the best time intervals for traffic lights. As all events in an intersection have probable times and uncertainty, using a mathematical model is difficult, as a result, we have used a simulation to investigate the contributing factors. A complex intersection with a 3-phase traffic light was selected for simulation.
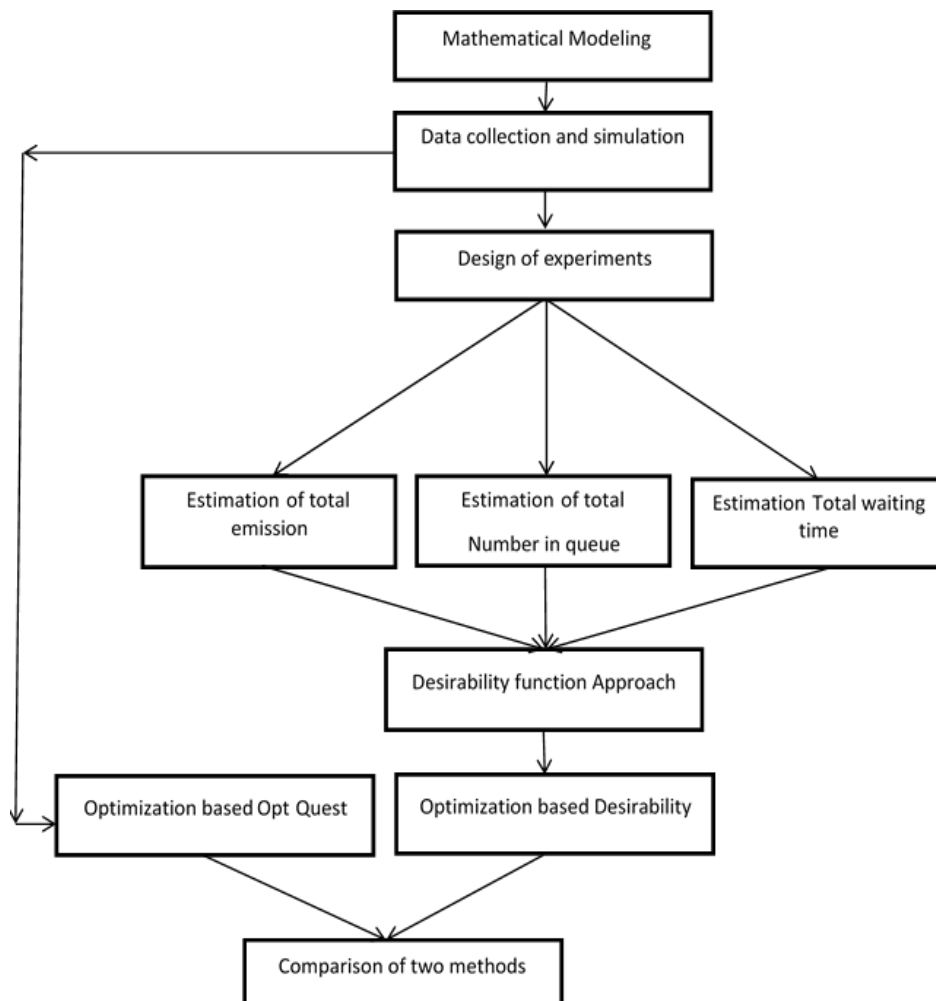

Figure 2. The proposed approach

Given that all the events that happened at an intersection are uncertain in terms of time, using a mathematical model is rather difficult. Hence, a simulation model is used for different factors. In this study, a complex intersection with three-phase traffic lights is simulated. As shown in Figure 2, first we defined a mathematical model for the objective functions. Because of the probability of parameters, the simulation was used. The central points of the response variables were studied by the use of a two-stage full factorial design, and for each of the objective functions, a mathematical regression model was provided. Next, a desirability function was used to find the optimal response for each of the three response variables. Ultimately, the obtained responses were used as initial responses to optimize each of the objective functions in OptQuest software and the results were analyzed.

OptQuest is a generic optimizer in ARENA software that makes it possible to separate successfully the optimization solution procedure from the simulation model. This design adaptation of meta-heuristic methods lets you create a model of your system that includes as many elements as necessary to represent the "real thing" accurately. While the simulation model can change and evolve to incorporate additional elements, the optimization routines remain the same. Hence, there is a complete separation of the model that represents the system and the procedure that solves optimization problems defined within this model, which provides maximum efficiency in identifying new scenarios. the advantages of OptQuest are Efficient, Intelligent, Flexible, and Aggressive.

3. MATHEMATICAL MODEL AND OBJECTIVE FUNCTIONS

To optimize the model, a mathematical model is presented.

This model has three objective functions. The first objective is to minimize the average wait time. Minimizing the average number of vehicles in the queue is also very important. Pollutant emission is also the third objective in this model.

$$TWT = MWTa_1 + MWTa_2 + MWTb_1 + MWTb_2 + MWTb_3 + MWTc_2 + MWTc_3 \quad (1)$$

$$TNQ = MNQa_1 + MNQa_2 + MNQb_1 + MNQb_2 + MNQb_3 + MNQc_2 + MNQc_3 \quad (2)$$

$$TE = Ea_1 + Ea_2 + Eb_1 + Eb_2 + Eb_3 + Ec_2 + Ec_3 \quad (3)$$

$$Ea_1 = \sum_{i=1}^{n_a} r_i wt_i \quad (4)$$

Eq. (1) shows the mean of wait time for all intersections, which is obtained from the sum of all means of wait times in different lines. Eq. (2) shows the mean the number of cars waiting in the queue, which is the sum of means in different lines. Eq. (3) shows the total amount of emissions created by vehicles. Eq. (4) shows the aggregate pollutant emission of the vehicles in the queue, which is the sum of emissions by each vehicle. The amount of emission of each vehicle is obtained by multiplying the vehicle wait time by its emission rate. To obtain the amount of emission of each vehicle, we used the Euro 4 standard, which is the standard currently used in Iran. Table 1 shows the amount of emission for each vehicle per minute in four main categories based on European emission standards [30].

Table 1. Emission rate by Euro 4 Standard

Row	Date	CO	NOx	HC+NOx	PM	g/Km	g/min
Category 1	Jan-05	0.5	0.25	0.3	0.03	1.43	1.075
Category 2	Jan-05	0.5	0.25	0.3	0.03	1.43	1.075
Category 3	Jan-06	0.63	0.33	0.39	0.04	1.85	1.39
Category 4	Jan-06	0.74	0.39	0.46	0.06	2.20	1.65

4. SIMULATION

The following set of hypotheses were considered in our simulation.
1. No accident or breakdowns results in a stop.
2. The cars that are going towards the exits will not get in any queues.
3. The cars in the queue of the last line of C will only move into B, and the car in the queue of the middle line of C will only move into A (those who want to follow a straight line in C will move on through the first line of C, without getting into any queues).
4. If the cars wait more than 90 seconds, 90% of the drivers will turn their cars off to reduce emissions.
5. The four types of vehicles entering the intersection are in accordance with the Euro standard.

Figure 3 shows a schematic plan of the intersection. Based on the above-mentioned explanations and a real model, the present study presents a simulation model generated by Arena software, as shown in Figure 4. Each of the modules used in
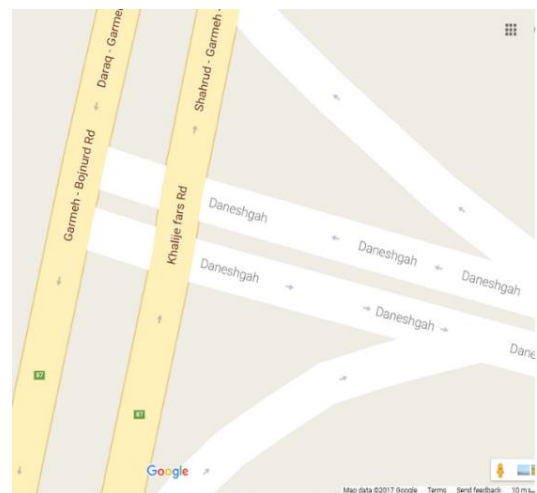
the model is discussed as follows.

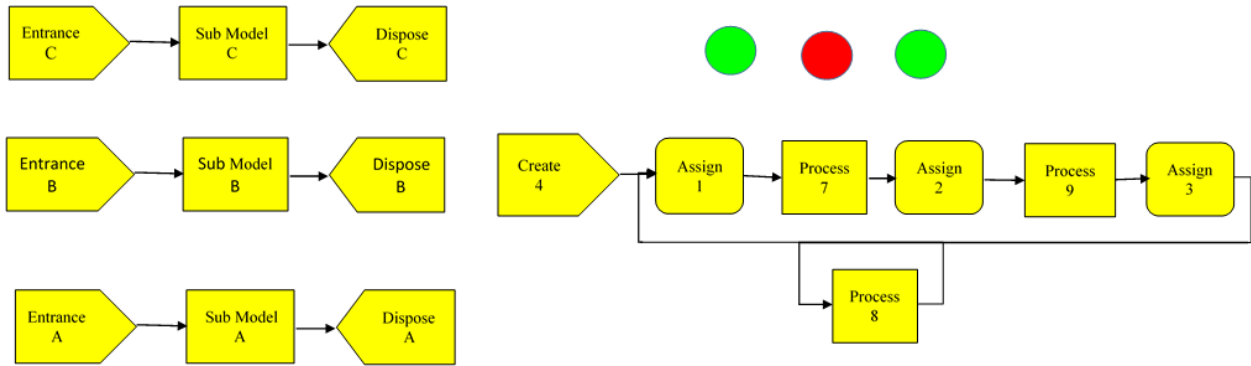**Figure 3.** Schematic of the simulated location

Figure 4. Simulated model

Figure 4 shows the model which is simulated for the intersection. It consists of four main parts: three of which (A, B, and C) are the main intersection entrances and the other one is the time length of each traffic light. Each one of the entrance simulation models has a sub-model that Appendix1 shows it.

4.1 Warm-up

Considering that the results of a simulation cannot be used until the model reaches a stable state, obtaining the WU time is very important. As such, a graph (Figure 5) is used to show the approximate time of reaching a stable state. The horizontal index presents the time and the vertical index, the mean the number of vehicles in queue. As shown, the stable state happens after about 40 minutes. This period is considered as WU.
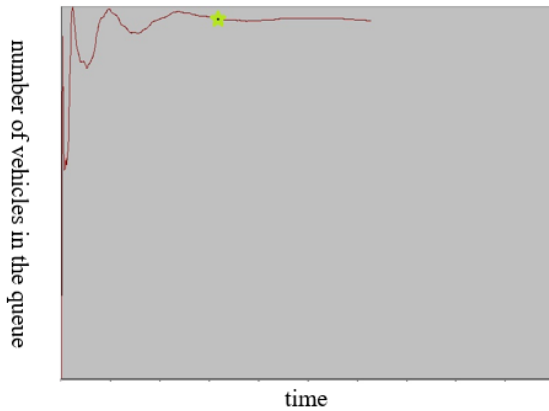

Figure 5. Warm up period

5. EXPERIMENTS DESIGN

The main purpose of the design of experiment (DOE) is to obtain the maximum amount of data with a minimum number of experiments

5.1 Obtaining high and low levels

To obtain the high and low levels for each decision, Opt Quest software was used for each decision variable. To this purpose, we assumed that the objective of the whole simulation is to minimize the wait time for each of the decision variables. To minimize the mean, wait time, the decision variable must be at its highest value. The value of -1 was assigned for the low level of each decision variable; thus, -1 is the minimum time required for a vehicle to cross the intersection. The high and low levels for each of the decision variables are shown in Table 2.

Table 2. High and low levels of the variables

	High level	Low level
Time a	260	9
Time b	400	9
Time c	470	9

5.2 Design of experiments

To do the experiments, a full-factorial design was used with 3 decision variables. The experiment was simulated four times for the central points and each of the corners, and the results are shown in Tables 3, 4, and 5.

Table 3. Results of simulations for design of experiments for mean of wait time

time a	time b	time c	Total waiting time(min)			
			Replication1	Replication2	Replication3	Replication4
-1	-1	-1	3.1707	3.1523	3.6739	3.1721
1	-1	-1	1,937.72	1,939.26	1,954.31	1,933.73
-1	1	-1	1,543.39	1,568.49	1,555.31	1,552.42
1	1	-1	859.01	854.68	846.05	855.80
-1	-1	1	1,963.95	1,952.34	1972.21	1,950.94
1	-1	1	1,249.96	1,247.40	1,259.39	1,247.63
-1	1	1	831.14	831.11	826.09	824.11
1	1	1	39.9175	42.7596	48.1784	46.0691
0	0	0	24.0286	30.3630	29.7507	23.3526

Table 4. Results of simulation for design of experiments for mean of number of vehicles in queue

time a	time b	time c	Total number in queue			
			Replication1	Replication2	Replication3	Replication4
-1	-1	-1	9.2097	10.1411	9.4696	10.9055
1	-1	-1	7,967.61	8,131.74	8,082.71	8,007.59
-1	1	-1	5,815.35	5,927.18	5,937.46	5,929.42
1	1	-1	4,387.88	4,432.48	4,464.65	4,477.32
-1	-1	1	5,827.67	5,826.43	5,864.84	5,755.47
1	-1	1	4,324.84	4,387.62	4,313.66	4,492.83
-1	1	1	1,788.16	1,872.16	1,863.22	1,819.59
1	1	1	82.4994	102.42	120.87	134.01
0	0	0	52.5650	106.57	60.9502	71.9519

Table 5. Results of simulation for design of experiments for the aggregate emission

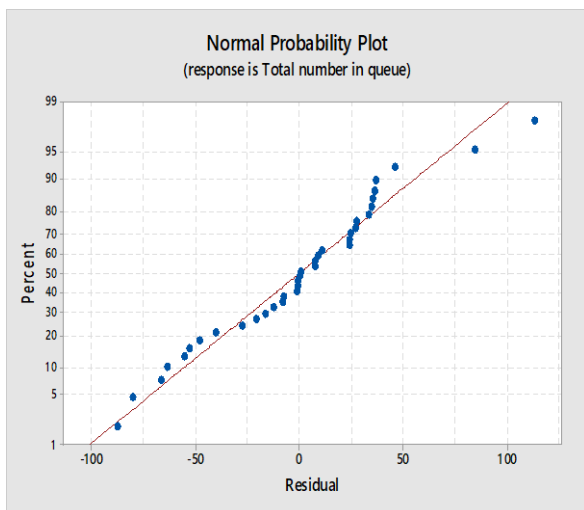| time a	time b	time c	Total emission(gram)			
			Replication1	Replication2	Replication3	Replication4
-1	-1	-1	4,157.83	4,259.82	4,147.35	4,214.76
1	-1	-1	33,341.03	28,182.85	33,295.75	30,727.49
-1	1	-1	20,797.25	16,121.83	20,700.04	14,442.45
1	1	-1	7,790.56	10,790.15	8,074.65	10,927.50
-1	-1	1	17,726.63	17,665.41	17,041.98	18,356.61
1	-1	1	12,518.55	9,301.62	8,411.55	10,190.79
-1	1	1	7,255.96	8,081.18	9,187.53	6,076.61
1	1	1	5,085.93	7,275.59	6,025.86	5,319.77
0	0	0	4,018.05	4,175.02	4,135.41	4,041.14

5.3 Results of design of experiments

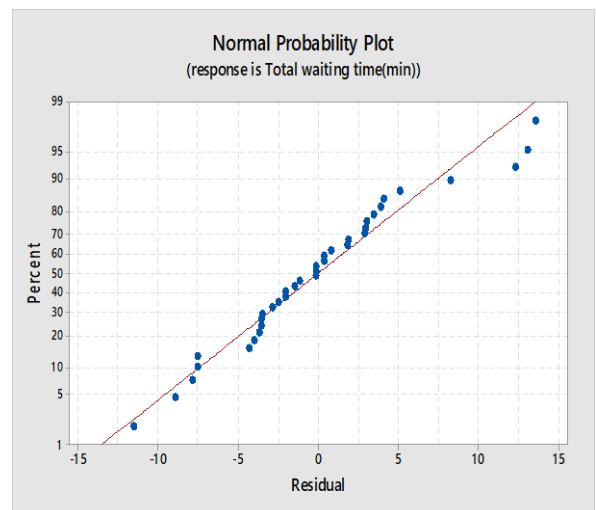To verify the design variables, a two-stage full factorial design with central points is used. Table 6 shows the results of the three objective functions.

Table 6. Analysis of variance total emission total number in queue total waiting time
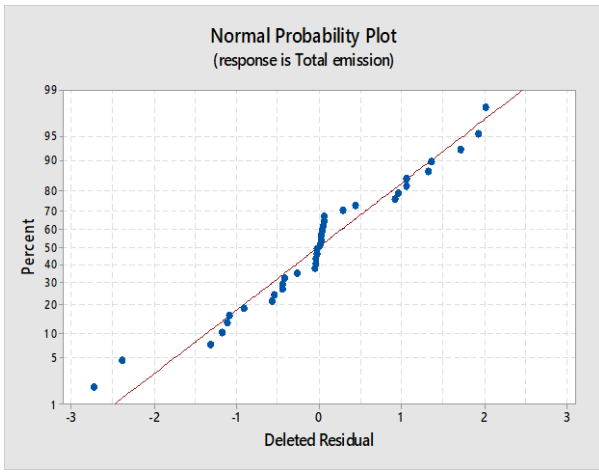
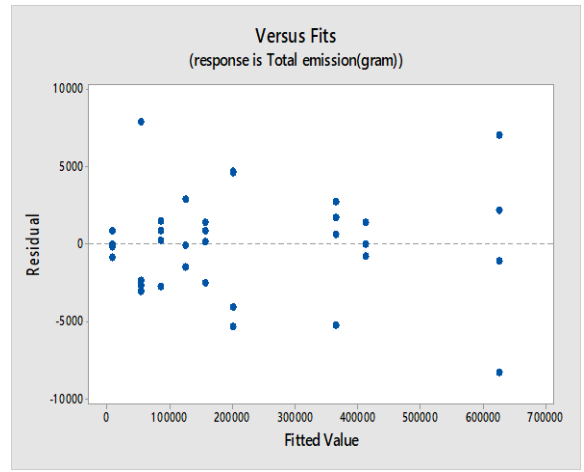|	total emission		Total number in queue		total waiting time	
	Coef	P-Value	Coef	P-Value	Coef	P-Value
Constant	1054.58	0.000	3818.04	0.000	13047	0.000
time a	-31.96	0.000	426.38	0.000	1157	0.001
time b	-234.30	0.000	-745.88	0.000	-2800	0.000
time c	-33.75	0.000	-782.03	0.000	-2702	0.000
time a*time b	-339.26	0.000	-1223.28	0.000	-3743	0.000
time a*time c	-341.20	0.000	-1217.55	0.000	-3486	0.017
time b*time	-350.36	0.000	-1317.27	0.000	-757	0.000
time a*time b*time c	320.48	0.000	1151.54	0.000	5210	0.000

A= total in queue

B= total waiting time

C= total emision

Figure 6. Distribution of errors

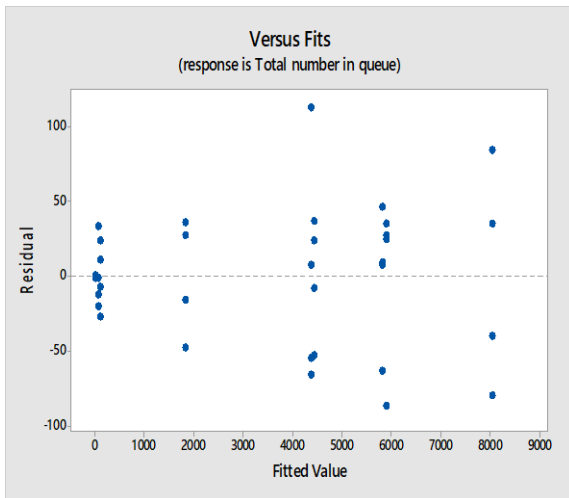C= total emision

Figure 7. Dispersion of errors

5.4 Normality test

The normal graph is drawn for each of the errors (Figure 6). As the images show, the errors are approximately on a straight line in each case. This indicates the normality of errors for any of the response values. Statistical tests could also be used to examine the claims.
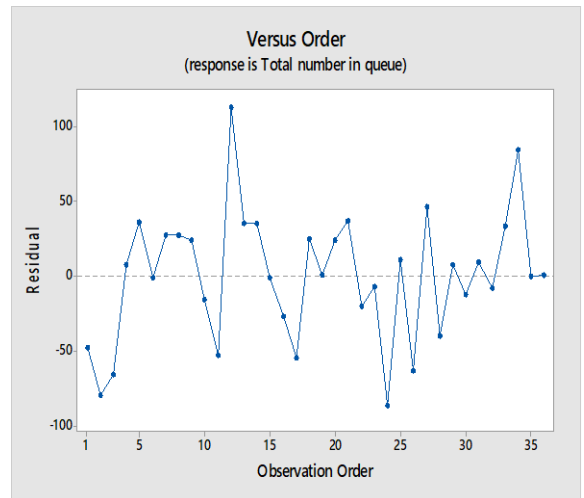
5.5 Dispersion index

Another index to take into account is the equality of distribution of errors for each of the stages. As shown in Figure 7, a slight difference in dispersion levels can only be seen for the emission response. However, these values are not considerable and the distribution in each stage is approximately equal for the other two responses, and there are no outliner data.
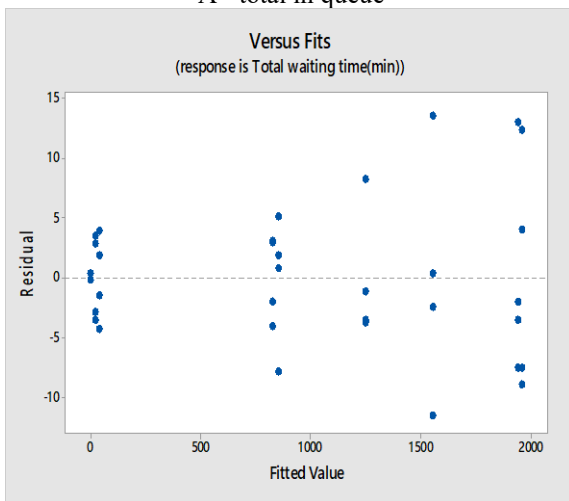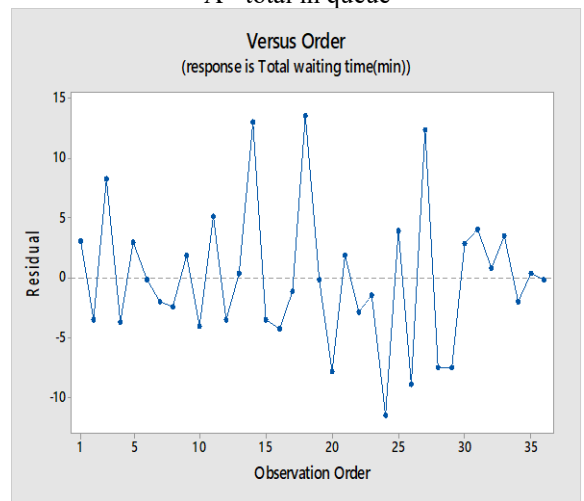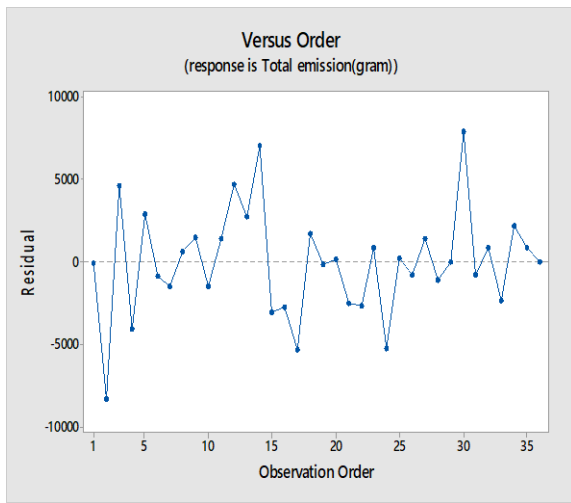
5.6 Correlation

A= total in queue

A= total in queue

B= total waiting time

B= total waiting time

796

C= total emision

Figure 8. Correlation errors for each response variable

Figure 9. Interaction effect of the decision variables on response variable of number of cars in queue

The lack of correlation or any specific relations in the data should also be considered. As shown in Figure 8, the data is distributed randomly, and there is no special correlation for any of the responses.

As each of the response variables has the required features to use the experiment design and regression lines, we can use the obtained results. To investigate the decision variables, a two-stage full factorial design with central points is applied. The results for the three objective functions are shown in Table 6.

5.7 Analyzing the effect of each factor on response variables

Figure 9 shows the main as well as the interaction effect of each factor on the response variable of the number of vehicles in the queue. There is an interaction between each of the three decision variables. Considering the main effect of each factor in minimizing the number of cars in queue, the number of cars in time A should be at a low level, and time B and C, at a high level.

Figure 10 shows the main and interaction effect of each decision variable on the mean of wait time. As seen, interaction is present in all factors in the response. The decision variables A and C have an insignificant effect and the responses in various levels are not much different.
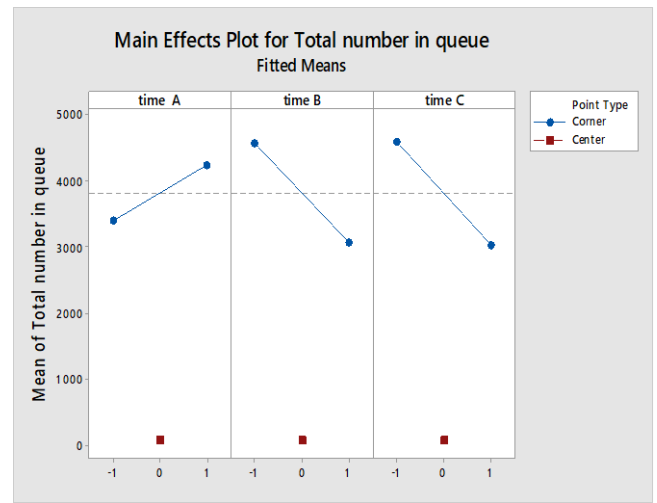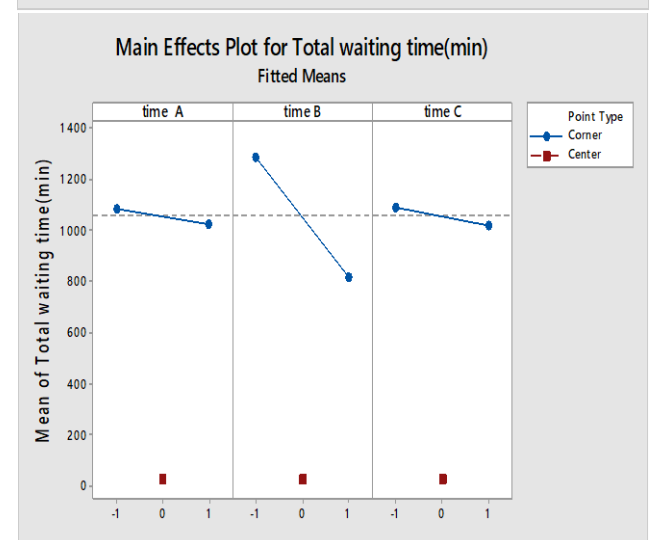

Figure 10. Interaction effect of the decision variables on response variable of mean of time

Figure 11 shows the main and interaction effects of decision variables on the response variable of the amount of emission. As seen, the decision variables A and B, as well as A and C do not have a significant interaction effect.
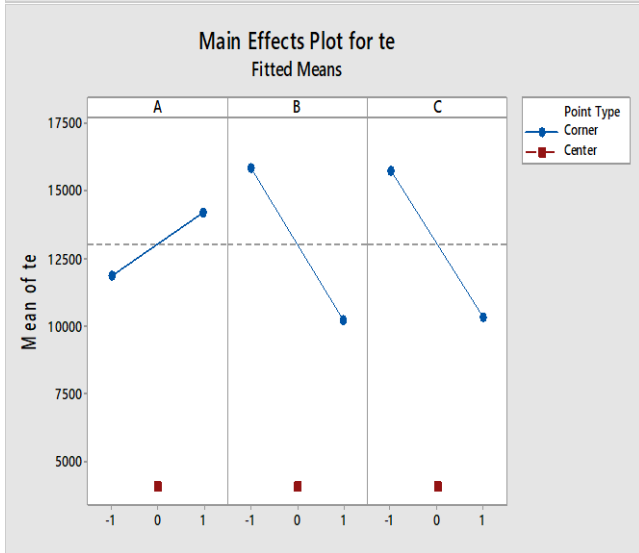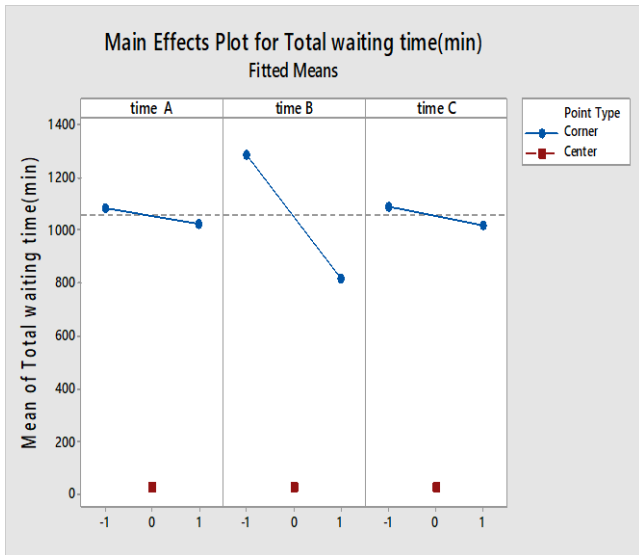
Figure 11. Interaction effect of the decision variables on response variable of total emission
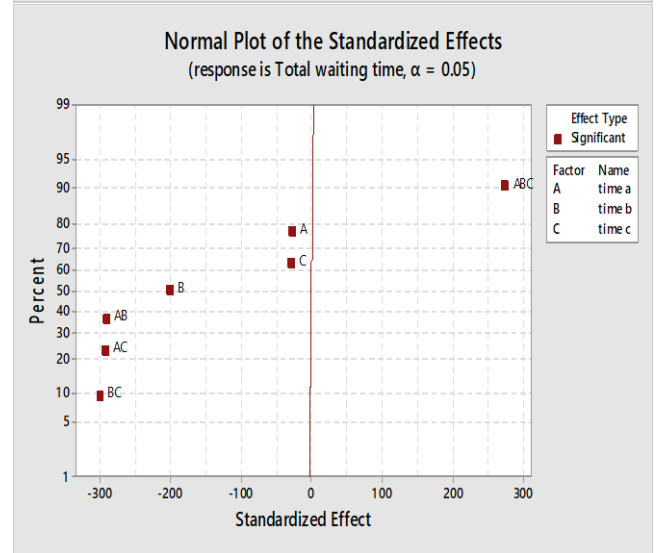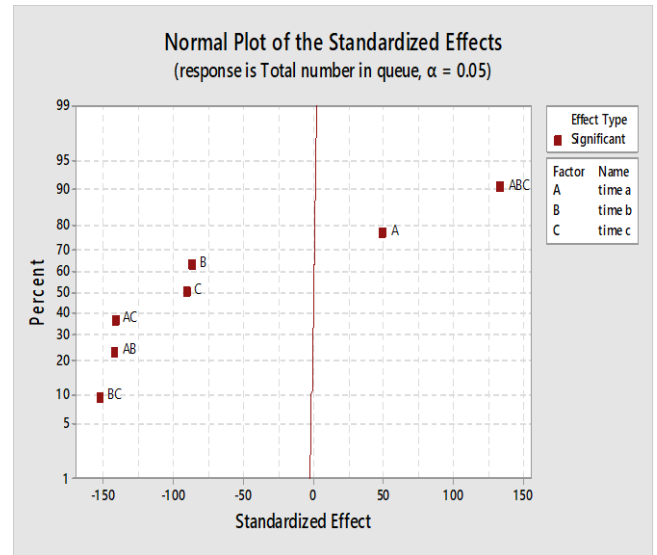
Figure 12. Factors affecting each response variable

Figure 12 shows the factors affecting each of the response variables. All of the decision variables and their interaction effect on each other have a main effect on all of the response variables.
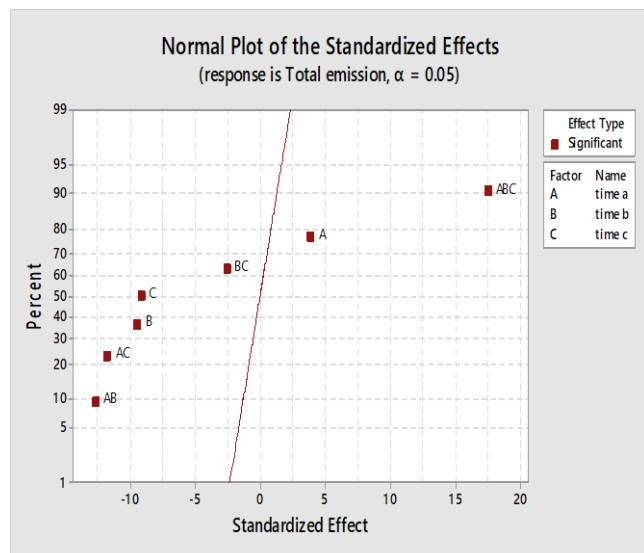
5.8 Regression equations

A regression model is used to predict each of the objective functions. The regression model consists of a first-order regression and the interaction effect between them [31].

A general model for the first-order regression with three factors and the relationship between the factors is shown in the Eq. (5).

$$D = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1,i<j}^{3} \beta_{ij} x_i x_j + \in \qquad (5)$$

Based on the results of ANOVA and the design of experiments, a regression equation is defined for each of the objective functions. The regression equation of the mean of total waiting time is shown in Eq. (6) and the mean of total vehicles in the queue is shown in Eq. (7). The total amount of emission is shown in Eq. (8).

$$
\begin{aligned}
TWT = 1054.58 &- 31.96 \times a - 234.30 \times b \\
&- 33.75 \times c - 339.26 \times a \times b \\
&- 341.20 \times a \times c \\
&- 350.36 \times b \times c \\
&+ 320.48 \times a \times b \times c
\end{aligned} \qquad (6)
$$

$$TNQ = 3818.04 + 426.38 \times a - 745.88 \times b$$
$$- 782.03 \times c$$
$$- 1223.28 \times a \times b$$
$$- 1217.55 \times a \times c \qquad (7)$$
$$- 1317.27 \times b \times c$$
$$+ 1151.54 \times a \times b \times c$$

$$TE = 13047 + 1157 \times a - 2800 \times b$$
$$- 2702 \times c - 3743 \times a \times b$$
$$- 3486 \times a \times c \qquad (8)$$
$$- 757 \times b \times c$$
$$+ 5210 \times a \times b \times c$$

each response variable.

$$d_i(\hat{y}_i(x))$$
$$= \begin{bmatrix} 0 & \hat{y}_i(x) < L_i \ \text{اگر} \\ \left(\dfrac{\hat{y}_i(x) - L_i}{U_i - L_i}\right)^s & L_i \leq \hat{y}_i(x) \leq U_i \ \text{اگر} \\ 1 & \hat{y}_i(x) > U_i \ \text{اگر} \end{bmatrix} \qquad (9)$$

$$d_i(\hat{y}_i(x))$$
$$= \begin{bmatrix} 1 & \hat{y}_i(x) < L_i \ \text{اگر} \\ \left(\dfrac{U_i - \hat{y}_i(x)}{U_i - L_i}\right)^t & L_i \leq \hat{y}_i(x) \leq U_i \ \text{اگر} \\ 0 & \hat{y}_i(x) > U_i \ \text{اگر} \end{bmatrix} \qquad (10)$$

6. OPTIMIZATION APPROACH FOR DESIRABILITY FUNCTION

When the optimization procedure involves more than one response variable, it cannot be optimized separately [32]. One of the methods that are widely used for multi-objective optimization is the desirability function approach [32]. This approach attempts to simultaneously minimize the distance from the optimal solution for each of the response variables. Since our objective is to minimize or maximize the response variable, we define a separate desirability function for each of the response variables. To maximize the response variable, Eq. (9) is used, and to minimize it, Eq. (10) is applied. In these equations, L_i and U_i show the minimum and maximum limit of each response variable. T and s indicate the significance of

To optimize the two response variables simultaneously, the total desirability function is defined concerning Eq. (11).

$$D = (d_1(x) \times d_2(x) \times \ldots \times d_k(x))^{\frac{1}{k}} \qquad (11)$$

6.1 Optimization case study

The present study applies the desirability function approach described above. In this approach, the desirability function for each response variable is obtained and the total desirability function is then defined.

$$d(TWT) = \frac{2060 - (1054.58 - 31.96 \times a - 234.30 \times b - 33.75 \times c - 339.26 \times a \times b - 341.20 \times a \times c - 350.36 \times b \times c + 320.48 \times a \times b \times c)}{2060 - 180}$$

$$d(TNQ) = \frac{8877 - (3818.04 + 426.38 \times a - 745.88 \times b - 782.03 \times c - 1223.28 \times a \times b - 1217.55 \times a \times c - 1317.27 \times b \times c + 1151.54 \times a \times b \times c)}{8877 - 1091}$$

$$d(TE) = \frac{33341 - (13047 + 1157 \times a - 2800 \times b - 2702 \times c - 3743 \times a \times b - 3486 \times a \times c - 757 \times b \times c + 5210 \times a \times b \times c)}{33341 - 4018}$$

$$D = \left[\left(\frac{2060 - (1054.58 - 31.96 \times a - 234.30 \times b - 33.75 \times c - 339.26 \times a \times b - 341.20 \times a \times c - 350.36 \times b \times c + 320.48 \times a \times b \times c)}{2060 - 180} \right) \right.$$
$$\times \left(\frac{8877 - (3818.04 + 426.38 \times a - 745.88 \times b - 782.03 \times c - 1223.28 \times a \times b - 1217.55 \times a \times c - 1317.27 \times b \times c + 1151.54 \times a \times b \times c)}{8877 - 1091} \right)$$
$$\left. \times \left(\frac{33341 - (13047 + 1157 \times a - 2800 \times b - 2702 \times c - 3743 \times a \times b - 3486 \times a \times c - 757 \times b \times c + 5210 \times a \times b \times c)}{33341 - 4018} \right) \right]^{\frac{1}{3}}$$

Table 7. Results of desirability function optimization

			a	b	c	Results from regression			
						D	TWT	TNQ	TE
TWT	TNQ	TE	9	9	9	0.9979	3.2	9.9	4194
TWT			134.5	204.5	239.5	0.9975	-	-	4092
	TNQ		9	9	9	0.9999	-	9.9	'
		TE	9	9	9	0.9999	3.2	-	'

To optimize the total desirability function, Lingo software was used. The results are shown in Table 7.

Each of the objective functions was optimized separately (the results are presented for comparison). The result of optimization by OptQuest software is also provided for comparison. These results were tested in the simulation model (Table 8).

As seen in Tables 7 and 8, only when the objective is to minimize the TWT, the result of optimization using Opt Quest software is better. In other cases, the result of desirability function optimization is better.

Table 8. Results of the optimization by using Opt quest,
Results from Opt Quest

		a	b	c	Results from Opt Quest		
					TWT	TNQ	TE
TWT		9	9	17	2.02	5.07	4431
	TNQ	9	9	17	2.02	5.07	4431
		TE	178	227	315	24	53	3595

7. CONCLUSION

The present study attempted to use a desirability function along with simulation to calculate the optimal intervals for a traffic light at an intersection. A new approach with combining the design of experiments, simulation, and desirability function was presented. Given that most of the parameters are in a state of uncertainty, to obtain the required information, Arena software was used to simulate a complex intersection. Also, we attempted to minimize the waiting time and the queue length, as well as the amount of emission at an intersection. To this purpose, first, the regression equations for each of the response variables were obtained through the design of experiments and a full-factorial design, and then a desirability function approach was applied to find the optimal amount of time for each traffic light at the intersection. Finally, the results were compared for each objective function using Arena OptQuest software

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APPENDIX