Energy-consumption-related Robust Optimization Scheduling Strategy for Elevator Group Control System

F. Wang, J. Tang, Q. Zong

***Abstract*— Group elevator scheduling (GES) problem is an optimization problem. In this work, a robust optimization scheduling method is proposed to solve elevator group control system problem with passenger traffic flow uncertainty. An uncertain optimization model of elevator group scheduling is set up based on considering both energy consumption and waiting time. When considering the uncertainty of passenger traffic flow, the model is an uncertain optimization problem. It is tuned into its robust counterpart (RC) based on robust optimization theory. The simulation experiment presents the proposed scheduling method's scheduling performance.**

I. INTRODUCTION

With the acceleration of urbanization, more and more high-rise intelligent buildings emerge, elevators and the number of groups at increased sharply. Elevator group control system has attracted a lot of attention for improvement of transportations in high-rise buildings. GES algorithm is the key factor in elevator group control system, there are a lot of GES algorithms, including minimum waiting time method, static zoning method [1, 2], and the advanced intelligent algorithms [3-6]. The pursuit of efficiency considerations in passenger waiting time, riding time alone, may led to a disproportionate growth in energy consumption and great loss of energy and waste, so the energy consumption of the elevator gradually become the subject of the researchers. There are some researchers considered the energy consumption in elevator group control system [7-9].

GES problem is an optimization problem in view of operational research. Uncertain factors of GES include passenger traffic flow, destination floors and others. When consider uncertainty of passenger traffic flow, GES problem becomes an uncertain optimization problem. Thus when the passenger traffic flow takes value different from the nominal value, the dispatching scheme of GES may infeasible. This raises the question of considering the passenger traffic flow uncertainty and designing scheduling approaches that are immune to uncertain passenger traffic flow. The methodology for generating robust solution of uncertain optimization problem, were proposed in papers [10-16], the solution that is immune to the uncertain data is called robust solution ,and the methodology which is used to find robust solution is called robust optimization. After it was proposed, it was applied in network flow, investment, production management [17-19] and so on.

In this paper, uncertain passenger traffic flow is analyzed and defined in a reasonable closed and bounded interval; uncertain GES optimization model with the uncertain passenger traffic flow is developed and transformed into its robust counterpart via robust optimization in the second section. In the third section, the simulation is done to test the effectiveness of the proposed method. At last, some conclusions and the research in the future are given.

II. ROBUST OPTIMIZATION THEORY

We know that, in theory, when we set up the model of an optimization problem, we often assume that all of the input data is all known. But in practical problems, some inputs are not precisely known, i.e. a part of input data may be uncertain, and these uncertain data may have a bad influence on the feasibility or optimality of the solution. In this case we need to consider the method which can find the solution immune to uncertain data.

Consider the following general uncertain optimization problem [16]

$$\min_x \left\{c^T x \,:\, Ax \le b\right\}_{\xi=(A\ \ b\ \ c)\in U} \tag{1}$$

Here, $U$is the uncertain parameter set.

The RC of formulation (1) can be written as following

$$\min_x \left\{ \sup_{\xi=(A,b,c)} c^T x \,:\, Ax - b \le 0, \forall(A,b,c) \in U \right\} \tag{2}$$

According to [16], the feasible or optimal solutions of (2) are treated as uncertainty-immunized solution of uncertain problem (1). An uncertain-immunized solution of (2) satisfies all realizations of the constraints associated with $\xi = (A,b,c) \in U$, while the optimal uncertainty-immunized solution optimizes the guaranteed value of the uncertain objectives.

For the uncertain problem, there are many methods to find its RC. In this paper, considering the characteristics of GES problem; we choose the method proposed by Bertsimas [12].

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III. GES PROBLEM FORMALTION

In this paper, we adopt the idea of layer dispatching, that is to say, only one elevator in GES is assigned to serve the outcall every time. Some notations are defined at first.

m , number of building's floor,

n , number of elevator,

T , car capacity,

i , subscript of floor that the elevator needs to move upward,

j , subscript of floor that the elevator needs to move downward,

x_{ui} , dispatching solution of up outcall on the i_{th} floor,

x_{dj} , dispatching solution of down outcall on the j_{th} floor,

$x_{ui}^T = (x_{ui1}, \cdots, x_{uin})$, $x_{dj}^T = (x_{dj1}, \cdots, x_{djn})$,

$(1, \cdots, 1) x_{ui} = 1$, $(1, \cdots, 1) x_{di} = 1$,

$(1, \cdots, 1) x_{dj} = 1$, $(1, \cdots, 1) x_{dj} = 1$,

x_{uik} , whether the k_{th} elevator is assigned for the up outcall on the i_{th} floor or not, when it is assigned $x_{uik} = 1$ otherwise, $x_{uik} = 0$, $k = 1, \cdots, n$.

x_{djk} , whether the k_{th} elevator is assigned for down outcall on the j_{th} floor or not, when it is assigned, $x_{djk} = 1$ otherwise, $x_{djk} = 0$, $k = 1, \cdots, n$.

In this paper, passenger traffic flow is considered as uncertain parameter. Through observation and analysis, passenger traffic flow is a stochastic variable, vary feature of it is similar to the cases that passengers in the bus stop in unit time, customers that a seller receives in unit time, and the landing planes in an airport in unit time, they all can be predicted by the Poisson distribution. As in [20, 21], the Poisson distribution is used to predict the passengers in this work, through this way, the uncertain passenger traffic flow on the GES can be predicated and formulated as

$$\overline{P}_{ui} \in [P_{ui} - \tilde{P}_{ui}, P_{ui} + \tilde{P}_{ui}] \tag{3}$$

$$\overline{P}_{dj} \in [P_{dj} - \tilde{P}_{dj}, P_{dj} + \tilde{P}_{dj}] \tag{4}$$

$\overline{P}_{ui}$, up outcall passengers actual value of i_{th} floor,

$\overline{P}_{dj}$, down outcall passengers actual value of j_{th} floor,

P_{ui} , up outcall passengers predictive value of i_{th} floor,

P_{dj} , down outcall passengers predictive value of j_{th} floor,

$\tilde{P}_{ui}$, up outcall passengers disturbance limit of i_{th} floor,

$\tilde{P}_{dj}$, down outcall passengers disturbance limit of j_{th} floor.

A. Objective Functions

Energy consumption and waiting time are chosen as objective functions.

Energy consumption include two parts, (a) During the process of elevator's starting and stopping, the energy for starting the brake, (b) When carrying passengers to the destination floor, the elevator does work to overcome the gravitational potential energy.

Fig.1 shows the movement principle of elevator [8]. **(see Appendix) .**

The energy consumption objective function of the k_{th} elevator serve the up outcall on the i_{th} floor is

$$f_{eu}(i,k) = E_{su}(i,k) + E_{pu}(i,k)$$

Here, $E_{su}(i,k) = N_u(i,k) \times E_0$ (5)

$$E_{pu}(i,k) = \left| W_u(i,k) - W_{const} \right| \times h(i,k) \tag{6a}$$

$$W_u(i,k) = W_{car} + W_i \tag{6b}$$

$$W_{const} = W_{cwt} - W_{car} \tag{6c}$$

$$W_{cwt} = W_{car} + \tfrac{1}{2} W_s \tag{6d}$$

Based on (6a)-(6d), we can get the following

$$E_{pu}(i,k) = \left| \tfrac{1}{2} W_s + W_i - W_{car} \right| \times h(i,k) \tag{7}$$

So, the energy consumption of the k_{th} elevator serve the up outcall on the i_{th} floor is given by

$$f_{eu}(i,k) = \left| \tfrac{1}{2} W_{su} + W_i - W_{car} \right| \times$$
$$h(i,k) + N_u(i,k) \times E_0$$

Here,

$E_{su}(i,k)$, the energy consumption of k_{th} elevator's starting and stopping when assigned to the up outcall on the i_{th} floor,

$N_u(i,k)$, the stopping and starting times when the k_{th} elevator serves the up outcall on the i_{th} floor,

E_0 , the energy consumption one stop and start,

$E_{pu}(i,k)$, the energy consumption of k_{th} elevator's work to overcome the gravitational potential energy, when it serves the up outcall on the i_{th} floor,

$W_u(i,k)$, the load weight of the k_{th} elevator when serves the up outcall on the i_{th} floor,

W_{car} , the tare of the elevator and it is a constant,

W_{ui} , the sum of passengers' weight when the elevator move upward,

W_{cwt}, the weight of counterweight,

W_s, the standard loads of the elevator and is a constant,

$h_u(i,k)$, the distance between the current floor and the requested floor when the k_{th} elevator serves the up outcall on the i_{th} floor.

Here, formula (5) and (6) is according to [8].

By the same method, the energy consumption objective function of the k_{th} elevator serves the down outcall on the j_{th} floor is

$$\begin{aligned} f_{ed}(j,k) &= E_{sd}(j,k)+E_{pd}(j,k) \\ &= \left|\tfrac{1}{2}W_{sd}+W_i-W_{car}\right|\times h(j,k)+N_d(i,k)\times E_0 \end{aligned}$$

Passenger waiting time: $T_{wu}(i,k)$, the time difference between the i_{th} floor's passengers up outcall time and the assigned k_{th} elevator's arrival time

$$T_{wu}(i,k)=t_{wik}-t_b$$

Here, t_{wik} is the time when k_{th} elevator's arrival time to the floor the i_{th} floor, t_b is the time when the outcall is at birth.

Service cost of the k_{th} elevator assigned to the up outcall on the i_{th} floor is as following

$$c_{uik}=\begin{pmatrix}\alpha_u & 1-\alpha_u\end{pmatrix}\begin{pmatrix}T_{wu}(i,k)\\ f_{eu}(i,k)\end{pmatrix}$$

Here $\alpha_u, 1-\alpha_u$ represents the weighted factor of $T_{wu}(i,k), f_{eu}(i,k)$, respectively.

Then service cost matrix for the up outcall on the i_{th} floor is

$$c_{ui}=(c_{ui1},c_{ui2},\cdots,c_{uin})^T.$$

Service cost of the k_{th} elevator assigned to the down outcall on the j_{th} floor can be represented as,

$$c_{djk}=\begin{pmatrix}\alpha_d & 1-\alpha_d\end{pmatrix}\begin{pmatrix}T_{wd}(i,k)\\ f_{ed}(j,k)\end{pmatrix}$$

Here, $\alpha_d, 1-\alpha_d$ is the weighted factor of $T_{wd}(i,k), f_{ed}(i,k)$, respectively.

So service cost matrix for the up calls on the i_{th} floor is

$$c_{dj}=(c_{dj1},c_{dj2},\cdots,c_{djn})^T$$

B. GES Model

After the analysis, energy-consumption GES uncertain optimization model can be developed as followings

$$\begin{aligned} &\min \sum_{i=1}^{m-1}\overline{P}_{ui}c_{ui}^T x_{ui}+\sum_{j=2}^{m}\overline{P}_{dj}c_{dj}^T x_{dj} \\ &s.t.\begin{cases}\overline{P}_{ui}\in[P_{ui}-\tilde{P}_{ui},P_{ui}+\tilde{P}_{ui}]\\ \overline{P}_{dj}\in[P_{dj}-\tilde{P}_{dj},P_{dj}+\tilde{P}_{dj}]\\ x_{uik}=0or1, x_{djk}=0or1\end{cases} \end{aligned} \tag{8}$$

Here the uncertain parameters $\overline{P}_{ui}$, $\overline{P}_{dj}$ are obtained from the uncertain integral sets U_1, U_2

$$U_1=[P_{ui}-\tilde{P}_{ui},P_{ui}+\tilde{P}_{ui}]$$
$$U_2=[P_{dj}-\tilde{P}_{dj},P_{dj}+\tilde{P}_{dj}]$$

For i ($i=1,\cdots,m-1$), the subscripts of $\overline{P}_{ui}$, they compose the uncertain set I_u. For j ($j=2,\cdots,m$), the subscripts of $\overline{P}_{dj}$, they compose the uncertain set J_d. Define $T_u\in[0,|I_u|]$, $T_d\in[0,|J_d|]$ to adjust the robustness of the solution, that is to say, when the number of passengers vary, it can adjust the scheduling solution through adjusting T_u and T_d. Before the robust counterpart of the uncertain model is obtained, uncertain parameters (a part of $\overline{P}_{ui}$, $\overline{P}_{dj}$), are determined in I_u, J_d. In general, $\overline{P}_{ui}$, $\overline{P}_{dj}$ vary from the time in GES problem. There is the case that the passenger in the current time is not the same to the next time.

C. RC of GES Model

Define and introduce the relaxed variable F, according to [12], robust counterpart of formula (8) can be written as

$$\begin{aligned} &\min F \\ &s.t.\begin{cases}\sum_{i=1}^{m-1}P_{ui}c_{ui}^T x_{ui}+\sum_{j=2}^{m}P_{dj}c_{dj}^T x_{dj}+\delta_u+\delta_d\le F\\ \delta_u=\max_{B_u}\left\{\sum_{i\in Q_u}\tilde{P}_{ui}c_{ui}^T x_{ui}+(T_u-\lfloor T_u\rfloor)\tilde{P}_{ut_u}\right\}\\ \delta_d=\max_{B_d}\left\{\sum_{j\in Q_d}\tilde{P}_{dj}c_{dj}^T x_{dj}+(T_d-\lfloor T_d\rfloor)\tilde{P}_{dt_d}\right\}\\ B_u=\{Q_u\cup\{t_u\}\,|\,Q_u\subseteq I_u,|Q_u|=T_u,t_u\in I_u\setminus Q_u\}\\ B_d=\{Q_d\cup\{t_d\}\,|\,Q_d\subseteq J_d,|Q_d|=T_d,t_d\in J_d\setminus Q_d\}\\ x_{uik}\in\{0,1\}\\ x_{djk}\in\{0,1\}\end{cases} \end{aligned} \tag{9}$$

For given x_{ui}^*, x_{dj}^*, i.e. when the optimal elevator scheduling scheme is at birth, according to proposition 1 of [12], δ_u Equals to

$$\max \sum_{i \in I_u} \tilde{P}_{ui} c_{ui}^T x_{ui}^* w_{ui}$$

$$s.t. \begin{cases} \sum_{i \in J_u} w_{ui} \le T_u \\ 0 \le w_{ui} \le 1 \quad \forall i \in I_u \end{cases} \tag{10}$$

δ_d Equals to

$$\max \sum_{j \in J_d} \tilde{P}_{dj} c_{dj}^T x_{dj}^* w_{dj}$$

$$s.t. \begin{cases} \sum_{j \in J_d} w_{dj} \le T_d \\ 0 \le w_{dj} \le 1 \quad \forall j \in J_d \end{cases} \tag{11}$$

Furthermore, based on dual theory, the dual formulation of (10) is given by

$$\min \sum_{i \in I_u} r_{ui} \quad + T_u w_u$$

$$s.t. \begin{cases} w_u + r_{ui} \ge \tilde{P}_{ui} c_{ui}^T x_{ui}^*, i \in I_u \\ r_{ui} \ge 0, \forall i \in I_u \\ w_u \ge 0 \end{cases} \tag{10*}$$

The dual formulation of (11) is

$$\min \sum_{j \in J_d} r_{dj} \quad + T_d w_d$$

$$s.t. \begin{cases} w_d + r_{dj} \ge \tilde{P}_{dj} c_{dj}^T x_{dj}^*, j \in J_d \\ r_{dj} \ge 0, \forall j \in J_d \\ w_d \ge 0 \end{cases} \tag{11*}$$

Then the equal linear form of (9) is as following

$$\min F$$

$$s.t. \begin{cases} \sum_{i=1}^{m-1} P_{ui} c_{ui}^T x_{ui} + \sum_{j=2}^{m} P_{dj} c_{dj}^T x_{dj} + \sum_{i \in I_u} r_{ui} \\ + T_u w_u + \sum_{j \in J_d} r_{dj} \quad + T_d z_d \le F \\ w_u + r_{ui} \ge \tilde{P}_{ui} c_{ui}^T x_{ui}, i \in I_u \\ w_d + r_{dj} \ge \tilde{P}_{dj} c_{dj}^T x_{dj}, j \in J_d \\ x_{uik} \in \{0,1\} \\ x_{djk} \in \{0,1\} \\ r_{ui} \ge 0, \forall i \in I_u \\ r_{dj} \ge 0, \forall j \in J_d \\ w_u \ge 0, w_d \ge 0 \end{cases} \tag{12}$$

Based on the aforementioned section, we know that if we want to solve the EGS model (9), we only to solve its equal linear formula (12). If the corresponding values are given, the optimal solution of the formula (12) is a big optimization problem, which has a lot of variables and many constraints, and it can be calculated by software, such as MATLAB, LINGO (Linear Interactive and General Optimizer), and other tools.

IV. SIMULATION EXPERIMENT

The simulation which is used to evaluate the effectiveness of the proposed RO scheduling strategy is done under virtual elevator simulation environment of our laboratory [22]. Three scheduling algorithms' scheduling performances are evaluated by VC via importing algorithms' dll (dynamic link library) program. And certain optimization problem RC (12) is solved by LINGO software, an interface link between LINGO and VC is developed to realize the scheduling. Simulation conditions setting are shown in table I.

TABLE I

SIMULATION CONDITIONS

Number of Floors	16
Floor Distance(m)	3
Number of Elevators	4
Velocity (m/s)	1.8
Acceleration(m/s/s)	1.1
Jerk(m/s/s/s)	1
Car Capacity(person)	13
Time of Opening & Closing door(s)	4
Time of Passenger's Transferring(s)	1

Two peak passenger traffic flow patterns are used to do simulation, (a) up-peak traffic flow pattern, 300 persons/15minutes, (b) down-peak traffic flow pattern, 300 persons/15minutes.

Three kinds of GES algorithms are chosen to do simulation, static zoning (SZ) algorithm [23], multi-agent (MA) algorithm [21], and robust optimization (RO) algorithm.

The performance indices for comparison are as followings, average waiting time (AWT), and energy consumption (EC).

Results of the simulation are listed in table II and table III.

TABLE II

SIULATION OF UP-PEAK TRAFFIC FLOW

Algorithm	AWT(s)	EC(KJ)
SZ	36.67	10159.12
MA	40.34	11233.53
RO	27.83	12174.33

TABLE III

SIULATION OF DOWN-PEAK TRAFFIC FLOW

Algorithm	AWT(s)	EC(KJ)
SZ	36.59	9552.38
MA	108.54	10242.78
RO	28.62	13337.20

From the simulation results, compared with other two algorithms, RO scheduling could reduce the system's AWT effectively in two peak traffic flow patterns, Because it has the strategy of re-dispatching, and it takes the uncertainty of the traffic flow into account during the modeling process and set up the uncertain optimization model, then it turns the GES model into a certain optimization problem, and computes it. However, energy-consumption has been sacrificed to pursue the less AWT by RO strategy, the EC are a little more than that of MA and SZ in two traffic flow patterns.

V. Conclusions

Nowadays, energy problem is an important and imperative problem. In this paper, for GES problem with the uncertain passenger traffic flow, the energy consumption of elevator is choose as one of the objective functions. The GES model is developed after passenger traffic flow and objectives function are analyzed and formulated. Through finding its robust counterpart, the uncertain optimization model is transformed into a certain optimization problem

Simulation result and comparison analysis showed that the proposed scheduling method able to reduce waiting time, but it cannot reduce energy consumption in two peak traffic flows. It is our future research topic to improve the RO scheduling method to have a better scheduling performance both in average waiting time and energy consumption than in this paper.

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Appendix A

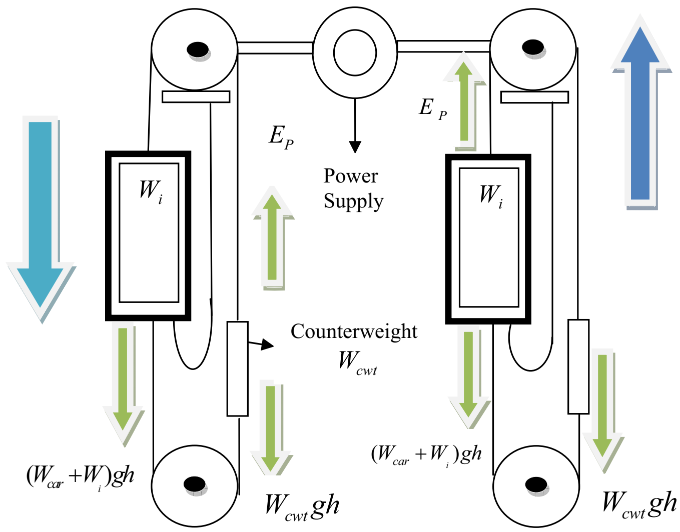

Fig.1 the movement principle of elevator