Lift Planning and Selection Graphs

Mirko Ruokokoski and Marja-Liisa Siikonen

KONE Corporation, P.O. Box 7, FI-02151 Espoo, Finland
mirko.ruokokoski@kone.com
marja-liisa.siikonen@kone.com

Keywords: Round trip time, Interval, Handling capacity, Lift selection graph

Abstract. In the lift planning phase of a building, the number of lifts, their sizes and rated speeds are selected. Traditional performance criteria for the lift selection are the nominal travel time, handling capacity and interval. In this paper a pure up-peak traffic condition is considered since it is the most demanding traffic situation from the viewpoint of handling capacity. If lifts can handle the up-peak situation, they have enough handling capacity for other traffic situations too. In addition, the values of the up-peak handling capacity as well as interval can be quite accurately calculated by using a theoretical up-peak round-trip time formula. Handling capacity and interval calculations for other traffic conditions require approximations or simulations. For common buildings, suitable lift installations can be pre-calculated and the results combined in a graph. The most appropriate lift configuration can be read from a selection graph for the given number of served floors and the given population in upper floors. This paper describes in detail the creation of the selection graphs and discusses when the graph can be created by utilizing rather simple mathematical formulas and when more sophisticated analysis methods such as simulations are needed.

1 INTRODUCTION

Lift selection in buildings is historically based on a pure up-peak traffic. During the pure up-peak traffic all people arrive at the entrance floor and are destined to populated floors of the building. Up-peak condition typically designates the morning traffic in commercial office buildings. It is the worst traffic situation from the viewpoint of lift group handling capacity. If lifts can handle the up-peak situation, they have enough handling capacity for other traffic situations. The number of people using the lifts in the building can be higher at other times of day, e.g., during lunch time. In mixed lunch-time traffic people arrive from many floors, and the lifts are not filled to the same extent as in up-peak since people can exit the lift before new people enter the car. Waiting times can become longer in mixed traffic situations with the same passenger arrival rate as in up-peak. Although residential buildings and hotels do not have similar morning up-peaks, the up-peak round trip time formula is the only generally accepted equation for lift traffic analysis, and it can be also applied to define a lift selection for these building types as well. Nowadays, mixed traffic profile is more and more used, so up-peak traffic calculation in such a case provides some initial guidance only for the lift selection.

The values of the up-peak handling capacity and interval can be calculated by using a theoretical round-trip time formula. Conventionally, the up-peak round-trip time equation is based on the probable number of stops and the highest reversal floor of the lift. The equation for the probable number of stops was first published by Jones in 1923 [1], and the equation for the average highest reversal floor by Schröder in 1955 [2]. Tables for probable number of stops and highest reversal floors in up-peak have been published, e.g., in IAEE [3]. There are many other up-peak formulas in the industry which are slightly different [4-13]. The equations produce, however, about the same answers for similar sets of inputs, and the differences are not too significant when considering lift selection. The round-trip time formula used in this paper is adopted from [8] which takes into account the exact flight times for different running distances in the up-peak situation.

Traditionally in lift selection, the nominal travel time, the up-peak handling capacity and interval criteria are used to define the number of lifts, their sizes and kinematic parameters such as rated speed. Different criteria may be used by different planning specialists. The mentioned selection criteria, however, have become more or less stable for certain types of buildings. Although lift planning professionals know how to utilize the up-peak equations, also, nomograms for lift selection have been published [13]. Lift companies have published selection graphs for architect use, see e.g. [14]. ISO 4190-6 [15] gives selection graphs for lift selection in residential buildings. This paper describes in detail the creation of general selection graphs, discusses when selection graphs are valid, and when more sophisticated methods such as simulations are needed. Values of the selection criteria may vary from a building type to another.

This paper is organized as follows. Section 2 presents the general round trip formula as well as the formulae for handling capacity, interval and nominal travel time. The round-trip time formula for unequal floor heights is presented in Section 3 together with the equations for the expected number of different running distances and their probabilities. Sections 4 and 5 describe the selection graph creation process, and a full selection graph is presented in Section 6. Section 7 discusses when the selection graphs are valid and conclusion follows in Section 8.

2 GENERAL ROUND TRIP TIME CALCULATION

Round trip time (RTT) is the time for a single lift to complete a cyclic path around a building, starting from the entrance level from the time the lift's doors start to open until the doors start to reopen after making a full trip up and down. It is assumed that calls are served in sequential order as in the conventional collective control system.

Traditionally RTT calculations for up-peak traffic are based on the average number of stops and average highest floor reached. The RTT can be calculated using the following expression:

$$RTT = 2 * H * \frac{d}{v} + (S + 1) * \left(t_o + t_c + t_{st} + t_{ph} + t_f(1) - t_{ado} - \frac{d}{v}\right) + 2 * P * t_p \qquad (1)$$

where:

H	is the average highest reversal floor;
d	is the floor height [m];
v	is the rated speed [m/s];
S	is the expected number of stops;
t_o	is the door opening time [s];
t_c	is the door closing time [s];
t_{st}	is the start delay [s];
t_{ph}	is the photocell delay before doors start to close after last passenger transfer [s];
$t_f(1)$	is the single floor flight time [s];
t_{ado}	is the advance door opening time [s];
P	is the average number of passengers carried;
t_p	is the average one way passenger transfer time [s].

The average highest reversal floor can be calculated using Eq. 2, [2]:

$$H = N - \sum_{i=1}^{N-1} \left[\frac{i}{N}\right]^P . \qquad (2)$$

The average number of stops (S) for N floors can be calculated using Eq. 3, [1]:

$$S = N\left[1 - \left[\frac{N-1}{N}\right]^{P}\right]. \tag{3}$$

The up-peak handling capacity ($HC5$) of a lift group is the number of passengers it can transport from the entrance level to upper floors in a period of 5 minutes during the up-peak traffic condition with a specific average car loading P. Let L denote the number of lifts in a group. A value of $HC5$ can be calculated by using the following equation

$$HC5 = \frac{300}{RTT} * P * L. \tag{4}$$

The $HC5$ is usually expressed as the ratio of the $HC5$ and the building population U and is given as a percentage, that is

$$\%HC5 = \frac{HC5}{U} * 100\ \%. \tag{5}$$

If we are given a requirement for the minimum $\%HC5$, the maximum number of persons the building can accommodate satisfying the requirement is

$$U = \frac{HC5}{\%HC5} * 100\ \%. \tag{6}$$

With a single lift, interval (INT) is the same as RTT. If a lift system includes L identical lifts, INT becomes:

$$INT = \frac{RTT}{L}. \tag{7}$$

Nominal travel time (NTT) is the time to travel at rated speed v from the lowest to the highest served floor of the lift group. Often NTT recommendations do not take into account the acceleration, deceleration or levelling and can be calculated as:

$$NTT = \frac{d * N}{v}. \tag{8}$$

3 ROUND TRIP EQUATUION CONSIDERING UNEQUAL FLOOR HEIGTHS

RTT Eq. 1 assumes the equal floor heights as well as the nominal speed of a lift is reached during a single floor flight. This leads to some approximations for high-speed lifts as it may take a flight of several floors to reach the nominal speed.

Roschier and Kaakinen [8] presented a round-trip time formula which takes into account the exact running times of each flight during the round trip. This section reviews the probabilities of lift runs, expressed in floor heights, and the expected number of them. The population can vary floor by floor. Round trip time formula used in this paper can be written in the following form:

$$RTT = \sum_{r=1}^{N} \left[\sum_{i=0}^{N-r} \left(q_{i,i+r} * t_f(i, i+r) \right) + q_{r,0} * t_f(r,0) + (W_r + D_r) * \left(t_o - t_{ado} + t_c + t_{ph} + t_{st} \right) \right] + 2 * P * t_p \tag{9}$$

where:

$t_f(i,j)$	is the exact flight time from level i to j;
q_{ij}	is the probability of a lift travel from level i to j;
W_r	is the expected number of r-floor runs upwards;
D_r	is the expected number of r-floor runs downwards.

Consider a general building. Suppose that the ground level, indexed as 0, is the entrance level, and the upper floors are indexed as $1, \ldots, N$. Let u_k denote the population on floor k, $1 \leq k \leq N$. The total population U is then:

$$U = \sum\nolimits_{k=1}^{N} u_k. \tag{10}$$

The population fraction on level k is defined as:

$$p_k = \frac{u_k}{U}. \tag{11}$$

The following inequalities give the probabilities for all run combinations [8]:

$$q_{0r} = \left(1 - \sum_{k=1}^{r-1} p_k\right)^P - \left(1 - \sum_{k=1}^{r} p_k\right)^P, \qquad 1 \leq r \leq N; \tag{12}$$

$$q_{i,(i+r)} = \left(1 - \sum_{k=i+1}^{i+(r-1)} p_k\right)^P - \left(1 - \sum_{k=i}^{i+(r-1)} p_k\right)^P - \left(1 - \sum_{k=i+1}^{i+r} p_k\right)^P + \left(1 - \sum_{k=i}^{i+r} p_k\right)^P, \qquad 1 \leq r \leq N-1, 1 \leq i \leq N-r; \tag{13}$$

$$q_{r0} = \left(\sum_{k=1}^{r} p_k\right)^P - \left(\sum_{k=1}^{r-1} p_k\right)^P. \tag{14}$$

The expected number of r-floor runs in the up-direction, W_r, and in the down-direction, D_r, can be derived from Eq. 12-14:

$$W_r = \sum_{i=0}^{N-r} q_{i,i+r}, \qquad 1 \leq r \leq N, \tag{15}$$

$$D_r = q_{r0}, \qquad 1 \le r \le N. \tag{16}$$

4 ASSUMPTIONS FOR BUILDING, LIFT AND SELECTION CRITERIA

This section lists all assumptions used in the graphs shown in this paper. The considered building type is assumed to have only one entrance floor at ground level and no express zone. The floor height and the population are expected to be the same on every floor. In addition, the following values are considered:

a. floor height 3.0 m;
b. maximum number of cars in group 3;
c. range of speed 1- 2 m/s;
d. acceleration 0.8 m/s^2;
e. jerk 1.2 m/s^3;
f. rated car capacity 8-13 persons;
g. initial value for the average car loading is taken P as 80% of rated car capacity;
h. advanced door opening 0 s;
i. start delay 0.7 s;
j. door widths and their operating times are given in Table 1. All doors are here assumed to be centre opening.

Table 1 Door widths and their operating times for considered lift capacities

Capacity [persons]	Door width [mm]	t_o [s]	t_c [s]	t_{ph} [s]	t_p [s]
8	800	1.7	2.5	0.9	1.15
10	900	1.4	2.7	0.9	1.1
13	1100	1.4	3.1	0.9	1.0

The selection criteria used in this paper are the nominal travel time, interval and handling capacity. Example values used in this paper are shown in Table 2. These values do not represent requirements for any specific building type.

Table 2 Example selection criteria

$\%HC5$ [%/5 min]	INT [s]	NTT [s]
12	30	32

5 CREATION A SELECTION GRAPH

This section illustrates how to create a selection graph for a general building by a simple example.

Firstly, consider a group of 3 identical 13-person lifts with nominal speed of 1.6 m/s. The region in which this group satisfies the $\%HC5$ requirement of 12% is illustrated in Fig. 1. The borderline of the region is obtained by calculating the total population above the entrance floor using Eq. 6 as a function of the number of upper floors.

Secondly, for a given nominal speed and NTT requirement, the maximum number of upper floors can be solved from Eq. 8, which gives the value of 17 floors for the selected speed of 1.6 m/s. Fig. 2 illustrates the feasible region after the NTT requirement is also taken into account.

Thirdly, the interval of the group, calculated as a function of the number of upper floors is depicted in Fig. 3. From this figure one sees that some part of the region is infeasible with respect to the INT requirement of 30 seconds which can be taken into account as follows. First calculate the RTT, and then INT according to Eq. 9 and 7, respectively. If INT is greater than the requirement, reduce the average car loading P by a certain amount, then recalculate RTT and INT. Repeat this until the INT requirement is fulfilled. Fig. 4 shows the interval after the requirement is taken into account. The region meeting the interval requirement is illustrated in Fig. 5.

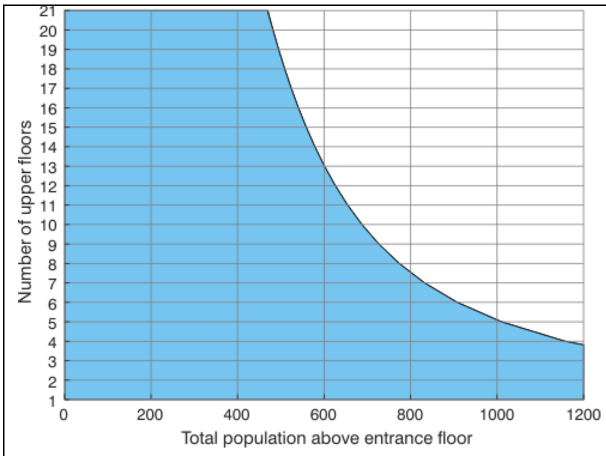

Figure 1 Feasible region of a group of three 13-person lifts with nominal speed of 1.6 m/s taking into account $\%HC5$ requirement

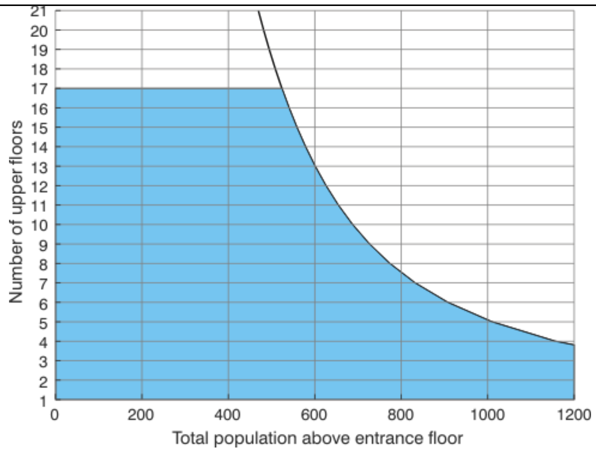

Figure 2 Feasible region of a group of three 13-person lifts with nominal speed of 1.6 m/s taking into account $\%HC5$ and NTT requirements

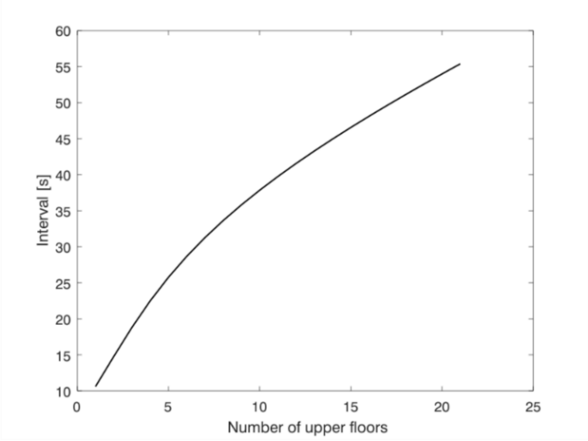

Figure 3 INT of a group of three 13-person lifts with nominal speed of 1.6 m/s

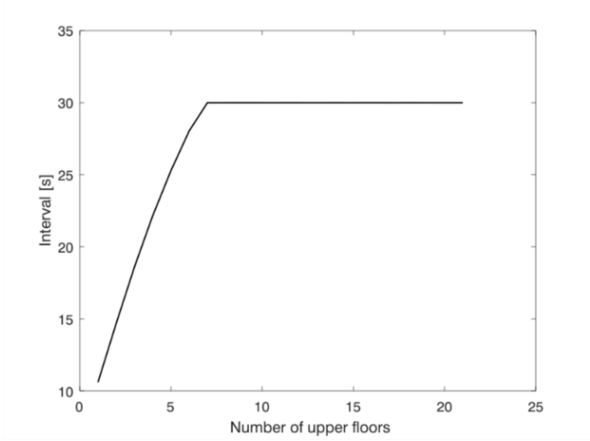

Figure 4 Interval of a group of three 13-person lifts with nominal speed of 1.6 m/s where the INT requirement is applied

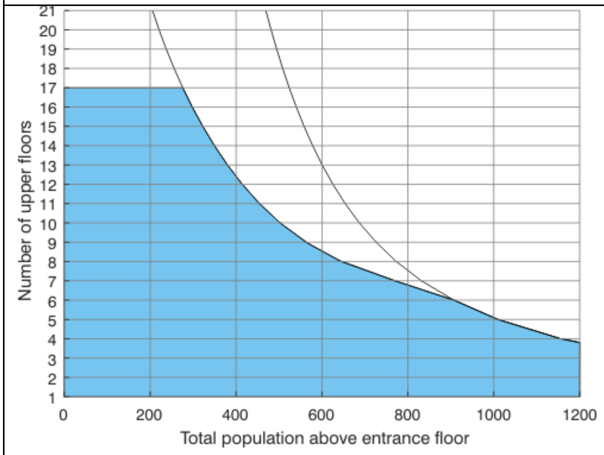

Figure 5 Feasible region of a group of three 13-person lifts with nominal speed of 1.6 m/s taking into account $\%HC5$, NTT and INT requirements

6 RESULTS

The selection graph is created by first calculating the feasible region for a lift group, as described in the previous section. A feasible area can be calculated for as many lift combinations as desired. Then the regions are combined into a single graph. With overlapping regions, the area with minimum arrangement, i.e., number of lifts, speed or passenger capacity, is selected. A graph with 11 feasible areas is shown in Fig. 6. The symbols used in the figure are given in Table 3.

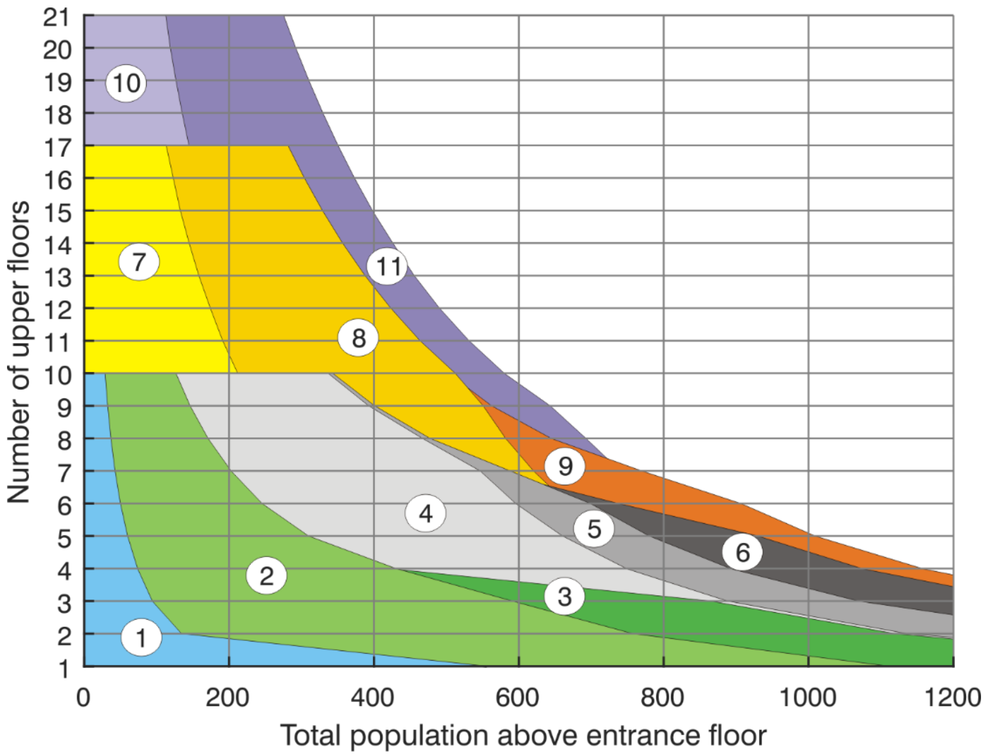

Figure 6 Lift selection graph

Table 3 Explanation of the symbols in lift selection graph

Id	Number of lifts	Capacity [kg]	Speed [m/s]
1	1	630	1.0
2	2	630	1.0
3	2	1000	1.0
4	3	630	1.0
5	3	800	1.0
6	3	1000	1.0
7	2	630	1.6
8	3	630	1.6
9	3	1000	1.6
10	2	630	2.0
11	3	800	2.0

7 DISCUSSION

Round-trip time formula presented in this paper implicitly makes some assumptions. This section goes through them one by one in detail, and discusses how they can be relaxed.

Number of entrance floors. The RTT formula assumes that there is only one entrance floor located at the lowest floor. The case of multiple entrances is considered in [17].

Passenger arrival process. Passenger arrivals at the entrance level are assumed to follow a uniform distribution. According to work of Alexandris [6], passenger arrivals follow a Poisson distribution. Poisson distributed loads can be taken into account by using travel probabilities presented in [18].

Control system. Conventional control with up and down call giving devices are assumed. In destination control with destination keypads, the lift control system has more information in call allocation. That is, it knows the exact number of passengers waiting at elevator lobbies and their destination floors (assuming that each passenger gives a destination call at an elevator lobby). The destination control system can utilize this information to gather passengers with the same destination floors in the same lift. This yields to shorter round trips, and therefore the round trip time formulae presented in this paper are not valid for destination controls. The first equations for estimating the up-peak round trip time for destination control were given in [19]. The equations were later improved in [20].

Express floors. No express floor was assumed. Express floors can be addressed by setting for each express floor f the population of it to zero, i.e., $u_f = 0$.

Heterogeneous lifts. Interval Eq. 7 assumes that all elevator are identical. Suppose for now that all lifts are unique. Let RTT_i be the RTT of lift $i = 1, \dots, L$, calculated using Eq. 9 and denote by P_i the number of passengers in the car i when it leaves from the entrance level. Handling capacity of the group is now

$$HC5 = \sum_{i=1}^{L} \frac{300}{RTT_i} * P_i, \tag{17}$$

and the interval becomes

$$INT = \left(\sum_{i=1}^{L} \frac{1}{RTT_i} \right)^{-1}. \tag{18}$$

Traffic type. In the round trip calculation, pure up-peak traffic condition is considered since it is the most demanding traffic situation considering the handling capacity. If lifts can handle the up-peak situation, they have enough handling capacity for other traffic situations. There are several works that extend the RTT formulae for other traffics such as down-peak and mixed traffic [9, 11]. All of these assumes that lifts follow the collective control principle. The collective control may not however lead to optimal control policy, except pure up-peak condition in a building with single entrance at the lowest floor, see [21]. This means that the lift group selected based on, for example, mixed traffic round trip time could be too large. Therefore if a traffic condition other than up-peak needs to be taken into account, we strongly recommend to use simulation techniques to calculate the border curves. Simulations though, may take some time.

Number of decks. All lifts are assumed to have single deck. Double-deck case is studied in [22]

Selection criteria. The selection criteria used in this paper are the nominal travel time, interval and handling capacity. Nowadays many set requirements for other criteria. Waiting time, ride time and journey time requirements can be taken into account by first deriving their distributions in an up-peak situation and then calculating the value of the requirements from them. Distributions of these requirements can also be used as a selection criteria [23].

As a summary, up-peak round trip time formula can be extended to cover a number of different cases. Extensions to traffic conditions other than up-peak, such as down-peak and mixed traffic, leads to some approximations since they do not take into account the impact of elevator controller. Therefore in such a case, simulation methods are recommended in selection graphs drawing. For complicated and unique buildings there is no sense to make selection graphs.

8 CONCLUSION

In this paper, a method for drawing lift selection graphs using up-peak equations is described. The up-peak round-trip time equation presented in [8] was chosen as a basis in this paper since it takes into account the exact flight times for different running distances in the up-peak situation. Other up-peak round-trip time equations can be used as well. In the selection graph, population and number of upper floors are defined as an input. From the graph, the number of lifts, their passenger capacities and speeds can be deduced. This paper also discussed the cases where the round trip time formula has been extended.

REFERENCES

[1] B. Jones, "The probable number of stops made by an elevator". *GE Review*, Vol. 26, No. 8, 583-587 (1923).

[2] J. Schröder, "Personenaufzuege". *Foerden und Heben*, No. 1 (1955).

[3] G.C. Barney, D.A. Cooper and J. Inglis, *Elevator & Escalator Micropedia*. IAEE Publications, Heron Syke, Brigsteer, Kemdal, Cumbria, England (1997).

[4] G.R. Strakosch, *Vertical transportation: Elevators and Escalators*. John Wiley & Sons, New York (1967).

[5] B. Powell, "Optimal Elevator Banking under Heavy Up Traffic". *Transportation Science*, No. 5, 109-121 (1971).

[6] N.A. Alexandris, *Statistical Models in Lift Systems*. PhD Thesis, Victoria University of Manchester (1977).

[7] G.C. Barney and S.M. dos Santos, *Elevator Traffic Analysis*. Design and Control, Peter Peregrinus Ltd., UK (1977).

[8] N-R. Roschier and M. Kaakinen, "New Formula for Elevator Round Trip Time Calculation". *Supplement to Elevator World*, No 3. (1980).

[9] R. Peters, "Lift Traffic Analysis: Formulae for General Case". *Elevator World*, No 12. (1990).

[10] M-L. Siikonen, "Customer Service in an Elevator during Up-Peak". *Transportation Research - B*, Vol. 31, No. 2, 127-139 (1997).

[11] H. Hakonen and M-L. Siikonen, "Generalized calculation of Round Trip Time". *Elevator Technology 16*, (2006).

[12] L. Al-Sharif, "Derivation of a universal elevator round trip time formula under incoming traffic". *BSERT*, Vol. 35, Issue 2, 198 - 213 (2013).

[13] J. Schröder, "Down-Peak Handling capacity of Elevator Groups". *Elevator World*, No. 5 (1983).

[14] KONE Corporation, *Lift Planning Guide for Commercial Buildings and Hotels*, KONE Corporation, (1978).

[15] ISO, *ISO 4190-6:1984 Passenger lifts to be installed in residential buildings - Planning and selection*. International Standard (1984).

[16] M-L. Siikonen, *Modeling of Lift Traffic and Control with a Computer*. Licentiate Thesis, Helsinki University of Technology (1989).

[17] L. Al-Sharif, "The effect of multiple entrances on the elevator round trip time under up-peak traffic". *Mathematical and Computer Modelling,* Vol. 52, Issues 3–4, 545–555 (2010).

[18] M-L. Siikonen, "Elevator traffic simulation". *Simulation,* Vol. 61, No. 2, 257-267 (1993).

[19] J. Schröder, "Elevator Calculation – Probable Stops and Reversal Floor M-10". *Elevator World*, No. 3, 40-46 (1990).

[20] J. Sorsa, H. Hakonen and M.-L. Siikonen, "Elevator selection with destination control system", *Elevator World,* Vol. 54, No. 1, 148-155 (2004).

[21] M. Ruokokoski, J. Sorsa, M-L. Siikonen M-L. and H. Ehtamo, "Assignment formulation for the Elevator Dispatching Problem with destination control and its performance analysis". *European Journal of Operational Research*, *252*(2), 397–406 (2016).

[22] M-L. Siikonen, "On Traffic Planning Methodology". *Elevator Technology 10,* Proceedings of ELEVCON 2000, Berlin, Germany, IAEE Publications, 267-274 (2000).

[23] L. Yutae et al., "Performance analysis of an elevator system during up-peak". *Math. Comput. Model.* Vol. 49, 423-431 (2009).

BIOGRAPHICAL DETAILS

Mirko Ruokokoski graduated from the Department of Engineering Physics and Mathematics, Helsinki University of Technology in 2008. Currently, he is finalizing his doctoral thesis at Systems Analysis Laboratory in the Aalto University, School of Science and Technology. He joined KONE in 2012 and has been working for R&D.

Marja-Liisa Siikonen received her MSc in Technical Physics, and later licentiate and doctoral degrees in Applied Mathematics from Helsinki University of Technology in 1997. She has worked in the Technical Research Center of Finland, Nokia, and since 1984 in KONE. Currently she is the Director of People Flow Planning in KONE Corporation.