A Systematic Methodology for Analysing Zoning Options for a Building Using Dynamic Programming

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Abstract. In the designing phase of a building, the number of lifts, their capacities and nominal speeds are selected. In case of high-rise buildings, it is a common practice to divide the building into fixed contiguous floor segments called zones to save core area taken by lifts. Typically, each zone is served by a group of lifts, and zones do not have common floors except the entrance floor. The zoning design aims at similar service quantity and quality among all zones. Each lift group should satisfy the traditional design criteria related to handling capacity, interval, and nominal travel time. Finding a good zoning solution is not an easy task since, in general, the number of different zonings increases exponentially as a function of the number of served floors. Current practice in the lift industry is more or less based on rules of thumb, duty table calculations, and the designer's expertise. This paper introduces a dynamic programming program for finding an optimal solution for the static zoning problem. It assumes the uppeak traffic condition. The developed method is an extension of Powell's work carried out almost 50 years ago. The solution to the optimization problem divides the upper floors of the building into fixed disjoint zones and, for each zone, specifies the number of lifts as well as their sizes and rated speeds. Optimal zonings with respect to uppeak filling time, core area occupied by all lifts in all floors, and the total number of lifts over all zones objectives are analysed for a large set of hypothetical office buildings. The results show in general how many zones and lifts per zone are needed, what is the impact of different objective functions on optimal zones and how much zoning decreases core area occupied by the lifts.

1 INTRODUCTION

In a building having up to 15-20 floors there is usually a single lift group serving every floor. As the building height increases, lift groups serving all floors occupy a bigger proportion of the building core area to satisfy lift traffic design criteria. In order to save core area, floors can be divided into contiguous floor segments called zones, and each zone is served by a separate lift group. Zoning reduces passengers' transit times in lifts and times to destination due to fewer number of intermediate stops between passengers' origin and destination floors.

In a typical case, a building requiring a large lift group is split into two zones, the low- and the high-rise. The low-rise lifts serve floors immediately above the entrance while the high-rise lifts express past the low-rise floors and serve only the top part of the building. Thus, about half of lift entrances are saved. Furthermore, the low-rise lifts can be designed with smaller rated speed than the high-rise lifts since the total travel is shorter. This allows smaller machineries, which are less expensive and consume less energy. In this manner, the building can be divided into as many zones as needed. Practical limit is about 4-5 zones. If lifts occupy too large area on the ground level, lift groups can be stacked on top of each other. Shuttle lifts transport passengers from the ground floor to a sky lobby from which local lift groups pick them up to their final destinations [1].

Core area can also be reduced by special lift solutions such as double-deck lifts, two independent lift cars in one shaft or multi-car systems [2-6]. In these systems, more than one lift car is placed in one shaft, which increases lift handling capacity per shaft. With double-deck lifts, the number of lifts shafts can be reduced by 30-40% and with multicar systems even more. In tall buildings, more than 50% of core area can be saved by sky lobby arrangements together with double-deck lifts [7]. Lift group control such as the destination control system (DCS) can decrease the number of stops per round trip too, enabling higher handling capacity - especially in uppeak traffic [8,9]. DCS has a wider upper bound to the number of lifts and served floors in a lift group. Firstly, the DCS reserves enough time for passengers to walk to their assigned lifts, which ensures efficient passenger transfer times. Secondly, the DCS reduces the number of stops per round trip, which is similar to the effect of zoning with the conventional control system.

In the selection of a zoning arrangement, the core area occupied by lifts is not the only thing to be considered. Building filling time should also be taken into consideration, which is expressed by a criterion for relative lift handling capacity [10,11]. Average passenger waiting time or lift departure interval from the main lobby should have a target or an upper limit for a good service quality. In addition, the selection of lift rated speed should satisfy nominal travel time criterion. Rated speed should not be too high so that lifts rarely reach the full rated speed and thus become unnecessarily expensive. Neither should it be too low since it decreases lift group handling capacity. Lift banks are preferably symmetric with equal car capacities, and often with an even number of shafts. Other possible design considerations are lift energy consumption, passenger journey times, evacuation time, round trip time or whatever is considered important in the building under consideration [13].

This paper focuses on the static zoning of a building without neither sky-lobbies nor any special lift solutions. Finding a good zoning arrangement is not an easy task since, in general, the number of different zoning grows exponentially as a function of the number of the served floors. For example, the number of different zonings for a building having 60 floors above entrance level is about 10^{18}, meaning that a simple enumeration method cannot be utilized. Therefore, more clever approaches are needed.

According to our knowledge, the first optimization method for zoning was introduced almost 50 years ago by Powell [10,11]. The method is based on a dynamic programming. It is capable of finding an optimal solution within seconds. The method did not, however, receive much interest from the lift industry. The current practice in zoning is more or less based on rules of thumb, duty table calculations, and the designer’s expertise. This may mean that the best zoning is not found.

In this paper, the Powell’s method is modified such that: i) the rated speed is selected based on the highest floor of a zone instead of the lowest floor; ii) the car load factor is a decision variable instead of being a constant fixed to 100 % (or to any other constant value) since using fixed car load factors may lead to over- or under-sizing; iii) the number of lifts in a zone should be at minimum and it can differ from values of other zones only by 2 but do not need to be even; and iv) round trip time formula presented in [14] is used which takes into account the exact running times of each flight during the round trip, instead of using flight time approximations.

The solution to the dynamic programming program divides the upper floors of the building into contiguous disjoint zones and, for each zone, specifies the number of lifts as well as their sizes and rated speeds. The traffic is assumed to be uppeak traffic [15], and group controller the conventional full-collective control - for which uppeak calculation is sufficient to guarantee proper lift service in all traffic situations. Optimal zonings with respect to uppeak filling time, core area occupied by all lifts in all floors, and the total number of lifts over all zones are analysed for a large set of hypothetical office buildings in order to see in general how many zones and lifts per zone are needed, what is the impact of different objective functions on optimal zones and how much zoning decreases core area occupied by the lifts.

2 BASICS OF ZONING

2.1 Two zones in an office building

In order to demonstrate the basic principles of zoning, an office building with 14 populated upper floors above entrance level is split into two zones. It is worth noticing that typically buildings with 15 or more floors require zoning [6]. For simplicity, the building has equal floor-to-floor distances of 3.3 m and a population of 145 persons on each upper floor. Typical design criteria applied are: uppeak handling capacity ($\%HC5$) of 12% of population per 5 minutes and up-peak interval ($UPPINT$) of 30 seconds. Three different zoning arrangements are considered. Table 1 shows uppeak calculation results as well as the parameters for each lift group under consideration: the number of lifts, L; rated speed, v; rated passenger capacity, CC, i.e., the maximum number of passengers that a lift car can accommodate; average number of passengers, P, in the car at departure from the main entrance floor, which is assumed to be $0.8 \times CC$. Parameter UPPINT@12% shows the interval during up-peak traffic when the traffic intensity is 12 % of the total population within 5 minutes. Other common parameters used for each lift group are acceleration 1.0 m/s^2, jerk 1.6 m/s^3, door closing time 3.1 s, door closing delay time 0.9 s, door opening time 1.4 s, door pre-opening time 0 s, start delay 0.7 s and passenger transfer time 1.0 s to enter or leave the car.

Table 1 Parameters and uppeak calculation results for simple zoning

Group	L	v	CC	P	$\%HC5$	$UPPINT$	$UPPINT@12\%$
Non-zoned	8	3.0	17	13.6	10.7%	18.8 s	N/A
Non-zoned – large cars	8	3.0	24	19.2	12.7%	22.4 s	21.3 s
Low-rise	4	1.6	17	13.6	14.0%	28.7 s	25.8 s
High-rise	4	3.0	17	13.6	12.9%	31.2 s	30.0 s

This lift group design assumes rated passenger capacity of 17 persons. The group of eight such cars does not reach the relative handling capacity criterion of 12%. The eight-car group can be split into two four-car groups that satisfy the design criteria. In addition to the main entrance (ground) floor, the Low-rise serves floors $1 \ldots 7$ and the High-rise floors $8 \ldots 14$. The rated speeds of low-rise lifts can be reduced to 1.6 m/s due to the shorter total travel. Another way to satisfy the criterion is to increase the car size to 24 person, but it requires more core area than the zoned solution does and that size lift cars are very rare in office buildings.

The performance graph shown in Figure 1 demonstrates the above lift traffic design with 17-person cars. The graph depicts interval as a function of handling capacity for car load factors (CLF) from 10% to 80%. Thus, each point corresponds to $UPPINT$ and $\%HC5$ calculated with $P_{CLF} = CLF \times PC/100\%$ passengers, e.g., $P_{10} = 1.7$. Interval at the given handling capacity criterion, i.e., $UPPINT@12\%$, should be used to decide whether service quality satisfies the requirement instead of the maximum $UPPINT$ with 80% CLF. Such a point can be deduced from the graph as the intersection of a particular plot with the 12% vertical line. For example, the Low-rise and the High-rise intersect 12% handling capacity with $P_{62} = 10.5$ persons and $P_{72} = 12.2$ persons, respectively.

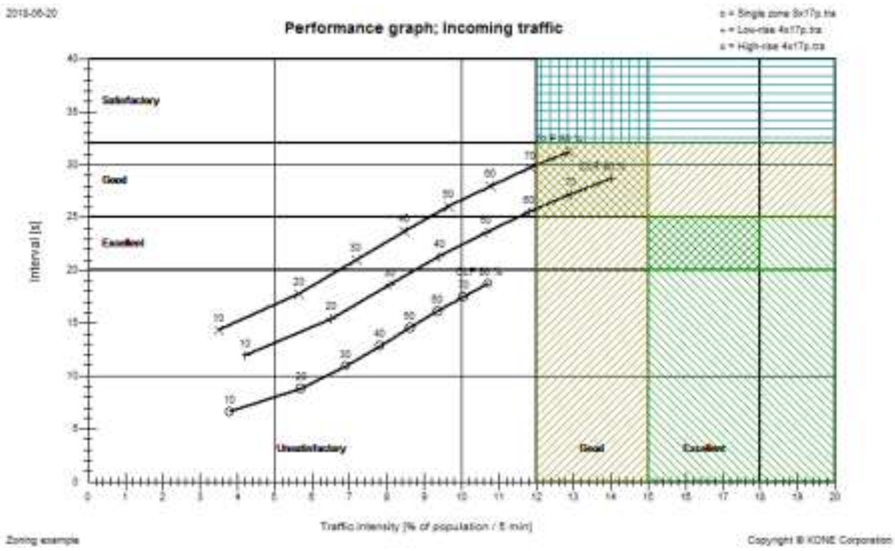

Figure 1 Uppeak interval with respect to traffic intensity with increasing CLF values

The performance graph can be used to guide the lift design process. A curve crossing through the shaded area represents an acceptable lift group design although the performance can be compared to the detailed design criteria. Since the zoning design aims at harmonized service quality between the rises, the curves of different rises should become as close to each other as possible. In this case, the Low- and the High-rise are rather unbalanced. The Low-rise has about 10% more handling capacity and about 15% shorter interval compared to the High-rise. As shown by this example, the express zone of the High-rise adds a constant time to round trip time, which easily makes interval longer than the criterion. The express zone can be compensated by increasing rated speed. In this case, notable improvements can be observed up to speeds of 3.5 or 4.0 m/s.

2.2 Impact of a transfer floor on zoning

A transfer floor is an upper floor, which is common to two or more lift groups. The transfer floor allows fluent interfloor traffic between the zones as passengers do not need to travel via the main entrance floor. During morning uppeak passengers, however, soon learn to use the fastest route to the transfer floor. Usually, the fastest route is with the higher group, for which the transfer floor is the first stop after the express zone. Therefore, lift traffic design should assume that the transfer floor population is served by the higher group to avoid under-capacity for that lift group.

The above example of an office building is continued by considering a transfer floor between the Low-rise and the High-rise on level 7. It is assumed that passengers can use both groups to reach level 7. Figure 2 shows performance graphs of the High-rise in the cases that 0%, 50% or 100% of level 7 population use it during morning uppeak. Clearly, level 7 population invalidates the original traffic design for the High-rise as both handling capacity and interval do not anymore satisfy the design criteria. This situation can be avoided in practice by, e.g., locking car calls to the transfer floor from the High-rise when lifts are on the main entrance floor [7].

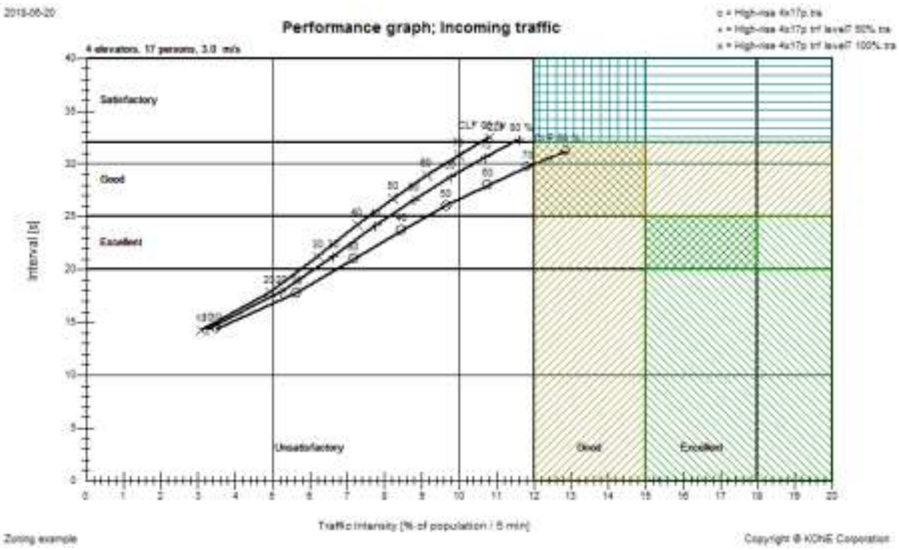

Figure 2 Different usage scenarios for the High-rise transfer floor 7

3 ZONING ALGORITHM

This section introduces a dynamic programming procedure to find an optimal zoning for a building.

3.1 Problem description and notation

Consider a general high-rise building containing N populated floors, indexed as $1 \ldots N$. Level 0 is the only entrance floor. The following constraints are assumed to hold for each zone:

(C1) Rated lift speed is subject to the nominal travel time (NTT) requirement, that is, time period for a lift to travel from the ground floor to the highest floor in the zone without any stops must be shorter than a predetermined value.

(C2) Relative handling capacity ($\%HC5$) must meet or exceed a predetermined value.

(C3) Interval ($UPPINT$) must be shorter than a predetermined value.

(C4) The number of lifts must be as small as possible.

(C5) The number of lifts in must be between n and $n + 2$.

(C6) The lift groups do not have common floors except the entrance level.

(C7) Rated passenger capacity, CC, of a lift is the same for all lifts.

Uppeak round trip time (RTT) of a lift begins when lift's doors start to open at the entrance level and ends when the doors again start to open at the entrance level after making a full trip up and down. During the round trip, the lift transports P passengers on average from the main entrance floor to their destination floors. The value of P may vary from one passenger to 80% of rated passenger capacity according to the traditional definition of handling capacity [12]. The RTT calculation used in this paper takes into account the exact running times of each flight during the round trip [14,15]. Let $RTT(i, k, v, P)$ denote the round trip time of a lift when it serves populated floors from i to k, its rated speed is v and the average number of passengers in the car is P at departure from the entrance floor.

Without constraint (C5), a building consisting of N populated floors can theoretically have Z combinations of different zoning arrangements,

$$Z = 2^{N-1}. \quad (1)$$

If the number of zones is restricted to m, then Z becomes

$$Z = \sum_{k=1}^{m} \binom{N-1}{k-1}, \tag{2}$$

where $\binom{N-1}{k-1} = \frac{(N-1)!}{(k-1)!*(N-k)!}$, and $n! = n * (n-1) * ... * 2 * 1$. If the number of lifts in each zone can differ at most by a certain value, that is, (C5) must hold, then there may not be a general formula for Z since it is now dependent on the building population distribution.

3.2 Dynamic programming algorithm

Three different zoning policies are considered: maximum filling time (FT), lift core area occupied on all floors (CA), and the total number of lifts in all zones (LL). Optimal zoning with respect to maximum filling time was first considered by Powell [10,11]. Denote by $M_Z^f(k)$ the objective value associated with objective function f when floors 1,2 ... k are served by Z zones, $Z \leq m$. Furthermore, let the objective functions are defined as follows

$$FT(i,k,v,P,L) = \frac{POP(i,k)}{P} \times \frac{RTT(i,k,v,P)}{L}, \tag{3}$$

$$CA(i,k,v,P,L) = (k+1) \times L \times A(CC), \tag{4}$$

$$LL(i,k,v,P,L) = L, \tag{5}$$

where L lifts serve levels i to k with total population $POP(i,k)$, and $A(CC)$ denotes the standard shaft dimensions of a lift with rated load greater than or equal to $CC \times 75\ kg$ [16].

The general idea of the algorithm is to iteratively split the building into m zones and then select the solution which minimize the objective value. Briefly, in the first step, the optimal 1-zone arrangement is defined when floors 1 to k are served. This is repeated for each $k = 1, ..., N$. Then, in the second step, the optimal 2-zone arrangement is generated by choosing the optimal splitting point x such that first zone serves floors $1, \ldots, x-1$, and the second zone floors $x, ..., k$. The optimal 1-zone arrangements read from the first step. This step is repeated for each $k = 2, ..., N$. Then, in the third step, the optimal 3-zone arrangement is found by selecting the optimal splitting point x such that third zone serves floors $x, ..., k$, and zones 1 and 2 serve floors $1, \ldots, x-1$. This step is repeated for each $k = 3, ..., N$. Notice that the optimal 2-zone arrangement is already generated in the second step. The method continues until the m-zone arrangement is generated. If at any step a zoning does not satisfy constraint (C5), it is considered as infeasible and the objective value of such a solution is set to infimum. After the last step, the optimal solution is selected.

Formally, the optimal zoning $M^f(N)$ with respect to objective function f for a building having N upper floors is obtained by the following dynamic programming recursion

$$M^f(N) = \min_{2 \leq n \leq 10} \left\{ \min_{1 \leq Z \leq m} \left[\min_{Z \leq x \leq N} F\left(M_{Z-1}^f(x-1), f(x,N,v^*,P^*,L^*)\right) \right] \right\}, \tag{6}$$

where v^* satisfy (C1), and P^* as well as L^* are selected so that constraints (C2)-(C5) are satisfied. The lower bound of P is one passenger and the upper bound $0.8 \times CC$. The aim of the first policy is to find a zoning arrangement where the filling times of all zones are as nearly equal as possible and as small as possible. This is achieved by minimizing the maximum filling time. Hence, F corresponds to the maximum of M_{Z-1}^f and f. The other policies, i.e., the minimum core area and minimum number of lifts, are additive in nature and, therefore, function F is a summation for them.

4 OPTIMAL ZONING SOLUTIONS FOR OFFICE BUILDINGS

This section provides the computational results for a large set of office buildings, which is obtained by varying the number of populated floors between 1 and 60, and varying the number of persons per floor from 5 to 200 in steps of five. Table 2 gives lift and building parameters that are used in all cases and Table 3 shows feasible lift kinematic parameters.

Table 2 Common lift and building parameters

Door opening time [s]	1.4	Start delay [s]	0.7
Door closing time [s]	3.1	Passenger transfer time [s]	1.0
Door closing delay time [s]	0.9	Rated passenger capacity [persons]	21
Door pre-opening time [s]	0.0	Floor-to-floor distance [m]	3.3
Shaft area [m^2]	6.75		

Table 3 Feasible rated speeds as well as the used accelerations and jerks for each speed

Speed [m/s]	1.0	1.6	2.0	2.5	3.0	3.5	4.0	5.0	6.0	7.0	8.0
Acceleration [m/s^2]	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Jerk [m/s^3]	1.2	1.2	1.2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6

The maximum number of zones is set to 20. The number of zones in tall buildings is in practice limited to 4 or 5, therefore 20 is too large. The upper bound for the zones is however kept in 20 in order to see what is the optimal number of zones. The lift group design criteria for each zone are: handling capacity of 12% of population per five minutes, interval of 30 seconds, and nominal travel time of 25 seconds. Nominal travel time is defined in constraint (C1).

4.1 Optimal number of zones

Figure 3 displays the optimal number of zones when the core area (left), the total number of lifts (centre), and the maximum filling time is minimized (right). As an example, for a 40-storey building with 100 persons per floor, the optimal number of zones are 4, 3, and 20 with respect to the core area, total number of lifts, and the maximum filling time, respectively. The colours in the figure represent the values in the cells, green being small number of zones, then turning to yellow and red as the number of zones increases.

Objective function / Number of persons per floor — Core Area

Floor	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	2	2	3	3	3	3	4	4	4	5	5	6	6	7	7	7	8	8	9	10
58	2	2	2	2	3	3	3	4	4	5	5	5	6	6	7	6	8	8	9	9
56	3	2	2	2	3	3	3	4	4	5	5	6	5	6	6	6	7	8	9	9
54	3	2	3	3	3	3	3	4	4	4	5	5	5	6	6	6	7	7	8	9
52	2	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7	8	8
50	2	2	2	2	3	3	3	3	4	4	5	5	5	5	6	6	7	7	8	9
48	2	2	3	2	2	3	3	3	4	4	5	5	5	5	6	6	6	7	7	8
46	2	2	2	2	2	3	3	4	4	4	4	5	4	5	5	6	6	6	7	8
44	2	2	2	3	2	2	3	3	4	4	4	5	4	5	5	6	6	6	7	8
42	1	2	3	2	3	3	3	3	4	4	4	4	4	5	5	5	6	6	6	7
40	2	3	2	3	3	2	2	3	3	4	4	4	4	4	5	5	5	6	6	7
38	2	2	2	2	3	2	3	3	3	3	4	4	4	4	4	5	5	5	6	7
36	2	2	2	2	2	2	2	3	3	3	3	4	3	4	4	5	5	5	5	6
34	2	1	2	3	3	2	3	2	3	3	3	4	3	4	4	4	5	6	5	6
32	2	2	2	2	2	2	2	3	3	3	3	3	3	5	4	4	5	5	5	6
30	2	2	3	2	2	3	3	2	3	3	3	3	3	3	4	5	5	4	5	5
28	1	2	3	2	2	2	2	3	3	3	3	3	4	4	3	4	5	5	4	5
26	1	2	2	2	2	3	2	2	3	2	3	3	3	3	3	4	3	4	4	5
24	1	1	2	3	2	2	2	2	2	2	2	3	3	4	4	4	3	4	4	4
22	1	2	2	2	2	2	2	2	2	3	2	3	2	3	3	3	3	3	3	4
20	2	2	2	1	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	4
18	2	2	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3
16	1	1	2	2	2	1	3	2	3	2	2	2	3	3	3	3	3	3	3	3
14	1	1	2	1	2	2	2	2	2	2	2	2	3	2	2	3	3	3	2	2
12	1	1	2	2	1	2	2	1	2	2	1	1	3	2	2	2	2	2	2	2
10	1	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
8	1	1	2	1	1	1	2	2	2	2	2	1	2	2	2	2	2	2	2	2
6	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	1	1	1	1	2
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Objective function / Number of persons per floor — Total number of lifts

Floor	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	1	1	1	2	2	3	3	3	4	4	4	5	5	6	6	7	7	7	8	8
58	1	1	1	2	2	3	3	3	3	4	4	5	5	6	6	6	7	7	8	8
56	1	1	1	2	2	2	3	3	3	4	4	5	5	6	6	6	7	7	7	8
54	1	1	1	1	2	2	3	3	3	4	4	4	5	5	6	6	6	7	7	8
52	1	1	1	1	2	2	2	3	3	4	4	5	5	5	5	6	6	6	7	7
50	1	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7
48	1	1	1	1	2	2	2	3	3	3	3	4	4	5	5	5	6	6	6	7
46	1	1	1	1	2	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6
44	1	1	1	1	1	2	2	2	2	3	3	4	4	4	5	5	5	5	6	6
42	1	1	1	1	1	2	2	2	2	3	3	4	4	4	4	5	5	5	6	6
40	1	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	5	5	5	6
38	1	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4	5	5	5
36	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4	4	4	4	5	5
34	1	1	1	1	1	2	1	2	2	2	3	3	3	3	3	4	4	4	4	5
32	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4	5
30	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4	4	4	4
28	1	1	1	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4
26	1	1	1	1	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4
24	1	1	1	1	1	1	1	1	1	2	2	2	2	2	3	2	3	3	3	4
22	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3
20	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3
18	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	3
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Objective function / Number of persons per floor — Maxium filling time

Floor	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	20	20	20	20	19	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
58	20	20	20	20	19	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
56	20	20	20	20	20	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
54	20	20	20	20	20	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
52	20	20	20	20	20	20	20	19	20	20	20	20	20	20	20	20	20	20	20	20
50	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
48	20	20	20	20	19	20	19	20	20	20	20	20	20	20	20	19	20	19	20	20
46	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	19	20	20	20
44	20	20	20	20	20	20	20	20	19	20	20	20	20	20	20	19	19	19	20	19
42	20	20	20	19	19	20	20	19	19	20	20	20	20	19	19	20	20	20	19	20
40	20	20	20	18	18	20	20	19	20	20	20	20	20	19	19	20	20	20	20	20
38	19	19	19	17	17	20	20	20	20	20	20	20	20	19	19	20	20	20	19	19
36	18	18	18	16	16	20	20	20	20	19	20	20	20	19	20	20	20	20	20	20
34	17	17	17	15	15	20	20	20	20	19	20	19	20	19	19	20	20	20	20	20
32	16	16	16	14	14	20	20	20	20	20	20	19	20	19	19	20	20	20	19	19
30	15	15	15	13	13	20	20	20	20	20	20	20	20	19	19	20	20	20	19	19
28	14	14	14	12	12	20	20	20	20	20	20	20	20	19	19	20	20	20	17	17
26	13	13	13	11	11	20	20	20	20	20	20	20	20	19	17	20	20	18	15	15
24	12	12	12	10	10	18	20	20	20	20	20	20	20	17	15	20	20	16	13	13
22	11	11	11	9	9	16	18	19	19	19	19	19	19	15	13	18	18	14	11	11
20	10	10	10	8	8	14	16	17	17	17	17	17	17	15	13	16	16	12	9	9
18	9	9	9	7	7	13	14	15	15	15	15	15	15	13	11	14	14	12	9	9
16	8	8	8	6	6	11	12	13	13	13	13	13	13	13	11	12	12	10	7	7
14	8	8	8	6	6	10	11	11	11	11	11	11	11	11	9	10	10	8	7	7
12	7	7	7	5	5	9	9	9	9	9	9	9	9	9	9	8	8	8	7	7
10	7	7	7	4	4	7	7	7	7	7	7	7	7	7	7	6	6	6	5	5
8	5	5	5	4	3	6	6	6	6	5	5	5	5	5	5	4	4	4	4	4
6	4	4	4	4	4	3	3	4	4	4	4	4	4	4	4	3	3	3	3	3
4	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 3 The optimal number of zones when the core area is minimized (left), the total number of lifts is minimized (centre), and the maximum filling time is minimized (right).

In general, the optimal number of zones increases as a function of populated floors as well as the number of persons per floor. However, when minimizing the filling time, the optimal number of zones is strongly related to the number of upper floors. The number of floors per zone is very small, typically between one and three. Such a static zoning is impractical. The results above indicate that filling time objective contradicts with both the core area and the total number of lifts objective. Thus, the zoning should be considered as a multi-objective optimization problem, where the filling time objective puts weight on solutions that have as equal filling time and handling capacity as possible and either the core area or the number of lifts objective prefers solutions with the minimal number of shafts.

4.2 Maximum number of lifts over all zones

Figure 4 shows the maximum number of lifts over all zones when the core are is minimized (left), the total number of lifts is minimized (centre), and the maximum filling time is minimized (right). The figure reveals that for the core area and the maximum filling time objectives, the optimal number of lifts over all cases considered is always less than or equal to 8. This value corresponds to the maximum practical number of lifts that has been used in case of conventional control. For the total number of lifts objective, the maximum number of lifts goes up to 14, which is not common in the lift industry but is a possible with destination control.

Objective function / Number of persons per floor

Floor	Core Area																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	4	6	6	7	7	7	7	7	8	7	7	6	7	6	6	7	6	6	6	6
58	4	6	7	8	7	7	7	7	7	7	7	7	6	7	6	8	6	6	6	6
56	4	6	7	8	7	7	8	7	7	7	6	6	7	6	7	7	7	6	6	6
54	4	5	5	6	7	7	7	7	7	7	6	7	7	7	7	7	6	6	6	5
52	4	5	6	7	7	7	7	7	7	7	6	6	6	6	6	7	6	6	6	6
50	4	5	6	7	6	7	7	7	7	7	6	6	6	7	6	7	6	6	6	5
48	4	5	5	7	7	7	7	7	6	6	6	6	6	6	6	6	7	6	6	5
46	4	5	6	7	7	6	7	6	6	7	7	6	7	6	7	6	6	6	6	5
44	4	5	6	5	7	7	7	7	6	6	6	6	7	7	6	6	6	6	6	5
42	4	5	5	6	6	6	7	7	6	6	6	6	6	6	6	6	6	6	6	5
40	3	4	5	5	5	7	7	7	7	6	6	6	6	6	6	6	7	6	6	5
38	3	4	5	6	5	7	6	6	6	7	6	6	6	6	7	6	6	6	6	5
36	3	4	5	6	6	7	7	6	6	6	6	6	7	6	7	6	6	6	6	5
34	3	5	5	5	5	6	6	7	6	7	6	6	7	6	6	6	6	5	6	5
32	3	4	5	5	6	6	7	6	6	6	6	6	6	5	6	6	5	5	6	5
30	3	4	4	5	6	5	5	7	5	6	6	6	6	6	6	5	5	6	5	5
28	3	4	4	5	5	6	6	5	5	6	6	6	5	5	7	6	5	5	6	5
26	3	4	4	5	5	5	6	6	5	6	5	6	6	6	6	5	7	6	6	5
24	3	4	4	4	5	5	6	6	6	6	6	5	6	5	5	5	6	5	5	5
22	3	3	4	4	5	5	5	6	6	5	6	5	6	5	6	6	6	5	6	5
20	2	3	4	5	4	5	5	5	5	6	6	6	5	5	5	5	5	5	5	5
18	2	3	4	4	4	4	5	5	5	5	6	6	6	5	5	5	5	5	5	5
16	2	3	3	3	4	5	4	5	4	5	5	5	5	5	5	5	5	5	5	5
14	2	3	3	4	4	4	4	4	5	5	5	5	4	5	5	4	4	4	5	5
12	2	3	3	3	4	4	4	5	4	4	6	6	4	5	5	5	5	5	5	5
10	2	2	3	3	3	3	3	4	4	4	4	4	4	4	4	4	5	5	5	5
8	2	2	2	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4
6	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	3
4	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3
2	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Floor	Total number of lifts																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	6	9	12	8	9	7	8	9	7	8	9	7	8	7	7	6	7	7	6	7
58	6	8	12	7	8	7	7	8	9	7	9	7	7	7	7	8	6	7	6	6
56	6	8	11	7	8	10	7	8	9	7	8	7	7	6	6	7	7	6	7	6
54	5	8	11	14	8	9	7	8	9	7	7	8	7	7	6	6	8	6	6	6
52	5	8	10	13	8	9	10	7	8	7	7	6	6	7	7	6	7	7	6	7
50	5	7	10	13	8	8	10	7	8	9	7	7	8	7	7	7	6	7	8	6
48	5	7	9	12	7	8	9	7	7	8	9	7	7	6	7	7	7	6	6	6
46	5	7	9	11	7	8	9	10	7	8	8	7	7	8	6	6	8	6	6	7
44	5	7	8	11	13	7	8	9	11	7	8	6	7	7	6	6	7	7	6	6
42	4	6	8	10	13	7	8	9	10	7	8	6	6	7	7	6	6	7	6	6
40	4	6	8	10	12	7	7	8	9	7	7	8	9	6	7	7	7	6	6	6
38	4	6	7	9	11	7	7	8	9	6	7	7	8	6	6	7	8	6	6	7
36	4	6	7	9	11	6	7	7	8	6	6	7	7	8	6	6	7	7	6	6
34	4	5	7	8	10	6	13	7	8	9	6	6	7	7	8	6	6	7	7	6
32	4	5	6	8	9	11	12	7	7	8	9	6	6	7	7	6	6	6	6	5
30	4	5	6	7	8	10	12	6	7	7	8	6	6	6	7	7	5	6	6	6
28	3	5	6	7	8	9	11	12	7	7	7	8	9	6	6	6	7	7	6	6
26	3	5	6	7	7	8	10	11	12	6	7	7	8	9	6	6	7	7	7	5
24	3	4	5	6	7	8	9	10	11	6	6	7	7	8	5	9	6	6	6	5
22	3	4	5	6	6	7	8	9	10	11	6	6	6	7	7	8	5	5	6	6
20	3	4	5	5	6	6	7	8	9	10	6	6	6	6	6	7	7	8	5	5
18	3	4	4	5	6	6	7	7	8	9	9	10	11	6	6	6	6	7	7	5
16	2	3	4	5	5	5	6	6	7	7	8	9	9	10	5	5	5	6	6	6
14	2	3	4	4	5	5	6	6	6	6	7	8	8	9	9	10	5	5	5	5
12	2	3	4	4	4	5	5	5	6	6	6	6	7	7	8	8	9	9	5	5
10	2	3	3	3	4	4	4	5	5	5	5	5	6	6	6	6	7	7	8	8
8	2	2	3	3	3	3	4	4	4	4	4	4	5	5	5	5	5	5	5	6
6	2	2	2	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	5
4	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3
2	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Floor	Maxium filling time																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
58	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5
56	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5
54	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5
52	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
50	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
48	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
46	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
44	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
42	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4
40	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4
38	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4
36	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4
34	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4
32	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4
30	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4
28	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4
26	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4
24	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	3	3	4	4	4
22	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	3	3	4	4	4
20	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	3	3	4	4	4
18	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	3	3	4	4	4
16	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	3	3	4	4	4
14	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	3	3	4	4	4
12	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4
10	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4
8	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
6	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
2	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Figure 4 Maximum number of lifts over all zones

4.3 Savings in core area by zoning

The savings in core area as a function of floors is shown in Figure 5 for buildings with 100, 150, and 200 persons per floor. In this case the core area was used as an optimization objective. Saving is calculated with respect to the single zone arrangement. From the figure one can see that it is possible to save core area up to 60 % by zoning the floors in an optimal way in a building with about 60 floors and 150-200 persons per floor.

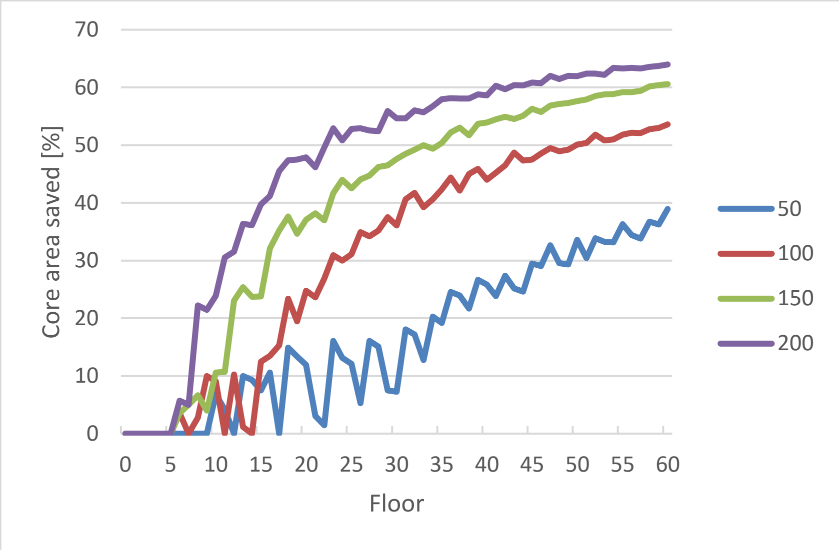

Figure 5 Saving in core area by zoning for buildings containing 50, 100, 150 and 200 persons per floor

4.4 Optimal solutions for a 60-storey office building

The optimal solutions with respect to the core area and the number of lifts are depicted in Figures 6 and 7, respectively, for a building containing 60 floors with the population of 50, 100 and 150 persons per floor. In the figures, each vertical bar represents a lift group and the number above each bar describes how many lifts there are in the group. Light blue colour represents served floors while white colour represents express floors and dark blue the entrance level. The highest floor of the zone is shown on the left and the rated speed on the right. The optimal solution for the filling time objective is not illustrated since the number of zones in all cases is 20.

Objective values for the optimal solutions for each objective are given in Table 4. Values for a single zone solution is reported as well. The number of lifts and core area are close to each other if core area (CA) and number of lifts (LL) is optimized. In a single zone solution and maximum filling time (FT) optimization, the number of lifts and core area can be about twice as big compared to the core area and the total number of lifts optimization when the number of lifts is not restricted.

Table 4 Objective values for different population per floor

Parameter	Population	Single zone	Max *FT*	*CA*	*LL*
Number of lifts	50	20	64	18	17
	100	39	72	30	29
	150	58	79	39	39
Core area [m^2]	50	8235	13811	5029	5380
	100	16058	16693	7452	7803
	150	23881	179993	9416	9794
Filling time [min]	50	40.1	14.9	41.6	40.3
	100	41.2	16.4	41.2	41.7
	150	41.5	19.6	41.5	40.9

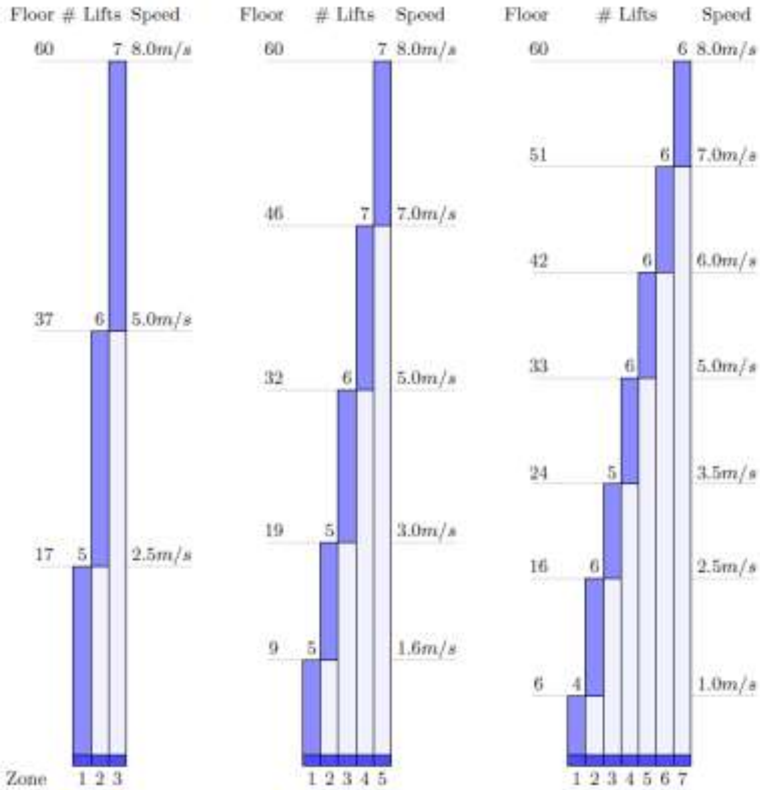

Figure 6 Zoning solutions by optimizing core area for a 60-floor building with 50 (left), 100 (centre), and 150 (right) persons per floor

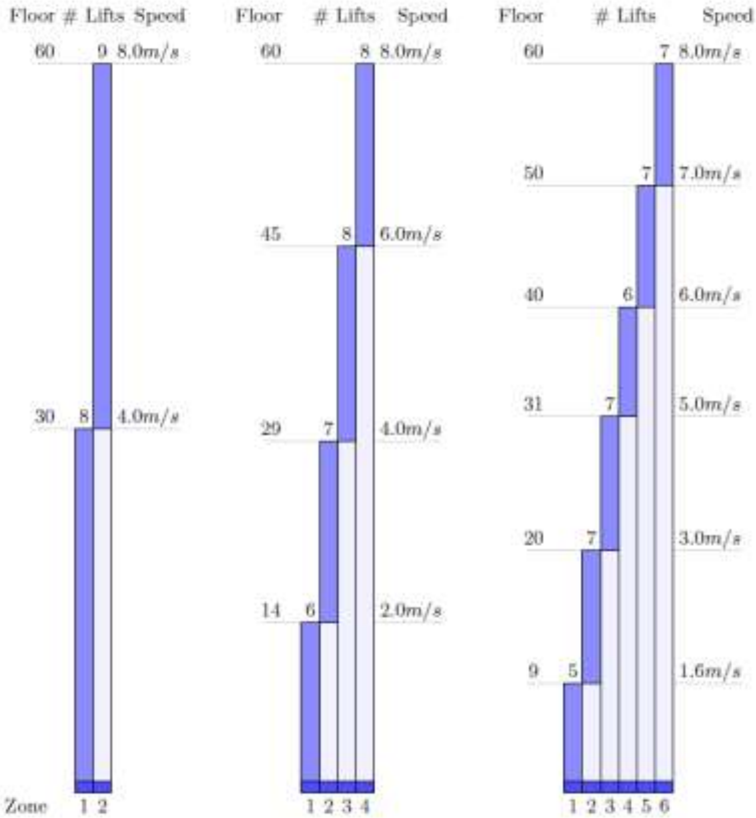

Figure 7 Zoning solutions by optimizing the number of lifts for a 60-floor building with 50 (left), 100 (centre), and 150 (right) persons per floor

4.5 Lift group size distribution

From Fig. 6 and 7 one can see that there is a trend in the number of lifts, they increase as function of zone index, the higher zone the more lifts. Figure 8 shows the division of the number lifts between zones. This is calculated over all optimal solutions (2400 in total) when the core area is optimized, and the results are shown separately for solutions containing 2, 3, .., 10 zones. For example, for optimal solutions containing 2 zones, the lower zone contains about 40 % of the lifts while the upper zone contains 60 %.

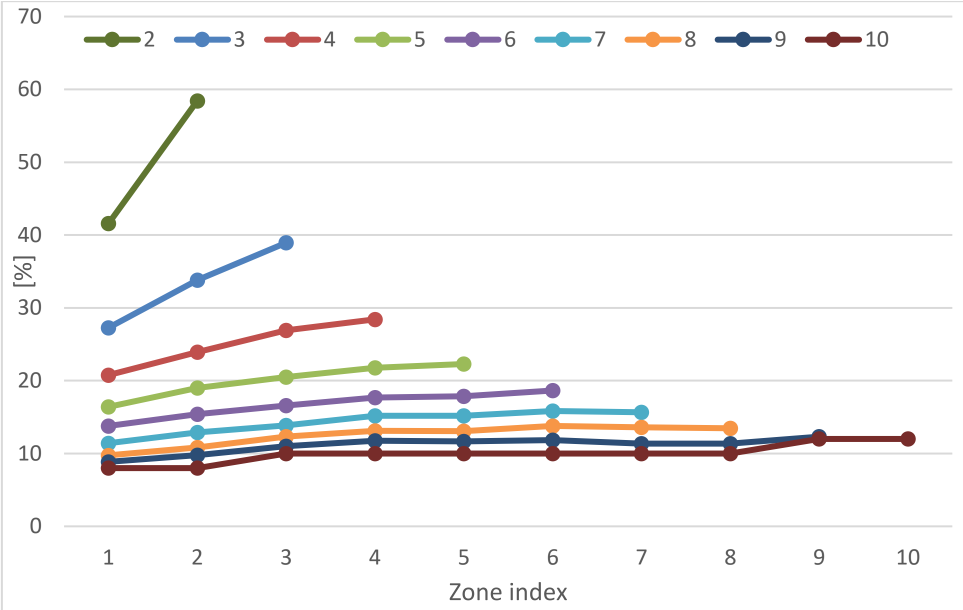

Figure 8 The number of lifts per zone when core area is optimized

5 CONCLUSION

This paper introduced a dynamic programming algorithm to find an optimal lift zoning for a building under design with the conventional control system. Destination control requires a separate consideration. The program models uppeak traffic as a basis of the design. The program minimizes either the maximum filling time, the lift core area or the total number of lifts over all zones. Since zoning reduces the number of stops per round trip, it increases lift group handling capacity. The increased handling capacity, on the other hand, allows area savings in lift core: either some lift shafts can be eliminated or car sizes can be reduced.

Numerical experiments show that the dynamic programming algorithm is capable of defining zones for any kind of a multi-storey building. However, none of the studied objective functions alone may not produce practical zoning arrangements. Thus, the static zoning should be studied as a multi-objective problem or additional constraints should be incorporated in the model. Also, interfloor traffic should be taken into account in the design phase, meaning that lift traffic simulations with group control system are needed. For the maximum filling time and the core area objectives, the optimal solutions consisted of lifts groups with at most eight lifts. This means that the traditional rule for designing lift groups with at most eight lifts with the conventional control has a sound basis.

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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.

Janne Sorsa is Head of People Flow Planning in KONE Major Projects, Finland. He obtained the degree of D.Sc. (Tech.) in applied mathematics in 2017 from Aalto University School of Science, Finland. He has developed optimization models and numerical algorithms for lift group control systems. His research interests include all aspects of modelling people flow in buildings such as transport planning, simulation, behaviour, human factors and evacuation.

Marja-Liisa Siikonen is the Director People Flow Planning in KONE Corporation, Finland. She received her M.Sc. in technical physics from Helsinki University of Technology. Later she obtained her Lic.Sc. (Tech.) and D.Sc. (Tech.) degree in applied mathematics from Helsinki University of Technology. She has published numerous articles and patents in the field of lift control systems and energy consumption, lift traffic planning, building traffic simulation and evacuation, and people flow in buildings. The latest experimental surveys and research interests are on people movement inside buildings and energy consumption of transportation devices.