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Current and future trends in vertical transportation

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ABSTRACT

In the middle of the 19th century, the invention of a safety device that prevented elevators from falling enabled the construction of tall buildings and skyscrapers. In the middle of the 20th century, control systems started to serve the given calls automatically by relay technology, and later by electro-mechanical systems. In the 1970s-80 s, software-based control systems invaded elevator technology. Passenger service levels improved with the application of mathematical methods such as artificial intelligence. When the old relay boards of the skyscrapers in New York were modernized by software-based group controls, passenger waiting times dropped to less than half. In this millennium, the need to reduce elevator core space has further increased, since a significant number of buildings already exceed 300 m. The challenge in constructing tall buildings is that elevator groups can occupy the rentable area of a building. At the elevator planning stage, elevator core space can be decreased by zoning the building. The latest trends include systems with several elevator cars running in the same shaft. With modern control systems, passenger journey times can be decreased and handling capacity increased. This article deals with mathematical methods used in elevator dispatching problems. Building traffic simulation is utilized to search for an elevator arrangement that saves the most space in an example building. The design criteria of the ISO 8100–32 standard are used in selecting the elevator arrangements.

1. Introduction

The development of elevator technology has enabled the construction of tall buildings since people can easily reach the upper floors of a building with elevators. This article gives a short review of the development of vertical transportation in tall buildings.

To understand the short timeline of vertical transportation history, the global evolution of tall building structures is introduced as a background. Currently, the tallest building under construction is planned to be one kilometer high. It still misses about 600 m from the dream of a mile-high building by architect Frank Lloyd Wright (Zevi, 1991). His-dream was to build a mile-high building with a height of 1 584 m and 528 levels. In his original plan, the intended population was 100 000 persons with 44 elevators to transport them up and down. The elevators were to be powered by nuclear energy.

In the following, the available and potential future elevator solutions for tall buildings are briefly described. In planning elevators, the population of the building needs to be estimated. The selected elevator arrangement should be able to transport the population within a defined time without waiting for the elevators. Elevator planning methods and the use of the ISO standard (ISO 8100–32:2020) in selecting elevators are presented for an example building. The design criteria with service level requirements are chosen according to the building type, here the building type is assumed to be for office use.

For demanding projects, the simulation method is used in elevator selection. In the simulation, passenger traffic is generated in a virtual, non-existing building, where the suggested elevator solutions serve the traffic. The final elevator selection is always a compromise among various factors and is the result of numerous iteration rounds. The iteration process is handled together with investors, architects, construction companies, and the designers of vertical transportation. Architects and investors are interested in minimizing the elevator core space in the building to increase the rentable space. Elevator planning aims to guarantee a good service level for passengers. The design should not be "too" good, and the building budget sets its limits. In the design phase, the architect’s drawings and the elevator layouts are revised until a compromise between conflicting objectives is found.

The challenge in building megatall buildings over 600 m has been that the elevator solution may take more than 50% of the lobby area as all local elevator groups start from the ground floor. Therefore, the aim of elevator planning is to minimize the elevator core space. A case study is presented for a multi-tenant office building of over 300 m and about

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11 000 occupants. The elevator solutions are selected to fulfill the ISO design criteria. The core space demand for each solution is calculated, and the efficiency of the solutions is compared.

2. Evolution from high-rise buildings to supertall and megatall skyscrapers

The history of passenger elevators began when Elisa Otis invented the safety brake that prevented the elevator from falling down the shaft (Otis, 1861). After that, several other inventions have made traction elevators with ropes even safer. Such inventions include automatic elevator doors, call buttons inside the elevators and in the lobby, and drive systems that automatically detect the position of the elevator and start and stop the elevator for the assigned calls.

The first tall structure where passengers were transported by elevators was the Eiffel Tower in Paris, France. It was built by Gustave Eiffel for the 1889 World Exposition, which was to celebrate the 100th anniversary of the French Revolution (Wikipedia, 2023a). It is a sightseeing tower with a rooftop height of about 301 m.

Since 1930, most of the supertall buildings over 300 m (CTBUH, 2023a) have been built in North America. The Chrysler Building was the first occupied supertall building in New York. After its completion in 1930, it became the tallest building in the world (Wikipedia, 2023b). It has 77 floors and with the antenna spire, it is about 319 m tall. Four elevator groups started from the lobby. In total, 32 elevators were zoned to serve some parts of the building. Just a year later, in 1931, another supertall building was completed in New York, USA. The 381-meter high Empire State Building with 102 floors surpassed the Chrysler Building as the tallest building in the world. It originally had 64 elevators, but later the number was increased to 73 elevators (Wikipedia, 2023c). At the time, it had the fastest elevators in the world moving at 4 m per second up and down. From 1974 up to 1998 the tallest building in the world was still situated in North America. It was the Sears Tower, the current Willis Tower, an office building in Chicago, USA (Wikipedia, 2023d). The building has 108 floors and a height of 442 m. At the top level, there is an observation deck which is served by double-deck elevators.

Before the turn of the 21st century, in 1998, a supertall building reaching 451.9 m with an antenna was completed in Kuala Lumpur, Malaysia (Wikipedia, 2023e). The Petronas Twin Towers is an 88-story office building. Of the 76 elevators, all main passenger elevators are double-deckers, which thus increases the net usable area in the building. Petronas was surpassed in 2004 by Taipei 101 in Taiwan with an architectural height of 508.2 m (Wikipedia, 2023f). The passenger elevators are all double decks. The observation deck elevators run at a speed of 16.8 m/s, the highest elevator speed at the time (Nakagawa, Nakamura, Matsuo & Togashi, 2012).

In 2010, Burj Khalifa in Dubai, UAE, was opened (Wikipedia, 2023, g). It is currently the tallest structure in the world at 828 m. It has 163 floors and a population of 35 000 people serving 57 elevators in total. It is a mixed-use building for office, hotel, and residential purposes.

Since the turn of this millennium, most of the supertall buildings have been built in Asia or the Middle East. In the 2000s, the number of supertall buildings has grown to about 10 times more than it was in the 1990s (CTBUH, 2017). Most of the elevator systems in these buildings have been delivered by global elevator companies such as Hitachi, KONE, Mitsubishi, Otis, Schindler, Thyssen, and Toshiba. Currently, four occupied megatall buildings over 600 m are completed (CTBUH, 2023b). The tallest tower is naturally Burj Khalifa in Dubai. The second highest megatall building, the Merdeka 118 in Kuala Lumpur, Malaysia was completed in 2022 (Wikipedia, 2023h). It has 118 floors with an architectural height of 678,9 m. It is a mixed-use building with 87 elevators, mostly double-deckers and the harmonized dispatching system (Barker, 2018). The third tallest occupied construction is Shanghai Tower (Wikipedia, 2023i) which was opened in 2015 in Shanghai, China. It is a 632-meter-high mixed-use hotel-office building. It has the fastest elevator in the world, designed for an incredible 20.5 m per second. The fourth existing megatall building is in Meccah, Saudi Arabia (KONE, 2023; Wikipedia, 2023j). It is the 601-meter-high Makkah Royal Clock Tower with 102 floors. It is a mixed-purpose building for serviced hotels and apartments in the tower, and the podium for retail and hotel use. The Clock Tower has 96 elevators, and the podium below the tower has 79 additional elevators. The Jeddah Tower (former Kingdom Tower) in Jeddah, Saudi Arabia is still under development and construction. When completed it will be the tallest building in the world (Wikipedia, 2023k). The aim is to build it up to 1000 m (Fortune, 2015). This tower has the mile-high tower structure which was first introduced by Frank Lloyd Wright in the 1950s and has yet to become true.

3. Mathematical modeling of elevator dispatching

3.1. Elevator dispatching problem

In tall buildings, several elevators are required to serve the passenger traffic. The efficiency of passenger service can be improved by a common set of landing calls which is shared by a group of elevators. An elevator group control system (EGCS) delivers the registered landing calls or passenger calls between the elevators in the group which reduces the number of stops of each elevator during and thus decreases interval and passenger waiting times (Siikonen, 1997c). In the early software-based control systems, the dispatching commands of EGCS were based on rules that usually minimized average and maximum landing call times. Simultaneously EGCS obeyed some constraints of elevator behavior (Closs, 1970), such as

a) An elevator may not stop at a floor where no passenger enters or leaves the car.
b) An elevator may not pass a floor at which a passenger wishes to alight.
c) A passenger may not enter a car travelling in opposite to his/her required direction.
d) An elevator direction may not be reversed while carrying passengers.

With the evolution of software-based control systems and simulation methods, optimization of the elevator dispatching problem (EDP) has been widely researched (Fernández & Cortés, 2015; Markon, Kita, Hirosh & Bartz-Beielstein, 2006). With a conventional control system, the challenge in EDP has been that the number of possible solutions increases exponentially by the number of existing landing calls. The elevator dispatching problem (EDP) of a conventional control system has been formulated as an integer programming problem (Ruokokoski, Ehtamo & Pardalos, 2015). The result was that the method is too slow for a real-time application. EDP has also been formulated for the destination control system (DCS) (Ruokokoski, Sorsa, Siikonen & Ehtamo, 2016). In addition to constraints a) -d), the load of the elevator should not exceed the rated passenger capacity (Q) and elevator must serve all calls assigned to it. The paper formulates an assignment formulation to the DCS system by a routing formulation. The objective is to design optimal elevator routes to minimize waiting times (WT) for an elevator group, E, and a set of passenger calls, N. Here WT is defined from the instant passenger registers a call until he/she starts boarding the elevator (according to ISO 8100–32:2020 it is from the registration of the call until the serving car begins opening doors at the boarding floor). The article makes some assumptions of the boarding and leaving the elevator. Elevator is denoted by $e \in E$, and the set of their initial positions by T. Passenger call comprises a set of origin-destination floor pairs. Each passenger call $i = 1, \ldots, n$ is associated with the origin call floor i and with the destination call floor $j = i + n$. Passenger call is denoted by the origin call floor index i. The set of all origin floors is denoted by P, $i \in P$, and the set of all destination floors by D, $j \in D$. The set of unassigned call floors is denoted by P_1 and D_1. An elevator for which passenger call i is fixed, is indicated by $e(i)$, $i \in P_2 \cup D_2 \cup D_3$. The indexes P_2 and D_2 refer to sets of assigned call floors, and D_3 refers to a set of destination call floors where the passenger is already inside the car. S_{eij} refers to a subset of call floors that are ordered and assigned to elevator e. A set A_e comprises elevator trips between call floors k and g where $k < g$, and elevator e does not violate any other given constraints (3) - (13). According to Eq. (1) (Ruokokoski et al., 2016), passenger waiting times can be minimized as

$$\min \sum_{i \in P} \frac{\omega_i}{\Omega(P)} (t_i + \gamma_i) \tag{1}$$

where $\Omega(P) = \sum_{i \in P} |\omega_i|$, t_i denotes the arrival time of the car to call floor $i \in P$, and γ_i the elapsed time from the call registration of the call up to the current moment. For $i \in P$ the demand ω_i represents the number of passengers entering from the call origin floor i. The same number of passengers will exit the car ($\omega_j = -\omega_i$) at destination floor $j \in D$. Elevator cycle time cost τ_{ij}, includes passenger transfer times of call i and elevator performance time between call floors i and j. The performance time here consists of a door closing time at floor i, a flight time between floors i and j, and a door opening time at floor j. The flight time of an elevator comprises the acceleration time, the traveling time at rated speed, and the deceleration time to the destination floor. The rated speed is denoted by v, jerk by j, and acceleration by a. Assuming the elevator reaches the rated speed for the distance d, the equation of the flight time (t_f) is

$$t_f = \frac{d}{v} + \frac{v}{a} + \frac{a}{k}. \tag{2}$$

The kinematic equations for different flight times t_f in Eq. (2) were introduced by Motz (Motz, 1976), but are later referred in the literature (CIBSE, 2015; Siikonen, 2022). The elevator load upon departure from origin call floor i is denoted by q_i. According to Ruokokoski (Ruokokoski et al., 2016), Eq. (1) is subject to Eqs. (3) - (12)

$$\sum_{e \in E} x_{ei} = 1 \ \forall i \in P_1 \cup D_1 \tag{3}$$

$$x_{e,2n+e} = 1 \forall \ e \in E \tag{4}$$

$$x_{ei} = x_{e,n+i} \ \forall \ i \in P_1, \ e \in E \tag{5}$$

$$x_{e(i),i} = 1 \ \forall i \in P_2 \cup D_2 \cup D_3, \ e \in E \tag{6}$$

$$t_i + \tau_{ij} - M_{ij}(2 - x_{ei} - x_{ej}) \le t_j \ \forall e \in E, (i, j) \in A_e \tag{7}$$

$$t_i = 0 \ \forall i \in T \tag{8}$$

$$a_i \le t_i \le b_i \forall i \in P \cup D \tag{9}$$

$$q_i = \omega_i \ \forall i \in T \tag{10}$$

$$q_i + \omega_j - \min\{Q, \ Q + \omega_i\} \left(2 - x_{ei} - x_{ej} + \sum_{k \in S_{eij}} x_{ek} \right) \le q_j$$

$$\forall (i, \ j) \in A_e, e \in E \tag{11}$$

$$\max\{0, \omega_i\} \le q_i \le \min\{Q, \ Q + \omega_i\} \ \forall i \in P \cup D \tag{12}$$

$$x_{ei} \in \{0, 1\} \ \forall i \in P \cup D, \ e \in E \tag{13}$$

The constraints of Eqs. (3) and (4) make sure that only one elevator fixes an unassigned passenger call. A binary variable $x_{ei} \in \{0,1\}$ of Eq. (13) equals 1 if elevator e visits passenger call i, 0 otherwise. Eq. (5) ensures that each elevator starts its route from its initial position. According to Eq. (6), fixed passenger calls cannot be reassigned. Eqs. (7), (8) and (9) guarantee the consistency of time variables. The term $M_{ij} = \max\{0, \ b_i + \tau_{ij} - a_i\}$ in Eq. (7) relates to a situation where elevator does not visit both call floors i and j. Eqs. (10), (11) and (12) ensure that

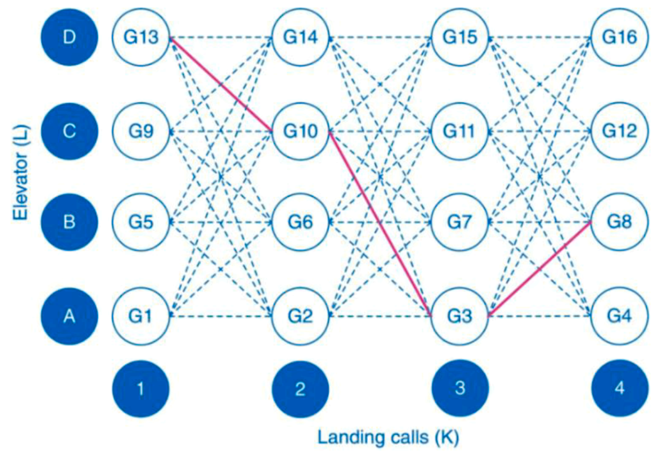


Fig. 1. Possible elevator routes in serving landing calls 1–4 with single elevators A-D (Siikonen, 2000a).

the load variables are consistent. In Eq. (10), the parameter ω_i characterizes the initial load of the elevator at the origin floor i $\in T$. The third term of Eq. (11) represents intermediate stops between call floors i and j. The EDP of double-deck (DD) elevators with DCS was considered as a stochastic bi-level problem (Shimizu, Ishizuka & Bard, 2012; Sorsa, Ehtamo, Kuusinen, Ruokokoski & Siikonen, 2018). On the upper level, EGCS allocates the call to the "best" double-deck elevator minimizing passenger waiting times. On the lower level, the objective function minimizes the route time to serve the assigned calls to the elevator (Sorsa, 2019).

Average passenger waiting times, journey time and interval and are most often referred measures of the quality of elevator service. With the more advanced control systems, multiple objectives (MO) can be optimized simultaneously, for instance, passenger waiting times and elevator energy consumption (Fernandez & Cortés, 2015; Sorsa, Hakonen & Siikonen, 2006; Tobita, Fujino, Inaba, Yoneda & Ueshima, 1991). MO can be optimized by evolutionary algorithms (Deb, 2001; Markon et al., 2006). In addition to MO optimization, the total experience of a passenger during an elevator journey needs to be considered considering user interfaces and guidance (Smith & Gerstenmeyer, 2013).

3.2. Elevator routing problem

With conventional control, all existing landing calls are reallocated continuously to the “best” elevators several times a second, i.e. in real-time. Landing call times are predicted from the distance between the location of the calls and the positions of the elevators and by using the elevator speed (Hirasawa, Kuzunuki, Iwasaki & Kaneko, 1978). The arriving elevator is signaled to the passenger at the last moment when the elevator had to decelerate to the call floor, and the landing call is canceled.

The assigned elevators to existing landing calls form a route as shown Fig. 1. It shows an example of four landing calls and possible routes of four elevators to serve the calls. One possible route is D-C-A-B, which is shown as the red line in the figure. In a conventional control system, the maximum number of elevator routes, K, to be calculated is

$$K = L^N, \tag{14}$$

where L is the number of elevators in the group and N is the number of existing landing calls.

For an eight-car group in a building with 20 floors, with collective control using up and down call buttons, the maximum number of landing calls is 40 (38). According to Eq. (14), the number of possible routes then becomes $8^{40} = 1.3e^{36}$. From all possible routes, EGCS should select the “best” route. The brute force method is not able to calculate all

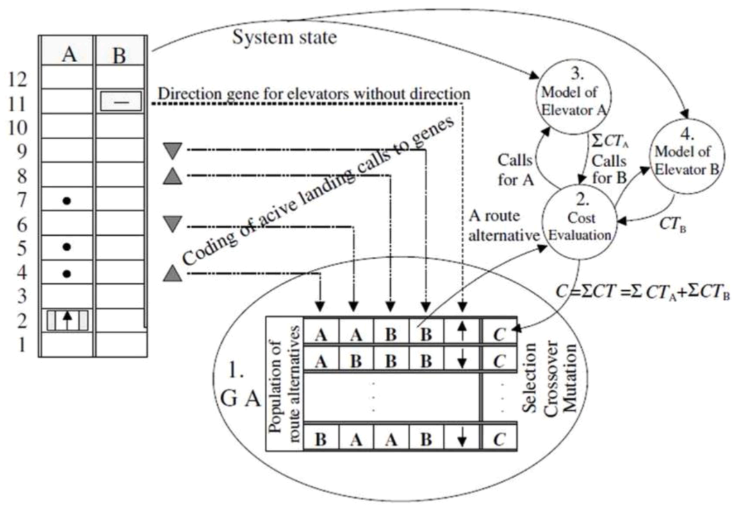


Fig. 2. Optimization of landing calls using Genetic Algorithm (Tyni, 2006).

routes in real time even with the current supercomputers. Heuristic optimization methods, such as genetic algorithm (GA), can solve the EDP in real time to find optimal, or nearly optimal results (Alander, Ylinen & Tyni, 1995; Cortés, Larrañeta & Onieva, 2003).

The Japanese elevator supervisory control systems have a different approach. Registered hall call is immediately fixed to the "best" car and is instantly signaled to the waiting passengers. Passengers have enough time to walk to the landing door of the serving car which is psychologically pleasant for the users. Without reallocation, the possibilities of the EGCS to react to new calls decreases since all the existing assignments constrain the optimization. With immediate call allocation, the number of possible routes to be calculated, K, correlates to the number of cars in group, L, and the number of floors

$$K = L(2N - 2). \tag{15}$$

According to Eq. (15), for an eight-car group serving 20 floors, the maximum number of routes to be calculated simultaneously decreases by 304 (Siikonen, 2022) where all routes can be calculated in real-time. Immediate allocation is used in most of the current DCS applications. There every passenger must give the destination call, and the maximum number of possible elevator routes during call registration correlates to the number of keypads, P, on each floor and to the number of floors, N, and cars, L, and is

$$K = LPN. \tag{16}$$

For 20 served floors with an eight-car group having eight destination keypads on each floor, according to Eq. (16), the maximum number of possible routes becomes 1280 which also can be easily calculated in real-time. With immediate DCS allocation, the computation time allows an EGCS to consider even all elevator zones in the building (Koehler & Ottiger, 2002). Simulation of future traffic or prediction of future passenger arrivals and elevator stops can improve the dispatching decision (Nikovski, 2003; Sakai & Kurosawa, 1984).

3.3. Routing with genetic algorithm

Genetic algorithm (GA) is a heuristic method to find the global or nearly the global optimum without calculating all possible elevator routes. Fig. 2 shows the application of GA chromosomes to four landing calls and two cars A and B. Each chromosome holds a possible elevator route for how four calls can be allocated to two cars. The fitness, for instance, average waiting time, is calculated for each chromosome. A new generation of chromosomes is generated from the ones with best fitness values by mutation and cross-over techniques. GA finds the

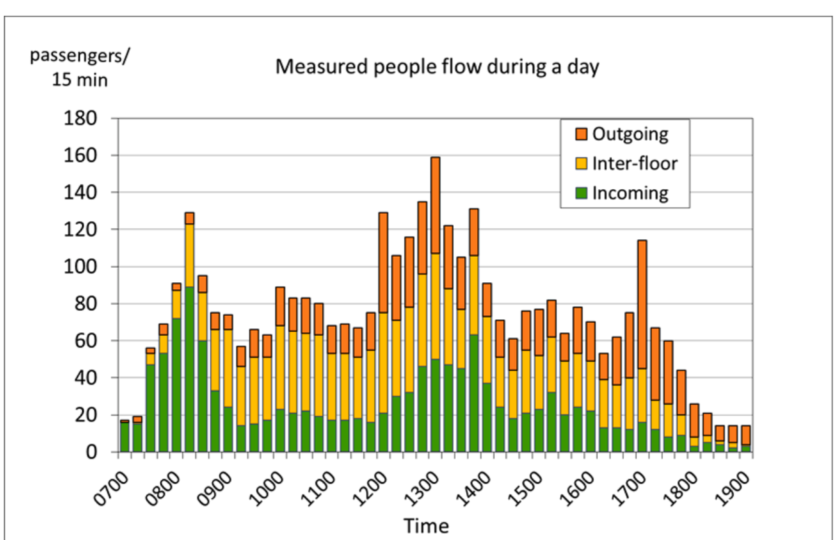


Fig. 3. Measured and learned the number of passengers using elevators per 15 min throughout the day (Siikonen, 1997a).

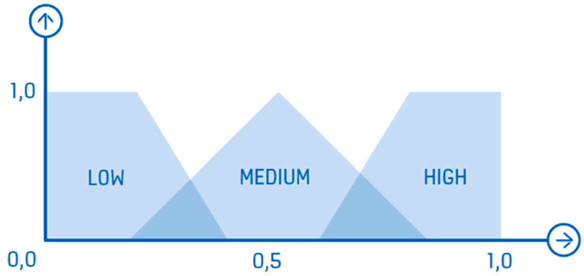


Fig. 4. Memberships of traffic components (Siikonen, 2022).

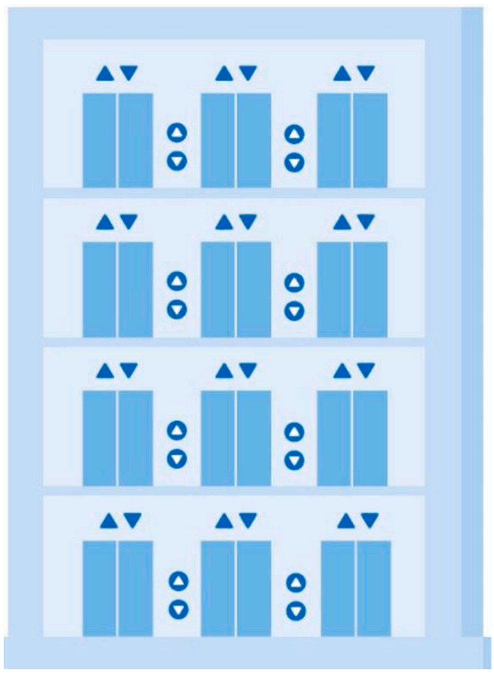


Fig. 5. Conventional elevator group of three elevators, four served floors, lanterns, and up and down call buttons (Siikonen, 2022).

optimum in real-time, especially when using innovations to reduce calculation of same routes, such as Gene Bank (Tyni et al., 1999).

3.4. Traffic prediction with artificial intelligence

Artificial Intelligence (Kameli et al., 1989), fuzzy logic (Powell & Sirag, 1993), and neural networks (Sasaki, Markon & Nakagawa, 1996) have been applied to learn the passenger and elevator traffic patterns during the call allocation. The control system could, for example, count and learn the number of people using the elevators throughout the day using load weighing devices in the measurement (Siikonen, 1997b). In a simple form, with *exponential moving average*, also called exponential smoothing, the forecast data adapts to the new data and forgets little by little the old data. The weighting of the old data, F_{p-1}, decreases exponentially, as shown in Eq. (17),

$$F_p = \begin{cases} x_0, & p = 0 \\ (1-\alpha)F_{p-1} + \alpha X_p, & p > 0 \end{cases} = F_{SMA,p-1} + \frac{X_p - X_{p-n}}{n} \tag{17}$$

where $0 < \alpha < 1$. The value of α can be determined statistically, or by other means. Values of α close to one give more weight to the recent changes in the data, while values closer to zero give more weight to the old data. Once a day, the measured data is combined with the learned data with the old forecast. The forecasts are used in the call allocation to predict future traffic situations, such as shown in Fig. 3, and the elevators could be dispatched to the peak traffic floors in advance.

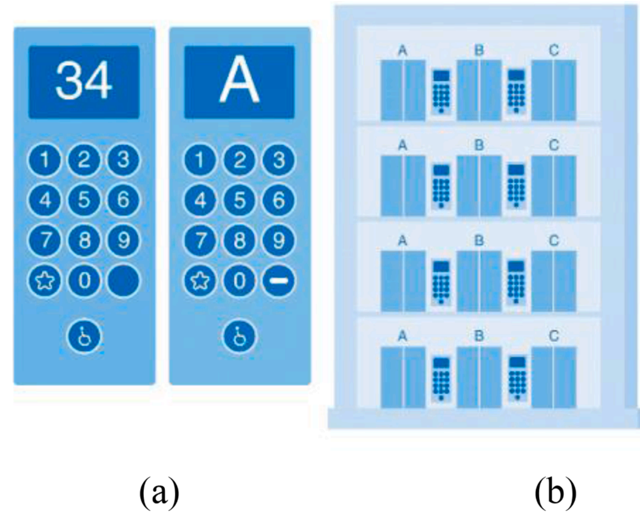


Fig. 6. Destination keypad with given destination and assigned elevator identifier (a), and the car entrances with elevator identifier (b) (Siikonen, 2022).

From the learned data, the traffic pattern can be recognized, e.g. by using fuzzy logic (Zadeh, 1965). The portions of the traffic components incoming, outgoing, or interfloor can be classified from membership functions to low, medium, or high, see Fig. 4. The traffic patterns can be recognized from fuzzy rules as shown in Eq. (18).

$$\begin{aligned} &IF\ intensity = HEAVY \\ &AND\ incoming\ traffic = HIGH \\ &AND\ outgoing\ traffic = LOW \\ &AND\ interfloor\ traffic = LOW \\ &THEN\ UP-PEAK \end{aligned} \tag{18}$$

4. Control systems

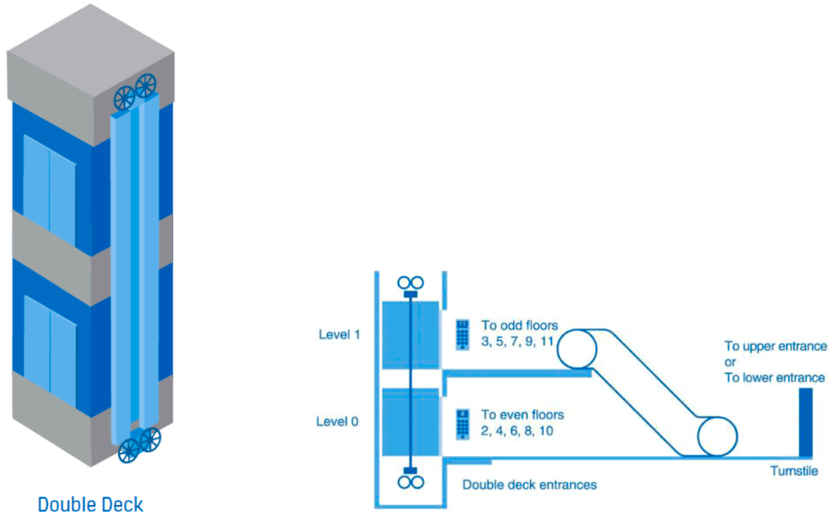
4.1. Conventional control system

Elevator groups were originally controlled by relays, similar hardware as was used in telephone centers. On landing floors, the elevators were called by buttons near the elevator well. Inside the car, an attendant was informed of the service needed by a bell or an indicator display (Gray, 2002). The doors and elevator movement were operated manually by attendants from inside the car by a car switch to prevent the doors from hitting passengers and the car from becoming overloaded (Strakosch, 1983).

Fig. 5 shows the functionality of conventional control which is still the most common control system. It has up and down call buttons on every floor. A passenger gives the up call when he wants to travel up, and a down call when travelling down. The arriving elevator and its direction are signaled by a lantern above the door opening at the stage when a serving car is stopping on the landing call floor. The control system searches continuously for the nearest or the “best” car for the landing call. The shortest waiting times are reached when the elevators are evenly spaced in the elevator shafts. In the worst case, the elevators are bunched moving side by side, and the service interval is close to the elevator round-trip time.

4.2. Destination control system

Destination dispatch was studied at Manchester University with the ACA algorithm (Barney & Dos Santos, 1977). It was discovered that the early information on passenger origin and destination floors would improve the optimization result. At that moment the time was not mature enough for new types of call-giving devices and guidance



(a) (b)

Fig. 7. Double-deck system with two attached cars (a), and the lobby arrangement of a double-deck system (b) (Siikonen, 2022).

methods.

The first destination control application was Miconic 10 (Schröder, 1990a), which was further developed into the Port system (Friedli et al., 1999). The user interface changed from the up and down call buttons to the destination panel (Fig. 6a). From the panel, each passenger dials his/her destination floor, and the panel immediately shows the identifier of the serving car. On each floor, the elevators are identified by IDs and passengers are guided to the selected elevator (Fig. 6b). Car call panels inside the cars are not necessarily needed. In some applications, the destination call can also be given by a mobile phone or by an access card. By the turn of the second millennium, all major elevator manufacturers introduced their own DCS applications.

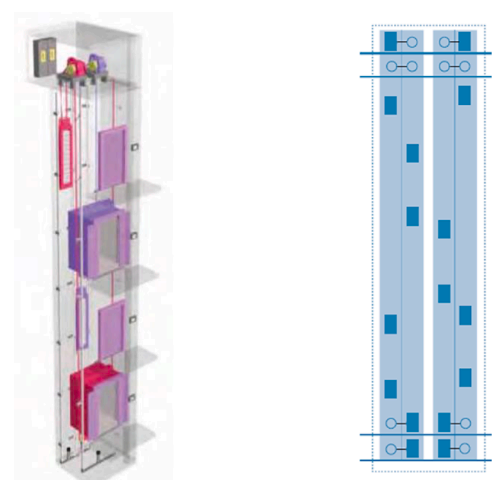
The passenger call of DCS consists of both an origin and a destination floor, which enables the DCS to make wiser decisions. It can, for instance, gather people with the same destination in the same car. In this way, the number of elevators stops can be reduced. The round-trip times become shorter, which increases the elevator group handling capacity (Smith & Peters, 2003) and reduces passenger journey times.

4.3. Two cars in one shaft

In the 1960s in North America, double-deckers were installed. At that time the control systems were not versatile enough but, in this millennium, double-deckers became popular again since microprocessor-based control systems could improve the service level in all traffic situations.

Double-decker (DD) is a multi-car system where two cars are attached in the same sling and the cars serve sequential floors simultaneously (Fortune, 1996) as shown in Fig. 7a. On the entrance floor, passengers are guided to the lower car if, for instance, they are destined for even floors and the upper car for odd floors, as shown in Fig. 7b. An escalator is usually needed to bring the passengers to the upper lobby. The benefit of having two decks and even-odd arrangement is that the number of stops on the way up is reduced. Depending on the control system, a DD with destination control can even triple the up-peak handling capacity compared to single-car elevators (Sorsa, Siikonen & Ehtamo, 2003). As the latest control development of the double-deckers is the harmonized elevator dispatching system. There, destination call panels with immediate allocation are placed at the main entrances and on upper floors destination calls are reallocated continuously (Barker, 2018).

In the 21st century also a concept in which two traction cars move independently in a single hoist-way, the TWIN concept, was deployed. Both elevators have their motors and counterweights, as shown in Fig. 8a. (Thumm, 2004). To prevent elevators from colliding with each other, a four-level safety system was developed, one of which is the DCS that prevents the car routes of the elevators from crossing each other.



(a) (b)

Fig. 8. TWIN system with two independent cars running in the same shaft (a) (Thumm, 2004), and a multi-car system with several cars circulating in two shafts (b) (Shoellkopf et al., 2016).

4.4. Multi-car systems

The first multi-car system, the paternoster, appeared already in the 1860s in England (Gray, 2005). A paternoster system is an open passenger elevator system without landing or car doors and call buttons where cabins with a fixed distance constantly in two parallel shafts. At present, paternoster does not fulfill the safety standards and cannot be used. A multi-car system where several cars move in the same shaft and can switch shafts horizontally was introduced in the 1990s (Barker, 1997), but was never launched as a product.

The latest development of a multicar system is the MULTI, where several ropeless elevators with linear motor technology circulate independently around two shafts (Jetter & Gerstenmeyer, 2015; Schoellkopf et al., 2016). It has a running prototype in a test tower in Germany. In the prototype, several cars circulate in two shafts (Fig. 8b). The cars are rather small, for instance for eight persons. Control method for a multi-car systems where the cars can move in opposite directions in the same shaft, have been introduced (Markon, Suzuki, Ikeda & Kita, 2007; Valdivielso et al., 2011).

5. Traffic analysis methods

5.1. Calculation method

At the elevator planning stage, the up-peak traffic situation is usually analyzed to define the number, sizes, and speeds of elevators. Up-peak traffic occurs typically in office buildings in the morning when people enter the building. It is a difficult situation, especially considering the elevator handling capacity since all passengers enter the elevators from one entrance floor. For up peak calculation, the round-trip time of an elevator is calculated. Already in 1923, an article was published about the probable number of elevators stops during up-peak (Basset-Jones, 1923). Schröder introduced the roundtrip equation in 1955 (Schröder, 1955). The formula given by Barney (Barney, 2003) is used in the recently published elevator selection standard (ISO, 8100–32:2020)

$$t_{rt} = 2Ht_v + (S+1)t_s + 2Mt_p. \tag{19}$$

In Eq. (19) H is the highest reversal floor, S is the probable number of stops during up trip, M is the average number of passengers in the car when leaving from the entrance floor t_p is passenger transfer time in or out from the elevator, and t_v is d/v, i.e. the travel time for distance d at rated speed. The time consumed to stop t_s in Eq. (20), includes elevator acceleration and deceleration times, door times, and other delays during a stop, but not the passenger transfer times (ISO 8100–32, 2020).

$$t_s = t_c + t_{sd} + t_f(1) - t_{pre} + t_o + t_{cd} - t_v, \tag{20}$$

where t_c is door closing time, t_{sd} is start delay, $t_f(1)$ is one-floor flight time, t_o is door opening time, and t_{cd} is door clearance time. By the definition, the stop time includes the acceleration and the deceleration of the elevator which is obtained by decreasing the running time with the rated speed from the one-floor flight time, $t_f(1)$-t_v. The elevator doors can start to open already in the deceleration phase, and to avoid double calculation the preopening time of doors t_{pre}, is subtracted in Eq. (21). The roundtrip time equation for different floor distances r was considered by Roschier (Roschier et al., 1979)

$$t_{rt} = \sum_{r=1}^{N} (T_r + D_r)(t_r + t_d) + 2Mt_p \tag{21}$$

where T_r and D_r are the probable runs with r-floor distance in an upward and downward direction, respectively, N is the number of floors, t_d includes the door opening and closing times, and the flight time for an r-floor distance is t_r. From the roundtrip time, elevator handling capacity, Ch, and interval, $tint$, for L elevators can be calculated for the up-peak situation.

$$C_h = \frac{300ML}{t_{rt}} = \frac{300M}{t_{int}} \tag{22}$$

The multiplier 300 in Eq. (22) scales the handling capacity to 300 s, i.e. to persons transported in five minutes. Relative handling capacity shows the percent of population elevators can transport in five minutes, and it is obtained from Eq. (22) by dividing C_h by the population of the served floors. In traffic analysis, the relative handling capacity and the interval must meet the design criteria of that building type. Roundtrip time Eq. (19) assumes uniform passenger arrivals and equal floor heights (Siikonen, 2022), and is incomplete in many senses, but it is accurate enough in most buildings and cases. For instance, it does not consider multiple entrances (Al-Sharif, 2010), or exact flight times of different running distances. Eq. (19) cannot be applied to DCS since DCS control system arranges people in certain cars according to their destinations. A formula to calculate elevator round trip time with DCS has been suggested (Schröder, 1990b; Sorsa et al., 2006). Generalized round-trip time equations for all traffic situations have been introduced (Al-Sharif, Alqumsan & Khaleel, 2014; Hakonen et al., 2005). Stochastic multicriteria analysis has been introduced to optimize simultaneously several objectives such as elevator handling capacity, passenger waiting times, elevator group price, and space demand (Hakonen, Lahdelma & Siikonen, 2006; Tervonen, Hakonen & Lahdelma, 2008).

5.2. Simulation method

In complex cases, such as groups with more than eight cars or more than 18 floors, groups with different types of elevators, or high-rise solutions such as two or more cars in one shaft, the up-peak calculation is not sufficient. Simulation of passenger traffic in a building is a more flexible analysis method than calculation since various traffic patterns, such as lunchtime traffic, and different group control systems can be studied. Occupant evacuation by elevators can be studied with traffic simulations (Bukowski, 2010; Kinateder, Hidomi & Kuligowski, 2014). After the attack on the World Trade Center in 2001, standardization organizations started to develop codes for the means to safely evacuate people from buildings using elevators (ASME A17.1, 2013; CEN/TS 81–76, 2011; ISO TS 18870, 2014). Evacuation codes are not yet obligatory but in most megatall buildings evacuation needs to be simulated at the planning stage. The generated passengers give landing or passenger calls according to their arrival-destination floor pairs at the elevator lobbies. The group control system allocates the given calls to the "best" elevators. Real or generic control system software can be implemented in the simulator. From the simulation results, waiting times, journey times, loadings, number of stops, energy consumption, and other parameters can be analyzed.

To simulate vertical traffic, building, and elevator data are given as input, and passenger traffic is generated from the building data (Kuusinen, 2015; Siikonen, 1993). Daily passenger traffic patterns in offices, and in hotels and residential buildings have been measure and standardized (Siikonen, 2000a, 2014). The passenger arrival–destination floor pairs are formed using the building data, and random arrivals are generated according to the elevator origin-destination matrix (Al-Sharif & Alqumsan, 2015; Kuusinen, Sorsa & Siikonen, 2014). This assumption of random arrivals is based on a study made by Alexandris (Alexandris, 1977) in office buildings. Later field studies revealed that social groups of one to five persons arrive at office elevator lobbies (Kuusinen, Sorsa, Siikonen & Ehtamo, 2012). Similar results were obtained in other types of buildings (Sorsa, Siikonen, Kuusinen & Hakonen, 2021). In a stochastic optimization study, uncertain future passenger arrivals were modelled as a Poisson and a geometric Poisson process. Numerical experiments show that the geometric Poisson for batch arrival process gives better forecasting accuracy than the Poisson process of individual arrivals (Sorsa et al., 2018). Theoretical up-peak traffic round trip time on a cruise ship was compared with Poisson and batch arrivals where modeling batch arrival equations gave a better fitting (Sorsa et al., 2014). There are several ways to validate elevator traffic simulation models (Bartz-Beielstein, Preuss & Markon, 2005; Siikonen, 2022).

Currently, for elevator planning purposes, three types of traffic simulators are used:

1) Monte Carlo simulation is based on building data and probabilities without the effect of a control system (Al-Sharif, Aldahiyat & Alkurdi, 2012)
2) One elevator group simulation in a building (Lustig,1986; Schröder, 1990b; Siikonen, 1993; Peters, 2020)
3) People flow simulation in buildings by modeling simultaneously passenger traffic in many transportation devices (Hakonen, Kuusinen

& Sorsa, 2023; Kuusinen, Sorsa, Siikonen, Hakonen & Ehtamo, 2017; Siikonen et al., 2000b)

The ISO 8100–32:2020 standard defines the parameters for the input and output of simulations and sets out the simulation design criteria for the different types of traffic situations and buildings. According to the ISO simulation method, in office buildings, simulations for both up-peak and lunch-hour traffic mixes need to be performed. The simulations are made for three constant demands starting from the demand of the required handling capacity. In the up-peak situation, the required handling capacity in a multi-tenant office building for local elevators should exceed 12% of the population in five minutes, and the average waiting times should stay below 30 s. For the lunch hour traffic, the required handling capacity is 11% in five minutes, and the average waiting times should stay below 40 s.

6. Space demand for elevators in tall buildings

6.1. Elevator zoning

Tall buildings often get narrower towards the top of the building, and thus there is less space for the elevators. Therefore, supertall and megatall buildings are often planned for mixed-use, such that they have retail and office tenants in the lower part of the building, with hotel tenants in the middle and apartments at the top. Passenger traffic is lighter in the apartment zone than in the office and retail zones, and thus these zones require fewer elevators.

If more than eight elevators are required, several elevator groups are needed. One elevator group can serve at most 18–25 populated floors. Elevator groups can be zoned such that each group serves a different part of the building. Typically, the building is divided into low-, mid-, and high-rise zones (Powell, 1971; Ruokokoski, Sorsa & Siikonen, 2018; Schröder, 1984). Elevators in the mid-rise group express to the served floor zone and bypass the low-rise zone, and the high-rise elevator group expresses over the low- and mid-rise zones. In selecting the local elevator groups for the zones their relative handling capacities should be about the same, and the elevator departure interval and the travel time should meet the given design criteria. For the upper zones, the elevators have higher speeds to meet the interval criteria.In planning elevators, also the situation where one car is out of service needs to be considered. Elevator handling capacity should not decrease below and waiting times should not exceed given limits. The final solution is always a compromise between all these criteria and is separately determined for each project.

Depending on the building tenants, population, floor heights, and elevator solution about 70–90 floors can be served by local elevator zones starting from the ground. If all elevator groups start from the ground, they take up a lot of the space on the lower part of the building. To decrease elevator core space, normally a sky-lobby arrangement is used. The local elevator group shafts are stacked on top of each other to reduce the elevator core space in the building. A shuttle elevator group transports people between the ground and the sky lobby without stopping on the way. It should be able to transport people from the floors above the sky lobby to the ground within a given time. One sky-lobby is normally sufficient for about 50–100 floors, and typically two sky-lobbies or more are defined buildings over 100 floors. The building is first divided vertically into two or three parts, where each part is served by local elevator groups (Schröder, 1989). Occupants destined below the sky lobby use a local elevator group from the ground. If they are destined above the sky lobby, they first take a shuttle elevator group which transports them directly from the ground to the sky lobby. From the sky lobby they continue their journey with local elevator groups to the upper floors.

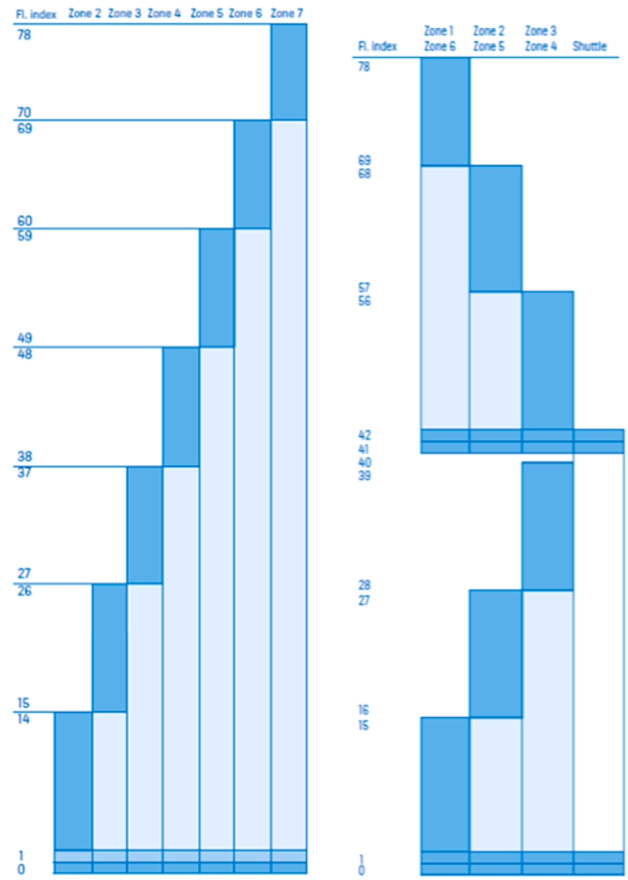


Fig. 9. A zoned building with seven elevator groups starting from the ground a), a sky-lobby solution with a shuttle group, and six local elevator groups (Siikonen, 2022).

6.2. Example zonings of a supertall building

In the following, the space demand for elevator solutions in a 312-meter-high building is compared. The example building has in total of 78 floors with the average floor height of four meters and 10 920 people. The elevator arrangements used in the example are shown in Fig. 9. The load of local elevator cars is 1 600 kg, and for the shuttle elevator cars 2 000 kg, and the double-deck elevators twice as much.

In a zoned elevator scenario, all seven elevator groups start from the ground floor. A more common design in supertall buildings is the sky-lobby solution. In the example case, three local elevator groups start from the ground and three local groups from the sky lobby. In the following, a total of six different elevator solutions are studied. The number of elevators for each solution is selected such that they fulfill the design criteria of the ISO 8100–32:2020 standard. Four elevator solutions were used for the zoned elevator arrangement:

1) Single elevators with conventional control system using up and down call buttons.
2) Single elevators with destination control system.
3) Double-deck elevators with conventional control system using up and down call buttons.
4) Double-deck elevators with destination control system.

and two solutions for the sky-lobby arrangement

1) Double-deck elevators with destination control system for all elevator groups.

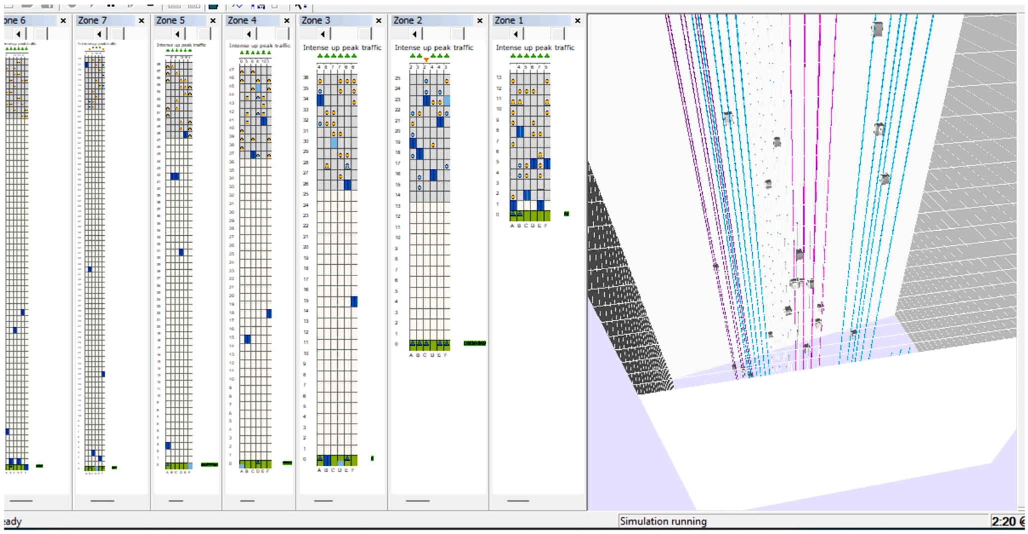


Fig. 10. 2D and 3D simulation views of KONE BTS™ (Siikonen et al., 2000b).

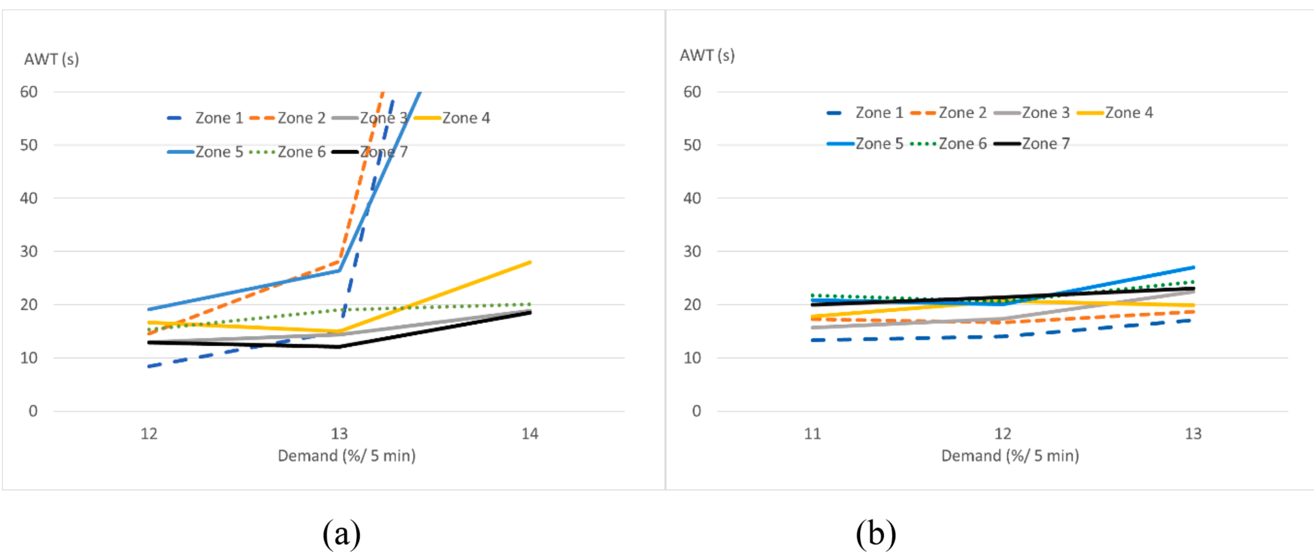


Fig. 11. Simulated average waiting times with the conventional control system for the up-peak situation (a), and for lunchtime traffic (b) (Siikonen, 2022).

2) Double-deck elevators with a destination control system for the local elevator groups, and a multi-car solution for the shuttle group.

6.3. Simulation study of the example building

Simulations were run for the six elevator solutions described in Section 6.1. The Building Traffic Simulator, KONE BTS™ was used in the simulations, see Fig. 10. In the figure, a 2D-view of seven elevator shafts each comprising six single deck elevator groups are shown. Each group is controlled by the DCS control system. In the 3D view, all elevators in the building are shown. In KONE BTS™, escalators and stairs can be defined as well. The simulation with all elevator groups can run 10 −100 times faster than in real time. It includes KONE specific or generic control systems which can be selected for each elevator group separately. It is also possible to simulate complex cases where some passengers must switch elevator groups on the way to their destination floors.

During the simulation, passengers use the required transportation devices to get to their destinations. From the simulated traffic events, for instance, average passenger waiting times can be analyzed. On the y-axis of Fig. 11a, the average waiting times are shown for the seven elevator groups in the up-peak situation, and in Fig. 11b for the lunch hour situation, respectively. The first demand is for the required handling capacity of the corresponding traffic type. In up-peak, passenger waiting times start to increase rapidly when the arrival rate (passenger demand) exceeds the elevator group handling capacity. In this case with a conventional control system, an arrangement of seven elevator groups fulfills the design criteria.

Similarly, passenger traffic for the other five solutions was simulated, and the elevator group sizes were selected to fulfill the design criteria. For the multi-car solution, the number of cabins was selected using the principle described by Gerstenmeyer (Gerstenmeyer & Peters, 2015). As a result, the sky lobby arrangement with the multi-car shuttles requires three circulating multi-car elevator systems with five cabins for eight persons in each. The layouts of the selected cars for each elevator solution are shown in Fig. 12 for the zoned building and the sky-lobby arrangement in Fig. 13.

The relative core space demand of different solutions is calculated considering a single elevator lobby area $A_{k,\ lobby}$, and shaft area $A_{k,\ shaft}$. Firstly, for the elevator group floor area, the single shaft and lobby areas

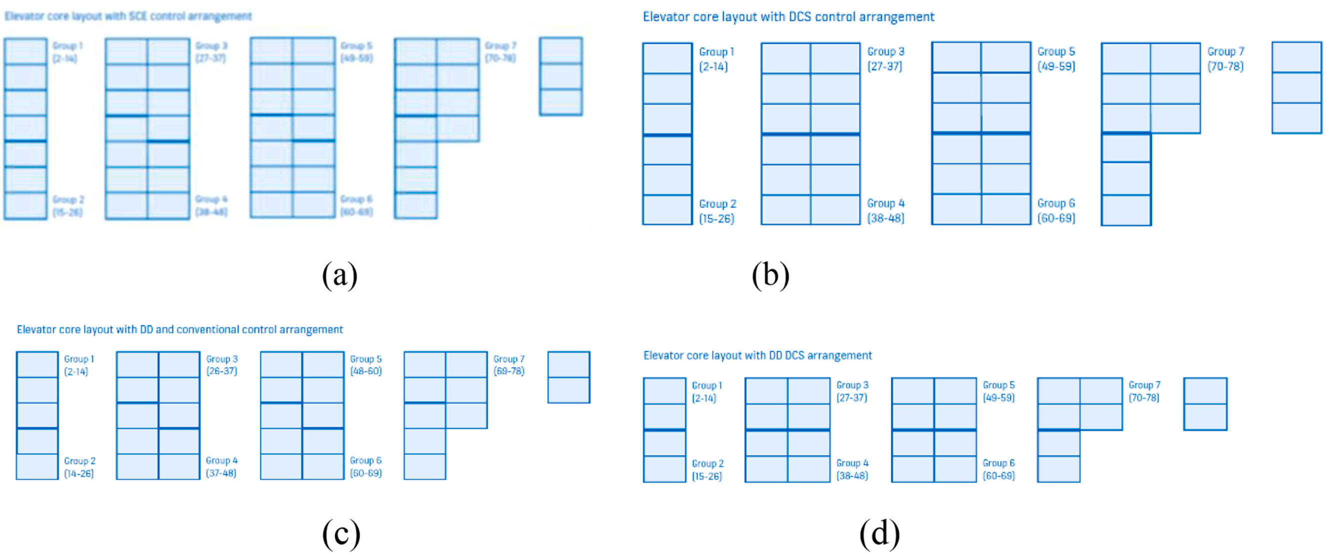


Fig. 12. Lobby layouts in a zoned building with conventional control system a), destination control system b), double-deck conventional system (c), and double-deck destination system (d) (Siikonen, 2022).

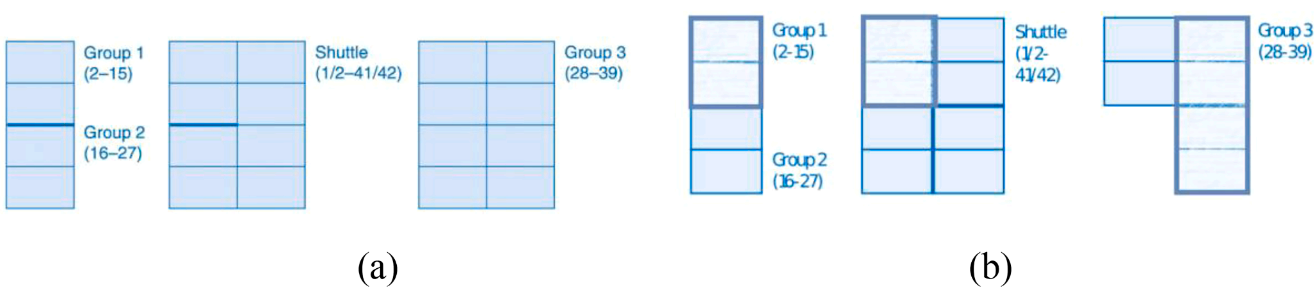


Fig. 13. Lobby layouts for a sky lobby arrangement with double-deck destination control system a), and multi-car system b) (Siikonen, 2022).

Table 1
Elevator core areas with different solutions.

Elevator arrangement	Zoned building (7 zones)				Sky lobby arrangement	
Elevator solution, see Chapter 6.1	1) Conventional control	2) Destination control	3) DD conventional	4) DD destination	5) DD destination	6) Multi-car shuttle
Number of shafts on the ground floor	48	42	35	28	20	18
Number of local group/shuttle group shafts	7	6	5	4	4 + 4 / 8	4 + 4 / 6
Number of cabins	48	42	70	56	64	63
Elevator core space (m3)	111,004	96,222	81,439	66,657	51,348	41,321
Relative core space	100%	87%	73%	60%	46%	37%

are multiplied by the number of shafts $N_{k,shafts}$ in local zones k. To obtain the core space, the elevator group floor areas are multiplied by the number of floors elevator zone k occupies $N_{k,floors}$ and by the average floor height in meters d_{floor}. Finally, for the elevator core space of the whole building, S, the core spaces for all zones N_{zones} are summarized as follows

$$S = \sum_{k=1}^{N_{zones}} N_{k,\ floors} d_{floor}\ N_{k,\ shafts}\left(A_{k,\ shaft} + A_{k,\ lobby}\right) \tag{23}$$

To obtain the lobby areas in meters, the dimensions of the elevators were roughly estimated according to the ISO standards (ISO 8100–1, 2019; ISO 8100–30, 2019). The elevator core space in m^3 by using Eq. (23) for different solutions is shown in Table 1. The relative core space is obtained by scaling the core spaces of different solutions to the result of the conventional control system.

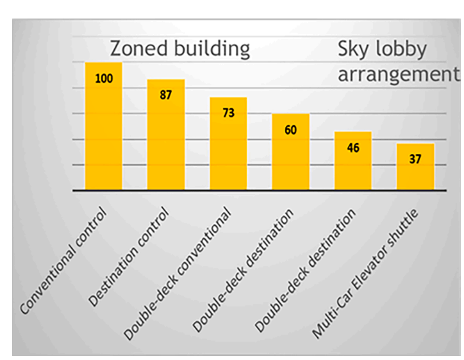


Fig. 14. Relative space demand of each elevator solution in the example of supertall building.

In the graph of Fig. 14, the relative core space of a conventional control is scaled to 100. The core space is calculated by multiplying the elevator lobby area including the shaft areas by the elevator group travel height. According to the figure, for example, in the zoned arrangement the double-deck destination control decreases the core space to 60% of the conventional system. A sky lobby solution with a multi-car shuttle decreases the core space by nearly one-third of the conventional system.

Design and control.

7. Conclusions

This article summarizes how mathematical methods are used to model elevator dispatching systems and are used in controlling elevators. Many of the models are based on measured traffic and people flow in buildings. Different elevator solutions are briefly described, and the solutions are used in a case study of a supertall building. Building traffic simulation has enabled us to study the effect of people flow and elevator solutions on passenger service level even before the building exists. A simulation comparison of the elevator solutions in the supertall building shows that with a shuttle arrangement using a multicar system, elevator core space can be decreased to about one-third of an intelligent conventional system.

Until now, the limiting factor in constructing tall buildings has been the required elevator core space,which may occupy too much of the rentable space. Another limiting factor has been the elevator speed, especially the one with the shuttle elevators. Elevator speed needs to be increased with the travel height to meet the design criteria of elevator interval and passenger waiting times. With a multi-car system using ropeless and counterweight-less technology, the speed limitation will disappear. The design criteria of waiting times and handling capacity can be met just by adding the number of cars in the shaft. A mile-high building would require three sky lobbies, depending on the floor area and the utilization of the floors. The local elevator groups can be constructed the same way as in the previous example, but more multi-car shuttle elevator groups are needed. According to the results of the previous study, with the multicar arrangement, Frank Lloyd Wright's dream of a mile-high building can come true.

CRediT authorship contribution statement

Marja-Liisa Siikonen: Writing – original draft, Writing – review & editing.

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