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High-resolution modeling of elevator power consumption

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Abstract

This paper proposes a framework for modeling the instantaneous power consumption of individual elevators and elevator groups based on passenger traffic. Though elevators have a key role in the modern urban society, they have remained as rather neglected appliances in the energy efficiency research. To accelerate the energy efficiency studies of elevators, this paper has two major contributions. First, we propose means to model the instantaneous power consumption of individual elevators and elevator groups and analyze the reliability of these means versus the complexity of the modeling. Second, we present an elevator group control scheme to organize the elevator dispatching according to the simulated passenger traffic. When combined, these methods yield enhanced predictions about the energy and power consumption of elevators in a specific type of building with measured or simulated movement of occupants.

Keywords: elevators, high-resolution modeling, power consumption, energy efficiency, passenger traffic

1. Introduction

Urbanization and sustainability have become major drivers for almost any industry. The elevator industry is a special case where urbanization and sustainability have strong synergy. First of all, elevators enable construction of tall buildings, increasing land use efficiency. Furthermore, the customer demand for energy efficient elevator systems is increasing [1]. Thus, the evaluation of energy consumption and power demand of these devices has become more important than ever before.

Elevators typically consume less than 10 percent of the building total electricity consumption annually [2, 3]. However, the ratios vary in time and between buildings and can be even up to 40% during peak usage hours [4, 5]. The energy efficiency of elevators has increased its importance in the elevator market with companies, researchers, and customers aiming to perform the life cycle assessments for elevators [6].

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Recently, the adaptation of energy efficiency classification in elevators has followed the trend of classifying household appliances according to their energy performance. The two most known approaches are the VDI 4707-1 guideline [7] and the ISO 25745-2 standard [8] , which are discussed, e.g., in [9, 10, 11].

The recent technological advances in tall elevator design and materials enable increased performance in passenger volumes, ride comfort, and energy efficiency [4]. Previously, it was considered that measures to decrease the energy consumption of vertical transports meant poorer service, i.e., depreciated transportation performance. Nevertheless, sophisticated multiobjective control algorithms, such as analyzed in [12, 13, 14], powered by the increased computing resources and large, long-term data sets enable designing optimized elevator systems which provide a satisfactory service level (handling capacity of passengers per time unit) while saving energy compared to traditional control schemes. Furthermore, elevator manufacturers aim to improve the operation and maintenance of the devices by introducing more remote monitoring features. For example, KONE Corporation aims to connect more than one million units to a condition monitoring platform running on the cloud in the next few years. Similar strategies to decrease breakdowns are also being executed by other companies in the field. A likely step is also moving towards remote monitoring of power consumption, such as demonstrated in [3].

For now, the instantaneous power consumption profiles of elevators, and especially elevator groups, is largely unknown. Some estimates of daily and annual consumption can be calculated for individual elevators, e.g., with the help of the ISO 25745-2 standard and the VDI 4707-1 guideline. However, due to the complex, intermittent nature of elevator usage, the intraday power consumption profiles are difficult to model. Typically, a simulator, such as depicted in [15, 16, 17] could be utilized for analyzing individual elevators or elevator groups. However, applying these simulators on a large scale is burdensome and often requires manual input of parameter values. Therefore, this paper aims to provide a framework and tools for modeling large amounts of elevators and their power consumption. The approaches can be employed by various parties, ranging from scholars to grid operators and elevator manufacturers. For example, elevator manufacturers can employ the power consumption data and energy consumption estimates to improve the energy efficiency of their products. Furthermore, knowing the elevator-related power consumption enhances the power grid planning and electrical system design of buildings.

The paper is structured as follows. Sections 2 and 3 present the modeling methods for power consumption and the applied group control algorithm, respectively. Section 4 contains the test results of the proposed methods against measured data. Section 5 discusses the utilization possibilities of the model and potential changes to be implemented to the model. Section 6 concludes the main findings of the paper. Appendix A introduces the presumptions employed in the simulation of the test cases, and Appendix B presents a procedure to reduce the complexity of the modeling.

2. Elevator power consumption modeling

Power and energy consumption of elevators can be modeled with many means depending on the desired granularity, accuracy and scope of the analysis. In this paper, the scope is on the system level rather than on the impact of individual components (see Section 5 for more details). The aim is to focus on the intermittent nature of elevator power consumption and the most significant contributors of energy efficiency.

Elevator energy consumption can generally be divided into two components: stationary consumption and running consumption:

$$E_{\text{tot}} = E_{\text{stationary}} + E_{\text{running}} \ . \tag{1}$$

Stationary (not running) energy consumption can either be constant or time dependent in case the elevator has energy saving modes. For example, the ISO 25745-2 standard proposes the daily non-running energy consumption to incorporate three power components: idle and 5-minute and 30-minute standby demand. The idle power demand is considered to occupy the first five minutes after the doors have been closed at the last destination floor. The 5-minute power demand is consumed between 5 and 30 minutes after the landing, and the rest of the time is contributed to the 30-minute standby power demand.

Running energy consumption, on the other hand, depends on the number of starts and the characteristics of those starts, mainly the direction, distance, and concurrent loading. A significant difference in the resulting energy consumption is also caused by the applied elevator technology. For example, from the hoisting perspective, elevators are commonly divided into traction and hydraulic elevators.

2.1. Traction elevators

Traction elevators comprise a significant majority of all elevator installations [2]. In traction elevators, the hoisting system includes a car and a counterweight. To reduce the running energy consumption and maximum power demand, the mass of the counterweight, m_{cw}, is typically sized to match the mass of an empty car, m_{car}, and a fraction of the nominal (rated) load, m_{nominal}:

$$m_{\text{cw}} = m_{\text{car}} + K \cdot m_{\text{nominal}} \ , \tag{2}$$

where K is commonly between 0.4 and 0.5 (40 – 50 percent).

To lift or lower a load of m_{load} in ideal conditions without losses, the elevator drive performs work equivalent to

$$\begin{aligned} E_{\text{potential}} &= m_{\text{net}} gh = \left((m_{\text{car}} + m_{\text{load}}) - m_{\text{cw}} \right) gh \\ &= \left((m_{\text{car}} + m_{\text{load}}) - (m_{\text{car}} + K \cdot m_{\text{nominal}}) \right) gh \\ &= \left(m_{\text{load}} - K \cdot m_{\text{nominal}} \right) gh \ , \end{aligned} \tag{3}$$

where m_{net} is the net mass on the elevator car side (negative if more mass on the counterweight side), g is the acceleration due to gravity (9.81 m/s^2), and h is the distance covered. If the net load is negative while lifting the car, energy is released to the elevator drive. The same situation occurs when the net load is positive and the elevator car is descending. When considering the hoisting efficiency, η, the following simplified equations can be used for a start i:

$$E_{\mathrm{running},i} = \begin{cases} \dfrac{E_{\mathrm{potential},i}}{\eta}, & \text{for } E_{\mathrm{potential},i} \geq 0 \\ \eta E_{\mathrm{potential},i}, & \text{for } E_{\mathrm{potential},i} < 0 \ . \end{cases} \tag{4}$$

Recently, elevator drives have increasingly been sold with regenerative capabilities. In these types of elevators, the energy recovered during a start is fed back to the electric grid of the building. As a rule of thumb, it can be presumed that $70 - 75\%$ of energy required to lift the same load can be recovered as electricity [11, 18]. This means that the hoisting efficiency is around 85 percent in modern installations. In elevator installations with brake resistors, the excess energy is converted into heat, and, from the power system point of view, $E_{\mathrm{running},i}$ equals to zero.

Though the above equations can be considered enough for simple analysis [19], it is difficult to estimate their suitability for analyzing the aggregated power consumption of multiple elevator units with varying characteristics. In this paper, we compare the performance of the above equations to an approach which also considers energy consumed during the acceleration and deceleration phases of an elevator start. In these phases, the inertia of the hoisting system induces additional component to the energy equation as it resists the change of speed. The model utilizes the following equations as default.

$$\begin{aligned} T_{\mathrm{M}}(t) &= \left(J_{\mathrm{M}} \ + \ \left(\frac{\omega_1}{\omega_{\mathrm{M}}}\right)^2 (m_{\mathrm{cw}} + m_{\mathrm{car}} + m_{\mathrm{load}})\, r^2 \right) \left(\frac{d\omega_{\mathrm{M}}}{dt}\right) + \left(\frac{\omega_1}{\omega_{\mathrm{M}}}\right) rgm_{\mathrm{net}} \\ &= \left(J_{\mathrm{M}} \ + \ \left(\frac{\omega_1}{\omega_{\mathrm{M}}}\right)^2 (m_{\mathrm{cw}} + m_{\mathrm{car}} + m_{\mathrm{load}})\, r^2 \right) \left(\frac{a(t)}{r}\right) + \left(\frac{\omega_1}{\omega_{\mathrm{M}}}\right) rgm_{\mathrm{net}} \ , \end{aligned} \tag{5}$$

$$P_{\mathrm{M}}(t) = T_{\mathrm{M}}(t) \cdot \omega_{\mathrm{M}}(t) = T_{\mathrm{M}}(t) \cdot \frac{v(t)}{r} \ , \tag{6}$$

where $T_{\mathrm{M}}(t)$ is the torque required from the motor to overcome the system inertia and move the elevator; J_{M} is the total inertia of the motor, wheels, and pulleys; $\frac{\omega_1}{\omega_{\mathrm{M}}}$ is the roping ratio; r is the radius of the sheave; and ω_{M} is the angular speed of the sheave.

During acceleration, the sign for acceleration is the same as for speed, and opposite during deceleration. The nominal values of deceleration and acceleration can also be different. In constant speed, acceleration is naturally zero, meaning that only the gravity is impacting the required torque through the net load. For simplicity, the rate of change of acceleration, or jerk, j, is considered infinite instead of the common value of around 1 $\mathrm{m/s^3}$. Nevertheless, in the context of the study, the differences in the resulting power and energy consumption are negligible.

As in Eq. (4), the negative values of Eq. (6) are multiplied by the hoisting efficiency and positive values divided by it. This determines the electric power required by the motor and drive:

$$P_{\mathrm{M,el}}(t) = \begin{cases} \dfrac{P_{\mathrm{M}}(t)}{\eta}, & \text{for } P_{\mathrm{M}}(t) \geq 0 \\ \eta P_{\mathrm{M}}(t), & \text{for } P_{\mathrm{M}}(t) < 0 \ . \end{cases} \tag{7}$$

As before, if the value is negative and the elevator is non-regenerative, the value is set to zero.

2.2. Hydraulic elevators

In hydraulic elevators, the elevator car is lifted by a pressurized piston. The speed of an hydraulic elevator is commonly constant, and the elevator is designed for short lifts with potentially heavy loads. Due to the lack of the roping system, hydraulic elevators do not typically possess a counterweight and regeneration, especially back to electricity, is non existent. Thus, we can model hydraulic elevators slightly simpler than traction elevators:

$$\Delta E_{\mathrm{potential}} = (m_{\mathrm{load}} + m_{\mathrm{car}})\, gh \ , \tag{8}$$

$$E_{\mathrm{running},i} = \frac{\Delta E_{\mathrm{potential},i}}{\eta} \ , \tag{9}$$

$$P_{\mathrm{M,el},i} = \frac{E_{\mathrm{running},i}}{t_{\mathrm{start},i}} \ . \tag{10}$$

If the resulting value is negative, i.e., the elevator is descending, the value is set at zero.

2.3. Instantaneous power modeling

In this paper, we model elevator power consumption in one-second resolution in order to analyze the impact of the power peaks caused by the intermittent movement of elevators resulting from the passenger traffic. As mentioned in Section 2.1.1, we compare two different approaches of determining the power profile. In the first approach, which we will denote as PA1, the power consumption during a start is constant and derived from the potential energy difference (from Eq. (4)). The average power consumption during a start entails both the mechanical and auxiliary consumption, e.g., power consumed by lighting and control electronics. In our model, we consider the auxiliary consumption to correspond to the idle power demand, P_{idle}, and an additional power dedicated to control electronics, P_{control}:

$$\textbf{PA1:} \quad P_{\mathrm{start},i} = P_{\mathrm{idle}} + P_{\mathrm{control}} + \frac{E_{\mathrm{running},i}}{t_{\mathrm{start},i}} \ , \tag{11}$$

where $t_{\mathrm{start},i}$ is the time between the origin and the destination floor and is calculated with Eq. (12).

$$t_{\mathrm{start},i} = t_{\mathrm{acc},i} + t_{\mathrm{constant\_speed},i} + t_{\mathrm{dec},i} \tag{12}$$

Note that this equation excludes door operations. Power consumption of the doors is added in the beginning and to the end of the start for a duration of t_{doors}. This also applies for the second approach.

The second approach, PA2, considers the power demand characteristics during the acceleration and deceleration phases separately according to the aforementioned Eq. 5 − 7. The total power profile can be formulated as

$$\textbf{PA2:} \quad P_{\text{start},i}(t) = P_{\text{idle}} + P_{\text{control}} + P_{\text{M,el},i}(t) \ . \tag{13}$$

As mentioned earlier, the stationary power consumption of the elevator is either constant or time dependent. In elevators without any power saving modes, the stationary power consumption is modeled as a constant, while elevators with power savings modes switch off certain auxiliary and support functions to reduce the energy consumption. Following the ISO 25745-2 standard, the stationary power consumption is divided into three parts:

$$P_{\text{stationary}}(t) = \begin{cases} P_{\text{idle}}, & \text{for } t \leq 5 \text{ min} \\ P_{\text{standby\_5min}}, & \text{for } 5 \text{ min} < t \leq 30 \text{ min} \\ P_{\text{standby\_30min}}, & \text{for } t > 30 \text{ min} \ , \end{cases} \tag{14}$$

where t is the time passed since the elevator has landed and the doors have been opened and passengers have alighted the elevator.

3. Group control algorithm model

As depicted in the previous section, elevator power consumption during a start is impacted by the nominal speed, net loading, and direction of the start. The distance traveled during a start dictates the resulting energy consumption. Another contributor to the overall energy consumption of an elevator and, especially, an elevator group is the methodology which is applied to response to the incoming landing calls.

A person calling an elevator expects both short waiting time and fast travel time. Typical good design rules of thumb are that the waiting time should be kept below 30 seconds [20]. An elevator group controller typically assigns the closest suitable elevator to answer the landing call. The travel time of the passenger is impacted by the number of stops prior to the destination floor, the nominal speed of the elevator, and the overall distance to be covered. A typical time to travel the whole elevator shaft length in nominal speed depends on the specifications of the installed elevator and takes around 20 − 60 seconds, averaging in under 30 seconds.

Performing optimal, multi-objective group control is a demanding task. In our simulation model, the group control is designed to resemble an immediate collective group control, where the landing call is allocated as soon as it has been given and not reallocated any more. This resembles the first microprocessor controls from the 1980s rather than a top-of-the-line system (see comparison in Section 3.3). Fig. 1 depicts the functionality of the group control algorithm.

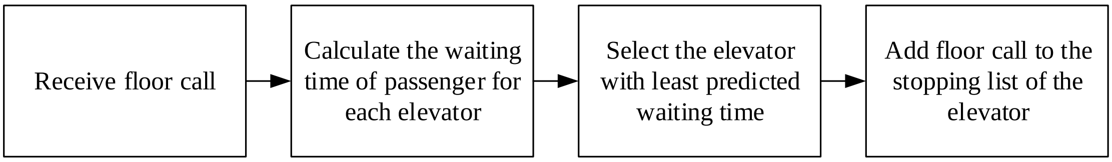

Figure 1: Simplified illustration of the collective group controller algorithm.

When a simulated passenger places a landing call (either downwards or upwards), the group controller calculates the waiting time of the passenger for each elevator in operation in the group. This calculation is based on the list of floors the elevator is stopping with prediction of possible added waiting time due to unanswered calls prior to the new floor. The direction of the new landing call determines in which position it is placed in the stopping list according to the bullet points below. Additionally, all the car calls must be served before an elevator can change its direction, i.e., the reversal floor can be shifted forward. The behavior of an elevator abiding these rules is demonstrated in Fig. 2.

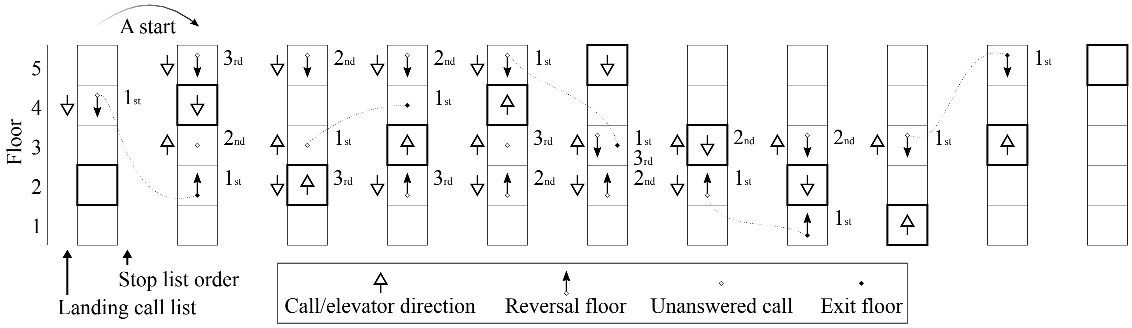

Figure 2: Example of a five-storey elevator following the control logic.

- If the call is in the same direction as the elevator is traveling to or the elevator has no previous calls, the floor is added to the stop list to the position in order of the nearest stop, provided that the floor has not yet been surpassed.
- Else, if the call is to the opposite direction than the current traveling direction of the elevator, the call is placed after the floor currently serving as the turning point of the direction. The order of floors beyond the reversal floor is once again either descending (current direction upwards) or ascending (current direction downwards).
- Otherwise, if the call is to the prevailing direction but already surpassed, the call is placed after the second reversal point (if exists) and the stopping order is kept to minimize the overall travel distance.
- The stopping list is updated only at landings, not during a start.

The waiting time for the prospective passenger is estimated by the procedure listed below.

1. Presume a disadvantageous case: add new, virtual stops between the old (unanswered) calls and the new one. More precisely, presume the boarding passengers from prior floors (in the stop list) to travel only a distance of one floor.
2. Calculate the total number of unique stops, n_{unique}, prior to the new call from the updated list.
3. Multiply the number of unique stops with stop time, t_{stop}.
4. Calculate the total distance covered prior to the new call and divide the distance by constant speed value (typically nominal speed). The result is t_{travel}.
5. The waiting time estimate is

$$t_{\text{wait}} = n_{\text{unique}} \cdot t_{\text{stop}} + t_{\text{travel}} + t_{\text{(un)load}} \cdot n_{\text{(un)load}} \ , \tag{15}$$

   where $t_{\text{(un)load}}$ is the average time for a person to load or unload the elevator, and $n_{\text{(un)load}}$ is the number of such passengers.

Fig. 3 presents an example of the estimation procedure.

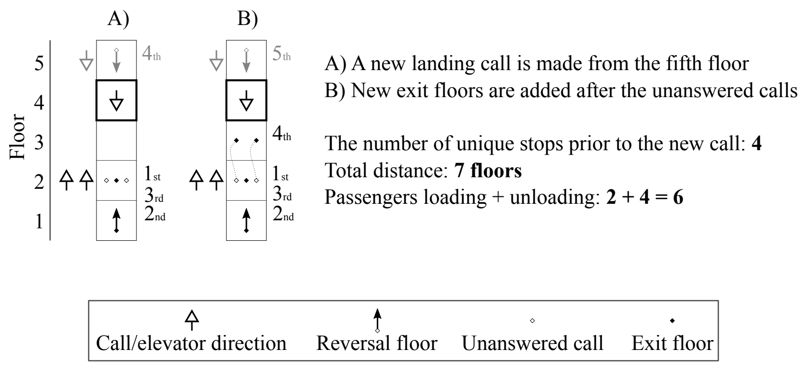

Figure 3: Example of calculating the variables of the waiting time estimate for a new landing call.

When the elevator stops to serve a new landing call, alighting passengers are first removed from the passenger list. Then, boarding passengers are added to the list provided that the maximum rated load is not exceeded. In the model, excess passengers will give a new landing call four seconds after the previous elevator departs. Each passenger loading or unloading event is considered to delay the stop by $t_{\text{(un)load}}$, following the same methodology as calculating the waiting time estimate.

The verification of the functionality and the suitability of the proposed control scheme is analyzed in Section 4.

4. Testing the model

There are two important factors for the model to satisfy: the performance of the elevator group control and the accuracy of the power consumption modeling. The design of these components was depicted in Sections 3 and 2, respectively. The combination of these two components impacts the accuracy of the long-term energy consumption (daily or annual consumption).

4.1. Group control test

Modeling the aggregated power consumption of a large fleet of elevators requires a control scheme which represents a typical elevator setup in the field today. To test the functionality of the proposed control method (see Section 3), we can benchmark its performance against various quality metrics existing in the literature. The performance is evaluated in a number of building types with a series of Monte Carlo simulations.

4.1.1. Criteria for group control

Handling the up-peak traffic is considered the most challenging task for elevator systems. The following equations represent a common formulation of the quantities related to the up-peak traffic [21]. For simplicity, we have presumed even distribution of building population between floors in the model and also in these equations.

- The average number of passengers to load the car in peak traffic:

$$P = \frac{capacity\ factor}{100} \cdot car\ capacity \tag{16}$$

  where the capacity factor is 80% in a traditional up-peak analysis [21] and car capacity is the rated capacity (in persons).

- The average highest reversal floor:

$$H = N - \sum_{j=1}^{N-1} \left(\sum_{i=1}^{j} \frac{1}{N} \right)^{P}, \tag{17}$$

  where N is the number of floors above the ground floor (main terminal).

- The average number of stops during a round trip:

$$S = N - \sum_{j=1}^{N} \left(1 - \frac{1}{N} \right)^{P} \tag{18}$$

- The round-trip time:

$$RTT = 2Ht_{\mathrm{v}} \ + \ (S+1)\, t_{\mathrm{s}} \ + \ 2Pt_{\mathrm{p}} \tag{19}$$

  where t_{v} is the time to travel two adjacent floors at nominal speed, t_{s} is the time delay per stop, and t_{p} is the average time to load or unload a passenger.

- The up-peak interval is the average time between elevator starts from the main entrance floor. Thus, the round-trip time is divided by the number of elevator units, L, in the group:

$$UPPINT = \frac{RTT}{L} \ . \tag{20}$$

This value can be considered to represent a high quality of service as the elevators would travel evenly spaced in the building with UPPINT differences from each other. This would minimize the average waiting times of passengers in the lobby. If the elevators were bunched, moving side by side around the building, the up-peak interval would equal to round-trip time, and can be considered to represent the worst service level, reducing the transportation efficiency.

- The number of passengers transported during a five-minute up-peak traffic period (handling capacity):

$$UPPHC = \frac{300 \cdot P \cdot L}{RTT} \tag{21}$$

4.1.2. Up-peak test results

For the test, we can consider several setups ranging, e.g., in group size, car capacity, capacity factor, and the number of floors. Here, we present three different cases which are simulated with the Monte Carlo method for 100 iteration rounds and 20-minute run times (4 periods of 5-minute up-peak traffic). A Monte Carlo-based technique to evaluate the round-trip times in up-peak traffic has also been applied in [22].

The probability distribution for the instances of people making the landing calls is presumed uniform, and the capacity factor is 80% both in the simulation runs and in the Eq. (16). In the simulation, the acceleration is set at 1 m/s^2 and jerk is considered infinite (or 10,000 m/s^3 in the calculation of benchmark values) for convenience as the maximum acceleration is typically achieved in one second, which is also the applied granularity in the simulations ran for this study. Nonetheless, depending on the desired accuracy and resolution, jerk could also be considered but, as mentioned in Section 2.1, the impact is usually minor. In the benchmark equations, improved up-peak formulation calculation is applied as presented in [21] to evaluate the so called flight time between floors. The delay per passenger boarding or alighting is set at 1 second in both methods. Door operations in total per stop are presumed to take 4 seconds.

The group control algorithm and the functionality of the model can be considered adequate if the modeled interval time is close to the calculated one (Eq. (20)) and the simulated amount of transported passengers is near the designed handling capacity.

We present three test cases here with distinctive characteristics. As the first case, we consider a multi-tenant office building with 15 floors above the ground floor with a total population of 375 persons. Let us presume a design request of 20% transportation capacity in five minutes (75 passengers). A typical solution with good service quality for this type of a transportation task is a group of four elevators ($L = 4$) with a nominal speed of 2.5 m/s and a nominal load of eight persons. The second case is a hotel with 20

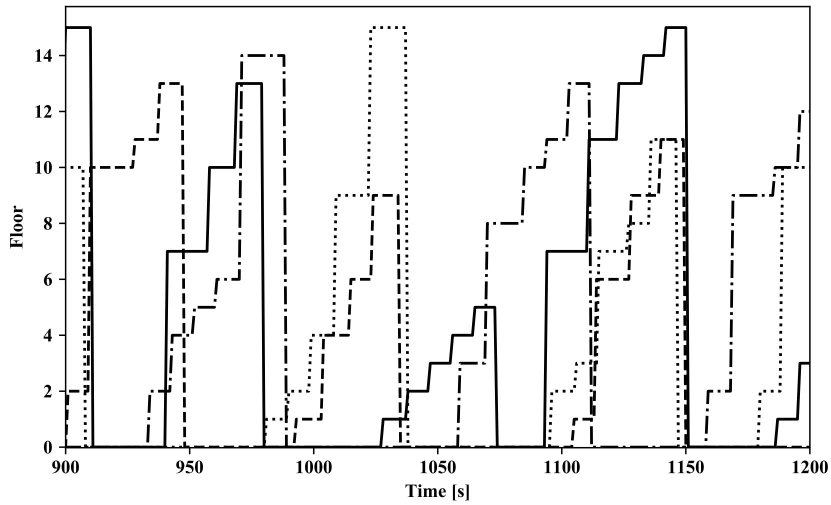

Figure 4: Elevator positions during a 5-minute simulation period in Case 1. Each line type represents one elevator (four units). Elevator positions are updated in the beginning of each start.

floors above the ground floor. The design request is 16.7% transportation capacity in five minutes (123 passengers). A common solution with good service quality for this type of a transportation task is a group of five elevators ($L = 5$) with a nominal speed of 3.15 m/s and a nominal capacity for 16 persons. The last test case presented here is a six-storey hospital with a transportation capacity request of 100 passengers in five minutes. A typical elevator system for this type of a setting is a group of three elevators ($L = 3$) with a nominal speed of 1.6 m/s and a nominal load of 13 persons. Table 1 depicts the benchmark values for the test cases calculated according to Section 4.1.1.

Table 1: Up-peak traffic benchmark values

Criterion	Case 1	Case 2	Case 3
RTT [s]	94.8	145.5	81.9
$UPPINT$ [s]	23.7	29.1	27.3
$UPPHC$ [persons]	81	131	114

The model is then run to simulate the up-peak traffic of 81, 131, and 114 persons, respectively, per five minutes for 20 minutes and the interval times (and 5-minute handling capacity) are recorded for each case from the latter 15 minutes of the simulation. The interval values are determined by calculating the time between consecutive starts from the ground floor, and the mean interval times for each iteration are then derived. Fig. 4 illustrates the recorded positions of elevators during a simulation run in Case 1.

Fig. 5 shows that the mean simulated interval times typically fell below the expected $UPPINT$ value. On the other hand, the elevator group was rarely able to transport all the simulated passengers during the

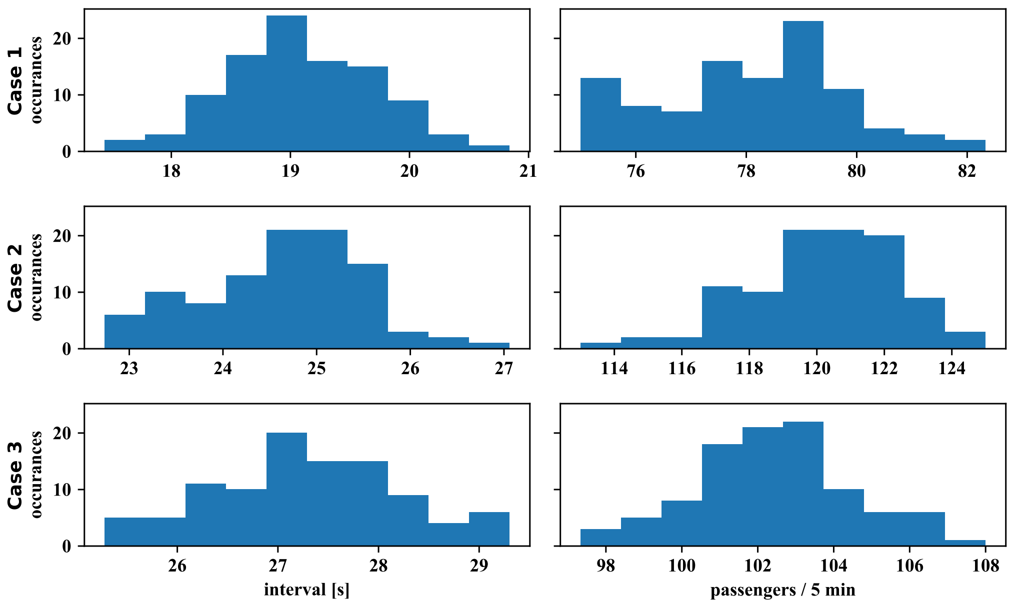

Figure 5: Histograms of simulated mean intervals and up-peak handling capacities (100 runs per case).

5-minute period. Nevertheless, the results appear realistic and coherent.

Overall, the up-peak traffic tests indicate that the group control model works consistently and has a performance nearly equivalent to the generic elevator systems represented by Eq. (16) – (21). Minor differences between the expected and simulated values can be explained with the aforementioned delay caused by the passengers who do not fit into the crowded elevators. Moreover, as explained in [18, Ch. 3], in actual elevator systems, the filled elevators typically bypass landing calls. This resembles a situation of an inactive elevator. For example, if the interval was 30 seconds for an elevator group with four active units, two filled elevators results in a new interval time of 60 seconds.

To test the overall functionality of the model, it is also necessary to analyze the average and maximum waiting and travel times occurring during the simulation of complete days. This is analyzed in Section 4.1.3.

4.1.3. Waiting and travel times test

For the waiting and travels times test, we adapt the same elevator groups as in Section 4.1.2 and employ corresponding building type specific traffic distributions (see Appendix A). Table 2 presents the number of daily starts per elevator acting as the base to derive the amount of passengers, following the methodology depicted in Appendix A. The number of starts is based on the ISO 25745-2 standard, Table A.1, and the values are chosen to represent traffic intensities higher than typical in the given usage category. These intensities can be considered a challenging test for the performance of the group controller.

Fig. 6 indicates that the group control model performs consistently as expected. However, as mentioned

Table 2: Number of starts per day per elevator.

Case 1	Case 2	Case 3
950	950	450

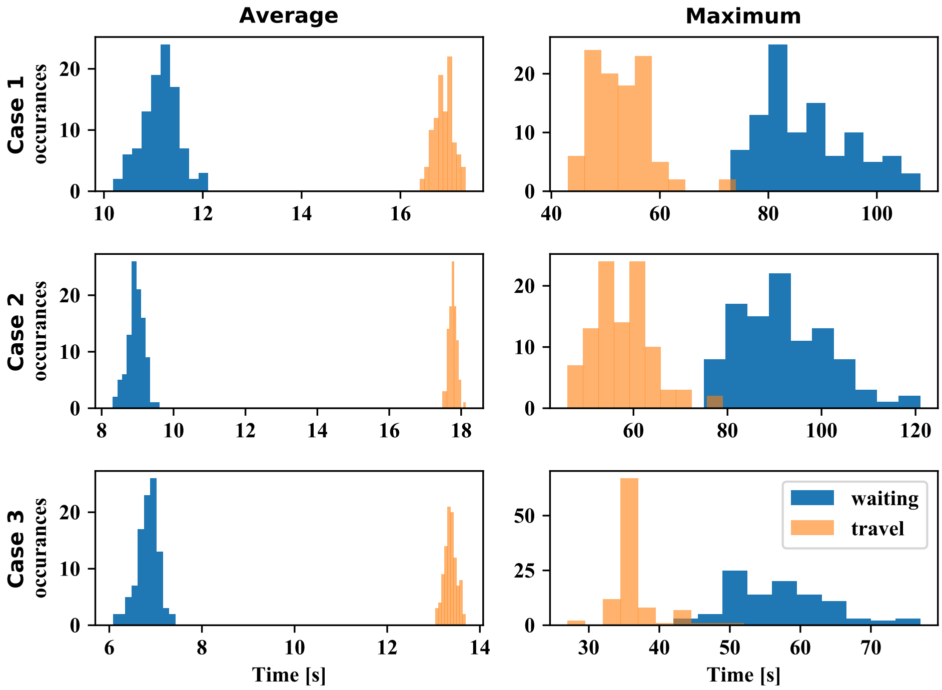

Figure 6: Histograms of simulated average and maximum waiting and travel times (100 runs per case).

in Section 4.1.2, the peak-traffic periods sometimes cause elevators to fill up, and, consequently, the interval times increase. As waiting times are typically 0.55...1.0 times the interval, these periods of peak-traffic also cause uncertainty in the waiting times. This is visible in the large difference between the average and maximum waiting times in all the simulated cases.

Concluding from the up-peak test results and the performance of the group control during the entire day with multiple passenger profiles and amounts of passengers, the model can be considered reliable enough to be applied in the modeling of typical elevator installations. Especially, when calculating the combined results of a variety of elevator groups, the individual characteristics and differences between the control algorithms tend to average out.

The rest of the Section 4 focuses on testing the modeled power and energy consumption occurring during the starts dictated by the group controller.

4.2. Power consumption test

The important part of the power consumption test is to ensure that the model produces reasonably accurate estimates of energy consumption during each start. Secondary targets for the model to fulfill are the duration of the start and the resulting instantaneous power profile within the start. For this test, we utilized previous measurements [11] as the reference, and employed the known values for car mass, system efficiency, and counterbalance ratio as well as an estimate for door motor power. Fig. 7a shows the results for a nine floor descent/ascent with various loads with a non-regenerative elevator. It is apparent that the modeling approach incorporating the impact of inertia (PA2) provides superior results in contrast to the model only applying the potential energy difference (PA1). It is also easy to understand that the gap between the two methods further increases when the nominal speed of the elevator system increases, i.e., when the buildings get taller.

Fig. 7b provides examples of the power profiles modeled for the downward travels with the second method which includes energy consumed during acceleration and deceleration. The peak power and duration of the starts were found to match the measurements with reasonable accuracy ($\pm 10\%$). Overall, the results were the more accurate the larger the distance traveled was. This is due to uncertainties related to the auxiliary consumption, such as fans and certain control electronics, which gain a more significant role in short-distance travels. Nevertheless, the error is relatively insignificant considering the overall complexity of the model and the intended target of utilization. Furthermore, the majority of the total energy consumption is typically either resulting from the high stationary power consumption or from long-distance elevator starts (more than a floor), depending on the type and height of the building.

In Section 4.3, the reliability of the model is tested during a daily test with actual measured traffic and monitored energy consumption.

4.3. Daily energy consumption test

In the daily energy consumption test, we analyze the performance of the overall model by simulating the power consumption during a weekday. The model will have an input of a recorded passenger traffic from an actual building (the same as in Section 4.2) from which the group controller decides which elevators to assign for each individual landing call. The power consumption for each start and during the stationary times is simulated based on the resulting elevator starts. Fig. 8 presents the outcome against the measured power consumption of the four-unit elevator group for different group control methods. In the first method, each call is assigned a random elevator which is not fully loaded at the time of the call. The objective of the second method is to minimize the waiting time of the passenger, as explained in Section 3. The third method presents an approach which aims to provide short waiting times as well as decreased energy consumption. The fourth plot is based on the actual starts decided by the multiobjective group controller with destination control system (DCS) in the observed office building. With DCS, the person placing a landing call will

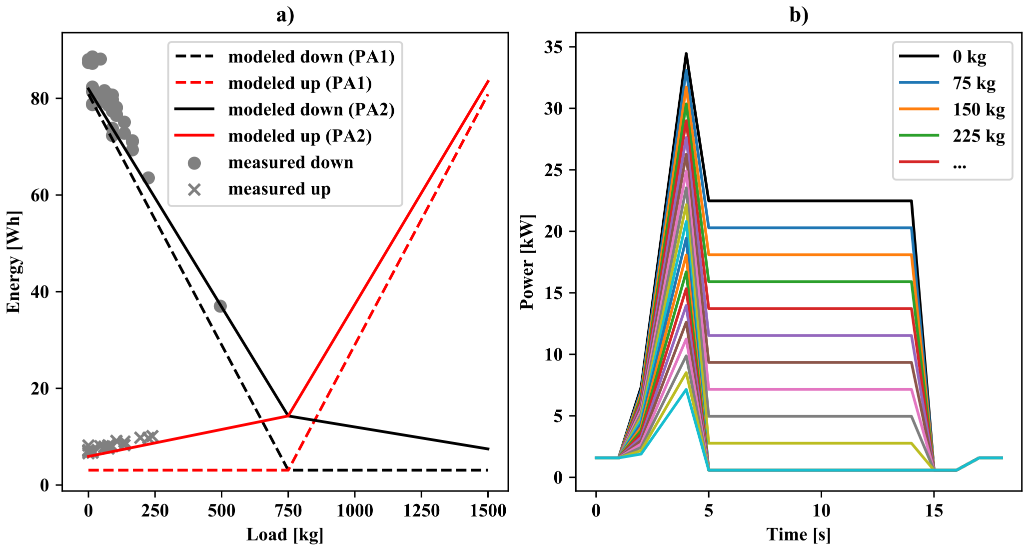

Figure 7: a) Modeled energy consumptions with the PA1 and PA2 method for different loads in a nine-floor descent/ascent and real-life measurements from an office building. b) Modeled instantaneous power profiles with the PA2 method as one-second averages for a nine-floor descent with various loads.

input the destination floor and, in some systems, also the number of waiting passengers. This additional information enables enhanced transportation performance. Such a group controller is rare in the installed base of elevators. Thus, when modeling a large quantity of elevators with varying characteristics, the waiting time-based group control approach could be applied as it provides waiting times and energy consumption around halfway between the random approach (where the landing calls are assigned randomly to elevator units) and the top-of-line control systems (see Table 3). Fig. 8d and Table 3 also verify that the power consumption model is highly accurate when the elevator parameters are well known. Furthermore, the commonly adopted VDI 4707-1 guideline and the ISO 25745-2 standard approaches provide less reliable daily energy consumption estimates by default.

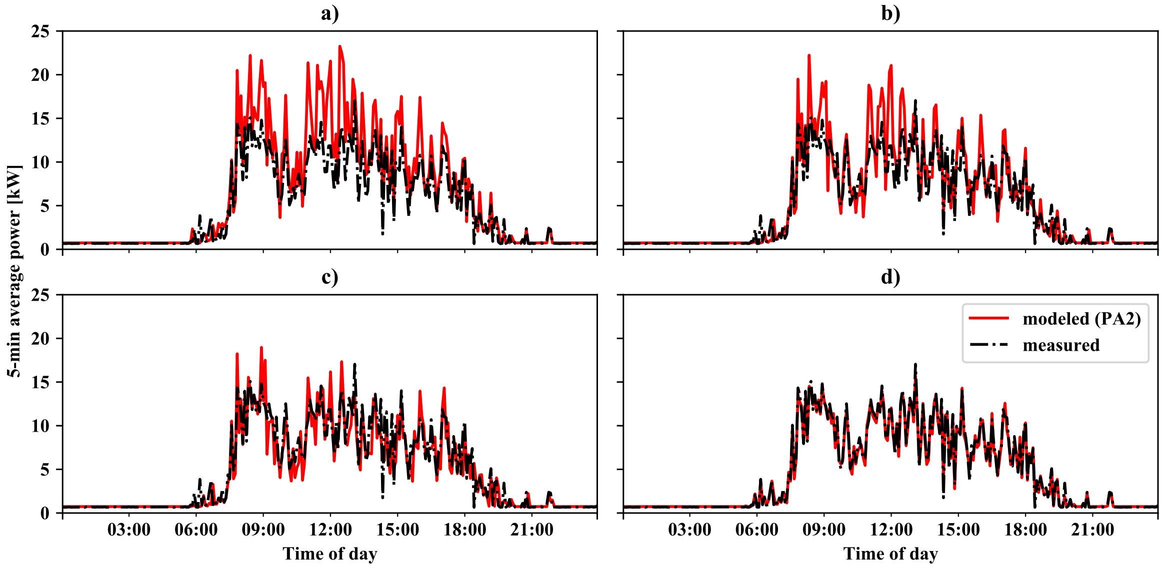

Figure 8: Simulated five-minute average power profile of the elevator group (using PA2) versus the measured power profile during a weekday with the same passenger traffic profile. The control methods are a) random, b) waiting time, c) hybrid. The power consumption based on actual starts is presented in d).

Table 3: A sample of simulated and measured values in the analyzed elevator group.

	Group control method			
	Random	**Waiting time**	**Hybrid**	**Actual**
Number of starts per day	4740	4188	3769	4047
Daily energy consumption [kWh] (VDI: 105.0, ISO: 128.1)[1]	149.0	126.3	111.5	114.5 (modeled) 116.0 (measured)
Waiting time mean / max [s]	12.4 / 117	6.4 / 106	6.7 / 107	8.2 / 91

[1] VDI 4707-1 estimate is calculated presuming default traffic parameter values, and the ISO 25745-2 estimate is based on the actual number of starts (4047). For more details, see [9].

5. Discussion

The framework, techniques, and approaches presented in this paper can be utilized for a variety of tasks. For example, the energy consumption and peak power demand of elevators in a building or region can be estimated more accurately than before. Additionally, the improved accuracy potentially eases power grid planning and electrical system design of buildings. Furthermore, the novelty of the framework is the attained instantaneous power profile which offers multiple benefits. One of the benefits is that the profile can be employed to unveil new prospects for utilizing elevators in demand response. For instance, the changes in the aggregated power consumption of a large fleet of elevators could be simulated in cases where nominal speed, acceleration, or the amount of active units would be adjusted. The obtained in-depth knowledge of power fluctuations is also advantageous when designing systems which require limiting of the peak power demand. This feature is likely to become more topical due to the increasing ratio of intermittent distributed generation combined with weak grids at the end of radial lines and especially in islanded microgrids. For instance, studies [23, 24] describes a model which assists in restricting the power taken from the grid when the elevator has multiple energy sources, including energy storage units.

The results clearly indicate that the power consumption model which includes the impact of inertia (PA2) is superior already in a mid-rise building in terms of accuracy. The added complexity of considering inertia and determining suitable dimensions and parameter values can be reduced by generalizations and simplifications presented in Appendix B.

A detail for improvement would be to separate the friction losses and the efficiency of the motor and make the motor efficiency dependent on the instantaneous power (load). This has been done, for example, in patent [25], which proposes using separate equations to calculate the forward and reverse system efficiencies. Moreover, increased friction after a long-period of immobility could be modeled. Both of these features would slightly increase the daily energy consumption of individual units and, consequently, raise the aggregate power profile moderately.

Finally, it should be noted that the model and simulation techniques applied in this study were focused to produce satisfactory results when the elevators are viewed as a system. For more detailed analyses of the impact of control techniques and individual components on the energy efficiency, transportation performance, and instantaneous power demand, other means should be used. For example, patent [25] demonstrates methods to consider the impact of rope masses and gearing on the energy performance. The patent also depicts the use of a common DC bus to adjust the net power demand of the elevator group visible to the grid.

6. Conclusions

This paper proposed approaches to model elevator power consumption in high-resolution instead of commonly utilized daily averages. The results act as an opening for future research and raise the awareness of energy efficiency and importance of vertical transportation to the power system design.

The test results confirm the usability and credibility of the proposed approaches. The introduced waiting time-based group control method works as a suitable approximation of an average elevator group. Both the energy consumption as well as the transportation performance were simulated to be in between the two extremes (elevator group controller based on random car selection versus multiobjective control with destination control system) found in the installed stock of elevators today. When the model parameters are near perfect, i.e., they match the actual installation and traffic patterns, the model yields highly-detailed and accurate results of the instantaneous power consumption of the installation.

For future purposes, this paper also analyzed the differences between simple potential energy based power consumption modeling and modeling incorporating the impact of inertia during acceleration and deceleration stages. As expected, the significance of inertia increases when the ratio of time spent in acceleration and deceleration rises. Therefore, in high-rise buildings, with large nominal speeds, employing power consumption models which consider acceleration and deceleration phases provides more accurate results.

Future research by the authors encompasses localized power imbalance issues occurring in sections of the distribution grid and on the building level. Especially, the building-level peak demand reduction is discussed in an upcoming paper by the authors. The authors also work on analyzing the aggregated power consumption of a fleet of elevators and means to reduce the total demand with elevator and group control to be able to participate in demand response.

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Appendix A.

This appendix contains the depiction of applied traffic distribution profiles and the derivation of the number of starts and the volume of passengers.

The number of passengers was derived from the number of starts and average load suggested by the ISO 25745-2 standard. After simulating the number of starts in various traffic distribution profiles, a compensation factor, cf, was introduced to reduce most of the excess starts (passengers) in the simulations of the case studies. The resulting equations are

$$n_{\text{passengers}} = \frac{n_{\text{starts}}}{cf} \cdot \%Q \cdot \frac{m_{\text{nominal}}}{m_{\text{passenger}}} \ , \tag{A.1}$$

$$cf = 0.00021 \cdot n_{\text{starts}} + 1.18 \ , \tag{A.2}$$

where n_{starts} is the number of starts for the day type to be simulated, $\%Q$ is the ratio of average load with respect to the rated load, and $m_{\text{passenger}}$ is the average mass of a passenger (here 75 kg).

The employed passenger distributions for each modeled building type are displayed in Fig. A.1.

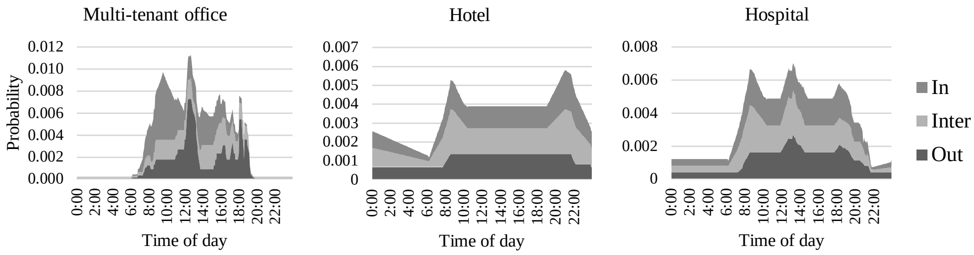

Figure A.1: Generalized passenger traffic distributions of the simulated test cases (5-minute resolution).

Appendix B.

This appendix depicts a way to select the modeling and simulation parameters. Parameters explained in the main text are not necessarily reintroduced.

Table B.1 presents parameters applied in the calculation of the elevator movement and consequent power requirement. The inertia constant is employed to represent a coefficient of the mass of a typical traction motor to achieve a certain rated power. The mechanical power demand equation (Eq. (6)) becomes

$$P_{\text{M}}(t) = v(t) \cdot ((C_{J_{\text{M}}} + (K \cdot m_{\text{nominal}} + 2 \cdot m_{\text{car}} + m_{\text{load}})) \cdot a(t) + g \cdot m_{\text{net}}) \,. \tag{B.1}$$

This simplified approach enables modeling a variety of elevators without presuming any physical dimensions for the motors.

Table B.1: Parameters for kinetics.

	Value
Car mass (kg)	$1.56 \cdot \textit{rated load} - 700$
Rated motor power [kW]	$\textit{rated load} \cdot g \cdot \textit{rated speed} \cdot (1 - K) /\ \eta\ /\ 1000$
Motor inertia [kgm^2], J_{M}	$0.06 \cdot \textit{rated power} - 0.3$
Inertia constant[kg], $C_{\text{J}_{\text{M}}}$	$280\ 1/\text{m}^2 \cdot J_{\text{M}}$
Roping ratio, $(\frac{\omega_1}{\omega_{\text{M}}})$	1:1

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