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Explicit method to predict annual elevator energy consumption in recurring passenger traffic conditions

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Keywords

Elevators, Energy classification, Energy consumption, Office buildings, Standby consumption, Traffic profile

Abstract

This paper proposes a method for simple projecting of annual elevator electricity consumption based on short-term energy measurements and identifies challenges in the determination of actual energy consumption based on kWh meter readings. The study also analyzes the impact of the employed elevator technology, building type, and seasonal variations in elevator usage on the calculation of the annual consumption. Thus, the method can be adopted in different regions with varying elevator usage. The approach employs elevator specific daily energy consumption measured on the prevailing day types. The reliability of the proposed approach was analyzed and the performance compared to actual measured annual consumption and estimates provided by commonly adopted energy efficiency classification schemes, VDI 4707-1:2009 and ISO 25745-2:2015. The results of the monitored office elevator indicated that the proposed method performs generally better than the competing approaches.

1. Introduction

Elevators are perhaps the most visible form of building services. Consequently, they consume energy while transporting passengers between floors. However, the amount of energy consumption is rarely measured, which hinders elevator-related cost analysis and budgeting. Knowing the consumption also enables planning investments targeted at improving the elevator energy efficiency and secures shortest investment payback times. For example, in residential buildings, the annual electricity costs can be so low that investments are unattractive, while office buildings may provide better payback.

Elevators have large differences in energy consumption that result from the installation location, passenger traffic and used technology [1], [2]. On annual level, the elevator energy consumption can be acquired with at least four different approaches:

1) Permanent installation of a kWh energy meter
2) Elevator simulators [3]-[6]
3) Energy classification schemes
    - VDI 4707-1:2009 [7],
    - ISO 25745-2:2015 [8]
4) Day type based prediction methods [9], [10]

Installing kWh energy meters certainly seems the most straightforward, reliable method, but it has some challenges related to the desired accuracy and costs, discussed more in Section 2.

Elevator simulation tools are often required to be able to sell an elevator for a certain energy class according to customer demands. After the installation, metering can be used to validate the simulation results. Simulations can provide a suitable level of accuracy but require a considerable amount of background information on the elevator setting and usage. Moreover, simulation tools are typically dedicated to analyzing intraday power consumption [3]-[6] and are unnecessarily complex for calculating the annual energy consumption. Therefore, simulation tools are excluded from later parts of this paper.

Energy classification schemes enable relatively accurate consumption estimates with high-quality traffic statistics and short-term power consumption measurements during specific running cycles. Unfortunately, the traffic data is seldom available and running cycle tests are difficult to perform during normal working hours, as they necessitate a certain travel cycle up and down, obstructing normal elevator usage.

Day type based prediction methods rely on the phenomenon that the passenger traffic is a recurring event. The traffic profiles depend on the building type, and the daily consumption is strongly related to the amount of traffic, as explained in Section 2.1.1. Typically, the weekly profile is presumed to repeat throughout the year, as supported by Fig. 1. However, in reality, seasonal differences in passenger traffic cause some variation between the weeks. Nevertheless, a complete year can be considered highly repetitive without major changes, e.g., in the occupancy rate.

This paper proposes a prediction method which utilizes the recurring weekly profile to calculate the annual energy consumption of an elevator. Instead of relying on unreliable day and building type specific ratios, presented in Section 2.1.1, the proposed method involves straightforward measuring of energy consumption over the most significant day types. The measured daily consumptions are then assumed to repeat each week for the given year. Additionally, the method can also incorporate the impact of seasonal variation in elevator usage.

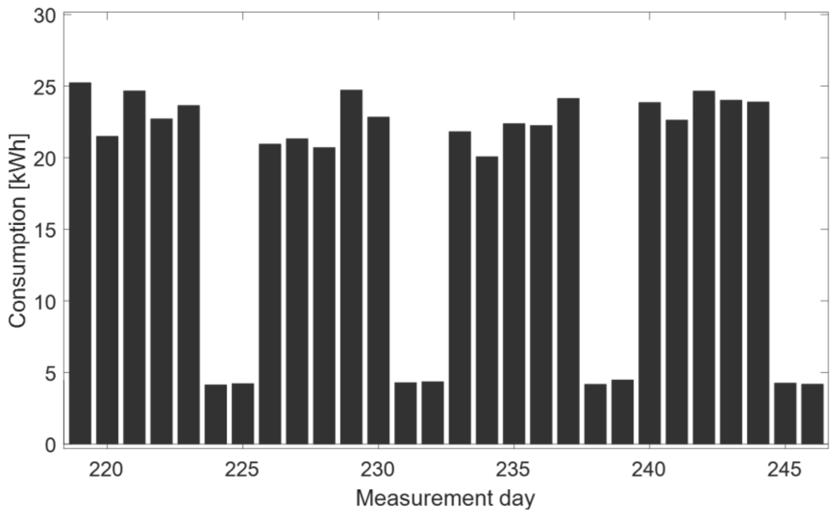

Fig. 1: Daily electricity consumption of an elevator in an office building during four weeks. The low bars represent weekends (Saturday and Sunday).

The previous approaches and the proposed methods are presented in Section 2 with the introduction of the employed metering equipment. Section 3 provides the actual logged results from the monitored site and presents the annual consumption projections based on cumulated energy consumption data. In addition, the performance of the proposed methods is compared to the measured annual consumption and to the estimates provided by the VDI 4707-1 guideline and the ISO 25745-2 standard. Section 4 discusses the applicability of the proposed methods, and Section 5 concludes the main findings and suggests future research.

2. Methods

The aim of the proposed model is to provide a sufficiently accurate prediction of the annual electricity consumption of an elevator or an elevator group by measuring the consumption for only a few days or weeks with a portable high-accuracy energy meter. In comparison to earlier estimation approaches, the model requires less background data on the elevator traffic, elevator technology and dimensions of the building. Furthermore, adopting the proposed method reduces the need to invest in additional energy consumption monitoring technology in buildings with repeating people flows. The savings can be achieved on multiple levels, including:

- Electrical design phase (less equipment)
- Data handling (logging interface, storage, analysis)

- Metering equipment (kWh meter, current transformers)
- Enclosure equipment (size, wiring)
- Installation costs (electricians)

The ever more detailed submetering also creates reliability issues, as the accuracy of common meters reduces with less measured flow. Especially, cost effective long-term monitoring of appliances with peaking power is a challenge. In elevators, the high currents during acceleration require the use of current transformers, which, on the other hand, are the most significant error source in low-demand standby, as the electric current may fall under 5% of the nominal primary current of the CT. In this current region, the specifications of the classification standard are less demanding or not even expected to apply [11]. The portable high-end energy meters often utilize specially designed CTs and algorithms to diminish these errors found in typical cost friendly kWh metering systems which utilize common transformers.

Nonetheless, the method also benefits sites with metering systems by providing an easy method to predict the annual consumption and its changes. Consequently, a change in the energy consumption trend can also signal a change in the number of people utilizing the building or in the way the building is occupied, which enables better design and faster reorganization of other building services. On the other hand, a shift in the energy consumption trend may also provide crucial information on acute maintenance needs.

2.1 Methods for annual consumption prediction based on day type

2.1.1 Earlier approaches

The electricity consumption of an elevator is mainly related to stationary power demand and running energy demand. The relation of these two parts of consumption is highly affected by the passenger traffic. Considering a typical building, the amount of people in the building and their intraday movements change by day type. In [10], eight different day types have been proposed:

1. Mondays to Thursdays (normal working period)
2. Fridays (normal working period)
3. Saturdays (normal working period)
4. Sundays (normal working period)
5. Mondays to Thursdays (holiday season)
6. Fridays (holiday season)
7. Saturdays (holiday season)
8. Sundays (holiday season)

A simpler approach separating only working and non-working days from each other may also be sufficient [9], [10].

With the segmentation of similar day types into categories 1…n, the total annual consumption can be calculated as follows [10]:

$$E_{\text{annual}} = \sum_{i=1}^{n} d_i E_i \,, \tag{1}$$

where d_i is the number of days in a year of the day type i and E_i is the corresponding daily energy consumption. In matrix form, the equation can be presented as

$$E_{\text{annual}} = \begin{bmatrix} d_1 & \dots & d_{\text{n}} \end{bmatrix} \begin{bmatrix} E_1 \\ \dots \\ E_{\text{n}} \end{bmatrix}. \tag{2}$$

Dissertation [10] also introduces a more detailed methodology concerning the amount of starts, energy consumption in each operation mode, and other components of energy consumption. Analyzing these parameters is crucial in energy classification schemes, such as the VDI 4707-1:2009 guideline [7] and the ISO 25745-2 standard [8], which provide annual energy consumption estimates based on the measured power consumption and traffic characteristics. The current research paper, however, focuses on a method which is simple but still provides a sufficient annual energy consumption projection. In this case, the sufficient accuracy is within ±50% of the actual energy consumption, which resembles the difference between two consecutive running energy efficiency classes in the VDI 4707-1 and ISO 25745-2.

Measuring the consumption of each day type may be burdensome and time consuming if the day types occur infrequently. To circumvent this issue, a straightforward approach is to apply intensity indices, where ratio 1 denotes a traffic intensity of an average weekday, for example. CIBSE Planning guide, v. 2005, [9] proposes ratios for weekdays, Saturday, and Sunday, as shown in Table 1. However, the intensity indices vary between regions, reflecting the culture and customs of the area. Moreover, the planning guide disregards the impact of holiday seasons, which, on the other hand, are clearly acknowledged by [10].

Table 1: Examples of traffic intensity indices according to CIBSE Planning Guide, v. 2005 [9].

Building type	**Intensity index**		
	Weekdays	**Saturday**	**Sunday**
Residential	1.0	1.0	1.1
Commercial	1.0	0.5	0.1
Retail	1.0	1.4	1.5

Instead of the intensity index, [10] discusses day type specific energy consumption ratios, r_i . This can be considered as the ratio of average consumed energy on day type i in contrast to a dominant day type 1:

$$r_i = \frac{E_i}{E_1}.$$

Compared to the CIBSE intensity index in Table 1, the above energy consumption ratio includes stationary power consumption and the effect of regeneration. This potentially yields more reliable results in conditions with low amount of background data on traffic characteristics and elevator technology. Fig. 2 explains the issue of knowing traffic intensity index only instead of the energy consumption ratio. The potential energy saving modes are more active during low traffic periods, which results in a logarithmic behavior of the base power demand as a function of start frequency [12]. Unlike in Fig. 2, the energy consumption can also start to saturate at high traffic due to a relation between the increased average car loading and the counterweight [13].

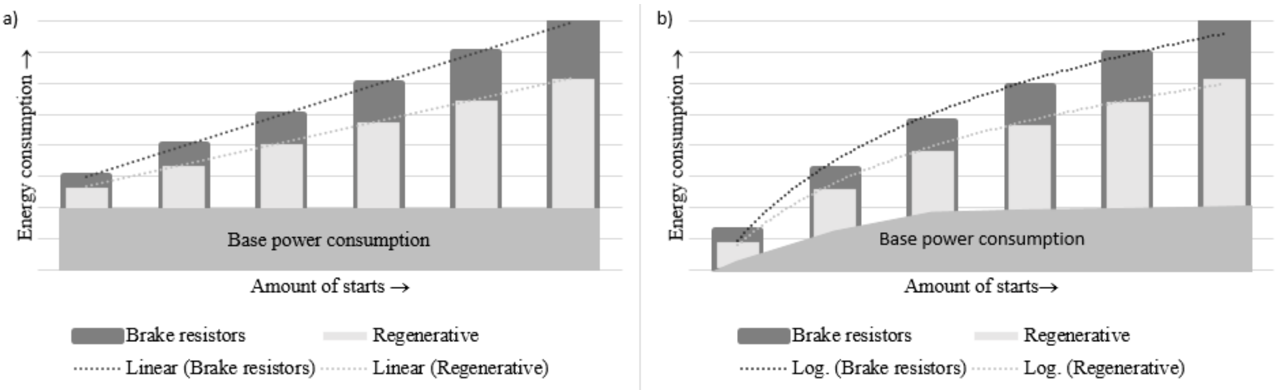

Fig. 2: Generalization of energy consumption as a function start intensity. a) No power saving modes. b) Power savings modes active while stationary.

With the determined ratios, the matrix form of the Eq. (2) can then be reformatted as

$$E_{\text{annual}} = [E_1][d_1 \quad \dots \quad d_{\text{n}}]\begin{bmatrix} 1 \\ r_2 \\ \vdots \\ r_{\text{n}} \end{bmatrix}. \tag{3}$$

Ideally, this resurfaced method enables predicting the elevator annual energy consumption with just one day of measurements. A drawback of the proposed method is that the daily consumption ratios vary between regions, buildings, and elevator units. Due to varying elevator technology and, e.g., building height, it is challenging to determine universal energy consumption ratios for different day types even inside a uniform region. In the long-term, this issue could be settled with equation-based ratios, which could be formulated from a large data set. These equations could consider the elevator technology and elevator shaft height, for instance. However, the ISO 25745-2 standard and the VDI 4707-1 guideline offer a viable alternative for annual consumption estimates in the case with detailed background data.

The previous methods based on differentiating the day types clearly have multiple issues related to the lack of information on traffic characteristics and installed elevator technology. Therefore, Section 2.1.2 of this current study proposes measuring and calculation methods that circumvent most of these issues.

2.1.2 Proposed methods

The proposed methods rely on measuring the energy consumption of the most prevailing day types and linearly extrapolating the annual consumption. The methods presume the elevator usage to be weekly recurring, as formulated in Eq. (4). To diminish the uncertainty related to the power consumption of the installed elevator technology and power saving modes, the method necessitates measuring of at least two major day types if more than one. The day types should represent both ends of the energy consumption spectrum and constitute a large share of the days of the year. The day type with the least consumption typically has little traffic, providing a good estimate of base power demand. However, knowing the high and low traffic days may be difficult, and measuring a full week is to be preferred.

$$E_{\text{annual}} = \frac{365}{7} \sum_{i=1}^{n} d_i \, E_i \quad , \qquad 1 \leq n \leq 7, \tag{4}$$

where d_i is the number of days of the day type *i* in a week and E_i is the corresponding measured daily energy consumption.

The seasonal changes in elevator usage can be considered by weighing the related number of days with coefficients which depend on the building type and region. To maintain the simplicity of the approach, all the out-of-the-ordinary week periods can be segmented into one group, dividing Eq. (4) into two parts:

$$E'_{\text{annual}} = \frac{365 - 7 * w}{7} \sum_{i=1}^{n} d_i \, E_i \; + \; w \sum_{i=1}^{n} c_i d_i \, E_i \, , \qquad 1 \leq n \leq 7, \tag{5}$$

where *w* is the number of out-of-the-ordinary weeks in a year and c_i is the out-of-the-ordinary period coefficient for the day type *i*. However, identifying these variables effectively is a challenge, especially if the building has both extraordinary high and low usage periods, creating the need for further seasonal separation. Moreover, the stationary power saving modes complicate the process even more. Therefore, Eq. (4) is to be preferred in most elevators assuming the daily energy consumption measurements are performed during the ordinary days. This should provide a sufficient prediction of annual energy consumption in majority of elevators.

Calculation example

A retail building has a steady but low volume of business during weekdays, Monday to Friday, and a busy Saturday. On Sundays, the building is closed from public. In this type of building, measuring the consumption over three days Friday to Sunday or Saturday to Monday can provide a suitable annual consumption estimate. Measuring the whole week is naturally preferred but may not be cost effective. The property owner knows that during the summer months (9 weeks), there is about 50% less people shopping. For simplicity and without better knowledge, the amount of elevator starts are also considered to decrease by half. The elevator has no power saving modes according to the owner.

The measured daily consumptions are 20 kWh for weekdays (Mon-Fri), 22 kWh for Saturday and 5 kWh for Sunday. The Sunday consumption is mostly standby consumption. The annual consumption prediction excluding seasonal variation in traffic is simply

$$E_{\text{annual}} = 365 * \left(\frac{5}{7} * 20\ \text{kWh} + \frac{1}{7} * 22\ \text{kWh} + \frac{1}{7} * 5\ \text{kWh}\right) = 6\ 620\ \text{kWh}.$$

Considering Sunday to represent a base power demand and that 50% less people decreases the running consumption approximately by half, the coefficients, c_i, can now be calculated:

$$c_1 = \frac{E'_1}{E_1} = \frac{0.5 * 15\ \text{kWh} + 5\ \text{kWh}}{15\ \text{kWh} + 5\ \text{kWh}} = 0.625$$

$$c_2 = \frac{E'_2}{E_2} = \frac{0.5 * 17\ \text{kWh} + 5\ \text{kWh}}{17\ \text{kWh} + 5\ \text{kWh}} = 0.614$$

$$c_3 = \frac{E'_3}{E_3} = \frac{0\ \text{kWh} + 5\ \text{kWh}}{0\ \text{kWh} + 5\ \text{kWh}} = 1$$

Now, the annual consumption can be predicted with Eq. (5).

$$E'_{\text{annual}} =$$

$$(365 - 7 * 9)\left(\frac{5}{7} * 20 + \frac{1}{7} * 22 + \frac{1}{7} * 5\right)$$

$$+ 9 * (0.625 * 5 * 20\ \text{kWh} + 0.614 * 1 * 22\ \text{kWh} + 1 * 1 * 5\ \text{kWh}) =$$

$$5\ 480\ \text{kWh} + 730\ \text{kWh} = 6210\ \text{kWh}$$

Thus, by considering the seasonal variation, the prediction reduced by 6%, and it could also be assumed as a more accurate estimate. However, as mentioned, the background information on traffic intensity or power savings modes is typically difficult to acquire, and a simple linear extrapolation-based approach, such as Eq. (4), is more convenient. Moreover, the traffic amounts are subject to other changes as well, for example, due to economic depression.

2.2 Competing methods

2.2.1 Energy efficiency classification schemes

Most of the earlier studies on elevators have divided the energy consumption into standby and running modes [2], [14]. The VDI 4707-1 and ISO 25745-2 schemes have a similar approach. The ISO additionally proposes differentiation of the standby energy into idle, 5-minute standby, and 30-minute standby demand. Nonetheless, the most significant difference between these two schemes is in the determination of energy consumed during running. The VDI utilizes the travel time in hours of the day to calculate the total distance the elevator is traveling in a day, while the ISO standard bases its calculations on the number of starts of the elevator. Further background and utilization examples of the VDI 4707-1 are presented in [15]-[17], and the ISO 25745-2 is thoroughly discussed in [16]-[19]. The authors of this current research work have contributed to some of these studies. In short, the annual energy consumption estimates are commonly based on:

- Energy consumption of a reference cycle (full shaft height up and down with door operations)
- Energy consumption of a short cycle (the same as reference cycle but not the full shaft height)
- Stationary power measurements
- Building characteristics

Section 3.1 presents the estimation results for the case building.

2.2.2 Electricity consumption monitoring equipment and elevator traffic statistics

Energy meters used for the data gathering fulfilled the ISO 25745-1:2012 [20] requirements for logging of elevator energy consumption. The running cycle measurements required by the energy classification methods and other short-term measurements were performed with a high-end power quality analyzer, Fluke 1760, with IEC 61000-4-30 [21] Class-A rating. In addition, long-term monitoring equipment was installed after the main switch of the elevator. The long-term equipment comprised of the following: one M-Bus data logger per site, one 3-phase energy meter per elevator, and three split-core current transformers (CTs) per meter. The rated primary current of the CTs was selected as 100 A with accuracy class 1, i.e., one percent error at rated current [11]. The accuracy class of the 3-phase meter was B (+/-1%). Finally, a 3G modem was connected to the data logger to enable remote monitoring.

Supporting statistics on the usage of the elevators were attained from an elevator usage statistics reporting system incorporated into the elevator system. The information used for this research paper included the total amount of starts in a year.

3 Results

3.1 Measurement location and measurements for competitive methods

This paper analyzes measurement data from a mid-rise office building in southern Finland. For simplicity, the results focus on one particular elevator unit. The basic characteristics of the elevator are presented in Table 2.

Table 2: Basic characteristics of the monitored elevator.

Nominal load	1500 kg
Counterbalance weight	Car + 50% of nominal load
Rated speed	2.5 m/s
Shaft height	59 m
Number of floors	16
Drive	Gearless PMSM (AC)
Regenerative braking	No

Table 3 presents values employed in the estimation process of annual energy consumption by the VDI 4707-1 guideline and the ISO 25745-2 standard. The resulting annual energy consumption estimates and provided in Table 4. With less than presumed amount of traffic, the estimate applying monitored traffic data is substantially lower than the estimate with the default traffic values. These VDI and ISO estimates can be considered to represent good baseline values when analyzing the performance of the annual consumption estimation method proposed by this paper.

Table 3: Traffic, energy, and power values for ISO 25745-2 and VDI 4707-1 of the monitored elevator.

	Monitored	ISO 25745-2 default	VDI 4707-1 default
Number of starts per day	421	750	n/a
Average running time	2.6 h	n/a	21
	Measured	Applied in ISO?	Applied in VDI?
Reference cycle energy (59 m)	140 Wh	Yes	Yes
Short cycle energy (39 m)	104 Wh	Yes	No
5-minute standby power	172 W	Yes	Yes

Table 4: Annual consumption estimates calculated with the energy classification schemes.

	ISO 25745-2	VDI 4707-1
Default traffic	8 130 kWh	9 490 kWh
Monitored traffic	7 060 kWh	8 690 kWh

3.2 Measuring the annual electricity consumption of elevators

Measuring the elevator electricity consumption is a challenging task, as explained in Section 2. Moreover, the error is increased with the split-core CTs employed in this research, as higher accuracy classes for the same current ratings are available in solid-core window-type design. Nevertheless, the use of split-core current transformers enabled a more convenient installation to the existing elevator system than traditional solid-core CTs. To diminish the errors induced by the cost-friendly meters and CTs, a method was created to compensate this measuring error in the logged five-minute power averages. The concurrent readings from the high-end power quality logger, Fluke 1760, were compared to the logged 5-minute readings of the long-term monitoring equipment. This comparison process provided a scatter plot of the measurement error. In the case building, the errors against the power logger were found to follow a natural logarithm of the measured five-minute power, and the error compensation equation was derived for each meter installed to monitor an elevator [17]. A similar error behavior following a natural logarithm has also been reported with non-regenerative escalators [22].

The annual consumptions were determined by calculating the average 5-minute power during the year and by multiplying it by 8760 hours. The resulting error-compensated annual consumption was 5 795 kWh for the monitored elevator (uncompensated 5 324 kWh). The use of the power-based error compensation method increased the annual electricity usage measurement result of the monitored elevator by nearly nine percent. This can be considered to resemble the best knowledge on the actual energy consumption. Fig. 3 shows the cumulative energy consumption value after each full day. The profile seems fairly stable and linear, which supports linear extrapolation idea of the proposed methods.

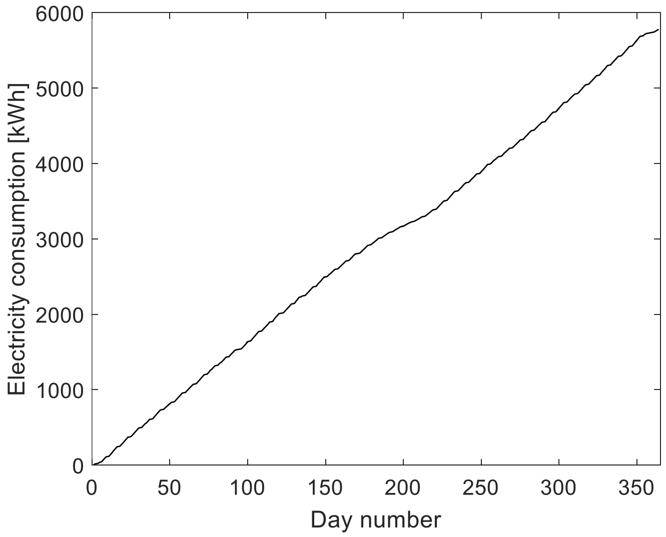

Fig. 3: Measured cumulative elevator energy consumption in the monitored office elevator after each day during the calendar year.

3.3 Impact of holiday seasons

Previous Fig. 3 reveals some decrease in the rising angle of the cumulative energy consumption during certain periods of the year. These alterations arise from maintenance breaks and changes in the passenger traffic due to holiday seasons, for example. Fig. 4 demonstrates the daily electricity consumption values of the monitored office elevator during one year. The days have been categorized into four types based on the Finnish calendar and typical holiday periods.

Apparently, the national holidays and other midweek holidays share the daily consumption characteristics of weekends. Seemingly, only few weekends had some activity in the office and majority of consumption was standby demand.

Workday consumption was relatively steady throughout the year with a slightly declining consumption approaching the most popular summer holiday season, July. Furthermore, before the longer holiday periods (Christmas and summer), there is a peak in the daily consumption trend. Seemingly, the people flows in the building increase with deadlines and tasks that have to be met before the holidays. Interestingly, holiday patterns of elementary school children can also be recognized from the energy measurements. Presumably, parents whose children are on holidays are having concurrent time out of the office. Naturally, the period when most workers are having their holidays shows even lower consumption. All of the above naturally vary between countries and, e.g., due to shifts in the economic situation.

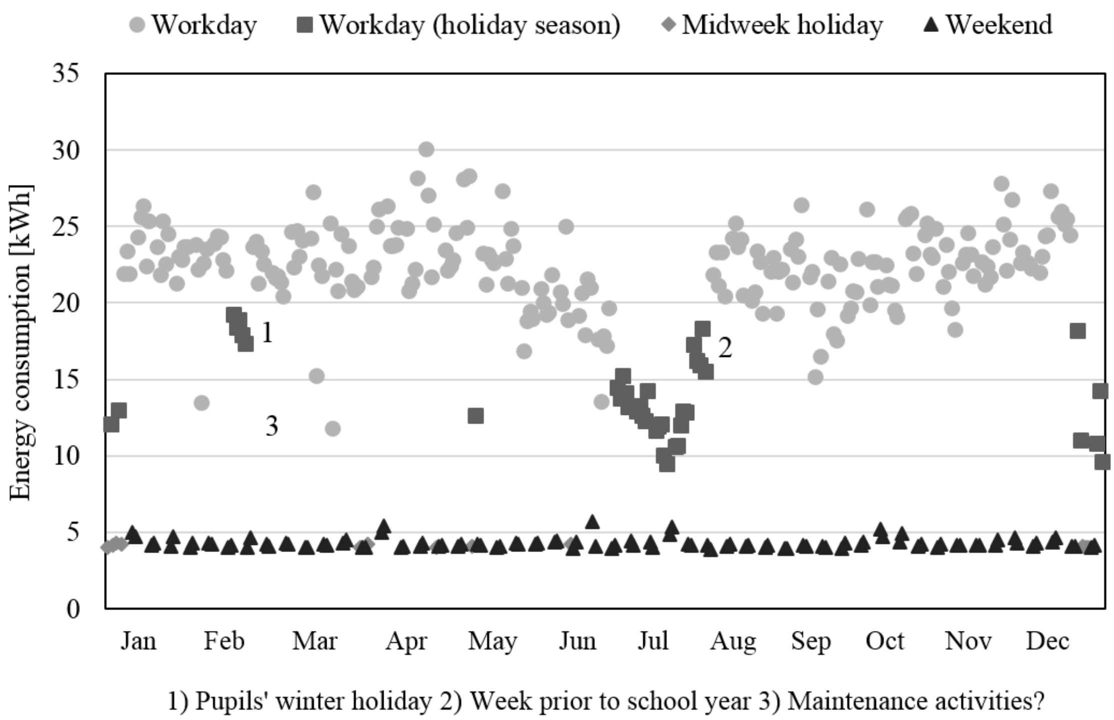

Fig. 4: Measured daily energy consumption of the monitored office elevator segmented into four day types.

Regarding the proposed methods of predicting the annual electricity consumption of the elevator, the impact of holiday seasons and midweek holidays on total annual energy usage was

$$E_{\text{holiday,impact}} = (E_{\text{work,holiday}} - E_{\text{work}}) * d_{\text{work,holiday}} + (E_{\text{midweek holiday}} - E_{\text{work}}) * d_{\text{midweek holiday}} =$$

$$(13\,873\text{ Wh} - 22\,496\text{ Wh}) * 38 + (4\,110\text{ Wh} - 22\,496\text{ Wh}) * 12 = -548\text{ kWh};$$

$$\%E_{\text{holiday,impact}} = \frac{E_{\text{holiday,impact}}}{E_{\text{annual}} - E_{\text{holiday,impact}}} * 100\% = \frac{-548\text{ kWh}}{5\,795\text{ kWh} + 548\text{ kWh}} * 100\% = -8.6\%,$$

where the average daily consumptions and number of days were determined from days identified as *workday*, *workday (holiday season)*, and *midweek holiday* in Fig. 4. The impact can be considered minor in contrast to errors provided by most of the competing methods. However, basing the annual prediction on measurements performed during the holiday season can lead to large errors. For instance, presuming a daily consumption in the middle of a holiday season to resemble a typical workday can easily lead to errors above 30%, as demonstrated later in Fig. 7.

Considering the proposed Eq. (5), the holiday seasons had an average coefficient of

$$c_1 = \frac{E'_1}{E_1} = \frac{13\,873\text{ Wh} * \frac{38}{38+12} + 4\,110\text{ Wh} * \frac{12}{38+12}}{22\,496\text{ Wh}} = \frac{11\,530\text{ Wh}}{22\,496\text{ Wh}} = 0.51$$

while the weekend consumption was considered stable throughout the year. The number of weeks inside this holiday season was 10.

3.4 Daily variance

Inspecting the daily variance in energy consumption in the monitored elevator further supports that the annual electricity consumption can be approximated with a decent accuracy based on plain historical consumption data. The daily consumptions within the same day type category were normally distributed (see Fig. 5). The deviation between different days inside the same day type category was relatively small during the monitored year, as demonstrated in Table 5. The relatively higher deviation of workdays during the holiday season compared to normal workdays resulted from categorizing all holiday season days into one category, though Fig. 4 clearly shows higher daily consumptions in certain weeks. However, further differentiating the holiday seasons would increase the complexity of the model. The difference in median and average daily consumptions also originated from limiting the number of day type categories. For example, the declining slope in June (see Fig. 4) decreased the average daily workday consumption while the median value remained larger. Nevertheless, the impact was relatively small on annual level.

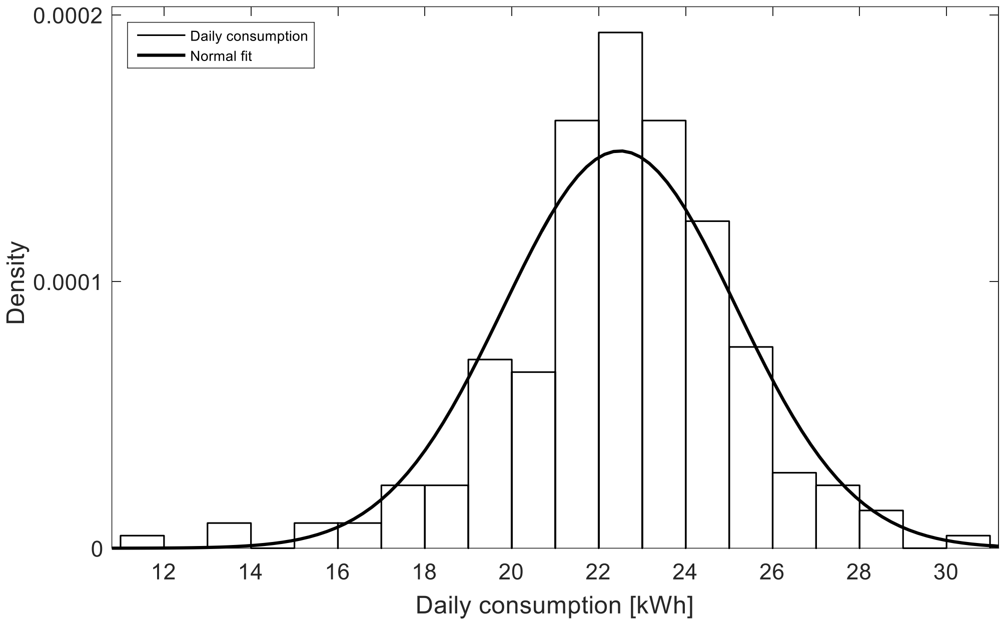

Fig. 5: Daily consumption distribution on normal workdays in the monitored office elevator.

Table 5: Monitored average electricity consumption and its variance.

	Workday	Workday (holiday season)	Midweek holiday	Weekend
Median [kWh]	22.6	13.1	4.1	4.2
μ_{d_norm} [kWh]	22.5	13.9	4.1	4.3
σ_{d_norm} [kWh]	2.7	2.8	0.09	0.3
$\sigma_{d\_norm}/\mu_{d\_norm}$	0.12	0.20	0.02	0.07

Furthermore, even the intraday power profile, in Fig. 6, shows only moderate fluctuation. The five-minute average power remained between the maximum and minimum curves during the monitored year. Furthermore, the 95% confidence intervals are relatively close to the average profile. The confidence intervals of average powers for each five-minute time bin have been calculated for gamma distribution. This can be considered a viable approach, as the amount of starts is dependent on the arrival rate of batches of people which has been found to follow a Poisson distribution [23].

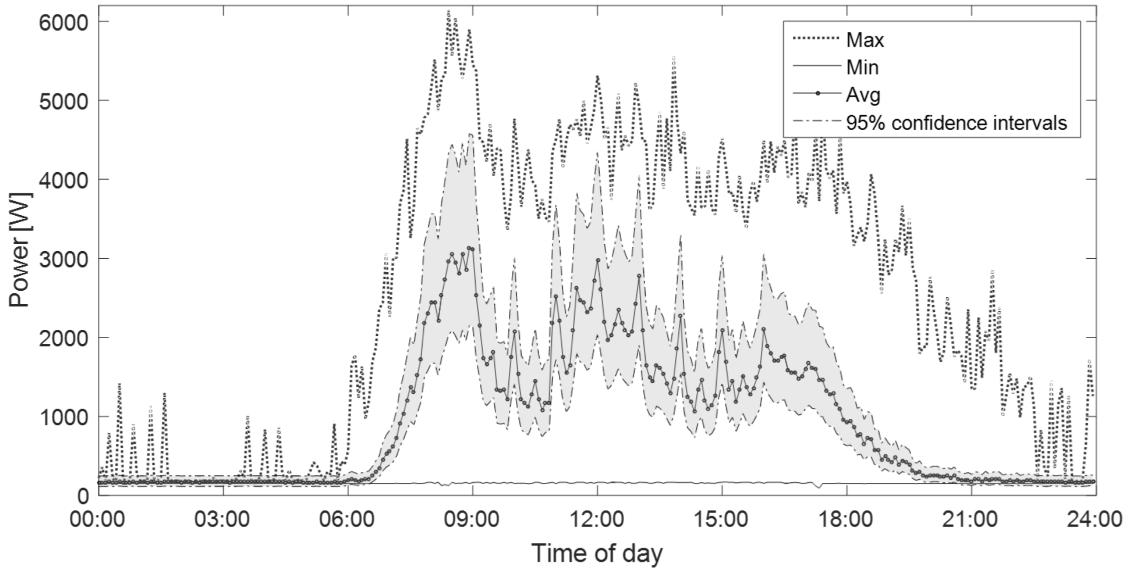

Fig. 6: Average, 95% confidence intervals, maximum, and minimum five-minute power values for the monitored elevator on normal workdays during the monitored year.

3.5 Applying the proposed methods

The proposed methods of Section 2.1.2 were applied with energy consumption data over two full days and one whole week, considering only two day types: weekends and workdays. The two-day measurement comprised Sunday and Monday, Sunday representing the weekend days and Monday the workdays (Mon – Fri). In the weeklong measurement, the weekend and workday consumptions were determined as the mean of the measured days. The impact of holiday seasons on workday consumption on average was presumed the same as calculated in Section 3.3, i.e., $c_1 = 0.51$. With 10 weeks of holiday season, this results in around 8.8% lower results by Eq. (5) than (4). Fig. 7 shows the outcome of the calculations. The employment of Eq. (4) is denoted by *Simple* and Eq. (5) by *Seasonal*.

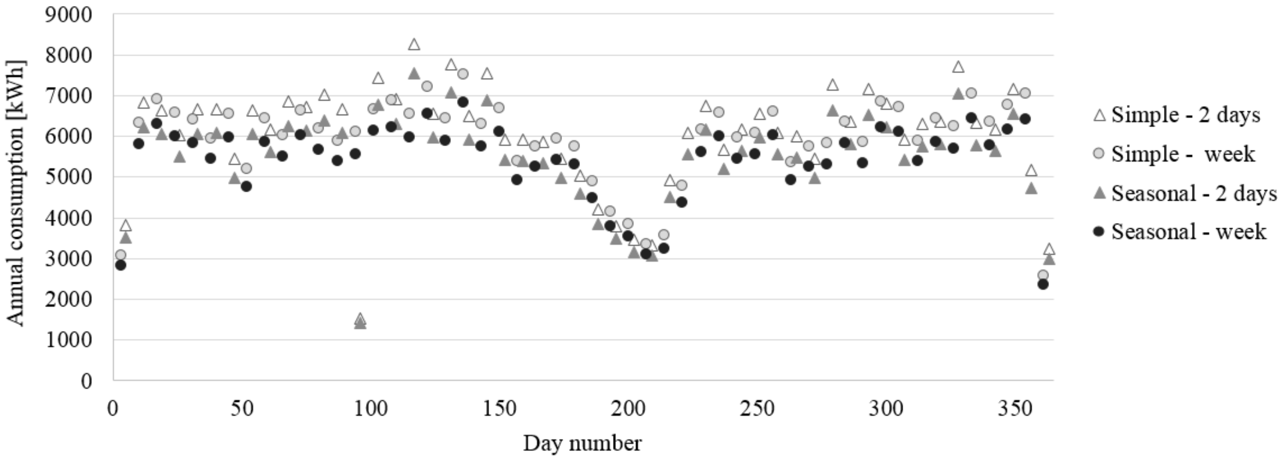

Fig. 7: Annual consumption predictions provided by the proposed methods during each week (52) of the measurement year. Two days comprised Sunday and Monday.

Clearly, the holiday seasons affect drastically the prediction result when the measurements are performed during the holiday season, as discussed already in Section 3.3. Thus, the measurements should be conducted during weeks that comprise the majority of the year. In office buildings, this is the period outside the holiday seasons.

Focusing only on predictions derived from measurements performed outside the holiday season, the results seem reliable and the error is relatively small. For example, with one week of measurements and employing Eq. (5), more than 80% of predictions remained within ± 10% error and even the maximum error was limited between -23% and +19% (see Fig. 8).

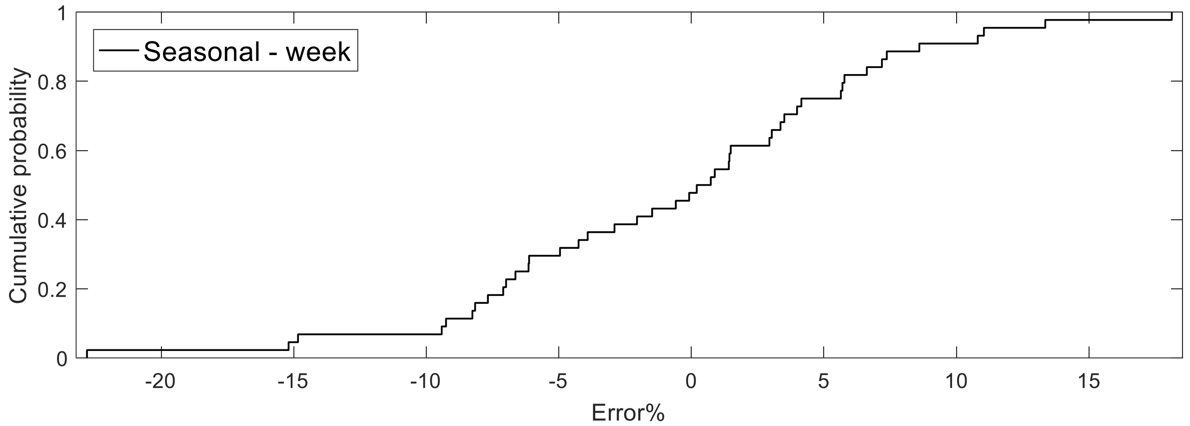

Fig. 8: Probability of achievable accuracy with the proposed method with one week of measurements during normal working periods.

3.6 Performance comparisons

Generally, the proposed methods provided better accuracy than the commonly employed ISO 25745-2 and VDI 4707-1 approaches in this case building. However, in [17], the ISO and VDI estimates could also achieve ± 10% error,

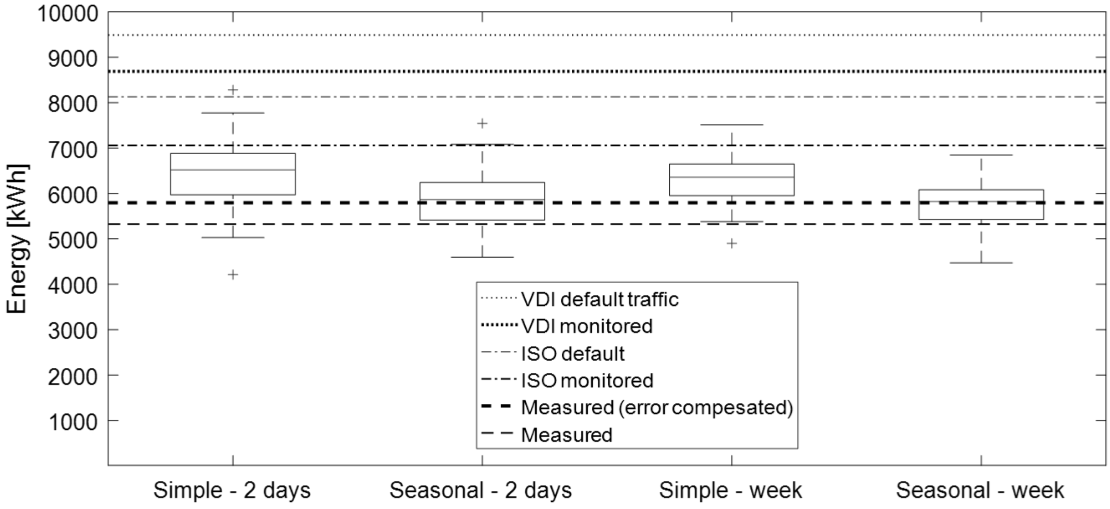

Fig. 9: Performance comparisons with a box plot of annual energy consumption predictions provided by the proposed methods on normal working weeks during the monitored year.

but these results were attainable only with high-detailed traffic data, which is commonly unavailable. Fig. 9 implies that especially by knowing the seasonal impact on energy consumption and applying Eq. (5), the attained annual consumption prediction is highly reliable. Furthermore, even the median of the *Seasonal - week* predictions is closer to the error compensated measurement value than the original measurement result.

Considering the target accuracy of ±50% (reasoned in Section 2.1.1), the method clearly fulfils this demand when data from normal working periods only is used. In contrast, if the annual consumption is calculated based on measurements collected during the holiday season or a maintenance break and applied as is, the 50% error threshold could be exceeded. This can be seen in Fig. 7 during the Christmas and end of summer holidays, for instance.

4 Discussion

The model presented in this paper is targeted at elevators, specifically at the electricity consumption of elevator units. Other indoor people transports, i.e., escalators and moving walks, can be expected to possess similar characteristics. For example, preliminary results in escalator measurements performed by the authors support this presumption. Furthermore, a resembling approach can surely be implemented for other building appliances and services as well. However, seasonal variation in the amount of sunlight, temperature, wind, and in other weather variables necessitates a more complex approach, e.g., for heating, ventilation, and air conditioning (HVAC).

With more measured sites, the energy consumption ratios for different day types, regions, and buildings can be identified to some extent. Nonetheless, measuring the consumption over the most prevailing day types provides presumably more reliable and easily attainable results even then. Section 4.1 discusses the impact of the elevator specific characteristics on the annual consumption, or more precisely, on the rise angle of the cumulative energy consumption.

4.1 Impact of elevator design, building, and traffic characteristics

Elevator energy consumption highly relates to the amount of people circulating in the building. In addition, the height of the building impacts the running consumption, as the start amounts and trip lengths increase with more floors. The overall consumption can also be significantly decreased by employing high-energy efficiency technology and sophisticated control schemes. Modern elevators serviced according to the maintenance plan have highly similar energy consumption characteristics under the same passenger traffic profile. In older installations, however, there is likely more variation due to differences in the condition of the elevator equipment. Despite of similar maintenance history, installed retrofit parts, and applied control scheme, the individual differences between elevators start to emerge during the lifecycle. For instance, Fig. 10 shows that an older elevator group has much more variation in consumption than a modern group in the same building type. Presumably, the two distinguishable subgroups in the retrofitted elevator group derive from different traffic patterns affected by the group controller.

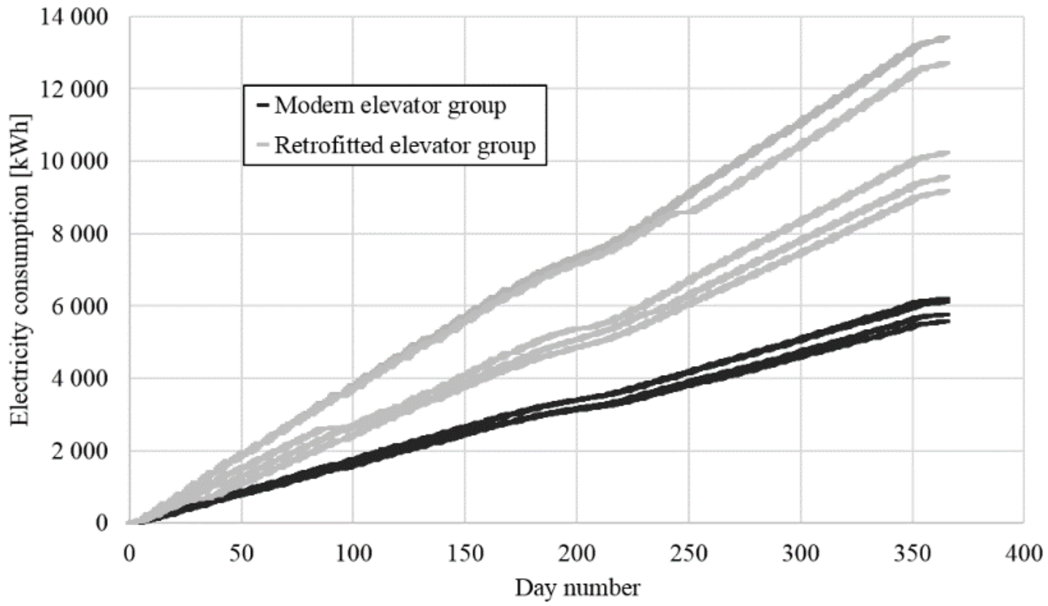

Fig. 10: Measured cumulative elevator energy consumption in two office buildings during a calendar year.

Fig. 10 also supports the proposed methods of linear extrapolation, as all nine monitored elevators behave similarly. Furthermore, a study [24] implies that the linearity can also be presumed in other regions, because the reported monthly elevator electricity consumption was relatively constant also in a commercial building in Shanghai, China. The only major difference in the monitored elevators was in the angle the energy consumption cumulates. Generally, the angle, or consumption, increases especially with

- higher stationary consumption
- less efficient hoisting system
- more starts
    - more serviceable floors
    - more frequent arrival rate of passenger batches
    - poorly designed control system

4.2 Role of metering

Though the impact of metering error in the case elevator was relatively small (-9%), the metering accuracy could be improved with higher accuracy CTs, such as class 0.2S. This can be considered a viable approach in new installations, where it is more convenient to install other than split-core window-type current transformers. Long-term monitoring also enables verifying the energy consumption, peaking power hours, seasonal variation, and development of consumption with time. This information may be useful for planning the maintenance activities, load scheduling, and other building automation processes for load shaving and decreasing electricity consumption related costs.

Determining energy efficiency classes according to the ISO 25745-2 or the VDI 4707-1 is becoming more common. As mentioned, performing the necessary electrical measurements requires accurate power loggers. The daily consumption measurements necessitated by the proposed prediction method of this current paper could be combined in the classification process to save time and on costs. For example, measuring the energy consumption of one elevator in the group for a few days could provide a more accurate prediction of the annual consumption of the group than the classification schemes.

5 Conclusions

This paper presented two methods to predict elevator annual electricity consumption based on short-term electrical energy measurements of a few days to a week. The simpler method relies on linearly extrapolating the annual consumption based on the attained daily consumption measurements. The other method additionally incorporates the effect of seasonal differences in the elevator usage, which are caused by, e.g., holiday seasons, and is expected to provide a more accurate prediction than the simpler method but requires more detailed data on the intra-year traffic patterns.

This paper analyzed the performance of the proposed methods with one elevator in an office building. Clearly, measurements, surveys, and other possibly employed methods for estimating and projecting the annual electricity consumptions of office elevators should be conducted outside the holiday season to gain reliable results, as the consumption heavily depends on the traffic. This claim is also supported by our findings of the elevator group having significantly lower average daily consumption on workdays during the holiday season. However, without accounting the effect of seasonal holidays, the annual usage estimate may result in a higher figure than actual. Nevertheless, both of the proposed methods provided adequate consumption projections of the entire year with the studied elevator. Furthermore, additional measurements in other office elevators support the idea of utilizing short-term measurements of energy over the most significant day types to predict the long-term energy consumption.

Competing methods, such as the VDI 4707-1 guideline and the ISO 25745-2 standard, seem to yield similar results as the proposed methods when applying high-quality traffic data. However, attaining reliable traffic data is a challenge in most elevator installations. Moreover, with the elevator analyzed in this paper, the VDI and ISO schemes estimated the annual consumption much higher than actual and performed worse than the proposed methods. Nonetheless, for a more solid analysis of the reliability of the results, significantly more sites with different varying usage and day types need to be monitored.

On the basis of the findings, this paper suggests the following considerations when estimating the annual elevator energy consumption:

- Base projections on measurements of most prevailing day types
- Consider the effect of seasonal differences, such as holidays

Future research will expand the performance analyses of the proposed methods to escalators and moving walks. Furthermore, the authors will focus on momentary and hourly average powers to analyze the potential of employing elevator control system in demand response-related operations. These operations could include limiting the number of units operating, reducing the elevator speed, and increasing the stop time in floors to allow more passengers aboard the elevator, decreasing the amount of starts and, consequently, power peaks in the grid of the building.

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