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Predicting the annual escalator energy consumption based on short-term measurements

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Keywords

Escalators, Energy consumption, Intermittent-operating escalators, Energy measurements, Passenger traffic;

Abstract

This article presents a novel approach for the annual energy consumption estimation in escalator technology. The method is based on short-term energy measurements of several day types within a week. It is best suitable for appliances where the passenger flow is weekly recurring. This article explores the implication of the method with seasonal changes, as well as stresses the impact of various day types and holidays on annual energy consumption estimation. The performance of the proposed method was compared with the existing approaches of energy consumption estimation in the standard ISO 25745-3 and annual energy measurement results. The approach is favorable among other existing approaches because it does not require additional passenger measurements, while providing more accurate results.

1. Introduction

An escalator is one of the best ways to transport a large mass of people from one floor to other levels of a building. The escalator is a very popular means of vertical transportation, especially in commercial and transportation buildings. In department stores, the escalator serves as a center of attraction, and the most desirable places are located in line or near the escalators. Often, the escalator increases the revenue of a commercial building by exposing and connecting the floors to customers more efficiently. Escalators are also found in various environments besides the main areas of application, the transportation and the commercial facilities. These include hospitals, schools, factories, sport arenas, office buildings, and museums [1].

According to the European Lift Association (ELA) statistics, in 2015, there were already 134,000 existing escalators in the EU and 4,700 were planned for installation [2]. Efficient escalator technology and escalator energy consumption are receiving increasing attention from researchers, property managers and building designers. Increasing awareness is led by the standardization of energy efficiency and widespread acknowledgment of building energy

certifications.

According to [1], three cost factors are taken into consideration during the design phase of the vertical transportation system of any building. They include installation costs, operational costs and the return of initial investment. The escalator energy consumption is a parameter that affects especially the two latter factors. First, knowing the passenger traffic patterns of a specific type of building helps to estimate energy consumption of the vertical transportation system, which is a part of the operational costs. Many building owners and architects strive to meet the requirements for green buildings. Among conditions necessitated by LEED or BREEAM certificates, for example, energy consumption calculations and measurements are necessary. Second, in certain conditions, when the traffic intensity is high, escalators can be equipped with a power feedback unit (PFU) to recover the energy from excessive number of passengers on the downwards escalators. Knowing the traffic patterns, taking energy measurements and calculating the energy consumption contributes to the understanding of the return of investment, partially achieved by feeding the energy back to the grid.

Normally, the escalator is not equipped with an energy measurement device. However, energy measurements help to ensure and to support the efficient and effective use of energy [3], [4]. It is required to verify periodically that the energy usage of an installed unit has not changed, as a part of energy verification requirements [3]. Knowing the annual energy consumption is useful not only for building owners and for service companies when modernization is necessary, which includes retrofitting and reduction of energy consumption; but also for maintenance companies, consultants, architects, inspecting authorities and third parties providing the classification services and support. It is helpful to correlate the calculated energy consumption with the expected operation and performance [5].

There are several methods to obtain the annual energy consumption values:

- Permanent installation of a kWh energy meter
- Escalator modeling [6], [7]
- Energy classification standard ISO 25745-3:2015
- Prediction methods (method presented in this article)

As mentioned above, usually, there are no permanently installed energy meters in escalators. Though submetering is beneficial, but besides being the most straightforward and accurate method, it increases the installation costs, which often is the main barrier for installation. Escalator modeling methods are accurate, but require more layers of gathered data, such as the amount and pattern of passengers, which are seldom measured. Energy classification standard provides a method to estimate the annual energy consumption of escalators with a certain accuracy, depending on the escalator parameters. The inaccurate estimation of annual consumption hinders proper budgeting, investment planning in the case of retrofits or upgrades, and maintenance during the later periods of escalator life cycle.

The target of this study is to raise awareness about energy efficiency and optimization of energy consumption in escalators further by introducing a method that obtains annual energy consumption estimates through short-term measurements. Our previous study [8] revealed that office elevators tend to have relatively constant weekly consumption profile throughout the year. Measuring the consumption pattern during a normal working week resulted in a reasonably accurate estimate of annual energy consumption. This paper expands the research made on elevators to escalators. The paper employs long-term measurement data from an escalator pair, operating in a shopping mall. It analyzes the feasibility of short-term consumption measurements with a portable energy analyzer to derive the annual energy consumption estimate.

Previous research on escalator energy consumption is presented in Section 2. Section 3 presents existing methodologies of annual energy consumption estimation and the proposed method. Section 4 presents the results and comparison of various methods. Section 5 discusses the shortcomings and applicability of the method. Section 6 concludes the findings of the article

and elaborates on the future research.

2. Previous Research

Among previous studies on escalator annual energy consumption is the E4 campaign [9], targeted to improve the energy performance of elevators and escalators in Europe. During the campaign, seven escalators were monitored, where measurements were carried out on empty escalators and annual energy consumption values were calculated by multiplying running consumption with a typical load factor. The estimation of the annual energy consumption values ranged from 4,000 to 10,000 kWh depending on the usage.

The E4 study lists several barriers for the penetration of energy-efficient technologies, including the lack of monitoring of energy consumption of installations. Since, as we mentioned, there are mostly no energy meters installed on devices, i.e., the energy consumption of escalators is not separated from the energy consumption of other devices in the building. Building owners and managers, when choosing the equipment, do not consider the expected energy demand of the equipment [9]. Therefore, the improvements in energy efficiency may become too generalized and may be roughly estimated.

Studies [10], [11], [12] present research about energy optimization and energy efficient technologies for escalators. Report [13] provides a guide for selecting and implementing energy saving technologies for escalators and moving walkways. Among best practices to improve escalator performance is the installation of energy meters, which not only helps to determine the potential energy savings, but also helps to notify the staff of necessary maintenance.

Additionally, among other research related to escalators and energy consumption are the studies about traffic estimation method through power measurements in escalators including articles by Carillo et al. [14] and Al-Sharif [15]. Kuutti et al. [16] compared the escalator power consumption to passenger data on a fixed-speed and intermittent-operating escalators. Another study [17] examines the relationship between the waiting time and the escalator energy consumption. Al-Sharif, in [18] and [19], provided the motivation, basis and framework for modelling the escalator energy consumption. This became the starting point for our research resulting in the following publications: Energy consumption of escalators in low traffic environments [20], Modelling the daily energy consumption of escalators with various passenger volumes [6] and the Impact of daily passenger traffic on energy consumption of intermittent-operating escalators [7].

In our article about elevator energy consumption prediction [8], a method for energy consumption estimation based on short-term energy measurements proved to be an upright way to get a trustworthy value of the annual elevator energy consumption. This article adopts the method for escalator technology, aiming to provide a reliable alternative to the existing standard estimation method presented in the ISO 25745-3 standard labeled Energy performance of lifts, escalators and moving walks – Part 3: energy calculation and classification of escalators and moving walkways [4].

3. Methods

3.1 Standardized methods

The ISO 25745-1 and ISO 25745-3 are international standards intended for building owners, developers, service companies, maintenance providers, inspecting authorities, consultants and other parties involved in escalator and moving walk specifications. The aim of the standards is to support and ensure the efficient and effective energy use in escalator and moving walk installations [3], [4].

In addition to energy classification and guidelines, the ISO 25745-3 standard provides a

generic method to estimate the energy consumption of escalators and moving walkways on a daily and an annual level. The standard method for calculating the annual energy consumption consists of two possible scenarios. Either the calculation method is based on estimated values for planning purposes, or it is based on the measured values. The method is applied in situations where a more complete or appropriate solution is not available [4].

The Energy consumption can be determined by multiplying the power consumption over the period of observation. For planning purposes, the total energy consumption of an escalator can be determined by the formulae, where power consumption values of the components are pre-estimated, pre-calculated, average values. These values depend on the parameters of a generic escalator, including dimensions, the average number of passengers over the time, their weight, weight of escalator parts, nominal speed, efficiency, friction and power consumption with no load.

Calculation based on measured values is more accurate. In this method, it is advised to make power measurements in all conditions according to the “Power demand cycle” [7] of the escalator.

The observation period consists of the length of periods of escalator operation in various modes, called the reference usage profile. The standard provides several reference usage profiles. However, some profiles, such as the case of our escalator, is not considered. Therefore, we have selected two reference usage profiles from the standard [4]. It should be noted that, in low traffic, when the average number of passengers over a day is lower than several thousand, using the reference usage profile induces an error for the estimation. Periods of operation values relate to the passenger flow and the number of passengers over the observation period [7]. The more accurate the reference usage profile is, the more accurate the estimation is. Hence, we added a custom usage profile, measured in [20], that was used to simulate times of operation in various modes and provides a more accurate reflection.

Fig. 1 presents the usage profile for the case escalator, previously analyzed in [20]. Stand-by, reduced-speed (slow-speed) and nominal-speed modes of the escalator claim for almost 99% of the working time. Table 1 presents the hourly values of the reference usage profile, required for calculation methods, provided by the standard. By default, the standard does not provide reference usage profiles for escalators which have both auto-start and slow-speed features. In the case of the observed escalator, the power consumption during the stand-by and auto-start modes were equivalent and assigned together as stand-by time in Fig. 1. The auto-start mode is active when the escalator is switched on, ready to carry passengers but is stopped (has zero speed) until a passenger is detected. In the stand-by mode, the escalator is switched on (connected to the power grid) but not in operation even if a person enters the escalator.

Fig. 1: Modelled distribution of time spent in various operation modes of the measured escalator.

Table 1: Reference usage profiles for the case escalator.

Operation mode	Slow speed (h) (ISO1A/ ISO2A)	Auto start (h) (ISO1B/ ISO2B)	Modelled (h) (ISO1C/ ISO2C)
t_{total}	24	24	24
$t_{nominal\ speed}$	10	10	4.7
$t_{standby}$	12	12	9
$t_{power\ off}$	-	-	-
$t_{slow\ speed\ (reduced\ speed)}$	2	-	7.3
$t_{auto\ start\ (stopped)}$	-	2	3

The calculation methods based on estimation will have a subscript ISO1(A) later in our article, and the estimates based on measurements will have a subscript ISO2(B), where the number relates to whether a method is through estimated or calculated power values, respectively. Letters A, B and C are the reference usage profiles for a designated method.

Energy consumption calculations imply using an average number of passengers over the period of observation. In the comparison calculations, we have used 1,500 passengers per day, according to Table 3 of the ISO 25745-3 standard, as a mean value of low traffic [4]. The same number of daily passengers was also employed to simulate the reference usage profile for the case escalator (methods ISO1C and ISO2C), explaining minor differences to Fig. 1.

The standard does not provide detailed information on the calculation procedure of the energy consumption over the year. In our comparisons, we applied the standard methods, mentioned in this section, to calculate the consumption over a day and multiplied it by 365, which was later used for comparison. It must be noted that this incorporates a small mistake, as on Saturdays and Sundays and some holidays, the opening hours of the shop are different.

3.2 The proposed method

In our previous article [8], a method for estimating annual energy consumption of elevators was proposed based on short-term energy measurements in an example of an office building. The idea behind this method is based on the conformity of the weekly energy consumption of vertical transportation systems. This article applies a similar method to estimate the annual energy consumption of escalators in an example of a shopping mall. Fig. 2 shows the recurrence of the daily energy consumption of an intermittent-operating escalator pair in several consecutive weeks.

Fig. 2: Daily energy consumption of an upwards-running escalator during a month.

The method relies on measuring the energy consumption of several day types and then linearly extrapolating the result to estimate the annual value. It assumes that the energy consumption is steady throughout the year. It can be formulated with Eq. 1 [8]:

$$E_{annual} = \frac{365}{7} \sum_{i=1}^n d_i E_i, \quad (1)$$

where, d_i is the number of days with this day type and E_i is the measured day type specific energy consumption.

To decrease the uncertainty in capturing the energy consumption related to the installed power-saving technologies of intermittent-operating escalators [7], the method necessitates measuring at least three day types: Saturday, Sunday and a Weekday. First, there are various passenger flows. Second, the working hours during different day types may vary, especially in commercial environments. The energy consumption measurements of the installation of more consecutive days within a week of operation increase the annual energy consumption prediction accuracy. To verify this presumption, we have calculated the estimate of annual energy consumption using two sets of days for each week: three days (Saturday, Sunday and Monday) and seven days (Saturday – Friday) of a week. Thus, in the three-day method, Monday is considered to represent an average weekday, while in the seven-day method, the day type specific energy consumption is the mean value measured over the five weekdays (Monday – Friday). The results are compared in Section 4 to other methods presented earlier (see Section

3.1).

3.3 Measuring location and equipment

Escalator energy consumption measurements were performed in a commercial environment in Helsinki Capital Area. The escalator pair is located inside a shopping mall. The characteristics of the monitored escalators are given in Table 2.

Table 2: Characteristics of the analyzed escalator

Application	Commercial
Rise	4.5 m
Step width	1000 mm
Inclination	35°
Gear type	Worm gear
Nominal Speed	0.5 m/s
Nominal motor power	7.5 kW
Regeneration	None

The energy measurements were conducted with a three-phase kWh meter. Direct metering was impossible, therefore, split-core CTs were used during the measurement. The accuracy of the measurements were verified by performing the error compensation (correction) with a three-phase power quality recorder, which matches the requirements set by the ISO 25745-1, ISO 25745-3 [3], [4], being IEC 61000-4-30 [21] class A equipment. The power consumption data acquisition had a 5-minute logging interval.

4. Results

This article provides a method for estimating the annual energy consumption of escalators. The principle is based on recurring weekly patterns of escalator energy consumption and passenger volumes. The method was evaluated with the existing method suggested in the ISO 25745-3 standard [4] against the measured consumption, and results are presented below.

The segregation of energy consumption by days and the annual energy consumption predictions are presented in Fig. 3. Analysis of method-estimated values and predictions are demonstrated in Fig. 5.

4.1 Implications from measurements

The measured daily energy consumption of the monitored escalator pair is presented in Fig. 3 A and C. Here, a year of data is segmented into eight day types.

Fig. 3: Measured daily energy consumption of the monitored escalator pair segmented into day types over one year and annual consumption predictions with the proposed method during each week (52) for the escalator pair. A, B – upwards, C, D – downwards.

The day types consist of:

- Monday-Thursday (“Weekdays” in Fig 3.),
- Friday,
- Saturday,
- Sunday,
- Holiday Monday-Thursday,
- Holiday Friday,
- Holiday Saturday, and
- Holiday Sunday.

The segmentation of day types provides insight about the effective usage of the method. The day type specific energy consumptions were found to be largely normally distributed, and the daily energy consumption on Sundays and during holidays is consistently lower than during other days. The reason for a lower consumption is that, during these days, usually, the opening hours in the store are less than normal. Peaks of energy consumption happen in summer, when many people are on vacation, and during the Christmas period. Fig. 4 presents the impact of seasons on energy consumption of this escalator. During summer months: June, July and August, the escalator experiences a slightly larger passenger flow.

Fig. 4: Impact of seasons on energy consumption.

The proposed method, described in Section 3, involves short-term energy measurements of the designated installation. Implications from Fig. 3 and Fig. 4 suggest that the result of the annual energy consumption estimation depends on the time of the year and specific days that the measurements are carried out. Since the number of holidays during the year is considerably smaller than ordinary days, it is suggested that measurements are not taken during holidays or potential out-of-ordinary days that imply reduced operating hours of the installation.

4.2 Prediction calculation and statistical analysis

Previous implications illustrate that the annual energy consumption estimate depends on the days and the week selected for measurements. Fig. 3 B and D also presents the annual energy consumption estimate depending on the measurement week for the escalator pair. The figure depicts the estimates derived from the 3-day- and the 7-day-long measurements for upwards-

and downwards-running escalators.

Fig. 5 presents the boxplots of annual consumption estimates for upwards- and downwards-running escalators, and Table 3 provides the statistical analysis of the results. In Fig. 5, the bottom and top of the box are the first and the third quartiles. The line inside the box is the median. The ends of the whiskers are the 1st percentile and the 99th percentile. The points outside of whiskers are the outliers. The dotted line across the whole figure is the measured annual energy consumption value.

The calculated estimates with the 7-day prediction give less dispersed values and practically eliminate the outliers, which are present with the 3-day estimates, which makes the resulting prediction much less vulnerable to non-ordinary day types.

Fig. 5: The 3-day and the 7-day predictions as boxplots for upwards and downwards-running escalators, respectively.

Table 3: Statistical analysis of energy consumption prediction for upwards- and downwards-running escalators

	Upwards		Downwards	
Measure	3-day	7-day	3-day	7-day
Mean (kWh)	6541.3	6425.2	4234.8	4312
Median (kWh)	6543.1	6400.2	4403.1	4379.9
Standard Deviation (σ) (kWh)	1144	712.6	1009	424.7
Coefficient of Variation (RSD)	17.49 %	11.09 %	23.78 %	9.85 %

4.3 Comparisons of methods:

To evaluate the proposed method, it was compared to the estimates calculated according to the ISO 25745-3 standard and to the actual energy measurement result. Fig. 6 and Fig. 7 present the comparison of various methods presented earlier in Section 3. In these figures, the mean values with their standard deviation from Table 3 of the 3-day and the 7-day annual energy consumption

prediction methods are compared with the two default methods described in Section 3.1 from the ISO 25745-3 standard. In both cases, upwards and downwards, the proposed method outperformed the competing approaches in terms of reliability.

Fig. 6: Comparison of various methods of annual energy consumption estimation for an upwards-running escalator.

Fig. 7: Comparison of various methods of annual energy consumption estimation for downwards-running escalator.

Evaluating the 3-day and the 7-day prediction, the 7-day method provides consistently results close to the measured annual consumption value. Furthermore, according to the data, even 70% of the 7-day prediction method estimates are at least on par with the most accurate calculation method based on the ISO standard in case of the studied downwards-running escalator. However,

if several precautions during measurements and estimation are considered, a better estimate is achievable. For example, the upwards-running escalator had more passengers per day (closer to the presumed 1,500), meaning that the usage profile was relatively similar to the modelled profile (see Table 1, case C). Combined with actual power measurements (ISO2C), the annual consumption estimate highly resembles the actual measured consumption. However, this degree of modelling necessitates in-depth knowledge about the escalator through measurements and adopting such modelling methods as in [6] and [7]. More precautions are described in the next section.

5. Discussions

The performances of the proposed method and the methods described in the standard depend on the overall recurrence of the passenger flow at the measurement area. The standard method also requires power measurements to achieve a better accuracy. The difference is that in the case of the standard method, the measurements are completed within a few hours, while the proposed method would need at least 3-days in a typical setup. However, for standard methods, neglecting the up-to-date usage profile and the number of passengers affects the accuracy drastically.

Unfortunately, the proposed method cannot take into consideration a sudden change in passenger traffic pattern or volumes. While it is possible to predict the shape of the passenger flow, it is hard to estimate the overall amount of passengers throughout the year. It is also problematic to acquire the accurate reference usage profile, as it requires additional installation of passenger counting devices or sophisticated analysis techniques to estimate the number of passengers from the power consumption profiles, for example presented in [14]. If there is passenger tracking, the estimation method could also include application of weighted moving averages or Kalman filters on the data. A good practice of using a smart meter would be to employ these techniques or other methods for passenger counting to monitor the changes in the passenger profile, and periodically update the annual energy consumption estimates, for example in cities with seasonal tourism. Adopting similar techniques to analyze the plain energy consumption measurement data would also provide enhanced estimates.

Generally, the 7-day prediction method is more accurate than the 3-day due to more available data, which decreases the variance when calculating the day type specific energy consumption value, E_{weekday} , used to calculate the annual consumption estimate with Eq. (1). Several means help to increase the accuracy of the annual energy estimation and to avoid the most deviated predictions:

1. Avoiding measurements on public holidays or sale days (ex., Black Friday).
2. Avoiding measurements in the middle of holiday seasons (July in Finland) and Christmas period.
3. Making sure the installation is not broken or needs maintenance, by checking with the owner or with visual/audial inspection. Usually, loud noises from the truss may speak of increased friction in escalator parts, which leads to increased energy consumption.

During the research, the long-term energy measurement raw data had to be compensated against a more accurate device, as mentioned in Section 3.3. The necessity to compensate the measured energy values rose because of the high harmonic content in the electric current in low load conditions [20] and due to the, in contrast, low sampling resolution of the measuring device.

The proposed method in this article only reflects on the already installed appliances. Although combining these findings with modeling techniques for fixed-speed escalators, described in article [19], and modeling the energy consumption of escalators in low traffic environments [20], or in

changing people volumes of intermittent-operating escalators [6, 7] together with using the ISO standard [4], would help to calculate the energy consumption of an escalator about to be built on the site.

This article introduces an approach to annual energy consumption calculation in an example of an escalator, where the prediction is ultimately compared to the measured energy consumption. The eligibility of employing the method with other appliances is supported by previous research, where we showed that other appliances in the same building segment had a similar traffic profile [7], or that buildings in another segment had a recurring passenger traffic [8].

6. Conclusions

This article presented a novel approach to annual energy consumption calculation for escalator technology. The principle is based on the weekly recurring passenger traffic. The method employs energy measurements and linearly extrapolates the value for one year to get the estimate. Of the proposed two ways of estimation, the 3-day measurements and the 7-day measurements, the latter one proves to be more accurate due to possessing more data points, reducing variance. The proposed methods showed, on average, better results to the existing methods presented in the standard. Standard methods require additional power consumption and passenger related data. Taking several advices into consideration presented in the discussions section might help to increase the accuracy of the energy consumption estimate.

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