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Vertical Transportation Demand Response: Cost of Lost Customer Hours

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Abstract—Vertical transportation systems are designed to enhance the people flow. The power consumption of escalators and elevators depends on applied technology, control strategies and passenger flow. Vertical transports are often equipped with energy saving technologies and are eligible for demand response (DR). DR for vertical transports results in induced costs related to increased passenger travel and waiting times. In this article, we analyze the cost of DR by means of speed reduction for elevators and escalators in terms of lost customer hours. We use modeling approaches to simulate passenger time delays and aggregated power consumption of a large number of escalators and elevators. The results further indicate positive applicability of such strategy in vertical transportation.

Index Terms—Vertical transportation, Elevators, Escalators, Demand response, Cost analysis

I. INTRODUCTION

Presently, the growing share of renewable energy sources (RES) in the power generation mix creates new challenges for the power system stability. The stochastic nature of RES causes more frequent imbalances and requires the power system to be comparatively flexible [1].

Deviations in frequency and decrease in the power systems inertia led to development of demand response (DR). DR is a measure of balancing supply and demand in the power system. It provides the opportunity to the customers to play a role in the balancing of the power system by means of reducing or shifting their power consumption. Aggregators can combine small-scale consumption to a larger entity to participate in various markets, for example in frequency containment reserve (FCR) markets [2].

Heating, ventilation and air-conditioning (HVAC) devices and lighting systems are frequent loads aggregated for DR outside of the residential sector [3], [4]. Among other large loads are vertical transport (VT) devices, which comprise elevators, escalators and moving walks. VTs may accommodate up to 50% of commercial building instantaneous power consumption [5]. While there is a lot of research about DR potentials of HVAC and lighting systems, there is little studies about VTs.

The DR strategy for VTs consists of curtailing the power consumption of the aggregated appliances. For escalators, the main strategy is reducing the travel speed [6]. Elevator power consumption can be decreased, e.g., by lowering the number of active units in an elevator group, decreasing the travel speed and/or acceleration, increasing the door closing time or

using regenerative elevators as virtual storage. Applying these methods to VTs, in turn, induces costs related to increased travel time, queuing of passengers and increased discomfort.

In this article, we evaluate the cost of DR events of different length at different hours of the day by simulating the speed decrease of the appliances. We use modeling approaches depicted earlier in [7], [8], [9] to simulate the passenger traffic, time delay and the power consumption profiles of the designated appliances.

II. METHODOLOGY

This section describes the applied models of vertical transportation. The DR events for both escalators and elevators in the applied models are similar. We have simulated 5-min, 10-min and 15-min length of DR events where the speed of the appliance was decreased to 50% of the nominal value. For each length, an event was simulated 20 times for each hour of the day, while the starting moment of DR inside the hour was selected at random (escalators) or fixed to the beginning of the hour (elevators).

A. Escalator model

Escalators can be fixed-speed and intermittent-operating. Fixed-speed escalators are constantly in motion, regardless of the passenger flow. Intermittent-operating escalators are equipped with a variable-speed drive (VSD), which enables energy saving during times when there is no passenger flow. In this article, we utilize the escalator model used in [6] to create 3000 intermittent-operating escalators. The approach involves creating each escalator separately. Unique parameters include, e.g., direction, dimensions, speed, no-load power consumption, energy class, daily number of passengers and passenger distribution. Fig. 1 depicts the distribution of the daily number of passengers per escalator used in the simulation. It includes distributions in a public transportation and a commercial building. About 30% of all escalators in the simulation are in public transportation. These profiles were obtained in previous research, discussed in [7], [10].

As mentioned earlier, for every escalator to participate in the simulated DR event, the requirement is to reduce the speed to 50% of the nominal value. One negative impact of speed reduction is the decreased passenger capacity which results in increased queuing. According to [11], [12], it is

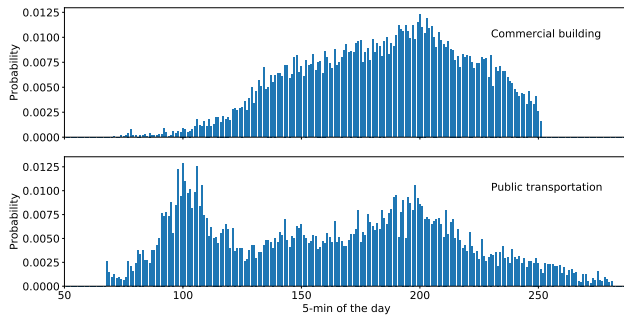


Fig. 1. Distribution of passengers entering an escalator in 5-min resolution (from the total number of daily passengers).

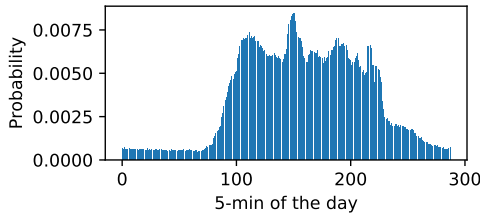


Fig. 2. Distribution of passengers calling an elevator for the elevator set in 5-min granularity.

allowed to change the speed of the intermittent-operating escalator only at times when there are no passengers on board. This safety measure may create a delay in the beginning of the speed reduction period and serves as a bottleneck for changing the speed back to nominal. Therefore, the length of the accumulated queue depends on the passenger traffic, hour of the day and the length of the DR event.

B. Elevator model

The impact of nominal speed decrease on the journey times of elevators was modelled with an elevator simulation framework depicted in [9]. The background distribution of nominal loads, group sizes, shaft heights and usage category (including building type) were based on the elevator metadata available at [13]. Due to the probabilistic method of generating the elevator groups, the amount of units and their characteristics vary with every elevator set. For simplicity, the results presented in this paper are derived from a single set of elevators, totaling in the amount of 2,885 units. The probability distribution of passengers is shown in Fig. 2.

All the elevators were modeled as traction elevators due to the low capability of controlling the power demand of hydraulic elevators. The speed was decreased by 50% for every unit having a new start during the active DR event, after which the speed setting was restored to nominal. For each iteration, a new passenger profile was drawn to incorporate the difference between unique days. The simulation started 5 min prior to the DR event to allow the system to settle closer to normal conditions, i.e., let the elevator positions and usage to reach a more realistic dynamic state.

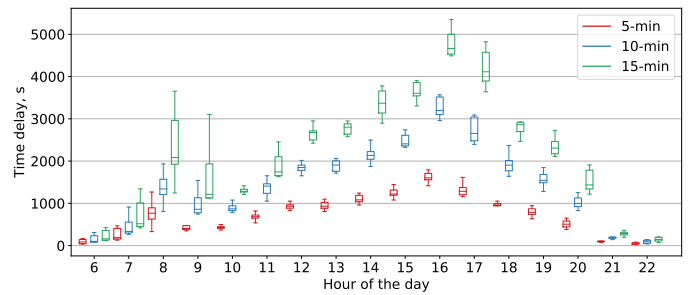


Fig. 3. Time delay as a consequence of a DR event for escalators.

C. Value of time

In transport economics, the value of time is the opportunity cost of the time that a traveller spends on a journey. In other words, it is the amount they would accept as a compensation for the lost time. The value of time varies not only with trip-related characteristics such as time of the day, trip purpose and comfort, but also with socioeconomic characteristics, such as income, employment status and others [14].

In this study, the DR costs are evaluated in terms of increased travel and waiting times as a consequence of DR. To quantify the delay in terms of cost, the study uses the figure of £8.82 (€10.14) per hour, per passenger, while the value is weighted depending on the activity of the passenger, which is 1.5 for the escalator and 2 for waiting on the platform [15] (similar to standing in the elevator). Therefore, the values of a "lost customer hour" used in this article are €15.21 for escalators and €20.28 for elevators.

III. RESULTS

This section analyzes the simulation results, where every unit of the modelled escalators and elevators participated in the 50% speed reduction DR event. The results are presented as mean values per unit.

A. Cost of DR for escalators

Fig. 3 depicts the boxplot of increased journey times (waiting + travel time) for every DR interval and every hour of the day. Time delay value is the average value per 3000 simulated escalators.

The peak of the waiting time falls onto 5 PM, when the traffic is also at its peak. The mean increased waiting time for passengers in a 15-min DR event at that time is around 4500 seconds per escalator. This means that on average, 400 passengers (from simulation results) are slowed for about 11 seconds per passenger per escalator. The total amount of passengers in the simulation was 22,654,505, where the mean number of passengers per escalator is 7552.

Fig. 4 depicts the mean cost of one DR event of the designated length per escalator, considering that there was only one event per day. It is seen that the overall correlation of time delay from the DR event duration is linear.

The shape of the increased journey times and DR costs profiles in Fig. 3 and 4 correspond with the passenger traffic

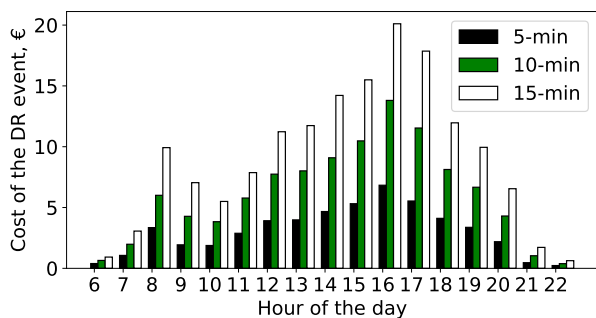


Fig. 4. Mean cost of the DR event per escalator during each hour of the day.

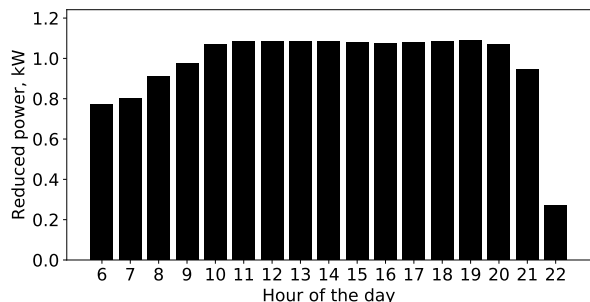


Fig. 5. Reduced power consumption per escalator as a result of DR.

profiles presented in Fig. 1. However, it can be identified from Fig. 5 that during the highest DR cost hour, the mean reduced aggregate power is actually slightly less than during its neighbouring hours. This means that the cost function of the DR event is not totally linear as the purely cost-based graphs might indicate.

This non-linearity of the cost function can be explained with the help of publication [7].

- 1) First, and foremost, the aggregated power reduction is mostly achieved from decreasing the mechanical power consumption related to overcoming the friction in the moving parts of the escalator rather than from slowing the movement of passengers. Even though the speed reduction also decreases the instantaneous power resulting from the passengers' mass, this impact is countered on the aggregate level due to the increased time the passengers spend on the escalators. Furthermore, during the peak traffic hours, most of the simulated escalators are operating with nominal running speed, which leads to a situation where the reduction of power (obtained DR) is highly similar between the peak hours, as shown in Fig. 5.
- 2) The slightly smaller DR power during the highest passenger traffic hour, on the other hand, mostly originates from the issue that the passenger frequency is so high that it obstructs more escalators to reduce the speed as fast as it happens during the non-peak traffic hours.
- 3) The same issue of speed change occurs also after the DR event is lifted, i.e., the frequency of passengers limits escalators from returning to the original speed which

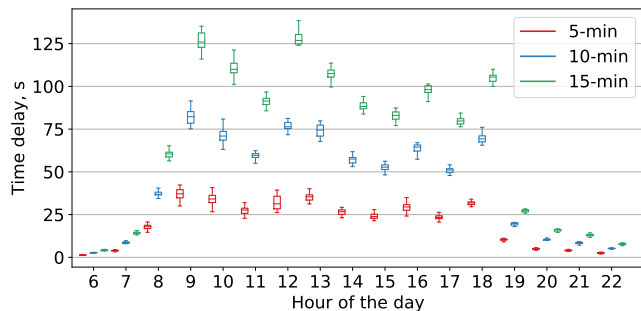


Fig. 6. Time delay (per unit) as a consequence of a DR event for elevators .

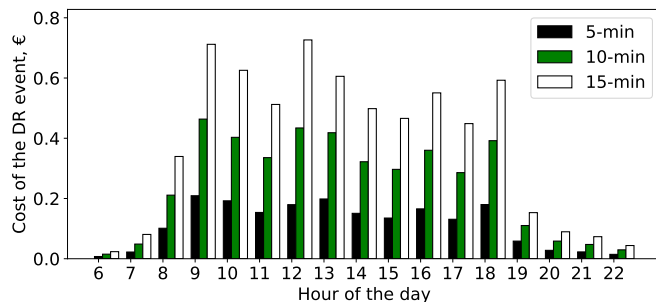


Fig. 7. Mean cost of the DR event per elevator during each hour of the day.

further increases the experienced journey delays.

There is a clear countering effect between phenomena 2) and 3), making it difficult to determine their individual impact and significance.

B. Cost of DR for elevators

Fig. 6 depicts the box plot of increased journey time as one of the consequences of the speed reduction. Similar to the case of escalators, it correlates with the traffic pattern presented in Fig. 2. During peak traffic, the mean increased total journey time for passengers resulting from a 15-min DR event was simulated to be approximately 120 seconds per elevator. This translates to an average of 10 passengers being delayed by 12 seconds (from simulation results). The total amount of daily passengers in the simulation was 641,787, i.e., the mean number of passengers per elevator was 222.

Examining the mean cost of the DR event, in Fig. 7, against the equivalent escalator values reveals that elevators process much less passengers per time unit, leading to less DR inconvenience in the aggregate in terms of lost customer hours.

Fig. 8 depicts the average value of the reduced power consumption in 30 minutes for elevators, thus, also taking into account the rebound effect occurring after the DR event has ended. The maximum values in the elevator graph are about 30 times less than that of the escalators. These results verify the limited potential of using speed reduction as a method for elevator DR. Similar to the impact of reducing the movement of passengers, explained in Section III-A, the reduced instantaneous power demand is countered on the

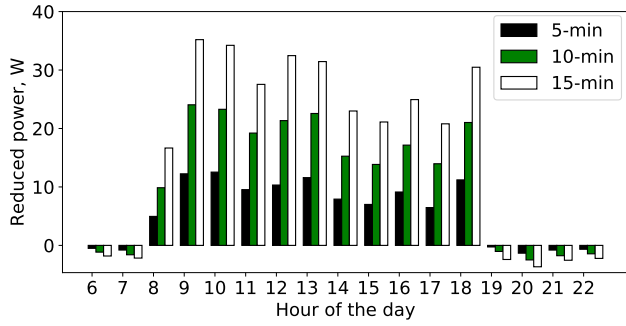


Fig. 8. Mean value of reduced power per elevator in 30-min span after a DR event.

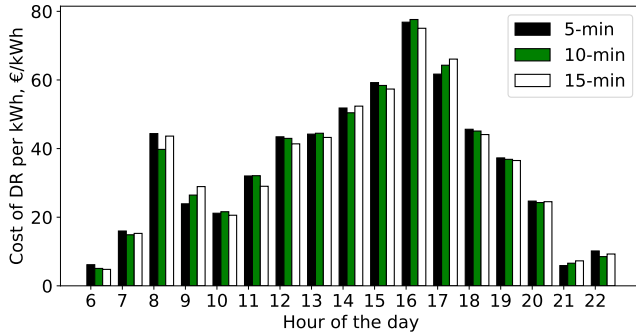


Fig. 9. Mean value of DR cost per kWh of energy during the day for escalators.

aggregate level due to the corresponding relative increase in the duration of the trip. Thus, the occurred power savings are generally obtained from the reduction of starts, and, to some extent, the increased average loading per start, which has reduced the net mass the elevators have to transport.

C. Comparison of costs of DR

Fig. 9 and 10 depict the hourly distribution of the cost per kWh of DR for escalators and elevators, respectively. For both, the 5-, 10- and 15-min values are close to each other during each hour. For escalators, the cost of DR per kWh corresponds to the traffic distribution presented earlier, where the peak is around 5 PM.

For elevators, all the negative values were removed from the figure for clarity and the large spike is due to small numbers of units used in that hour which causes uncertainty to the cost of a small DR. Small number of units is also the cause for negative saved energies, i.e., the characteristics of starts during those hours do not react positively to the DR control. This further emphasizes the need to focus DR control events only on units where they are beneficial, more predictable and provide least costs for a given DR output.

Table I presents the comparison of the simulated results of DR cost per kWh to the market situation in Finland in 2017. In the yearly market, the price is constant during the entire calendar year. All market participants receive the same compensation for maintaining reserve capacity [16]. This

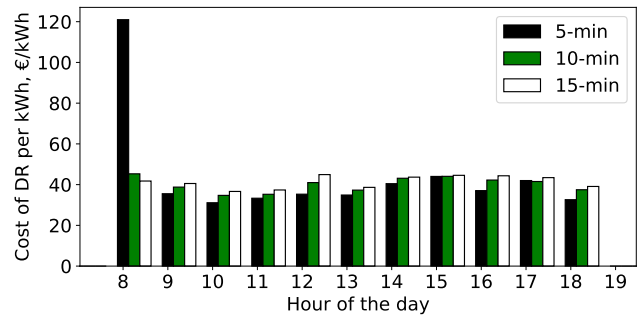


Fig. 10. Mean value of DR cost per kWh of energy during the day for elevators.

TABLE I
AVERAGE COST OF DR POWER/ENERGY, FINLAND 2017 [CITE FINGRID]

Resource	Simulated mean
Escalators	35.36 €/kWh
Elevators	41.91 €/kWh
Market type	Market prices 2017
FCR-N (yearly market, 2017)	13.00 €/MW,h
FCR-D (yearly market, 2017)	4.70 €/MW,h
FCR-N (hourly market ¹ , 2017)	20.86 €/MW (mean)
FCR-D (hourly market, 2017)	3.39 €/MW (mean)

¹ Reserve providers may participate in the hourly market by signing a contract with the TSO. The hourly market is used for additional procurement once a day if necessary [16].

means that, the aggregator who has signed the contract with the transmission system operator (TSO) would receive €41,172 per MW during that year for participating in the FCR-D, for example. Fig. 11 depicts the number of DR events, that would theoretically be possible to occur during a year for the DR to still remain profitable. The presented values are calculated with the average cost of DR per kWh for VTs and the market prices of FCR-N and -D markets for 2017 and 2018 [16], while excluding other external costs.

The results indicate that, for escalators, for example, in the FCR-N market, in 2018, there can be about 42 5-min DR events to still stay break-even with the calculated cost of DR. While disturbances happen infrequently, normal operation reserves are activated more often. Thus, VTs may better suit the DR in case of disturbances.

IV. DISCUSSIONS

It should be noted that the results are presented from the system perspective when every running unit is participating in the DR event and the study only considered typical weekdays. However, due the varying characteristics of vertical transports, the study should be expanded to the viewpoint of the devices, i.e., the owners of the VTs. Analyzing the DR events from the perspective of individual VTs and groups of VTs should reveal large differences between the impact (decrease in power demand) and experienced costs (mainly reduced passenger flows) of DR participation. Thus, VTs could be ranked in

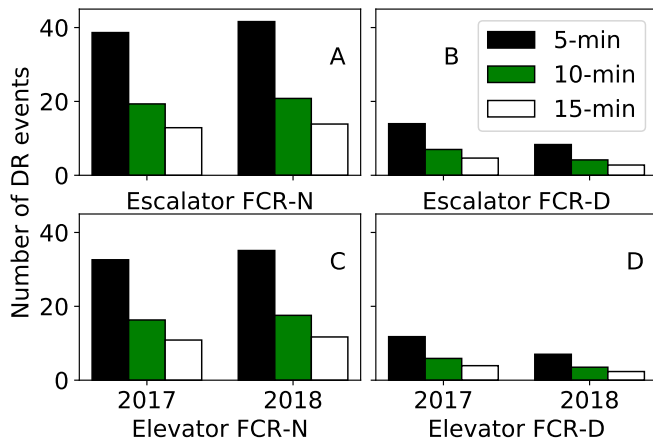


Fig. 11. Estimate of the number of DR events in the price range of the reserve market to remain profitable for: A, B- escalators and C, D- elevators in FCR-N and -D markets respectively.

terms of their DR potential, and a new cost function based on the ratio of DR activation in the VT population could be created to improve the overall DR benefits versus the induced costs.

Readers should also note that the elevator and escalator model did not take into consideration the loss of passengers who chose a staircase instead. For escalators, for example, it would help to reduce the power consumption even further, help to remove the queue faster and change the speed back to normal earlier than it would otherwise do if 100% of the passengers would still take the escalator. On the other hand, this has a complex impact on the overall comfort of riding, which is often subjective and ambiguous to model, and, thus, not considered in the model.

The authors would like to mention that modelling such cost of DR is in the "grey area". Hypothetically, in the case of a severe disturbance threat, when choosing between the economic impact of the increased passengers delay time and an impact of a blackout, there is little doubt that the hypothetical blackout would cause much more disturbance than even totally shutting down VTs. Thus, in a sense, the presented cost of DR is a "soft cost". First of all, the passengers can always opt-in to walk the escalator or choose the staircase, which decreases the queue and, therefore, decreases the cost of DR. Additionally, the aggregator is not paying the delayed passengers, and the employed cost analysis can be viewed more as an economic impact on the affected area.

V. CONCLUSION

This paper focused on the obtained reduction of power with DR in VT and the resulting cost of delay caused to passengers. More specifically, the paper analyzed the system-level impact of reducing the running speed of the VTs by 50% for different periods of time during weekdays. It follows that the cost of the DR event for VTs depends on the length of the event, passenger traffic and composition of the aggregate units, i.e., applied technology, physical dimensions and segment of

the appliances. The article presents the simulated mean price per kWh of curtailed energy consumption of escalators and elevators in comparison to the market prices in Finland.

The results indicate that it is possible to use VTs in DR without exceeding the costs of delayed passengers during the event in FCR-N and -D markets. While reserves for normal operation are activated regularly, reserves for disturbances are activated less frequently. It follows that it is more cost efficient to use VTs for DR during disturbances. The frequent use of VTs in reserves for normal operation results in the induced cost of the passengers delays which, in the span of a year, outweighs the benefits granted by the TSO.

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