Models for Evaluating the Power Consumption of Elevators

The Perspective of Power Systems and Demand Response

Toni Tukia
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Toni Tukia

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The field of power systems is experiencing multiple changes that affect the designing and operation of power generation and delivery. The most significant drivers of the transition are climate change and urbanization. The climate change has accelerated the installation of intermittent, renewable power sources, which has increased the need for demand-side flexibility, or demand response (DR). On the other hand, the accelerating urbanization alters the demand of power, especially the distribution of load types, necessitating updates to load modeling.

This dissertation focuses on developing power consumption models for an electric load type which has a rapidly increasing installed base due to the accelerating urbanization – the elevators. The main objective is to provide models which are relatively simple to adopt while providing adequate accuracy. The modeling has been divided into four stages.

The first stage of the modeling begins by assessing the diurnal, weekly, and seasonal energy consumption patterns of elevators with the help of literature and measurements. The results of the first stage indicate that elevator energy consumption is strongly recurring and the consumption patterns correlate with the day types, which can be obtained from the calendar. Furthermore, the intraday power consumption profiles are shown to result from the experienced passenger traffic patterns. The second stage of the modeling depicts an elevator model capable of providing the power consumption in high-resolution as a result of the simulated passenger traffic. The elevator model entails multiple layers. First, a collective group control algorithm is employed to minimize the waiting time of passengers in multi-unit elevator groups. Second, the power consumption profiles of each resulting trip are modeled by considering the mechanical and electrical properties of the elevator, the speed and direction of the trip, and the concurrent loading caused by the passengers. In addition, the stationary (standby) power demand is modeled to occupy the time between the trips. The third stage of the modeling employs the created elevator model to simulate the power consumption profile of a large elevator fleet with varying characteristics. The dissertation then assesses the power system-specific characteristics of the aggregated elevator power consumption in dense, urban areas with a high concentration of elevators. The fourth stage of the modeling is focused on evaluating the potential of elevators in demand response. With the combined simulation of elevator passenger traffic and the resulting power consumption, the model enables a detailed view of the performance of different control methods in terms of the obtained power change against the delay experienced by the passengers. Therefore, the approach can be employed to compare various elevator setups and apply DR actions only to the most favorable units to optimize the selection process of DR participation.

Keywords aggregate consumption, demand response, elevators, energy efficiency, frequency control, high-resolution load modeling, passenger traffic, vertical transportation

This doctoral thesis and the related research were conducted in the research group of Power Systems and High Voltage Engineering in the Department of Electrical Engineering and Automation at Aalto University between 2014 and 2019. The work was inspired by the initial support from the Energizing Urban Ecosystems (EUE) project and collaboration with KONE Corporation. The research continued with the support of Business Finland in the Finnish Solar Revolution (FSR) project and later with funding by the Academy of Finland in the project Flexible Customer. The additional financial support by the Walter Ahlström Foundation is also deeply appreciated.

My sincerest appreciation goes to Prof. Matti Lehtonen for introducing me to this interesting research area, which combines both practical and analytical aspects, as well as for all the guidance throughout my studies. I would also like to acknowledge the pre-examiners of this thesis, Prof. Jamshid Aghaei of Shiraz University of Technology and Prof. Karar Mahmoud of Aswan University, for their constructive feedback and suggestions.

I am also grateful for the continuing collaboration with KONE Corporation since the beginning of my master's thesis. This dissertation would not have been possible without all the discussions and measurements conducted with these professionals. Special thanks go to my co-authors Dr. Marja-Liisa Siikonen, Claudio Donghi, and the late Dr. Harri Hakala, who have opened the fascinating world of people flow and energy efficiency of vertical transportation for me.

I have also been blessed with great colleagues Semen Uimonen, Verner Püvi, Sabin Sathyan, Dr. Jussi Ekström, Dr. Mahdi Pourakbari Kasmaei, Arslan Bashir, Mehdi Tavakkoli, and countless others, with whom I have been able to share the laughter and problems related to research and life in general. I also appreciate Dr. Antti Alahäiviä’s great research work, which laid a stable foundation for expanding my work towards demand-side flexibility. Additionally, I am thankful to Dr. John Millar for all the discussions and guidance during my time in the research group. I am also indebted to Dr. Sasa Djokic of the University of Edinburgh for graciously hosting my research visit, and grateful for the ongoing collaboration. Furthermore, I would like to acknowledge Jarkko Tiirro of Wirebon Oy for all the assistance in meter installations and for the
positive can-do attitude.

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Toni Tukia
"Kaksi suuntaa hississä: up and down up and down ...  
Mahtava meininki hississä, rock and roll, rock and romamama ...  ”

(Kaksi kättä hississä, Seminaarinmäen Mieslaulajat, 1996)
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List of Publications

This thesis consists of an overview of the following publications which are referred to in the text by their Roman numerals.


Author’s Contribution

Publication I: “Practices to improve the annual elevator energy consumption estimates and measurements”

The main idea was developed by Toni Tukia, Marja-Liisa Siikonen, Harri Hakala, and Claudio Donghi. Harri Hakala initiated the idea to compare the estimate range to those of energy efficiency classes. Marja-Liisa Siikonen provided the elevator traffic data. Toni Tukia developed the methodology, performed the measurements, analyzed the results, and wrote the paper. Semen Uimonen and Matti Lehtonen contributed through comments and discussion.

Publication II: “Explicit method to predict annual elevator energy consumption in recurring passenger traffic conditions”

The main idea and methodology were developed by Toni Tukia, who also performed the measurements, analyzed the results, and wrote the paper. Semen Uimonen, Marja-Liisa Siikonen, Harri Hakala, Claudio Donghi, and Matti Lehtonen contributed through comments and discussion.

Publication III: “Predicting the annual escalator energy consumption based on short-term measurements”

The main idea and methodology were developed by Semen Uimonen and Toni Tukia. Semen Uimonen and Toni Tukia also performed the measurements. Semen Uimonen analyzed the results and wrote the paper. Marja-Liisa Siikonen and Matti Lehtonen contributed through comments and discussion.
Author’s Contribution

Publication IV: “High-resolution modeling of elevator power consumption”

The main idea and methodology were developed by Toni Tukia, who also performed the simulations, analyzed the results, and wrote the paper. Marja-Liisa Siikonen provided information on elevator traffic design regarding the up-peak handling capacity. Semen Uimonen, Claudio Donghi, and Matti Lehtonen contributed through comments and discussion.

Publication V: “Assessing the applicability of vertical transportation in power system inertial support”

The main idea and the majority of the models were developed by Toni Tukia who also wrote most of the paper. Semen Uimonen contributed to the escalator model part. Toni Tukia performed the power system simulations and analyzed the results. Matti Lehtonen contributed through comments and discussion.

Publication VI: “Modeling the aggregated power consumption of elevators – the New York City case study”

The main idea was created by Toni Tukia. Toni Tukia developed the overall methodology, performed the simulations, analyzed the results, and wrote the paper. Marja-Liisa Siikonen provided information on elevator traffic design regarding the elevator group sizing. Semen Uimonen, Claudio Donghi, and Matti Lehtonen contributed through comments and discussion.

Publication VII: “Evaluating the means and effectiveness of elevator demand response”

The main idea was developed by Toni Tukia. Toni Tukia created the methodology, performed the simulations, analyzed the results, and wrote the paper. Semen Uimonen, Marja-Liisa Siikonen, Verner Püvi, Claudio Donghi, and Matti Lehtonen contributed through comments and discussion.
# List of Abbreviations and Symbols

## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>aFRR</td>
<td>Automatic frequency restoration reserve</td>
</tr>
<tr>
<td>CPP</td>
<td>Critical peak pricing</td>
</tr>
<tr>
<td>DR</td>
<td>Demand response</td>
</tr>
<tr>
<td>ELA</td>
<td>European Lift Association</td>
</tr>
<tr>
<td>ETA</td>
<td>Estimated time of arrival</td>
</tr>
<tr>
<td>FCR</td>
<td>Frequency containment reserve</td>
</tr>
<tr>
<td>FCR-D</td>
<td>Frequency containment reserve for disturbances</td>
</tr>
<tr>
<td>FCR-N</td>
<td>Frequency containment reserve for normal operation</td>
</tr>
<tr>
<td>FRR</td>
<td>Frequency restoration reserve</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>mFRR</td>
<td>Manual frequency restoration reserve</td>
</tr>
<tr>
<td>NYC</td>
<td>New York City</td>
</tr>
<tr>
<td>RoCoF</td>
<td>Rate of change of frequency</td>
</tr>
<tr>
<td>RTP</td>
<td>Real-time pricing</td>
</tr>
<tr>
<td>TOU</td>
<td>Time of use</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission system operator</td>
</tr>
<tr>
<td>UC</td>
<td>Usage category</td>
</tr>
<tr>
<td>VDI</td>
<td>Verein Deutscher Ingenieure, The Association of German Engineers</td>
</tr>
<tr>
<td>VPP</td>
<td>Virtual power plant</td>
</tr>
</tbody>
</table>
List of Abbreviations and Symbols

VRE Variable renewable energy  
VT Vertical transportation

**Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\Delta f$</td>
<td>Change in frequency</td>
</tr>
<tr>
<td>$\Delta f_{nadir}$</td>
<td>Change in frequency nadir</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Change in power demand due to DR</td>
</tr>
<tr>
<td>$\Delta \text{Delay}$</td>
<td>Change in passenger delay (journey time) due to DR</td>
</tr>
<tr>
<td>$\Delta \text{Energy}$</td>
<td>Change in elevator energy consumption due to DR</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Hoisting efficiency</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$a$</td>
<td>Acceleration</td>
</tr>
<tr>
<td>$C J_m$</td>
<td>Inertia constant</td>
</tr>
<tr>
<td>$C K$</td>
<td>Load factor equation variable</td>
</tr>
<tr>
<td>$COST_{\text{DR}}$</td>
<td>Cost of a DR event</td>
</tr>
<tr>
<td>$E_a$</td>
<td>Annual energy consumption</td>
</tr>
<tr>
<td>$E_d$</td>
<td>Daily energy consumption</td>
</tr>
<tr>
<td>$E_{\text{ard}}$</td>
<td>Daily non-running consumption</td>
</tr>
<tr>
<td>$E_{\text{rav}}$</td>
<td>Average unloaded running cycle energy consumption</td>
</tr>
<tr>
<td>$E_{\text{rc}}$</td>
<td>Average energy consumed during the reference cycle</td>
</tr>
<tr>
<td>$E_{\text{rd}}$</td>
<td>Daily running consumption</td>
</tr>
<tr>
<td>$E_{\text{rm}}$</td>
<td>Energy consumption per meter of travel</td>
</tr>
<tr>
<td>$E_{\text{sc}}$</td>
<td>Average energy consumed during the short cycle</td>
</tr>
<tr>
<td>$E_{\text{spec}}$</td>
<td>Travel specific energy demand</td>
</tr>
<tr>
<td>$E_{\text{ssc}}$</td>
<td>Start/stop energy consumption per trip</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$i$</td>
<td>Index of a trip</td>
</tr>
<tr>
<td>$K$</td>
<td>Counterweight ratio</td>
</tr>
<tr>
<td>$k$</td>
<td>Load factor</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$m_{\text{car}}$</td>
<td>Car mass</td>
</tr>
<tr>
<td>$m_{\text{cw}}$</td>
<td>Counterweight mass</td>
</tr>
<tr>
<td>$m_{\text{load}}$</td>
<td>Mass of the load</td>
</tr>
<tr>
<td>$m_{\text{net}}$</td>
<td>Net load</td>
</tr>
<tr>
<td>$m_{\text{rated}}$</td>
<td>Rated load</td>
</tr>
<tr>
<td>$n_{\text{trips}}$</td>
<td>Number of trips per day</td>
</tr>
<tr>
<td>$P_{\text{control}}$</td>
<td>Increase in power demand of control electronics during a trip</td>
</tr>
<tr>
<td>$P_{\text{doors}}$</td>
<td>Power demand to operate elevator doors</td>
</tr>
<tr>
<td>$P_{\text{idle}}$</td>
<td>Idle state power demand</td>
</tr>
<tr>
<td>$P_{\text{M,el}}$</td>
<td>Instantaneous electrical power demand of an elevator drive/motor</td>
</tr>
<tr>
<td>$P_{\text{M}}$</td>
<td>Instantaneous mechanical power required to move the net load</td>
</tr>
<tr>
<td>$P_{\text{st30}}$</td>
<td>30-minute standby power demand</td>
</tr>
<tr>
<td>$P_{\text{st5}}$</td>
<td>5-minute standby power demand</td>
</tr>
<tr>
<td>$P_{\text{stationary}}$</td>
<td>Stationary power demand</td>
</tr>
<tr>
<td>$P_{\text{trip}}$</td>
<td>Instantaneous power demand during a trip</td>
</tr>
<tr>
<td>$Q$</td>
<td>Rated load</td>
</tr>
<tr>
<td>$R$</td>
<td>Weighing variable for stationary power components</td>
</tr>
<tr>
<td>$s$</td>
<td>Laplace complex frequency</td>
</tr>
<tr>
<td>$s_{\text{av}}$</td>
<td>Average travel distance of a trip</td>
</tr>
<tr>
<td>$s_{\text{nom}}$</td>
<td>Distance covered in nominal speed</td>
</tr>
<tr>
<td>$s_{\text{rc}}$</td>
<td>One-way travel distance of the reference cycle</td>
</tr>
<tr>
<td>$s_{\text{sc}}$</td>
<td>One-way travel distance of the short cycle</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$t_{\text{av}}$</td>
<td>Average duration of a trip</td>
</tr>
<tr>
<td>$t_{\text{doors}}$</td>
<td>Duration of door operations</td>
</tr>
<tr>
<td>$T_{\text{d}}$</td>
<td>Measuring delay</td>
</tr>
<tr>
<td>$t_{\text{journey}}$</td>
<td>Duration of a complete elevator journey</td>
</tr>
<tr>
<td>$t_{\text{nr}}$</td>
<td>Daily non-running time</td>
</tr>
</tbody>
</table>
List of Abbreviations and Symbols

$t_{\text{running}}$  Daily running time
$t_s$  Time since last stop
$t_{\text{transit}}$  Time passenger spends inside the elevator car
$t_{\text{waiting}}$  Passenger waiting time
$TH$  RoCoF threshold value
$v$  Speed
$v_{\text{nom}}$  Nominal speed
$\%Q$  Rated load percentage
1. Introduction

Power systems necessitate a constant balance in the demand and supply of electricity to preserve the frequency stability – a basic requirement of a functional electricity grid. To secure the normal operation of the grid, the power system operators employ forecasting models of consumption to schedule the power generation. Any mismatch in the power balance is handled with dispatchable generation. However, depending on the country, the season, and the level of power demand, the dispatchable generation can be expensive and emission intensive [1]. Especially, during peak-power demand, such as wintertime in Finland, the power balance is secured with peak power plants, usually burning costly natural gas or heavy fuel oil as energy source, emitting large quantities of carbon dioxide, CO$_2$ [2]. Moreover, the power imbalances are increasing and becoming more frequent with the increasing ratio of variable renewable energy (VRE) sources, mainly wind and solar, which are non-dispatchable [3]. The frequency stability is also jeopardized by the displacement of conventional power generation with the frequency converter connected VRE production due to the decrease in power system inertia. With the decreased inertia, the system is less able to dampen the rate of change of frequency in the case of a significant power imbalance resulting, e.g., from a major disturbance, such as a drop of a large power plant [4].

As the supply of power is becoming less predictable with degraded controllability, the flexibility is increasingly sought in the demand side and often referred to as demand response (DR) or demand-side management. During the last few years, the power system operators have been implementing new services and piloting new DR resources and related reserve and balancing markets. For example, the Finnish transmission system operator (TSO), Fingrid, has started a pilot enabling third party aggregators to merge DR resources from multiple consumers into a virtual power plant (VPP) to participate in the balancing energy markets [5].

Key characteristics of DR sources are the amount and activation rate of available flexibility as well as the potentially adverse impacts of the DR utilization, such as the incurred discomfort for the owners and users of the DR resource [6, 7]. Ranking the DR resources according to the provided DR capacity versus
the expected costs of the DR enables more efficient selection for the DR mixture, for example, for a VPP service. In this thesis, a relatively untapped source of demand response, vertical transportation (VT), is analyzed from the power systems point of view. Especially, the scope is on the most abundant form of VT – elevators (lifts).

1.1 Background

Elevators are an important part of a functional, modern society. From the viewpoint of the power systems, they are large, intermittent loads concentrated into the urban parts of the electricity distribution grid.

Power systems, as almost any field, is largely driven by megatrends. The term ‘megatrend’ is applied in depicting rapid, profound, and most importantly, global changes in the society or in any specific activity. To strive and succeed in this environment requires strategic planning and adaption from the organizations of the particular field [8, 9]. From the perspective of the field of power systems, two megatrends are having a major influence: urbanization and climate change. First, the composition of electricity use and the consumer habits are different between rural and urban areas, requiring different power system designs. Second, battling the climate change necessitates more energy-efficient appliances and displacement of fossil fuel based power generation with less or zero polluting options, such as wind and solar production [10].

The fast urbanization and climate change are also major factors accelerating the construction of tall buildings. According to [11], the development of tall building is also encouraged by several benefits and other motives. On a general level, building upwards improves the land use efficiency in expensive city centers, enabling better return on investment for the building developer. Furthermore, tall buildings have also been built to enhance the brand image of companies, cities, and countries. As a result of the above, the world has witnessed a global boom in tall building construction, exemplified by the rise in the number of new buildings reaching the height of 200 meters (see Figure 1.1).
Introduction

The dense, high-rise urban spaces are challenging for the smooth and efficient mobility of people and material both indoors and outdoors. Outdoors, the movement is typically horizontal with transportation means such as trains and subways. Indoors, the method of transportation is typically vertical. The VT devices, namely, elevators (lifts), escalators, and moving walks, are essential for the functionality of any decent size building and make the high-rise construction feasible [13]. With the ascending number of tall buildings, the number of elevators in the world is also increasing. Another factor supporting the growth in the installed base of elevators is the updated building regulations, which are demanding elevators into new lower-rise buildings than previously. In Europe alone, the European Lift Association (ELA) [14] estimates the total number of active elevators to be nearly 6 million with more than 100 thousand new installations every year. Furthermore, the daily number of passengers using vertical transportation is evaluated to exceed 1 billion. Combined, elevators in the EU-27 are estimated to consume around 20 TWh of electrical energy annually, corresponding to nearly 1 percent of the total electricity usage in the region [15].

The significance of elevators in the overall energy efficiency of buildings has recently been more acknowledged. For instance, the city of Hong Kong, China, which has the highest quantity of skyscrapers above 150 meters tall in the world [12], has executed long-term regulation of vertical transportation in connection with their building energy efficiency codes starting from the year 2000 [16]. Internationally, the energy efficiency awareness related to elevators has been raised by the VDI 4707-1 guideline [17] and the ISO 25745-2 standard [18], which provide approaches to classify the energy performance of elevator units. The resulting energy efficiency classes from A to G, which resemble the energy labels found in the common household appliances, enable customers to easily compare the offering of multiple manufacturers.

Figure 1.1. The number of new buildings reaching the height of at least 200 meters in the world by completion year according to [12].
1.2 Objectives and scope of the thesis

The overall objective of this dissertation is to provide methods to model and assess the impact of elevators on the power system. More specifically, this thesis has two main targets. The first target is determining the seasonal, weekly, and diurnal patterns of elevator usage and characteristics of elevator power consumption. The second target is evaluating the means and effectiveness of controlling the elevator loads in order to be able to provide virtual power plant (VPP) services through DR. When these two targets are combined, it is possible to estimate the elevator DR potential in any given moment within the limits of the background data.

Related to the objective, it is important to distinguish the two main areas of elevator designing: traffic design and engineering design [13]. Traffic design, in general, aims to fulfill the requirement of traffic performance (number of passengers in a period of time) in the given traffic conditions and building dimensions, whereas engineering design encompasses component sizing and securing the physical – electrical and mechanical – functionality of the elevator system. Out of these design perspectives, the scope of this dissertation is mostly in the engineering design with focus on the electricity demand of the elevator units. Nevertheless, understanding the basics of the traffic designing is also mandatory in order to be able to model the impact of passenger patterns on the elevator energy demand and, on the other hand, to assess the effect of elevator DR on the passengers.

1.3 Contribution of the publications

This thesis comprises seven peer reviewed publications. Their order reflects the research process and targets depicted in Section 1.2. The first publications focus on obtaining the background data on the traffic patterns and energy usage characteristics of elevators, followed by publications employing this information to compose modeling methods to analyze possible improvements in their energy efficiency and their potential in DR.

Publication I provides practices which aim at improving the annual energy consumption determination and estimation of elevator loads, which is a crucial starting point for the research presented in this thesis. The main contributions are related to the accuracy issues of both the actual measurements and the commonly applied annual energy consumption estimation methods. Furthermore, the study demonstrates the importance of energy efficiency of both standby and running modes in the total energy consumption.

Publication II proposes a simple method for projecting the annual elevator electricity consumption based on sample measurements of energy consumption during different day types. The main finding, which is also supported by previous literature, is that the daily energy consumption values within the same
(calendar specific) day type are usually normally distributed with a relatively small deviation. The novel implication of the study is that the energy consumption monitoring of elevators enables relatively straightforward and credible predictions of the daily, weekly, and annual energy consumption with just a few days of measurements combined with the knowledge of the local working calendar. Furthermore, the proposed approach necessitates no information about the technological or traffic characteristics of the analyzed elevator, while potentially providing more accurate estimates of annual consumption than do the commonly applied VDI guideline [17] and ISO standard [18] mentioned earlier in Section 1.1.

Publication III expands the applicability of the proposed method of Publication II to another type of vertical transportation – escalators. The study indicates similar weekly recurring energy consumption patterns for escalators as was monitored for elevators. Furthermore, as in Publication II, the methods provided, on average, more reliable estimates of annual consumption than the lately published ISO standard [19] on energy calculation and classification of escalators.

Publication IV introduces a high-resolution power consumption modeling approach for elevators, which is later employed in Publications VI and VII. The main contribution is an elevator group model which depicts an average elevator group performance from the perspective of traffic performance and energy consumption, while also yielding a high-resolution power profile for full days with simulated passenger traffic.

Publication V assesses the applicability of vertical transportation (here elevators and escalators) in supporting the frequency stability of the power system with virtual inertia. The most relevant results are related to the effect of reducing the aggregate power of elevators and escalators on the frequency nadir after a major power imbalance caused by the drop of the largest generation unit in the Nordic power system. First, depending on the control method, both elevators and escalators are able to provide virtual inertia and contribute to the arrestment of the frequency drop. However, this capacity is mostly available during day time when the VT units are in use. Second, while escalators have potentially more flexibility to offer unitwise, elevators are far more abundant and should not be neglected as a source of flexibility to the grid.

Publication VI presents a case study of simulating the aggregate consumption of a large elevator population in the high-rise city of New York. The important contributions include the proposed passenger traffic profiles in multiple building types and the impact of coincidental power demand on the aggregate profile.

Publication VII employs the methods of Publications IV and VI to evaluate the potential of elevator DR and the effectiveness of different control means in terms of obtained DR capacity versus the experienced delay of the passengers. The paper also proposes approaches which aim at maximizing the obtainable energy or power reduction and minimizing of cost of this reduction from the macroeconomic point of view.
1.4 Structure of the thesis

The structure of the thesis is as follows. Chapter 2 explains the challenges induced by the evolving power system which have motivated this thesis work. Chapter 3 describes the typical models of elevator power consumption as well as the ones applied in this thesis. Chapter 4 presents the measurement and simulation results of the applied models. Finally, Chapter 5 concludes the thesis with the summary of findings and the discussion of the practical applications of the presented models, related future research, and potential improvements.
2. Challenges of the evolving power system

Power systems are evolving from a purely centralized, controllable generation and predictable consumption into distributed, intermittent generation with new types of loads and potentially bidirectional power flows. This significant change in the operation of the power system and in the role of actors within necessitates enhanced flexibility of the system and better understanding of the modern load types. In this chapter, Section 2.1 presents the common approaches to load modeling, and Section 2.2 examines the typical characteristics of demand-side flexibility from the point of view of the DR programs as well as from the perspective of the controllable loads, or DR resources, participating into those programs.

2.1 Load modeling for power system analysis

Load modeling is imperative for power system planning, control, and analysis [20]. With the emergence of modern, controllable loads operated by power electronics, the interest in load modeling has again increased. Furthermore, the existing load models need to be regularly revised. This need is highlighted by the several failed attempts which aimed at reproducing the recently occurred blackouts in simulation software and computational analyses [21].

Load modeling studies are challenging due to the large diversity of load types and the resulting knowledge gap about the load composition. Moreover, the stochastic nature of many load types as well as dependency of the loading on the time of day, weekday, season, and the weather emphasize the complexity of the modeling.

Load models are typically divided into two broad categories – static and dynamic load models. The following paragraphs shortly describe their main characteristics.

Static load models

A static load model is, by definition, a time-independent load model. It can provide the relevant load information for the given system with known or
Challenges of the evolving power system

specified parameters [21]. Commonly, the load model outputs the active and reactive power demand as a result of the voltage magnitude and frequency at the loaded bus [20].

The most common types of load models are constant impedance (Z), constant current (I), and a constant power (P) models, or their combination (the ZIP model). In a 2011 survey [21], the most widely used steady-state analysis method was the constant power model. Furthermore, the survey reports that static load models were also often adopted in dynamic system studies.

**Dynamic load models**

Dynamic load models are applied in voltage stability studies [22]. Thus, they provide the active and reactive powers as a function of time in addition to the voltage [20].

The most widely adopted dynamic load model is the induction motor (IM) model [21], where the applied model is derived from the equivalent circuit of an induction motor with the stator and rotor resistances and reactances as well as the magnetizing reactance and rotor slip. Therefore, the model has a physical meaning [20]. It is reported that around 30% of utility companies and transmission system operators have adopted some version of the IM model in dynamic studies, while most are still utilizing the static load models [21].

In order to find or estimate the parameter values for each load model, two common approaches can be identified: the measurement-based and component-based approach. In the measurement-based approach, the parameter estimation begins by obtaining the measurement data of the location under the analysis. Then, the model structure, such as ZIP, needs to be selected and fitted to estimate and validate the model. The disadvantage of the measurement-based approaches is that the measurements need to be collected under various conditions and during disturbances to secure the credibility of the model in power system analysis [20].

The component-based approach, on the other hand, is a bottom-up approach, where the electric loads are divided into consumer classes, such as commercial, industrial, and residential classes. For successful modeling, three aspects are crucial:

1. individual component models (e.g., constant impedance for resistive loads, such as stoves and heaters);

2. the ratio of the different load components within the consumer classes;

3. class composition, the ratio of consumer classes in the aggregate load.

Thus, the typical load profiles of the consumer classes need to be known as well as the ratio of the load types within the classes. However, the most challenging
 task in load modeling is considered to be determining the load composition (ratio of load types in the total power profile) as new loads and control techniques reshape the underlying power demands [20]. At the same time, the accuracy of the load modeling directly impacts the reliability of the power system analysis [23].

The scope of this dissertation is to support the knowledge about the load composition by providing novel methods to model the aggregated electrical load caused by elevators in various consumer classes. Furthermore, the proposed modeling approaches also provide estimates on the different hoisting technologies installed with the existing elevator stock, which enables the further decomposition of the elevator loads into the aforementioned static and dynamic load models. While this decomposition and detailed analyses of the equivalent static or dynamic load model is out of the scope of this dissertation, it is considered as potential future research in Section 5.3.

2.2 Obtaining the flexibility for power systems

Demand-side flexibility can be obtained with various approaches and applied to mitigate both short-term (seconds to minutes) and more long-term (hours) power imbalances. The following subsections introduce the common categorizations of the DR programs and the DR resources, which can be harnessed for DR program participation.

2.2.1 Categorization and modeling challenges of DR programs

Demand response can be applied for a variety of task which have different requirements for the magnitude, rate, and duration of power demand change. From the utility planning perspective, a common division [24] for demand response is

- peak shaving – decrease consumption during peak demand,
- valley filling – increase consumption during low demand,
- load shifting – shift consumption from peak hours to hours of low demand,
- conservation – decrease consumption for all hours, and
- load growth – increase consumption for all hours.

From the consumer’s (end-user or owner of the DR resource) perspective, DR can be divided either into price-based or incentive-based programs [25].
Price-based DR

In price-based DR programs, the consumer benefits from the price differences of nearby hours according to the electricity market prices or signed contract by rescheduling (shifting) loads to cheaper hours or reducing (shaving) the power demand during peak pricing. The overall objective for the price-based DR is to decrease the total system-wide cost by encouraging consumption during periods of lower marginal electricity production prices (produced, e.g., by hydro, wind, or solar power) and discouraging excess electricity usage during periods of high demand [26], which often have high marginal price of generation and increased greenhouse gas emissions, as mentioned in Chapter 1.

Typical price-based DR programs [27] are

- Time-of-use rates (TOU) – agreement on different prices depending on the time of day, day type, and the season. Example: day- and night-tariffs.

- Critical peak pricing (CPP) – applied during contingencies with tight demand-supply balance on critical days at peak hours announced beforehand [28, 29]

- Real-time pricing (RTP) – prices vary daily and typically the consumers are informed day- or hour-ahead. Example: Nord Pool Spot.

For the customers (consumers), participating in the price-based programs provides cost saving opportunities [27]. However, the profits are not guaranteed, e.g., due to constraints in building automation or uncertainties in power consumption profiles. For instance, changing from a flat tariff to TOU can also substantially increase the electricity bill as has been reported in [30].

Incentive-based DR

In incentive-based DR programs, the consumer is compensated for the demand-side flexibility capacity, and the flexibility is typically reserved to secure the system reliability [26]. Every market place where the flexibility is offered can have unique technical requirements, reimbursement levels, and activation frequency. For example, the transmission system operator in Finland provides five market places where DR reserves and balancing power can be offered [31]. Moreover, the bid size of the offered flexibility typically needs to be placed in advance, requiring accurate forecasting of the available flexibility for different times of day to benefit from DR participation and to avoid possible penalties of not providing the agreed DR capacity when needed. Additionally, depending on the market place, the party placing the bid, e.g., the aggregator operating the VPP, might need to set a price for the offered flexible capacity. The price should relate to the experienced cost of the DR event similarly as the marginal production cost in the electricity spot markets, such as Nord Pool Spot. Moreover, as the bids are sorted in an ascending order for each hour in the hourly markets, the pricing will affect whether the bid is accepted or rejected.
Challenges of the evolving power system

Table 2.1. Reserve markets operated by Fingrid adapted from [34, 35].

<table>
<thead>
<tr>
<th>Reserve</th>
<th>Minimum offer</th>
<th>Full activation time</th>
<th>Activation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency controlled normal operation reserve (FCR-N)</td>
<td>0.1 MW</td>
<td>3 min</td>
<td>Local in frequency range 49.9 – 49.95 and 50.05 – 50.1 Hz</td>
</tr>
<tr>
<td>Frequency controlled disturbance reserve (FCR-D)</td>
<td>1 MW</td>
<td>5 s (50%), 30 s (100%)</td>
<td>Local in frequency range 49.5 – 49.9 Hz</td>
</tr>
<tr>
<td>Automatic frequency restoration reserve (aFRR)</td>
<td>5 MW</td>
<td>2 min</td>
<td>Central control</td>
</tr>
<tr>
<td>Manual frequency restoration reserve (mFRR)</td>
<td>5 MW</td>
<td>15 min</td>
<td>Central control</td>
</tr>
</tbody>
</table>

Examples of the incentive-based DR programs applicable in Finland are listed in Table 2.1. As can be deducted from the table, the frequency controlled normal operation reserve (FCR-N) is designed to maintain the frequency close to the nominal 50 Hz by allowing both up- and downregulation bids on the market place. The disturbance reserve (FCR-D), on the other hand, is activated more seldom, and the offered capacity needs to be activated rapidly when the rate of change of frequency (RoCoF) is high to constrain the frequency nadir above 49 Hz [32, 33].

The frequency restoration reserves (FRR) are employed to return the frequency back to nominal after a sudden, large frequency drop. The coordination with the FCR is illustrated in Figure 2.1.

Figure 2.1. Simplified illustration of FCR and FRR coordination during a frequency drop adapted from [35].
Challenges of modeling DR programs

Modeling the effectiveness of DR programs is generally considered as a demanding task. One of the main challenges is related to the price elasticity of demand and the value chains of DR. Thus, researchers have developed economic load models which consider the effect of penalties, incentives, and customer benefit of DR participation [36]. However, the irrational consumer behavior still necessitates automation and a large controllable fleet of devices to be able to better predict the baseline of consumption as well as the obtainable power reduction, especially when aggregating small loads or devices with irregular usage patterns [37].

Further issues with the modeling of DR programs include the uncertainty of predicting the actual need for different types of DR programs, resulting, e.g., from the stochasticity of renewable energy generation [38, 39]. Moreover, as the DR capacity of loads can be potentially offered to multiple DR programs, modeling the interactions and interdependencies between programs can be a significant challenge [37].

In this dissertation, the focus of modeling is mostly on the technical perspective, i.e., simulating the baseline and the obtainable power reduction with DR control means on different time scales from seconds to a full day of DR. Furthermore, also the performance of the elevator DR is calculated from the perspective of induced inconvenience and provided flexibility.

2.2.2 Categorization of DR resources

Demand-side flexibility is obtained by controlling the power intake of individual loads (devices) and possibly aggregating them into a virtual power plant (VPP), which can offer this flexibility to the DR programs, such as FCR. These individual loads have distinguishable characteristics which can be categorized according the responsiveness and availability of the load from the perspective of DR. Thus, the categorization supports the selection process of DR resources which are selected to participate in DR. Table 2.2 depicts a common categorization of the loads to response classes.
Table 2.2. Categories of load response classes obtained from [35, 40].

<table>
<thead>
<tr>
<th>Response class</th>
<th>Controllability</th>
<th>Example device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrollable loads</td>
<td>Cannot be controlled due to large end-user value</td>
<td>Computer</td>
</tr>
<tr>
<td>Curtailable loads</td>
<td>Consumption can be curtailed partly or fully</td>
<td>Variable speed drive escalator [41]</td>
</tr>
<tr>
<td>Uninterruptible loads</td>
<td>Cannot be controlled while in operation</td>
<td>Washing machine</td>
</tr>
<tr>
<td>Interruptible loads</td>
<td>Load can be shifted in time and operation can be continued later</td>
<td>Electric vehicle charging</td>
</tr>
<tr>
<td>Regulating loads</td>
<td>Short-term alteration possible with little impact on end-users</td>
<td>Ventilation [42]</td>
</tr>
</tbody>
</table>

When summarizing the response classes and their features, it is apparent that each class (and load type) has two important properties from the perspective of demand response – the obtainable power change through DR participation and the impact of the participation on the end-users, occupants, and building owners. The DR participation should be profitable, i.e., the received compensation (in incentive-based DR) or electricity bill savings (in price-based DR) should outweigh the experienced costs of DR participation. While the costs and overall inconvenience are relatively low in the last two response classes (interruptible loads and regulating loads), they might be significant with curtailable and uninterruptible loads. Elevators – the topic of this thesis work – resemble closest the response class of curtailable loads, because their consumption can be altered through various control methods discussed in Section 3.3. However, the consumption of individual elevator groups can also increase as shown later in Section 4.3.

Considering the above, this dissertation aims to provide means to assess the applicability of elevators in DR. To achieve this aim, Chapter 3 presents the developed elevator group model which can be used to simulate the passenger traffic while also providing detailed estimate of the instantaneous power consumption.
Challenges of the evolving power system
3. Modeling the elevator power consumption

This chapter presents the basic characteristics of elevators which affect their power consumption. The chapter also introduces the common modeling techniques for long- and short-term power demand and the models applied in this thesis. Furthermore, the chapter discusses the means with which elevators could provide demand-side flexibility.

3.1 Characteristics of elevator systems

The energy consumption and instantaneous power demand of an elevator and elevator group result from the experienced traffic patterns (usage) as well as from the applied elevator technology, including group control (dispatching) algorithm.

3.1.1 Traffic profiles and elevator design process

Buildings are designed to serve a specific purpose. This purpose can be categorized by a building type label, such as an office, a shopping center, or a residential apartment house. In power consumption forecasting, each building type has a unique power demand profile with confidence intervals which reflects the functionality of building services (appliances) and the actions of the occupants.

Passenger movement and elevator usage

Vertical transportation is a form of a building service which serves the need of people to move inside the building. Consequently, the movement of people causes the building type-specific traffic profiles for the VT units. Depending on the perspective and the modeling approach, the traffic profile distributions can be formed for the VT units or for the passengers of those units. For the transportation units, the distribution can, for example, be the division of up and down trips or the ratio of different operation modes, such as running and non-running periods with known average power consumptions [17, 18, 19].

As for the passengers, the distribution can be commonly represented with the ratio of people traveling up and down or in and out of the building or particular
part of it. Fig. 3.1 presents the equivalent distributions for an elevator group, where the number of passengers and the distribution of their movement objectives (in, out, and interfloor) are drawn from a residential weekday distribution proposed in Publication V, Annex A. While the number of up and down trips is nearly the same for each hour, the number of trips which transported passengers (labeled as “loaded”) has significant differences due to the passenger movements. The conclusion is easy to make – the elevator usage is a result of the passengers traffic. Furthermore, a large portion of total trips are made with an empty, non-loaded elevator car, as elevators often need to first move from the current position to the floor where a landing call (up/down) has been made to pick-up the passenger(s).

**Elevator system design and role of group control**

Elevators are designed to serve the landing calls as soon as possible and to provide adequate transportation performance during all traffic scenarios. The most challenging condition considered for an elevator system is the up-peak traffic [43]. Therefore, the elevator groups are typically dimensioned in terms of rated load, nominal speed, and number of elevator units to provide the desired five-minute up-peak handling capacity (quantity of transported passengers during five minutes). The handling capacity can be evaluated based on historical
Modeling the elevator power consumption

The user experience of elevators is strongly tied to the waiting time of passengers [44, 45], which should be kept below 30 seconds [13, 46]. The total journey time is a sum of the waiting and transit times:

\[ t_{\text{journey}} = t_{\text{waiting}} + t_{\text{transit}}, \]  

(3.1)

where \( t_{\text{waiting}} \) is the time between placing the landing call and the arrival of the elevator (to the origin floor), and \( t_{\text{transit}} \) is the duration between the passenger entering and alighting the elevator (to the target floor). While the transit time is perhaps not as crucial as the waiting time [47], it should be minimized to maximize the transportation efficiency, such as the five-minute up-peak handling capacity, as this metric is applied when comparing the performance of different elevator systems.

Another important factor affecting the performance of an elevator system besides the dimensioning is the applied control algorithm, which decides which elevators to dispatch for each landing call (group traffic control) or in which order the elevator should answer the landing and in-car calls (single elevator traffic control). Various approaches exist and have been proposed to enhance the performance of the dispatching [13, 48, 49]. According to the Elevator Traffic Handbook by Barney and Al-Sharif [13], these approaches can perform relatively similarly in certain traffic scenarios, e.g., during the up-peak traffic, while having dissimilar behavior under other traffic patterns, such as down peak. The handbook also states that the most common form of automatic control is a collective control, where an elevator stops according to the floor list of registered calls instead of the order in which the call buttons were pressed.

The elevator group simulated in Figure 3.1 employed an immediate collective group control, where the landing call is allocated as soon as it has been given and not reallocated later. The initial allocation objective was to minimize passenger waiting times. This approach is proposed and its performance is analyzed in Publication IV, where it is found suitable for estimating the operation of a typical elevator setup in terms of transportation performance and power consumption in the currently installed base of elevators. Overall, the decision of which elevator responds to which landing call resembles the estimated time of arrival (ETA) traffic control system presented in [13], as evaluating the waiting time of each new landing call for each elevator unit is based on the current list of stops containing the landing calls (origin floor) as well as the in-car calls (target floor) for that elevator. The employed approach, thus, allows dispatching idle units instead of just the closest by distance, which occurs in the simplest type of group control – the nearest car policy.

Traffic intensities

As mentioned and shown, the elevator power consumption is strongly dependent on the passenger traffic. Therefore, knowing the traffic profiles and intensities is crucial for credible estimates of elevator power demand profiles and energy
consumption. The literature provides some simple means to estimate the daily usage intensities of the elevators. As with many other load types which depend on the level of occupancy, the usage is day type dependent. In a 2005 guide about designing transportation systems in buildings [50], the traffic intensity of weekdays is taken as a baseline for each building type, i.e., the intensity index equals to 1. The traffic intensity on Saturday and Sunday are then used to signal whether these days have either lower or higher traffic volumes in the specific building type as exemplified by Table 3.1.

Table 3.1. Examples of traffic intensities according to [50].

<table>
<thead>
<tr>
<th>Building type</th>
<th>Weekdays</th>
<th>Saturday</th>
<th>Sunday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>1.0</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Commercial</td>
<td>1.0</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Retail</td>
<td>1.0</td>
<td>1.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The traffic intensities approach, thus, presumes that throughout the year, the elevator usage is relatively similar from one week to another. In the VDI 4707-1 guideline [17] and the ISO 25745-2 standard [18], which offer energy performance classification methods for elevators, only daily averages are applied for the number of trips over the days of operation. While these methods commonly apply 360 (ISO) or 365 (VDI) days of operation, the ISO standard also suggests the multiplier of 260 for office, administrative, and university buildings, indicating that most of the traffic occurs on weekdays, Monday – Friday, in these types of buildings.

In this thesis, the weekend days of Saturday and Sunday are lumped together due to simplicity and because their traffic volumes and patterns have become more similar due to loosened opening times in the retail business. Table 3.2 exhibits the adopted ratios for the number of trips during weekdays and weekends which are utilized in Publications VI and VII. In addition to the aforementioned planning guide [50], also observations of Publication II and [51] were considered as background information for these trip amount ratios. Naturally, the employed traffic volumes and traffic patterns should be updated and changed if the region-specific figures are available for analysis.
Table 3.2. The ratios between the number of trips during weekdays and weekend from Publication VI. Author’s estimates marked with asterisks (*).

<table>
<thead>
<tr>
<th>Building type</th>
<th>Weekday</th>
<th>Weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential [50]</td>
<td>0.95</td>
<td>1.0</td>
</tr>
<tr>
<td>Office Publication II, administrative*, and educational*</td>
<td>1.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Hotel [50]</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Public transport [51], airport*, garage*, and industrial*</td>
<td>1.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Retail [50]</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Hospital [50]</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Entertainment (e.g., museums and theaters)*</td>
<td>0.75</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Intraday traffic patterns

Modeling the power profiles necessitates the knowledge of the intraday traffic patterns, i.e., the distribution of the trips within a day. This distribution can either be known directly from measurements of the trips or estimated, e.g., with another information source, such as the volume of people flow in a building during different hours. Alternatively, a building type-specific traffic distribution profile, such as applied in Figure 3.1, can be employed to divide the known or estimated number of trips into different time periods.

There is little publicly available information on the traffic patterns of elevators in the large variety of buildings and elevator systems. Nevertheless, based on customer demand, elevator manufacturers can offer enhanced connectivity and remote monitoring services to customers, e.g., for traffic and usage reporting and preventive maintenance scheduling. For now, however, the employed traffic distributions in this thesis (Publication VI and Publication VII) are based on a few sample measurements and previous research as stated in Publication VI, Appendix A. Figure 3.2 presents the traffic patterns of three important building types in a dense, urban environment as estimated by Publication VI. In total, 10 different traffic patterns are applied in simulating the aggregate power profiles of large elevator populations later in Section 4.2.2 for both weekdays and weekends.
3.1.2 Elevator technologies

During the course of history, many elevator technologies have been utilized for different means, ranging from mine shaft elevators and dumbwaiters (small freight elevators for small goods and no people) to modern high-speed, double-deck passenger elevators with the common goal of vertical movement [53]. The most recent research interests are in modeling the traffic characteristics of two-dimensional elevator systems which apply linear motor technology for horizontal movement in specially designed shafts [54]. Additionally, even three-dimensional elevator systems have been discussed on a conceptual level [55]. In this thesis, the scope is on electrically driven passenger and freight elevators existing in a variety of building types in the current installed stock of elevators.

Figure 3.2: Applied traffic distributions in terms of passenger movement objectives in three dominant urban building types obtained from Publication VI. References: a = [52], b = Publication II, * = author’s estimate.
Elevators can be commonly divided into two main categories based on their hoisting technology: traction or hydraulic. Below, some of the most basic builds are discussed.

**Traction elevators**
In traction elevators, the elevator shaft accommodates both the elevator car and the counterweight, which are suspended on a hoist rope on the opposite sides of the traction sheave. The sheave is rotated by an electric motor either directly or through a set of gears. The counterweight is typically sized to match the mass of the empty elevator car and around half of the rated load with aims to improve energy efficiency and to decrease the maximum power required from the motor, enabling the downsizing of motor and drive components.

**Hydraulic elevators**
In hydraulic elevators, the elevator car is commonly lifted by a pressurized piston where the pressure is generated with a single-speed AC motor. In down travels, the pressure is released and commonly very little power is required from the power grid [56]. The hydraulic elevator systems are not usually equipped with a counterweight. The lack of counterweight enables easier installation and lower procurement costs. However, in contrast to counterweight-equipped systems, the power demand during upward trips is increased [57].

The differences in technical and operational characteristics of hydraulic and traction elevators as well as in their investment and running costs affect their purpose of use and the occurrence in the building stock. In the New York City elevator population model composed in Publication VI, around 22% of elevators were modeled as hydraulic elevators, which resembles the surveyed share of 23% in Europe [57]. Table 3.3 presents the generalized differences between the hydraulic and traction elevators in terms of their operational characteristics.

<table>
<thead>
<tr>
<th></th>
<th>Lifting height</th>
<th>Nominal speed</th>
<th>Rated load</th>
<th>Energy performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic</td>
<td>Low</td>
<td>Low</td>
<td>Low – High</td>
<td>Lower</td>
</tr>
<tr>
<td>Traction</td>
<td>Low – High</td>
<td>Low – High</td>
<td>Low – Mid</td>
<td>Higher</td>
</tr>
</tbody>
</table>

The applied power consumption models for the hydraulic and traction elevators are depicted in the following section.

### 3.2 Methods of time-domain modeling

This section presents the common and thesis-specific methods for the time-domain modeling of elevator energy consumption and power demand. Section
3.2.1 demonstrates the typical modeling methods for annual and daily energy consumption, while Section 3.2.2 focuses on the high-resolution power demand in seconds-level granularity.

### 3.2.1 Modeling the annual and daily energy consumption

The annual and daily energy consumptions are perhaps the most commonly discussed numbers in the existing literature related to elevator energy consumption. For instance, the traffic intensity indices of different building types on different weekdays, introduced in Section 3.1.1, are a relatively well-known and well-established concept. However, adopting the indices to directly scale the energy consumption is indistinctive if the running and non-running (stationary) power consumption characteristics, such as magnitudes and operation hours, are unknown. In this regard, the previously discussed energy efficiency labeling methods, the VDI 4707-1:2009 guideline [17] and the ISO 25745-2:2015 standard [18], offer a clearer estimation process for daily and annual energy consumption. These types of rating methods have also been said to be preferred by customers [15, 58] due to the successful adaptation of energy labels in, e.g., domestic electrical appliances [59].

The VDI guideline, which has been published prior to the ISO standard, has received considerable attention among the elevator manufacturers [60] as well as some among researchers [58, 61, 62, 63]. The more recent ISO standard has also gained traction [64, 65, 66] as it provides broader methods to rate the elevator energy efficiency [58].

Both the VDI guideline and the ISO standard necessitate reference cycle measurements at the site, or at least detailed equivalent simulations, with an energy measurement device capable to measure with less than 10% error. In the reference cycle, an empty elevator car is run up and down the full shaft length with doors opening and closing at both landings with at least 10 times [17, 67]. The average consumption during these cycles, $E_{rc}$, is then calculated. After this task, the paths of the VDI and ISO methods start to deviate.

**VDI 4707-1 daily and annual energy**

The VDI guideline begins the daily consumption estimation by deriving a travel specific energy demand value (mWh/kgm), $E_{spec}$. This value is obtained by dividing the reference cycle consumption with the rated load, $Q$, and cycle length, $2 \cdot s_{rc}$, and multiplying the result with a so called load factor, $k$:

$$E_{spec} = \frac{E_{rc}}{Q \cdot 2 \cdot s_{rc}} \cdot k,$$

where the value of $k$ depends on the counterbalance ratio of the elevator, denoted in this thesis as $K$. Majority of the traction elevators are counterbalanced to 40 – 50% of the rated load ($K$ is 0.4 – 0.5) for which the VDI suggests a load factor of 0.7. For elevators without a counterbalance (such as most hydraulic units) or for those counterbalanced up to 30% of rated load, the VDI recommends a load...
Modeling the elevator power consumption

factor of 1.2. The resulting value of $E_{\text{spec}}$ is also directly linked to the energy efficiency labeling, where a small number grants the elevator a label "A" while larger numbers lead to a poorer energy efficiency class up to "G".

The daily running consumption is calculated with Equation 3.3:

$$E_{\text{rd,VDI}} = E_{\text{spec}} \cdot Q \cdot s_{\text{nom}} ,$$  

where $s_{\text{nom}}$ stands for the total distance covered during the day presuming that the elevator moves continuously at nominal speed, $v_{\text{nom}}$, during all the running hours, $t_{\text{running}}$. The daily running time is usage category specific as explained in Table 3.4.

Table 3.4. Average values defining the usage category of an elevator according to VDI 4707-1 and ISO 25745-2. Estimate from Publication VI is denoted with c.

<table>
<thead>
<tr>
<th>Depiction of usage intensity</th>
<th>Usage category</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{trips}}$ (ISO), trips per day</td>
<td>very low</td>
<td>50</td>
<td>125</td>
<td>300</td>
<td>750</td>
<td>1500</td>
</tr>
<tr>
<td>$t_{\text{running}}$ (VDI), in hours per day</td>
<td>low</td>
<td>0.2</td>
<td>0.5</td>
<td>1.5</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Typical number of floors above the ground floor</td>
<td>medium</td>
<td>2 – 5</td>
<td>6 – 10</td>
<td>11 – 25</td>
<td>25+</td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>6</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>very high</td>
<td>6</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The estimate of daily total energy consumption, $E_d$, is then completed with the addition of the daily non-running energy consumption, $E_{\text{nr}}$, caused by the standby demand during the daily non-running time, $t_{nr}$:

$$E_{\text{nr},\text{VDI}} = P_{st5} \cdot t_{nr} ,$$  

$$E_{d,\text{VDI}} = E_{\text{rd,VDI}} + E_{\text{nr},\text{VDI}} ,$$

where the $P_{st5}$ refers to the average standby power value that is measured after the elevator has been inactive for five minutes, as instructed in the ISO 25745-1:2012 standard [67], which offers instructions on energy measurements for elevators, escalators, and moving walks.

It should be mentioned that, as a default method, the VDI 4707-1 actually proposes the usage of multiple reference trips with specified loads and giving the reference trips different weights in the derived reference cycle. This method is referred to as the load spectrum approach. However, this method is clearly more demanding in terms of field measurements and the result is heavily affected by the applied weights of the individual reference trips. On the other hand, the use of the load spectrum measurements removes the need to use the load factor, $k$, the value of which contains similar uncertainty.
Modeling the elevator power consumption

The annual consumption is obtained by multiplying the daily energy consumption with the number of days the elevator is in operation:

\[ E_{a,VDI} = E_{d,VDI} \cdot d_{op} \quad , \]

where the \( d_{op} \) is commonly 365 as mentioned in Section 3.1.1.

**ISO 25745-2 daily and annual energy**

The ISO standard has two methods to estimate the daily energy consumption. The suggested method is slightly more complicated than the VDI approach, whereas the alternative method closely resembles the VDI. The more resembling method first calculates the average unloaded running cycle energy consumption simply by dividing the running cycle consumption with the one-way travel distance of the reference cycle and multiplying it with the average travel distance of a trip:

\[ E_{-rav} = E_{rc} \cdot \frac{s_{av}}{s_{rc}} \quad . \]

The primary method, on the other hand, applies also a second set of measurements where the elevator does not travel the whole shaft length but rather only a portion of it before returning to the starting position. This is referred to as the short cycle. The short cycle enables estimating the start and stop related energy consumption, which relates to the energy demand during the acceleration and deceleration stages of each elevator trip as well as to the door operations:

\[ E_{rm} = \frac{1}{2} \left( E_{rc} - E_{sc} \right) \quad , \]

\[ E_{ssc} = \frac{1}{2} (E_{rc} - 2 \cdot E_{rm} \cdot s_{rc}) \quad , \]

where

- \( E_{rm} \) is the energy consumption per meter of travel;
- \( E_{sc} \) is the average energy consumed during the short cycle;
- \( s_{sc} \) is the one-way travel distance of the short cycle; and
- \( E_{ssc} \) stands for the start/stop energy consumption per trip.

The more detailed average unloaded running cycle energy consumption becomes as

\[ E_{rav} = 2 \cdot E_{rm} \cdot s_{av} + 2 \cdot E_{ssc} \quad . \]

The daily running energy consumption proposed by the ISO standard is (for both methods)

\[ E_{rd,ISO} = \frac{k \cdot n_{trips} \cdot E_{rav}^{(-)}}{2} \quad , \]

where the average number of daily trips, \( n_{trips} \), can be retrieved from Table 3.4 according to the usage category of the elevator unit if no better information is available. For the load factor, \( k \), the ISO standard provides more definitions than the VDI guideline, and the value of \( k \) depends not only from the counterweight ratio, \( K \), but also on the average loading percentage:

\[ k = 1 - (\%Q \cdot C_{K}) \quad , \]

38
where the value of $\%Q$ is known or obtained from a table in the standard with the knowledge of the rated load and usage category. The value of $C_K$ is also provided in the standard for different values of $K$.

In the ISO approach, the non-running energy consumption has three different levels of power demand, $P_x$, as described later by Equation 3.18, with three different ratios $R_x$ which describe the contribution of each non-running power demand level, i.e., the time spent in each stationary mode. One of them, nevertheless, is the same as with the VDI: $P_{st5}$. This value can also be applied alone if the elevator system is not equipped with energy saving modes, such as switching off in-car lighting after a period of inactivity.

$$E_{\text{nr}, \text{ISO}} = t_{nr} \cdot \sum P_x \cdot R_x,$$

where the non-running time is estimated with the help of average trip duration which is either measured or calculated as follows.

$$t_{av} = \frac{s_{av}}{v_{\text{nom}}} + \frac{v_{\text{nom}}}{a} \cdot \frac{a}{j} + t_{\text{doors}},$$

$$t_{nr} = 24 - n_{\text{trips}} \cdot \frac{t_{av}}{3600},$$

where $j$ is the jerk (rate of change of acceleration), which is typically 2.0 m/s$^3$ or less due to ride comfort [13]. In the high-resolution power models represented next in Section 3.2.2, the value of jerk is considered infinite, i.e., the elevator reaches its maximum acceleration and deceleration values instantly. This simplifies the modeling while having relatively minor impact on the overall power demand with respect to the other components of the various submodels. The time for door operations, $t_{\text{doors}}$, includes the time for opening, staying open, and closing the doors at the landings.

The daily and annual energy consumptions have similar appearance as with the VDI approach:

$$E_{d, \text{ISO}} = E_{rd, \text{ISO}} + E_{\text{nr}, \text{ISO}},$$

$$E_{a, \text{ISO}} = E_{d, \text{ISO}} \cdot d_{\text{op}},$$

where the $d_{\text{op}}$ is commonly 360 for most buildings and 260 with office, administrative, and educational buildings as mentioned in Section 3.1.1.

The accuracy and functionality of the various approaches provided in the VDI guideline and the ISO standard are compared in Publication I to the measured values of an office elevator. Furthermore, Publication II benchmarks the ISO and the VDI annual consumption estimates against straightforward, short-term, day type-based projections. These results are analyzed later in Section 4.1

### 3.2.2 Simulating the high-resolution power demand

Elevators are highly intermittent electrical loads. During a start, they can consume thousands of times more power than during standby. From the perspective of the instantaneous power balance of a power system, and from the
power quality point of view, it is important to evaluate the characteristics of individual elevator trips and the aggregate, coincidental power consumption of these large, alternating loads. Furthermore, the detailed, high-resolution power consumption modeling enables enhanced modeling and simulation of the long-term energy consumption and the effect of energy efficiency improvements, for example, achievable by retrofit technology.

The high-resolution running power demand is typically based on mechanical equations of required power and the related kinematic equations [68] for calculating the instantaneous acceleration, speed, and position of the elevator car as well as the time it takes to reach the rated values and arrive at the target floor. Figure 3.3 demonstrates the kinematics when the change in acceleration is instantaneous, a presumption of this thesis to simplify the modeling as mentioned earlier with Equation 3.14. If a jerk value of 1.0 m/s³ would be considered, the total time would be 7 seconds as also given by the same formula.

![Graph](image)

**Figure 3.3.** Simplified example of acceleration, velocity, and distance with regards to time when traveling two floors with a total distance of 8 meters.

In this thesis (Publications IV, VI, and VII), the high-resolution power demand is modeled with the following simplified approach for the time of standby (stationary or non-running time) and for each elevator trip (running time).

When stationary, the power consumption follows the approach suggested by the ISO 25745-2 standard [18] with three different stages of power consumption as depicted by Equation 3.18.

\[
P_{\text{stationary}}(t_s) = \begin{cases} 
  P_{\text{idle}}, & \text{for } t_s \leq 5 \text{ min} \\
  P_{\text{st5}}, & \text{for } 5 \text{ min} < t_s \leq 30 \text{ min} \\
  P_{\text{st30}}, & \text{for } t_s > 30 \text{ min }
\end{cases} \tag{3.18}
\]

where \( t_s \) is the elapsed time since the last stop. In a large ratio of the existing elevator groups, the stationary power consumption is constant, i.e., the power demand equals to \( P_{\text{idle}} \).

For each elevator trip \( i \), dictated by the passenger arrivals and consequent traffic controller decisions (explained in Section 3.1.1), the instantaneous electric power demand of the elevator drive at time \( t_i \) depends on the masses to be
hoisted, the counterweight ratio, $K$, the sign and magnitude of speed, $v$, and acceleration, $a$, at time $t_i$ as well as the hoisting efficiency, $\eta$:

$$ P_{M,el}(t_i) = \begin{cases} 
\frac{1}{\eta} P_M(t_i) & \text{when } P_M(t_i) \geq 0 \\
\eta P_M(t_i) & \text{when } P_M(t_i) < 0 ,
\end{cases} \quad (3.19) $$

where, for traction elevators,

$$ P_M(t_i) = v(t_i) \cdot \left( (C_{J_M} + m_{load} + m_{car} + m_{cw}) \cdot a(t_i) + g \cdot m_{net} \right) , \quad (3.20) $$

where the counterweight mass, $m_{cw}$, and the net load, $m_{net}$, are

$$ m_{cw} = m_{car} + K \cdot m_{rated} , \quad (3.21) $$

$$ m_{net} = m_{load} - K \cdot m_{rated} , \quad (3.22) $$

and where

$C_{J_M}$ is the inertia constant, which aims to mimic the effect of inertia of the motor, wheels, and pulleys on effective mass;

$m_{car}$ is the car mass;

$m_{load}$ is the mass of the load;

$m_{rated}$ stands for the rated load; and

g is the acceleration due to gravity.

For hydraulic elevators, the equation is simpler:

$$ P_M(t_i) = v(t_i) \cdot ((m_{car} + m_{load}) \cdot g) . \quad (3.23) $$

The sign of speed in Equations 3.20 and 3.23 is selected positive when the elevator car moves upwards. In non-regenerative elevators, all the negative values of $P_M$ are set to zero. For simplicity, the speed of the hydraulic elevator is presumed as a constant (nominal speed, $v_{nom}$) due to the low operational speeds, and they are also considered to be non-regenerative.

The total power consumption during a trip is modeled as

$$ P_{trip,i}(t_i) = P_{idle} + P_{control} + P_{M,el,i}(t_i) , \quad (3.24) $$

where $P_{control}$ depicts the increase of power demand by the control electronics during a trip. Additionally, the power consumed by the door operations, $P_{doors}$, is added before and after the trip for a time of $t_{doors}$ as in Publication IV. The $t_{doors}$ can be set lower than with the ISO daily consumption estimate (see Equation 3.11), because the duration of required power is shorter than the actual door operations which include the time of staying open. Figure 3.4 illustrates the typical power profiles of a non-regenerative elevator in different loading conditions obtainable with the equations when the acceleration and deceleration are 1.0 m/s$^2$ and the nominal speed is 2.5 m/s. The figure also shows that employing these equations and considering the acceleration and deceleration phases produce reliable results in terms of energy consumption.
Modeling the elevator power consumption

In Section 3.1.2, the hydraulic and traction elevators were stated to have different energy performance with hydraulic units having typically a lower energy efficiency and traction system a higher efficiency. This generalization is also supported, e.g., by a reference manual [69] for the ANSI/ASHRAE/IES Standard 90.1-2016, which provides energy standards for buildings. Additionally, the traction elevator hoisting system can be directly driven or powered through a linkage of gears. Instead of considering all these variables in the model, a simplified approach is employed where the differentiating factor between the large variety of elevator systems is modeled with the difference in the aforementioned hoisting efficiency, $\eta$. In Equation 3.19, this efficiency relates to the actual mechanical power needed to move the elevator in contrast to the electric power drawn from the electricity grid of the building.

### 3.3 Flexibility of elevator power demand

Elevators are designed to move passengers and goods with focus on safety and transportation efficiency. Recently, also the energy efficiency has received a significant role in the elevator design due to the rising awareness and the aforementioned energy efficiency labels.

Literature provides little means and reported outcomes of obtaining flexibility with elevator demand response. One reason for the lack of activity in the past is due to the perception that elevators are essential, non-flexible loads [70]. However, due to the rising need for new sources of demand response, discussed in Section 2.2, and the improved control and communication features of modern
Modeling the elevator power consumption

elevator installations, they should not be ignored. Furthermore, as discussed in Publication V, elevators have a clear advantage in contrast to, e.g., household appliances. The advantage is the relatively small additional cost to enable elevator DR participation, especially, compared to the large initial investment of the elevator system itself. In addition, the rate of retrofits and new installations offer a relatively frictionless path for new technology, which can be amplified by regulatory means, for example, to enable automatic inertial support in large elevator systems.

In this thesis (Publications V and VII), the focus is on DR methods which do not require major investments in additional components. However, some of these power altering methods are described for general knowledge.

3.3.1 Energy storage devices

Elevator systems are a candidate for various power demand altering methods. The selection depends on the characteristics of the elevator system, such as the employed elevator technology, elevator group size, dimensions, and building type. Some of the power demand altering methods necessitate additional components or other types of updates into the elevator system. This includes elevator system-connected energy storage devices, such as supercapacitors and batteries [71]. Additionally, in a multi-unit elevator group, a common DC bus could be employed to alter the net power demand of the elevator group visible to the electricity grid [72]. These types of systems could also enhance the energy efficiency of the elevator system and increase the safety aspects by providing evacuation during a power failure.

3.3.2 Energy awareness displays

A relatively popular research topic related to elevator usage has been to analyze the impact of promoting stair usage for health and energy conservation purposes [73, 74, 75, 76, 77]. In general, promoting the health benefits and notifying about the elevator energy demand or power generation emissions have had little success in decreasing the elevator energy consumption. When focusing on DR, study [77] reports that promoting the elevator usage (with a green color code) during hours of low power generation emissions and discouraging the usage (with a red color code) during the emission-intensive hours had the intended effect of increasing the use of stairs. However, the impact on the elevator energy consumption was noticed negligible and the study concludes that the obtainable flexibility with energy awareness displays seems minor.

3.3.3 Adjusting the perceived inconvenience of usage

In contrast to energy awareness displays, the so called inconvenience factor has been shown to yield more energy savings, i.e., fewer elevator trips.
As mentioned in 3.1.1, the passenger inconvenience is correlating highly with the time the customer has to wait for the elevator after placing the landing call. Additionally, any delay that is perceived as unnecessary tends to irritate the passengers. For example, slow moving doors can be viewed as annoying. Elevator door operation times affect the time to reach the destination floor, and slower acting doors also enable more time for new passengers to board the elevator at the origin floor. If the transit time increases enough during peak-traffic hours, it decreases the overall traffic performance and the number of trips. Fewer trips and the increased average loading both tend to reduce the elevator energy consumption [78].

Other drawbacks of slowing the door movements are the increased waiting time and possible congestions. This can also hurt the reputation of the elevator manufacturer in the long term. These reputational issues can be considered as costs when assessing the profitability of the control action. However, this sort of reputational aspect of demand response is not evaluated in this thesis.

Another possible long-term effect is that those aware of the increased door times would start to favor the stairs for short transitions while avoiding unnecessary elevator usage, further decreasing the elevator energy consumption [76]. This tendency is not analyzed in this thesis, however, due to the lack of necessary data and reported models.

### 3.3.4 Number of elevators in service

Reducing the number of elevators in service in a multi-unit elevator group has a similar but presumably amplified effect on the number of total trips and net loading as increasing the elevator door delays. Even though reducing the number of active units in an elevator group is perhaps the most established method of elevator DR, only little information is available on its performance. Report [79] reviews a peak-load program case study which depicts an office building where two elevators in a larger elevator group have been de-energized during peak-demand hours, and the participating units have been cycled. However, the effect on the building power demand profile is discussed no further than that the consumption is shifted due to passengers waiting for the units still in operation.

Conference paper [80] states that there are limited conditions in which energy consumption can be reduced by decreasing the number of elevators in service. Moreover, in their simulations, with little traffic, the energy consumption deflated when the number of active elevator units was increased. However, their simulations were limited to one elevator group with only 3 serviced floors and seem to ignore the impact of changes in loading and the effect of potential energy saving modes when the elevators are stationary.

Our simulation results of the impact of changing the amount of elevators in service on the energy consumption are analyzed in Section 4.3 for a variety of elevator groups. The performance of this type of control is then compared to the results obtainable with travel speed reduction, presented next.
3.3.5 Travel speed and acceleration

Reducing the travel speed and/or acceleration of an elevator reduces the instantaneous power requirement of the elevator drive. However, the energy consumed by the trip is not significantly changed as also the duration of the travel is increased proportionally. Moreover, the energy consumed by travel-specific control electronics is likely to increase in the same proportion, as modeled in Equation 3.24. Nevertheless, for very short term power imbalance conditions, or facilities at the end of a weakened grid or in an islanded-operating microgrid, the elevator speed and acceleration control can alleviate the stress to the power system. Travel speed and acceleration reduction and limiting the number of simultaneous starts in an elevator group also help to reduce the momentary peak power demand and, potentially, the monthly base fee of distribution if it is based on instantaneous peak power instead of hourly averages. Peak power reduction for individual facilities is considered as potential future research in Section 5.3.

Reducing travel speed for a longer period of time also increases the average car loading and decreases the number of trips during a time span. Thus, most of the means to control the elevator power demand relate to reducing the number of trips and improving the net loading profile during the time slice of required demand response action.

The results of the travel speed reduction are presented in Section 4.3 alongside with the aforementioned unit deactivation approach.

3.3.6 Energy storage with regenerative drives

Traction elevators are moving large masses consisting of the elevator car, in-car load, and the counterweight. When the elevator is not in use (not loaded by passengers nor goods), the net mass is on the counterweight side. This net mass ranges from equivalent mass of a few persons to thousands of kilograms. For example, in the recently built One World Trade Center, located in New York City, the combined mass of the 73 elevator counterweights exceeds 450,000 kilograms [81]. Presuming a 50% counterbalance ratio and all the elevators unloaded, the net mass on the counterweight side would equal to more than 225,000 kilograms.

Theoretically, the heavy counterweights could serve as a storage of potential energy, especially when pooling a large quantity of elevators [82]. The applicability, however, is limited to elevators which are equipped with a bi-directional regenerative drive, which can convert the stored potential energy back into electricity. Therefore, this DR method is not discussed more thoroughly in this thesis.
3.3.7 Counterweight adjusting

To enhance the previous method of harnessing the stored potential energy of the heavy counterweights, the counterweight size (mass) adjustment could also become relevant. Case study [78] reveals that the optimal sizing of counterweight mass can potentially induce significant savings in elevator energy consumption. Depending on the traffic profile, also the intraday adjusting of the counterweight mass can further improve the energy efficiency of an elevator. The idea in the counterweight adjusting is to reach the lowest daily energy consumption by minimizing the net loads to be lifted. However, changing the counterweight size after the commissioning is rare and intraday adjusting is non-existent in the current installed base of elevators.

From the perspective of demand response, counterweight ratios even above the common 50% could be considered. For example, when preparing for a time increased probability of power system instability, the counterweight size could be increased and lifted to the maximum position to provide amplified frequency control reserves compared to the proposition of Section 3.3.6. To limit the peak power increase caused by lifting the heavier counterweight into position, the speed and acceleration could be decreased. However, as the applicability to adjust the counterweight size is not part of a typical product offering by elevator manufacturers, this DR control method is excluded from this thesis.

3.3.8 Objective of dispatching

As discussed earlier in Section 3.1.1 and shown, e.g., in [83, 84], the employed elevator traffic control algorithm can have a major impact on the elevator energy usage and traffic handling performance. For DR purposes, the objective function of the dispatching could be altered to favor energy efficiency more than traffic performance, e.g., during hours of high electricity price. Figure 3.5 indicates noteworthy differences in the traffic and energy performance for elevator groups utilizing different objective function weights for waiting time and energy consumption. However, this method is not assessed further in this thesis but is considered as potential future work in Section 5.3.
3.4 Dissertation-specific methods and assumptions

This section condenses the characteristics of the methods and assumptions employed in this dissertation and related publications. Additionally, the sources and other justifications behind the parameter or method selection are listed for convenience.

As introduced in Section 1.2, this thesis has two main targets: first, to determine the usage patterns of elevators and the resulting power demand profiles and, second, to evaluate the effectiveness of means to impact this power demand. Table 3.5 lists the main methods and assumptions applied in the models and simulations presented in this dissertation.
Table 3.5. Main methods and assumptions applied in this dissertation.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Method</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of daily trips</td>
<td>Derived from the ISO 25745-2</td>
<td>Trip ratios as in Table 3.2</td>
</tr>
<tr>
<td>Intraday traffic profiles</td>
<td>10 building type-specific profiles in 5-minute resolution for weekdays and weekend</td>
<td>Weekdays are Mon-Fri and weekend comprises Sat-Sun. Sources listed in Publication VI, Appendix A</td>
</tr>
<tr>
<td>Traffic component ratios (incoming, outgoing, interfloor)</td>
<td>Building type-specific 5-minute ratios</td>
<td>Equal daily ratios of incoming and outgoing traffic. Other assumptions listed in Publication VI, Appendix A</td>
</tr>
<tr>
<td>Traffic handling algorithm</td>
<td>Immediate collective group control with waiting time minimization objective</td>
<td>Introduced and evaluated in Publication IV</td>
</tr>
<tr>
<td>Power consumption modeling (Publications IV, VI, and VII)</td>
<td>Trip-specific power profile containing acceleration, constant speed, deceleration, and door operation phases</td>
<td>Infinite jerk. Hydraulic units have constant speed and no counterweight. Control electronics draw additional power during the trip. Hoisting efficiency used to convert the power to move the net mass into power required from the electrical grid</td>
</tr>
<tr>
<td>Demand response</td>
<td>Unit deactivations and speed reductions</td>
<td>Deactivation of 1, 2, or 3 units (maximum 50%). Top speed reduced by 25% or 50%.</td>
</tr>
<tr>
<td>Power system inertial support modeling (Publication V)</td>
<td>Duration of each trip and amount of power derived from [57, 85] to represent an average European elevator</td>
<td>Daily trips weekday / weekend: tertiary 895 / 545 residential 175 / 175</td>
</tr>
</tbody>
</table>

Simulink model of Nordic power system [32]
4. Measurement and simulation results

This chapter presents the overview of the obtained measurement and simulation results regarding the long-term elevator energy consumption and short-term power demand of elevators. Furthermore, the chapter analyzes the effectiveness of the chosen control methods (see Section 3.3) which could enable DR participation of elevators.

4.1 Analyses of annual and daily energy usage

This section assesses the accuracy of estimating the annual elevator energy consumption with the widely recognized ISO 25745-2 standard and VDI 4707-1 guideline. The accuracies of these approaches are also compared to the straightforward projection of annual consumption based on a few days of measurements and considering a recurring passenger traffic. In addition, the recurrence of elevator usage is evaluated based on long-term energy consumption measurements of actual elevator setups.

The monitored elevator setups consist of two office elevator groups with four and six units. The results of these monitored office elevators comply with the presumptions presented in Section 3.1.1, i.e., elevator usage is recurring and clear differences can be observed between different day types which can be identified from the calendar, region-specific holidays, and the schedule of the school year. An example of the annual consumption pattern is provided in Figure 4.1. The pattern highlights that different day types largely impact on the elevator energy consumption. Furthermore, the region-specific calendar can be adopted for daily and annual consumption estimation. The recurring day type-specific profiles are also observed in a Danish study [77] which presents the electricity consumption patterns of one elevator and the number of staircase door openings in a residential building in one-hour resolution.
Due to the typical, recurring nature of elevator traffic and the resulting energy consumption, Publication II proposes a straightforward projection method of annual elevator energy consumption, where a sample of daily energy consumption is measured for all common day types. In a typical Finnish office, this corresponds to two day types: weekdays (Monday – Friday) and weekend days (Saturday – Sunday). When compared to calculations and results presented in Publication I about the ISO and VDI annual consumption estimates (introduced in Section 3.2.1 of this thesis), the annual consumption projection with short-term measurements appears to provide consistent and more precise results. Figure 4.2 shows that for the majority of the time, the measurement-based projection of annual consumption is closest to the true value. Furthermore, if the impact of seasonal changes on daily consumption is known, the median of the predictions nearly matches the actual, measured value which has been error compensated.

The error compensation is performed for five-minute average power values to mitigate most of the error caused by using standard current transformers and an affordable energy meter with remote monitoring capabilities for long-term measurements. The correction factors have been derived by comparing the five-minute power averages of the installed energy meter and a high-accuracy, portable power logger, as explained in Publication I and Publication II. Utilizing the error compensation increases the measured annual consumption by approximately 9%.
Measurement and simulation results

Figure 4.2. Performance comparisons of annual consumption projection methods proposed by Publication II against the VDI 4707-1 and ISO 25745-2 estimates in an example office elevator. Adapted from Publication II. "Simple" refers to a straightforward extrapolation based on either two or seven daily measurements, while "Seasonal" predictions have prior knowledge about the ratios of daily consumptions during holiday season and normal working weeks. Default traffic relates to usage class-specific values shown in Table 3.4

Publication II additionally reports that the nine other monitored elevators were also observed to support the linear extrapolation method, acting as the basis of the proposed annual consumption prediction method. Furthermore, when the method was applied to another form of vertical transportation, escalators, in Publication III, the results were highly similar (see Figure 4.3), indicating the general applicability of the method and underlining the common feature of vertical transportation – the recurring passenger traffic patterns.
Figure 4.3. Comparisons of annual consumption projection methods proposed by Publication II when adjusted to escalators in Publication III against the ISO 25745-3 standard [19] estimates in an escalator pair installed inside a shopping mall. Adapted from Publication III. Values of “ISO1” and “ISO2” refer to estimated and measured power demands, respectively. Estimates with letters “A” and “B” are calculated with the reference usage profiles of the standard, while estimates labeled with “C” are based on the modeled usage profile of the measurement site.
4.2 High-resolution power profiles

As explained in Section 3.2.2, the power demand of an elevator can change rapidly in just a few seconds, causing intermittent power peaks. The following sections of this chapter exemplify the visible differences in power demand depending on the averaging period and the number of analyzed elevators.

4.2.1 Unit, group, and building level power demand

The individual trips of elevators can be clearly identified from their power consumption profile. Especially, down trips for traction elevators (see previous Figure 3.4) and up trips for hydraulic elevators typically draw large currents from the electricity grid of the building. Depending on the building, these peaks can be identified from the total power demand profile of the building as demonstrated in Figure 4.4. When the number of elevator units in the building increases, their power peaks will start to be more frequently concurrent, as discussed more in the following Section 4.2.2.

Figure 4.4. Measured power profile of a low-rise (three floors) office building in 200-ms resolution, and a snapshot of the power profile during an afternoon.
According to a general rule in the literature [15], elevators consume up to 10 percent of the total electricity consumption in a building. The four-unit elevator group monitored and analyzed in Publication I and Publication II composed around 1.7% of the building total annual electricity consumption [86], being the only elevator group in the office building. The hourly consumption ratios are presented in Figure 4.5.

![Figure 4.5](image.png)

**Figure 4.5.** Measured power demand of an office elevator group with respect to the building total on a typical weekday in one-hour resolution. Adapted from [86].

In higher resolution, depending on the building characteristics and applied elevator technology, the instantaneous share can reach half of the building total [87]. This significant ratio of elevators in the total, short-term power demand of the building is easily understandable with an example from the monitored office building. Presuming other electric load types relatively consistent in their power demand, as suggested by the measurements of another office building earlier in Figure 4.4, and considering the elevator power profiles illustrated in Figure 3.4, concurrent trips of multiple elevators can easily add up to a significant ratio of the momentary power demand.

Instead of individual buildings, the following section aims to analyze the role of elevators on the grid level, i.e., from the perspective of power systems.

### 4.2.2 Aggregate consumption of large elevator populations

In an urban distribution grid, elevators of multiple buildings can be connected to the same node. Even though evaluating and simulating several unique elevator setups create complexity to the analysis of aggregate consumption, they also potentially alleviate the modeling in future research. This is because the sum of coincidental power demands of several intermittent loads tends to be more predictable when the number of loads increases.
The aggregate consumption of large elevator fleets necessitates some background information of the underlying elevator population. In Publication VI, a dataset of New York City (NYC) elevators [88] was employed in generating probability distributions of the underlying characteristics of elevators, such as the group size, number of floors, and rated load. The elevators were then distributed into building types according to the drawn height (in number of floors above the ground floor) with the help of NYC building stock data [89]. The probability of a given building type was based on matching the listed addresses in the elevator dataset to the building stock data.

In Publication VI, the combination of the building type and number of floors also determined the usage category as suggested by the ISO 25745-2 standard. Figure 4.7 presents the stacked hourly average powers by usage category and building type. It can be seen that the elevator groups with the highest usage intensity also compose the largest share in the aggregate power demand during daytime. When segmented into building types, the results of the NYC case study imply that the most significant contributors during weekdays are office elevators. Residential elevators are also major consumers on weekdays, and their role is amplified during weekends when elevator usage is decreased in many other building types, such as offices.
Figure 4.7. Composition of simulated aggregated power demand by usage category (UC) and building type in one-hour resolution during a weekday (top row) and weekend day (bottom row) as in Publication VI.

With the help of the high-resolution modeling approach of elevator power consumption proposed in Publication IV and depicted earlier in this thesis in Section 3.2.2, it was also possible to analyze the aggregate power demand in one-second resolution. Figure 4.8 illustrates that due to the large quantity of elevators in NYC, the aggregate power profile tends to follow the hourly average profile relatively smoothly. However, it is good to note that the aggregate power demand can alternate even seven megawatts within just a few seconds. The results also suggest that even though the weekend and weekday power profiles appear to yield largely different daily energy consumption values, the simulated weekend consumption is only 20% less. The reason for the relatively minor difference is due to the stationary power demands causing the nighttime consumptions to be nearly similar. Furthermore, as illustrated in Table 3.4, even the busiest elevators tend to spend most of their time stationary.
Measurement and simulation results

Figure 4.8. An example of simulated aggregate power profiles for NYC elevators in one-second resolution. Number of elevators: 70,034. Adapted from Publication VI.

A useful figure in evaluating the coincidence of concurrent power demand of multiple individual loads is the so called diversity factor. It describes the ratio of maximum noncoincidental demand (sum of individual maximum powers) and the aggregate, system level demand. Due to the intermittent nature and large short-term power peaks, hundreds of elevators are required to form any credible prediction of the momentary power demand of the aggregate. Nonetheless, the results in Figure 4.9 imply that when inspecting the situation on the city level with thousands of elevators, the peak power demand (for example, for each hour of the day) of the elevator population can be relatively well calculated with the help of the diversity factor. However, as the curves in the figure and the reported elevator population characteristics in Table 4.1 suggest, the employed diversity factor should be evaluated for different cities or city areas separately for more precise results.

Table 4.1. Simulated elevator population characteristics which have been analyzed in Figure 4.9.

<table>
<thead>
<tr>
<th></th>
<th>Number of elevators</th>
<th>Average group size</th>
<th>Average number of trips weekday / weekend</th>
<th>Average number of floors</th>
</tr>
</thead>
<tbody>
<tr>
<td>NYC</td>
<td>70,034</td>
<td>1.62</td>
<td>615 / 425</td>
<td>12.8</td>
</tr>
<tr>
<td>Manhattan</td>
<td>40,158</td>
<td>1.84</td>
<td>736 / 451</td>
<td>15.2</td>
</tr>
</tbody>
</table>

The major contributor to the difference between the NYC and Manhattan elevator populations is the average height difference. The Manhattan elevators are, on average, taller, affecting their simulated building type distribution, usage category, and, thus, increasing the number of trips and the overall power demand. The diversity factor is impacted mainly due to the more frequent trips during peak traffic hours, resulting in a higher probability of coincidental trips, reducing the diversity factor.
4.3 Applicability of elevators in demand response

This section assesses the applicability of elevators in demand response. More specifically, the DR potential is viewed from the perspective of price- and incentive-based DR. Additionally, Section 4.3.2 evaluates the possibilities of optimizing elevator group and DR control method selection in order to maximize the aggregated power reduction while minimizing the adverse impact (additional delay) on passengers. At this stage of research, the focus is on demonstrating the viability of DR control method selection based on the given objective and target of the DR participation, rather than on optimal execution.

4.3.1 Incentive-based DR with elevators

In incentive-based DR, the power demand flexibility of elevators would be harnessed, e.g., by a VPP that is participating in reserve or balancing markets that aim at securing the stability of the grid during power imbalances and unexpected disturbances. In Finland, the most suitable markets are the aforementioned frequency containment reserves.

For a DR resource to be applicable to a given market, it needs to comply with the set technical requirements. As listed in Table 2.1, the common target is to provide the agreed amount of flexibility fast enough. The applicability of elevators in incentive-based DR depends on the selected control method and the
quantity and quality of the elevators participating. Focusing on the power profile characteristics of the simulated Manhattan elevator population at the beginning of a DR event (presented later in Figure 4.15), triggered for example by a large RoCoF, provides an estimate of the applicability. It appears that without special attention to maximizing the initial, fast response, the elevator aggregate is unable to reduce its power demand rapidly. Instead, it takes around 200 seconds to reach the maximum level of reduction. Nevertheless, this performance would still be relatively suitable, e.g., for FCR-N.

When special attention is provided for the fast initial response, elevators can also enhance their response rate. The rapid response can be obtained by preventing all new trips or even adjusting the operation of units in midtravel, e.g., during a condition where the level of acceptable RoCoF is being violated.

In Publication V, a RoCoF threshold of 0.027 Hz/s was employed in simulating the response of an elevator population with 100,000 units having the average characteristics of European elevators, reported in [57, 85]. The participation of elevators in inertial support was analyzed with the control block depicted in Figure 4.10. The input of the change in frequency and the impact of changed aggregate power of elevators on the frequency was modeled with a Simulink model of the Nordic power system [32, 90], where the inertia constant and load self-regulation values were selected to correspond to a low load summer day.

![Control Block Diagram](image)

Figure 4.10. The control block modeling the participation of elevators in inertial support adapted from Publication V. TH stands for the RoCoF threshold, and Td represents the measuring delay (here 100 ms).

The focus of Publication V was on the effect of elevator DR on the frequency nadir, visualized in Figure 4.11. The rapid drop in frequency is caused by losing a generation equal to 1450 MW, the largest generation unit in the Nordic power system. Most of the frequency control visible in the graph is caused by the modeled change in the power output of hydro power plants.
Figure 4.11. Example of the effect of demand response with 100,000 elevators on frequency and frequency nadir in the Nordic power system model at 8 a.m. on a weekday. From Publication V.

The electrical load of the elevators was adjusted with two methods, both with a 50% decrease in nominal speed. The first method only alters the speed of new trips occurring during the RoCoF violation. The second method decreases the speed of all running units (including those already executing a trip). However, it is good to note that the simulations were simplified, excluding such factors as acceleration and deceleration and the large variance in elevator characteristics. Figure 4.12 shows the obtained power reductions (positive values of $\Delta P$ in these graphs) and the rebound in power due to the prolonged trip durations.

Overall, the obtained changes in power seem relatively minor. Compared to other currently available DR sources analyzed in [32], an average elevator, during its hours of operation, has around the equal inertia support performance as do 30 refrigerators, while it would require around 50 elevators to match the performance of one direct electric heated house. Nevertheless, direct electric heating is mostly abundant during the wintertime, when the Nordic power system typically has more rotating masses and less need for additional inertial support from the consumption side.
The small aggregate power reduction obtained from elevators is also reflected on the minor impact on the frequency nadir, as the nighttime change is less than 1 mHz, and even the daytime maximums are less than 4 and 10 mHz for speed reductions in new trips and in all running units, respectively. Moreover, when analyzing the results of 100,000 units and considering that the total number of elevators in the Nordic countries (here Denmark, Sweden, Finland, and Norway) is around 265 thousand [57, 85], it is apparent that the speed reduction in a low-rise, low-traffic elevator population provides little inertial support by itself. Nevertheless, focusing the inertial support enabling technology on high-power elevators with frequent usage, such as on tall hotel and office elevators, could provide better performance than the simplified, average approach applied in Publication V suggests. Furthermore, complete prevention of new trips during a large RoCoF and even forcing of regenerative trips in elevators with bidirectional drives should amplify the initial, rapid DR performance.

Figure 4.12. Examples of power reductions during the frequency drop (starting at 5 seconds) with 100,000 residential and tertiary elevators at 8 a.m. on a weekday. Adapted from Publication V.
4.3.2 Price-based DR with elevators

In the price-based DR, elevators would reduce their power demand during peak prices of electricity (peak shaving). Occasionally, high-prices could be more longer-term, justifying conservational procedures, such as full-day DR. The effectiveness of employing elevators in both peak shaving and conservation of energy has been evaluated in Publication VII. These results are analyzed next.

Maximizing the aggregated power reduction

Maximizing aggregate power reduction in the elevator population relates to applying the most suitable DR control method to each elevator group depending on its characteristics. These characteristics can include, e.g., building type, usage class (number of trips), group size, dimensions, and elevator technology.

Practically, an elevator setup in the interest of the aggregator or property manager could be modeled in detail, and the performance of various DR control means, such as listed in Section 3.3, could be tested or simulated with it. Considering a larger elevator population with varying, partially uncertain characteristics, a more probabilistic and average approach can provide an approximate on the applicability of elevators in DR.

Publication VII demonstrates through simulations that a large elevator population tends to have notable differences in the effectiveness of the applied DR control method (see Figure 4.13). While a number of properties impacts the performance of a control method in an elevator group, the number of trips, i.e., the usage intensity, proves to be a major contributor. This is no surprise, as the elevator has to be in use in order to significantly reduce its consumption.

Another interesting observation that can be made on the basis of Figure 4.13 is that, with light traffic (small delays), the most common long-term DR control methods appear to increase the energy consumption of the elevator group. This is a noteworthy finding, as the majority of the elevator installations are actually with relatively little usage. Figure 4.14 further illustrates that in low-traffic (for the specific observation period) elevator groups, both the deactivation of units and the speed reduction tend to increase the consumption, while the deactivation of more units also provides the greatest change in the energy demand of the group. Nevertheless, when the applied DR methods and participating elevator groups are selected more carefully (with a visual inspection of the boxplots for combinations of elevator groups with different number of trips and group sizes), the effect on the aggregate power demand decrease can be amplified as demonstrated in Figure 4.15. Furthermore, the experienced rebound in the aggregate demand peak after the DR event has seized is reduced in contrast to the DR method based solely on unit deactivations.
**Figure 4.13.** The simulated effectiveness of elevator DR control methods in terms of obtained energy savings (negative values of $\Delta$Energy) and increased delay to passengers ($\Delta$Delay) during a full-day DR event on a typical weekday. (a) Speed reduction in all groups. (b) Unit deactivations in multi-unit groups. Average tendency of the groups and its 95% confidence intervals near the origo for (c) speed reductions and (d) unit deactivations. Adapted from Publication VII.
Measurement and simulation results

Figure 4.14. Boxplots of the change in energy consumption of the elevator group as a result of one-hour DR participation for each analyzed DR control method as a function of the number of trips during observation period (1-hour DR + 30-min rebound). Outliers excluded. Obtained from Publication VII.

Figure 4.15. Power profiles (one-second granularity) of the simulated Manhattan elevator population on a typical weekday with randomized DR control methods, enhanced energy reduction method, and the baseline without DR. The DR event starts at 4 p.m. and ends at 5 p.m., after which, a 30-min rebound period is also observed. Adapted from Publication VII.
Minimizing the cost of elevator DR

Minimizing the cost of elevator DR means decreasing the elevator energy consumption while considering also the adverse impact on passengers. In this thesis, the cost is defined as the ratio of the increased delay to passengers and the obtained energy reduction:

\[
COST_{DR} = \frac{\Delta \text{Delay}}{|\Delta \text{Energy}|} \quad (4.1)
\]

When the resulting value is multiplied by a cost factor, such as the hourly wage in the region (or building), it can be used to compare the cost of elevator DR to other flexibility resources, such as home appliances or heating, ventilation, and cooling. However, this calculated cost is virtual in the sense that it is unlikely that elevator passengers or their employers would be compensated financially for their lost time, at least directly. Nonetheless, this approach has a clear analogy to the macroeconomic approach, adopted to estimate the customer interruption costs for distribution faults [91].

Comparing to the approach of maximizing the energy reduction, the cost minimization relates to choosing the elevator groups and DR control methods which, visually speaking, have the steepest decline from the origo in Figure 4.16. The energy reduction maximization, on the other hand, aims to find the control methods which move each elevator group as down the y-axis as possible. In both objectives, considering the need for upregulation by the power system, all groups which appear to be increasing their consumption due to the DR participation should remain uncontrolled. However, due to the uncertainty of actual trip characteristics in elevator groups with less traffic and due to the simplified DR control method selection process of visual inspection of boxplots (for energy and for cost), the end-result presented in Table 4.2 is only enhanced compared to random, not optimal.
Measurement and simulation results

**Figure 4.16.** Comparison of the change in energy consumption and total journey delay to the passengers due to DR participation with enhanced selection of DR control methods.

**Table 4.2.** Obtained aggregate changes in energy consumption and induced excess delay to passengers in different control approaches during a one-hour DR event and 30-min rebound period. * = random (sub-optimal) control method selection as in Fig. 4.15. Obtained from Publication VII.

<table>
<thead>
<tr>
<th>Speed DR*</th>
<th>Unit DR*</th>
<th>Energy [MWh]</th>
<th>Cost [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>-13.8</td>
<td>-17.9</td>
<td>-6.5</td>
</tr>
<tr>
<td>ΔDelay [1000 h]</td>
<td>8.2</td>
<td>10.7</td>
<td>16.9</td>
</tr>
<tr>
<td>ΔDelay [h]</td>
<td>1.5</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>
5. Discussion and Conclusions

This chapter concludes the main findings and discusses the potential application areas and future research around the topic of elevator power consumption modeling.

5.1 Summary of the findings

This dissertation aimed to analyze elevator energy and power consumption from the perspective of power systems. Especially, the scope was on the applicability of elevators in demand response (DR).

Starting the analysis of elevator DR potential first necessitates knowledge on their current electricity consumption patterns. Publications I – II focused on understanding the basic characteristics of elevator energy consumption in annual and daily resolution. Furthermore, intraday power profiles were monitored and evaluated in case study office elevators. The results of these publications imply that the weekly consumption patterns, and even intraday power profiles, are highly recurring, due to the handled traffic which is strongly day type specific. The recurrence of traffic and energy consumption patterns of vertical transportation devices were also observed in escalators analyzed in Publication III, thus, supporting the existing literature on the topic. Furthermore, the annual consumption projection methods proposed and employed in Publications II and III were found to deliver, on average, more reliable results than the commonly applied ISO 25745-2/3 standards and VDI 4707-1 guideline.

For the purposes of power system analysis, the elevator power consumption modeling needs to be more generic and expandable to a larger elevator population with varying characteristics than the earlier methods created in the industry or presented in the literature. In response, Publication IV proposes a relatively simple high-resolution power consumption modeling approach for both traction and hydraulic elevators. The key feature of the proposition is the combination of an elevator traffic control algorithm and power consumption equations which mimics the behavior of typical elevator setups in the currently installed elevator stock in terms of passenger traffic performance and energy consumption.
Discussion and Conclusions

The combined modeling approach was employed in Publication VI to simulate the aggregate power consumption of New York City (NYC) elevators. While it is impossible to verify the outcome of power profiles and energy consumption before the submetering of elevator power consumption becomes more widely adopted, the results seem reasonable, and the methodology can potentially be applied in estimating the elevator power demand characteristics in both dense, urban areas as well as nationwide. Comparing to energy efficiency monitoring campaign of European elevators, discussed in [15], the results seem comparable. In NYC, our results suggest the contribution of elevators to exceed 1% of total electricity consumption in the region, while in the EU, the ratio is just under 1%. Furthermore, the simulated intraday power consumption ratios of 0.5% – 3% are similar to the hourly power ratios of various case study buildings.

The knowledge of modeling large elevator populations was also employed in Publications V and VII in the pursuit to evaluate the applicability of elevators in DR. In Publication V, the scope of the analysis was on securing the grid stability during a large power imbalance and induced frequency drop. While the majority of elevator units are unlikely to be able to provide any inertial support during a short-term power system disturbance, focusing the suitable power altering technology on the largest and most frequently used elevators could be a cost-efficient means to enhance the grid stability in the future. Compared to other currently available DR sources analyzed for the similar inertial support task in previous research [32], the impact of one typical European elevator appears to match 30 refrigerators during the daytime, when elevators are in operation, while having inferior per-unit performance in contrast to direct electric heated houses with a ratio of 50 elevators to 1 house. Nevertheless, direct electric heating is mostly abundant during the wintertime, when the Nordic power system typically has more loading, and, thus, more rotating masses, making the system less vulnerable to sudden power imbalances. Consequently, harnessing elevators into a virtual power plant (VPP) service which would combine multiple DR resources with dissimilar but predictable power patterns could be a viable option to participate in reserve and balancing power markets, such as frequency containment reserves (FCR).

On the other hand, the power demand flexibility of elevators can also be applied to price-based DR. The results of Publication VII indicate that with careful selection of the control method and the participating elevator group, the energy consumption of the group, and, correspondingly, the aggregate power demand of a large elevator fleet can be greatly adjusted, depending on the day of the week and the time of day. In the case study of Manhattan, the simulated decrease in the aggregate power of elevators during power system peak hour was approximately 20 MW, or 25%, achievable within a few minutes after activating the analyzed DR control methods in the selected elevator groups.

Due to the significant variance and quantity of different electrical loads connected to the power grid, it is important to be able to compare their DR performance, i.e., the obtained power reduction and the potentially adverse effects
caused by DR participation. In Publication VII, a macroeconomic approach was considered to evaluate the cost of elevator DR. In theory, the obtained power or energy consumption reduction would have a cost equivalent to the value of lost working hours in the specific building or region, thus resembling the method of assessing the customer interruption costs during distribution system faults. While certain DR control methods appear to provide a lower cost, the simulated difference in the ratio of delay to passengers and saved energy was relatively minor (around 20%) while the amount of saved energy reduced by more than 60% between DR control method selection focused on minimizing the cost and maximizing the energy reduction during a one-hour DR event (see Table 4.2).

5.2 Practical applications

This dissertation has provided many approaches which can be employed in practice for energy policy assessments and power system analysis. In the future, it is likely that understanding and simulating the momentary power balance of buildings, clusters of buildings, and even regions becomes more topical when companies and communities seek to improve their energy self-sufficiency. Furthermore, as Figure 4.4 revealed, even in low-rise buildings, elevators are a crucial contributor to short-term power balance, meaning that their dynamic characteristics should be better acknowledged. In distribution systems, the presented approaches to evaluate the elevator power consumption during different day types, seasons, and in high-resolution also provide methods which can assist in locating possible bottlenecks in urban networks.

With regard to energy efficiency, the approaches proposed and analyzed in this dissertation provide a relatively straightforward framework to analyze the impact of various energy efficiency improvements in elevator technology, potentially enhancing the knowledge of the EU-wide monitoring program of [15] and expanding the analysis into new regions, such as North America and urbanized Asia. Hong Kong, China, already requires that each installed elevator, escalator, and moving walk should be provided with metering devices with long-term logging capability of hourly values [92]. While this type of data could be utilized directly to assess the current electricity consumption, simulations would still probably provide enhanced evaluation of the effect of major changes in the elevator stock.

In addition to Hong Kong, the remote monitoring of elevators is also provided by many of the elevator manufacturers. Though most of these services at the moment relate to traffic monitoring and preventive maintenance, the number of units under energy consumption monitoring can be expected to increase in the near future. The combination of traffic, equipment condition, and energy consumption data enables better evaluation of the performance of the various potential DR control methods mentioned in Section 3.3. The long-term monitoring would also help verifying the obtained benefits and adverse effects. Further-
more, the detailed measurement data would also assist, e.g., a VPP operator in selecting DR participating units and in bidding.

5.3 Future work

Many interesting research topics and potential improvements related to elevator energy demand can be identified which would complement the results presented in this dissertation. First, the passenger traffic model could be incorporated with the tendency of people to arrive in batches instead of one by one [93]. This would probably induce slightly fewer trips and less energy consumption than the current model when considering the aggregate power demand profile of the entire elevator population. Second, including the effect of rope mass [72] in tall elevator installations would increase the inertia, which, in turn, would inflate the elevator power consumption, especially in taller installations. Third, analyzing the means and benefits of momentary peak power reduction on the building level could expand the applicability of elevators in DR. Fourth, as discussed in Section 3.3, the effectiveness of momentarily changing the objective function of the elevator group control should be analyzed, as this method could provide a cost-effective means to enable elevator DR participation. Fifth, a combination of DR control methods could amplify the desired effect of the DR in certain elevator groups.

Additional research work can also be recognized in the field of load modeling, discussed in Section 2.1. First of all, the spatial and temporal variations in load type ratios could be further analyzed, and especially, the spatio-temporal lags of elevator usage could be measured and modeled with more remote monitoring data. The load models could be created for different hoisting technologies and elevator generations. Furthermore, the manufacturers and research institutes could identify and report model-specific parameters through laboratory experiments [94, 95, 96]. The research about the power quality aspects, such as harmonic injection models, of elevators and especially their interactions with other loads would also inform if elevator systems should be equipped with more harmonic filtering or simultaneous starts limiters to preserve the power quality in large buildings or urban distribution grids.
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Errata

Publication II

Fig. 4 should have explanations of the marked clusters 1 – 3 as in Figure 4.1 of this dissertation.

Publication IV

After the publishing, it has been noticed that the proposed group control algorithm model in Section 3 of the publication highly resembles the estimated time of arrival (ETA) traffic control system presented, e.g., in [13]. Moreover, the updated versions of the appendices A and B to model generic elevator groups are provided in Publication VI.
Elevators are perhaps the most visible form of building services, enabling the construction of tall buildings and urban living. The number of elevators is continuously increasing, as is also the interest in their power consumption profiles and energy efficiency. This dissertation provides methods to model these highly intermittent electrical loads from the power system perspective. The models can be applied to evaluate the long-term energy consumption of individual elevators, while they can also be applied to calculate the high-resolution aggregated power consumption of a large elevator fleet with thousands of units. With these features, the dissertation evaluates the potential of applying elevators as a controllable load to participate in demand response programs, where the focus can be either to secure the electrical grid stability or to minimize the system level costs. Combining the simulation of passenger traffic and the resulting power demand pattern, the dissertation also provides an approach to calculating the delay caused to passengers as a result of demand response participation.