LIFT & ESCALATOR SYMPOSIUM

14TH SYMPOSIUM ON LIFT & ESCALATOR TECHNOLOGIES

Volume 14

September 2023

ISSN 2052-7225 (Print)

ISSN 2052-7233 (Online)

www.liftsymposium.org

Lift and Escalator Industry Association LEIA

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FOREWORD

It is with great pleasure that we present the proceedings of the 14th Symposium on Lift and Escalator Technologies, 20-21 September 2023, organised by The Lift and Escalator Symposium Educational Trust.

The objective of The Lift and Escalator Symposium Educational Trust is to advance education in lifts, escalators and related technologies. The Trust is a Registered Charity No: 1170947 and is supported by The University of Northampton, The Chartered Institution of Building Services Engineers (CIBSE) and The Lift and Escalator Industry Association (LEIA).

Proceedings from the full conference series (since 2011) are available to download from www.liftsymposium.org. The proceedings are indexed in Scopus as "Symposium on Lift and Escalator Technologies", starting from the 2015 Symposium. Scopus is the world's largest abstract and citation database of peer-reviewed literature (scientific journals, books and conference proceedings), see https://blog.scopus.com/about.

The Lift Engineering programme offered at The University of Northampton includes postgraduate courses at MSc/ MPhil/ PhD levels that involve the study of the advanced principles and philosophy underlying lift and escalator technologies. The programme aims to provide a detailed, academic study of engineering and related management issues for persons employed in lift-making and allied industries.

The CIBSE Lifts Group is a specialist forum for members who have an interest in vertical transportation. The group meets regularly to promote technical standards, training and education, publications and various aspects of the vertical transportation industry. The CIBSE Lifts Group directs the development of CIBSE Guide D: Transportation systems in buildings, the de facto reference on vertical transportation.

LEIA is the UK trade association and advisory body for the lift and escalator industry with a membership covering some 95% of the lift and escalator industry. LEIA members supply passenger and goods/service lifts, stairlifts, homelifts, lifting platforms, escalators, passenger conveyors and a range of component parts for such products. LEIA members undertake the maintenance and modernisation of more than 250,000 products falling within the scope of the Association. LEIA provides advice on health, safety and standards matters, promotes education and training, especially through its distinctive distance learning programme.

The Symposium brings together experts from the field of vertical transportation, offering an opportunity for speakers to present peer-reviewed papers on the subject of their research. Speakers include industry experts, academics and postgraduate students.

The papers are listed alphabetically by first author surname. The requirement was to prepare an extended abstract, but full papers were accepted where the speakers preferred to offer them. The submissions are reproduced as they were submitted, with minor changes in formatting, and correction of obvious language errors where there was no risk of changing meaning.

Professor Stefan Kaczmarczyk, and
Dr Richard Peters
Co-Chairs and Proceeding Editors

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Temperature Phase Plan Map and Poincare Section for Escalators

Ali Albadri

Keywords: escalator, gearbox, temperature, monitoring, phase plan map, pointcare section

Abstract. Our interest in finding a tool that can be used to understand and record the behaviour of electro-mechanical machines is continuing in this study. We have chosen escalators in our studies because their natural electrical and systematic designs are based on systematic cyclic and periodic behaviour. Escalator nature of operation has given us an excellent platform to determine how regular or irregular or chaotic the behaviour of an escalator is, especially when some sort of malfunction develops in it. We used two tools to achieve our objectives [1-6], the fractal dimension concept and the phase plan map as well as the Poincare section.

In this study, we will concentrate our efforts on the behaviour of the gearbox which drives the escalator. The parameter which will be looked at is the temperature of the gearbox. Temperatures were measured from different locations in the gearbox. The phase plan maps and Poincare sections of various traces from various temperature sensors have been plotted, and they have presented some interesting and useful patterns. The plots can be used as reference maps for the normal and abnormal operating conditions of an escalator.

1 INTRODUCTION

In our previous studies, we have proven the fractal nature of escalator behaviour during operation [1-6]. We plotted the phase plan map and the Poincare section for escalator behaviour [7,8,9]. There were useful and interesting patterns. They showed the patterns of stress level attractors in the machines, how they behave, and how they change paths and layout or embedment regions. The general pattern was repetitive, but there were some differences which are a reflection of the local from which the measurement was taken.

In this study, our attention will be on the temperature distribution in the escalator gearbox, see Figure 1. Motor gearboxes are used to drive a machine like an escalator. The function of the gearbox is to transmit mechanical power from the motor through the gearbox to the escalator top drive shaft. A gearbox consists of a worm shaft (drive/input shaft), a newel wheel sprocket, and then the output shaft. Using a prognostic technique to monitor and study the behaviour of a gearbox can be a useful tool in achieving maximum efficiency from the gearbox.

The behaviour of a complex system like a compressor has been monitored and looked at by many studies [10-13]. The raw-measured signals were used for fault diagnosis. Research concerning the modelling of reciprocating compressors uses phase space trajectories, Poincare maps, and Lyapunov exponents for identifying the chaotic behaviour of a reciprocating compressor system with subsidence rub-impact fault [14,15].

Nonlinear and chaotic dynamical systems can be analysed by using tools like the phase space diagram and Poincare plot [16]. The Poincare map has been used for visualising the nonlinear chaotic behaviour of faults in gears and bearing elements [16].

This study will give an insight into the behaviour and pattern of operation of the escalator gearbox during normal and abnormal conditions.

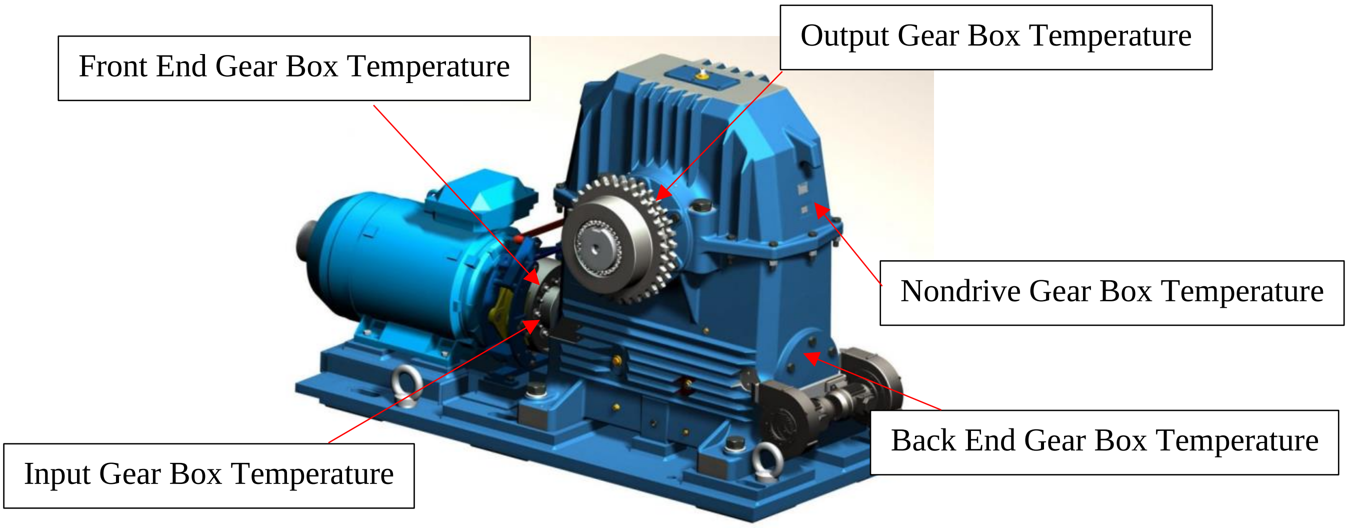

Figure 1 The escalator motor gearbox with the distribution of temperature sensors.

2 CONSTRUCTING THE MAP

Temperature sensors were distributed at different locations on the gearbox, as shown in Figure 1. The data/traces were logged into a data logger, see Figure 3, and then downloaded on a computer for analysis. The period of the run was divided into two regions, region 1 and region 2. Region 2 includes a shutdown period, to impose a stage of variation in the measurements. It is our intention to see whether the adopted technique in this study will or will not detect this variation.

The Poincare space map and the phase plane map for the nonlinear behaviour of a machine like an escalator have been constructed using the traces from the temperature sensors. The Poincare space map is constructed by using the pseudo-phase plane method (also called the embedding space method). For one degree of freedom system with measurement x(t), one plots the signal versus itself, but delayed or advanced by the fixed time constant [x(t), x(t+T)]. The idea is that the signal x(t+T) is related to x`(t) and should have properties similar to those in the classic phase plane [x(t), x`(t)]. If the motion is chaotic, the trajectories do not close.

When the state variables are greater than three (position, velocity, time or any other parameter), the higher-dimensional pseudo-phase-space trajectories can be constructed using multiple delays. For example, a three-dimensional space can be constructed using a vector with components (x(t), x(t+T), x(t+2T)) [1].

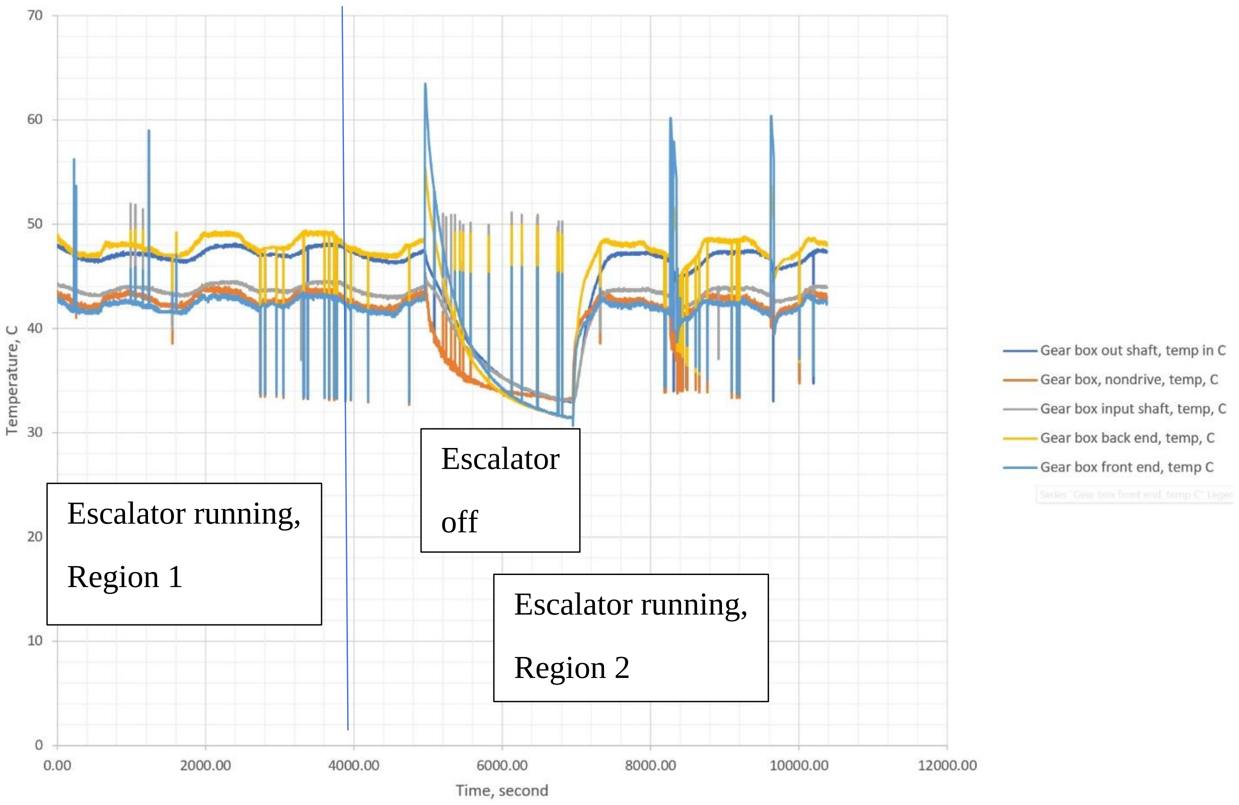

Figure 2 Presents the temperatures against the running time.

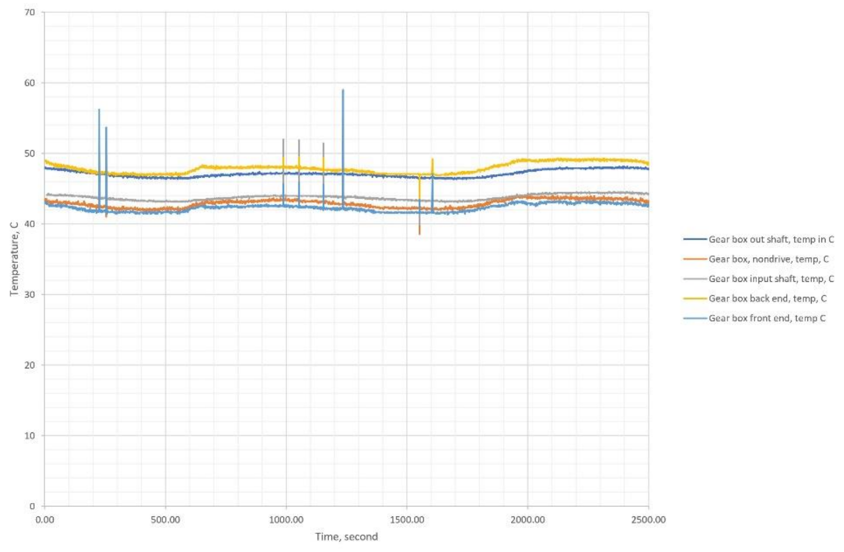

Figure 3a A magnification view for region 1 (0-4000 seconds) in Figure 2.

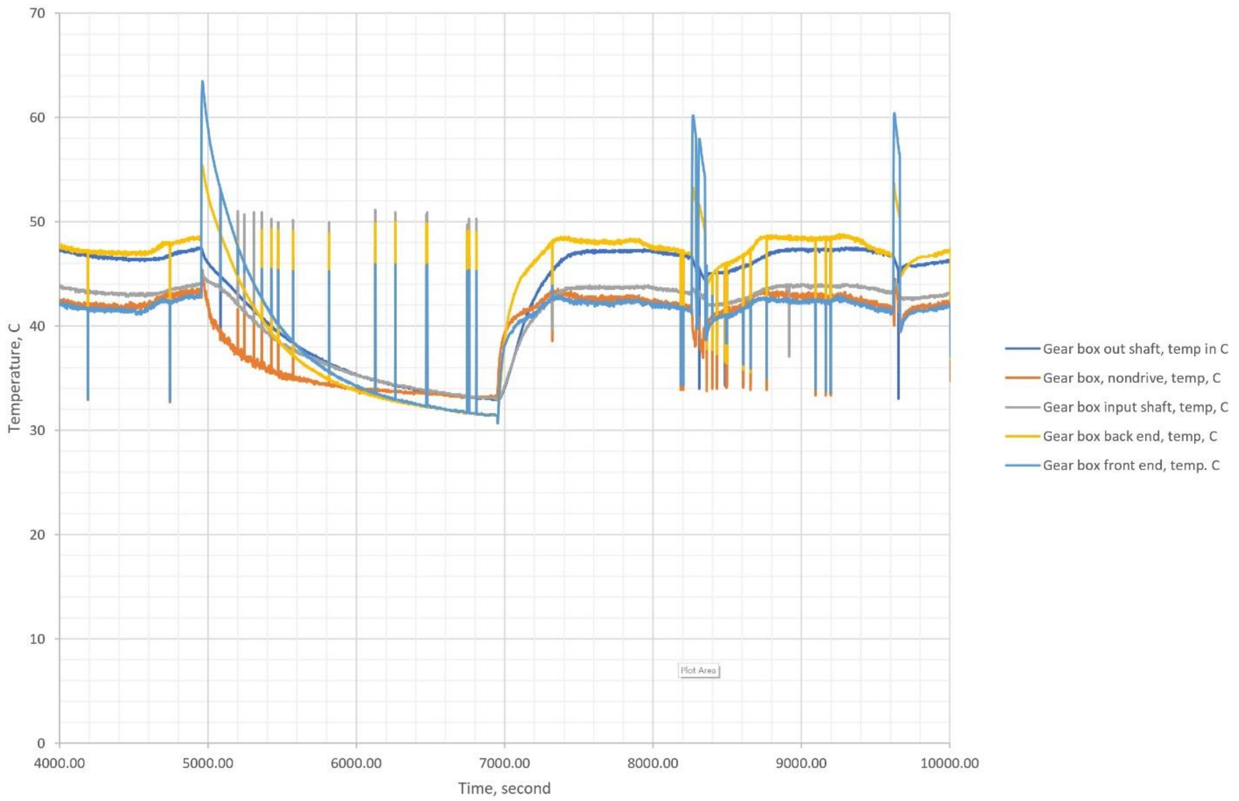

Figure 3a A magnification view for region 1 (4000-10000 seconds) in Figure 2.

3 RESULTS AND DISCUSSION

Figures 4 to 13 show plots for the Poincare section and the phase plan map for each trace. It is very interesting to observe that the patterns and shape of the plots are very regular and systematic in the running period 0.0-4000s, region 1. However, the data in region 2 shows a different systematic pattern to those observed in the first period. They are certainly not chaotic but periodic, forming different loops (periodic behaviours), which reflect the variation that happened in the escalator during the shutdown period.

4 CONCLUSIONS

This study has proven that the phase plane map and the Poincare section are interesting tools to be used to monitor the behaviour of gearboxes. Beautiful and interesting patterns were developed in the maps and sections of temperatures measured from the gearbox. Variations in the behaviour of the gearbox temperature were noticed too, in the shape of other periodic patterns and shapes.

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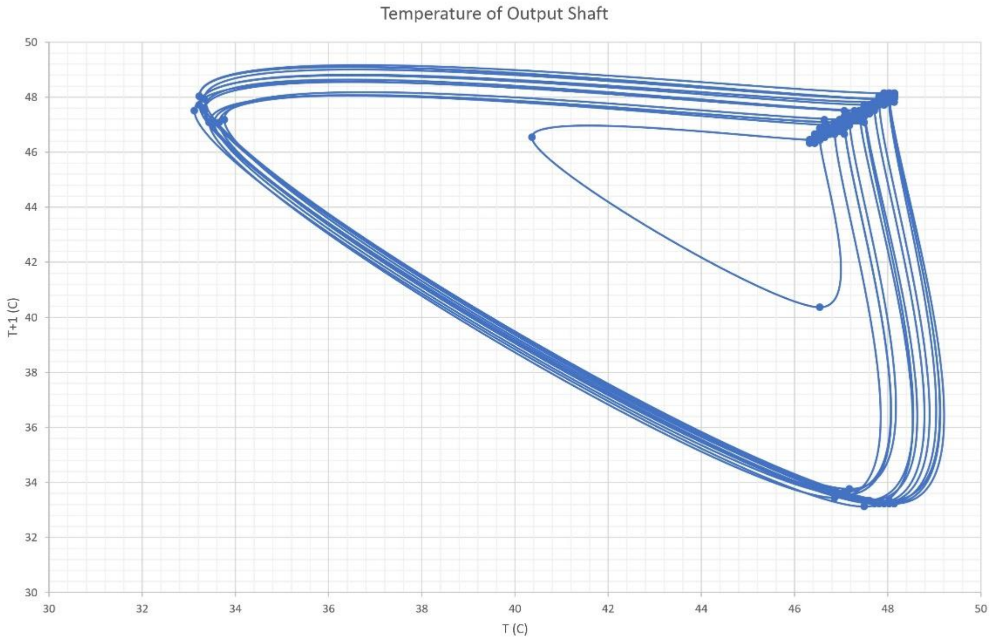

Figure 4a Shows the Poincare section for output gear box shaft between 0.0-4000 seconds.

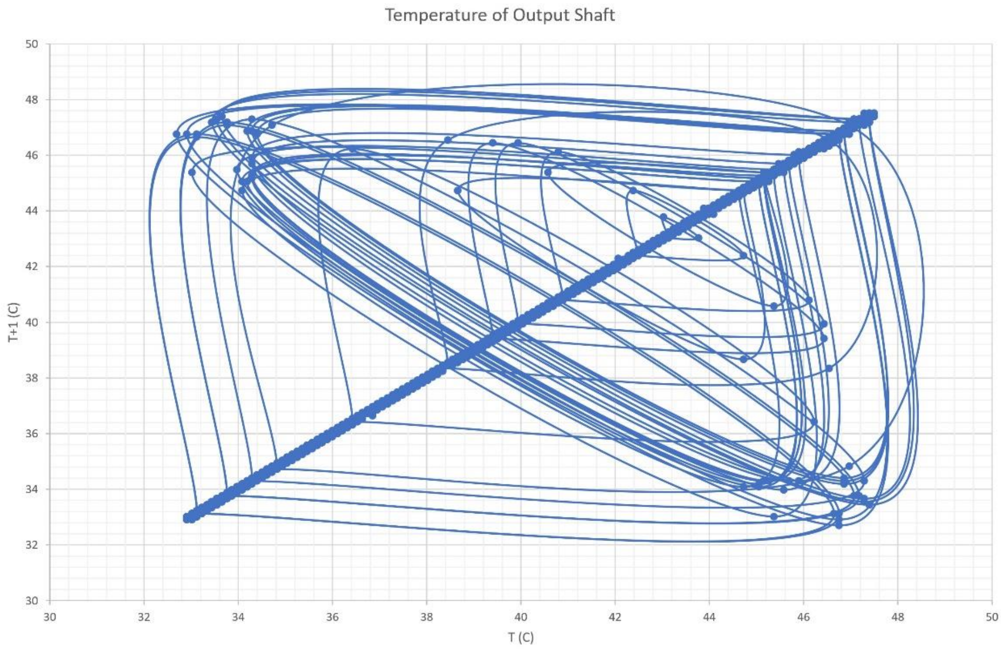

Figure 4b Shows the Poincare section for the output gear box shaft between 4000-10,000 seconds.

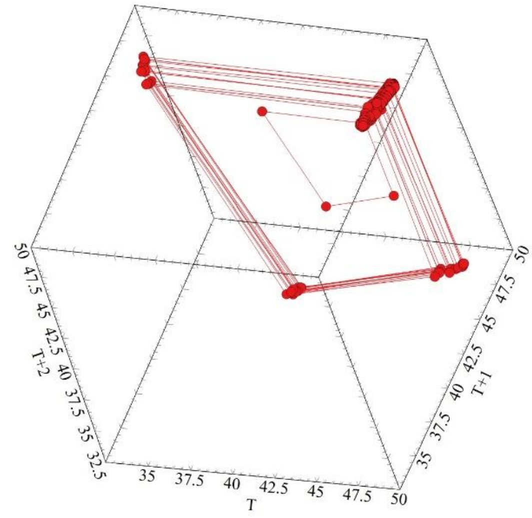

Figure 5a Shows the Phase Plan Map for the output gearbox shaft between 0.0-4000 seconds.

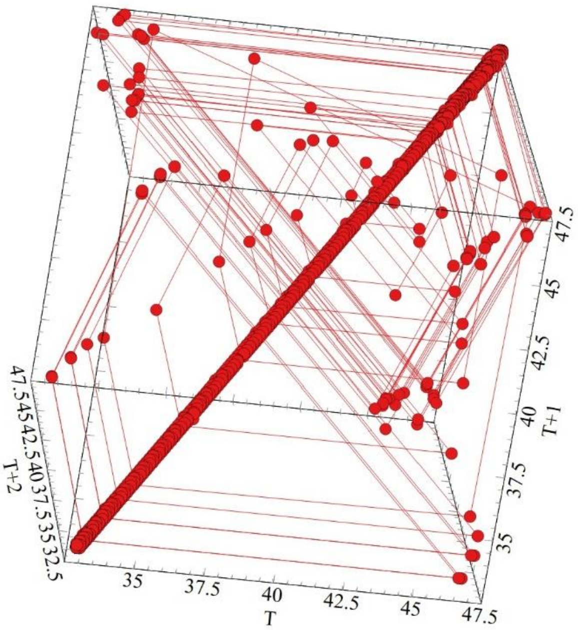

Figure 5b Shows the Phase Plan Map for the output gearbox shaft between 4000-10,000 seconds.

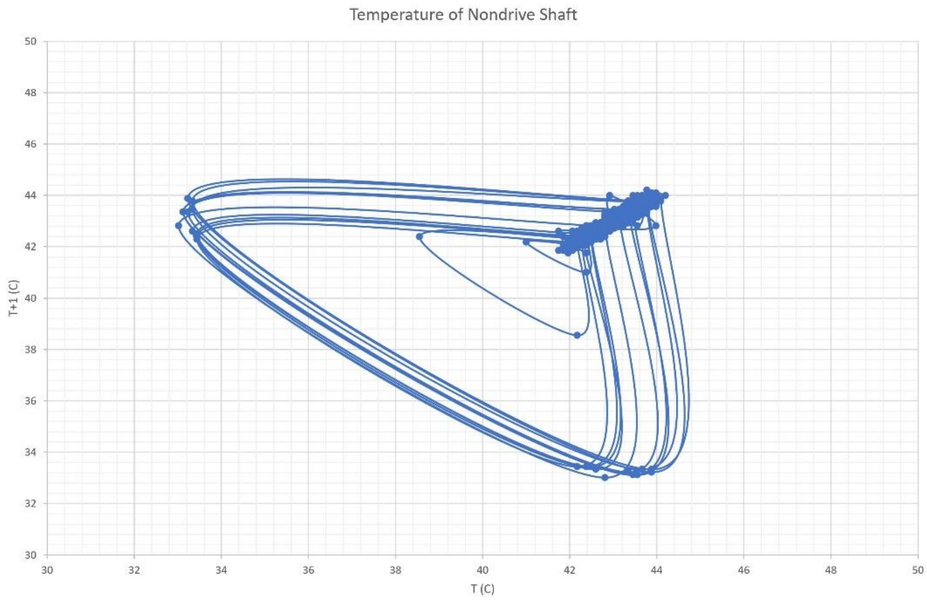

Figure 6a Shows the Poincare section for the non-drive gearbox shaft between 0.0-4000 seconds.

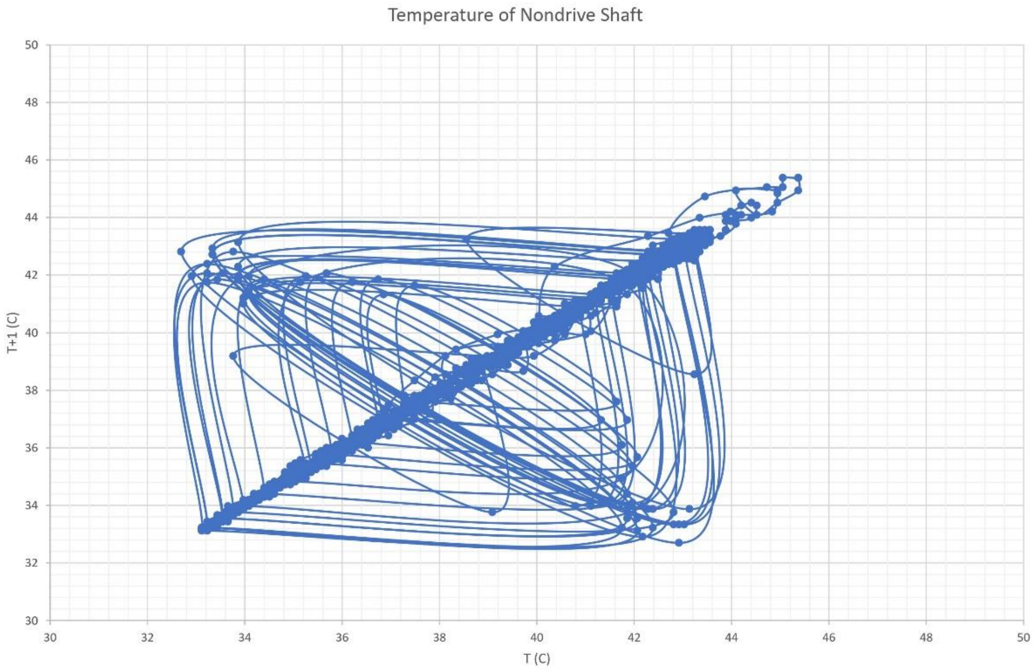

Figure 6b Shows the Poincare section for the non-drive gearbox shaft between 4000-10000 seconds.

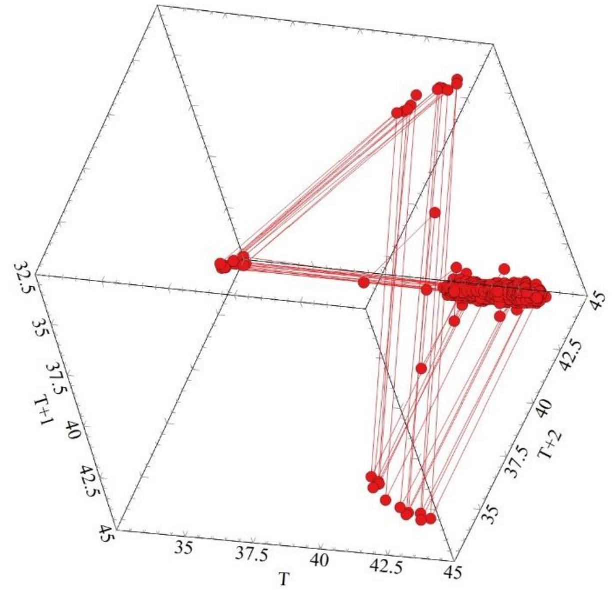

Figure 7a Shows the Phase Plan Map for the non-drive gear box shaft between 0.0-4000 seconds.

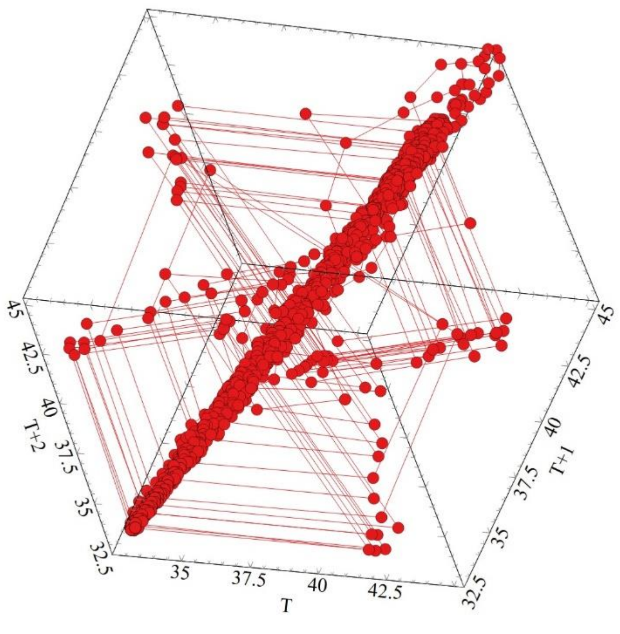

Figure 7a Shows the Phase Plan Map for the non-drive gearbox shaft between 4000-10000 seconds.

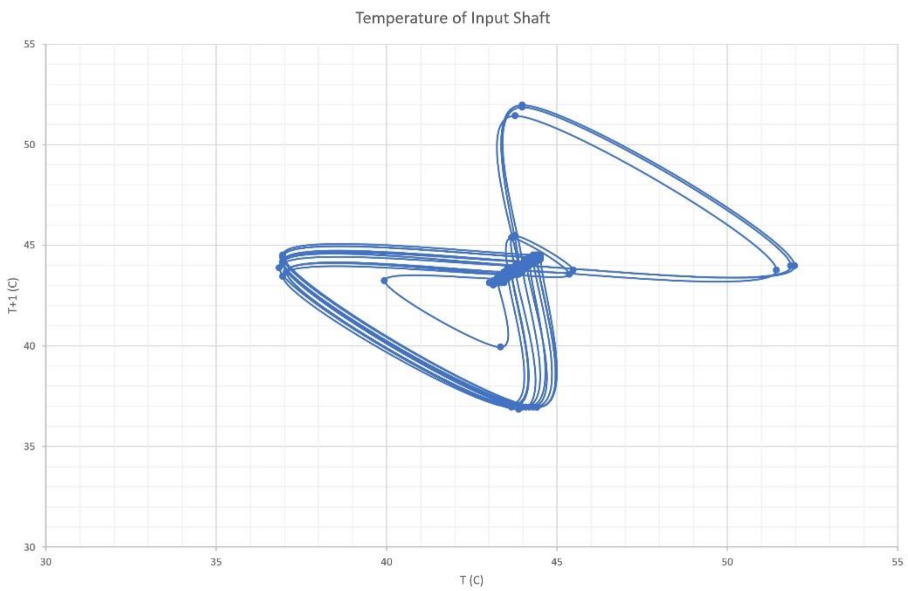

Figure 8a Shows the Poincare section for the input gearbox shaft between 0.0-4000 seconds.

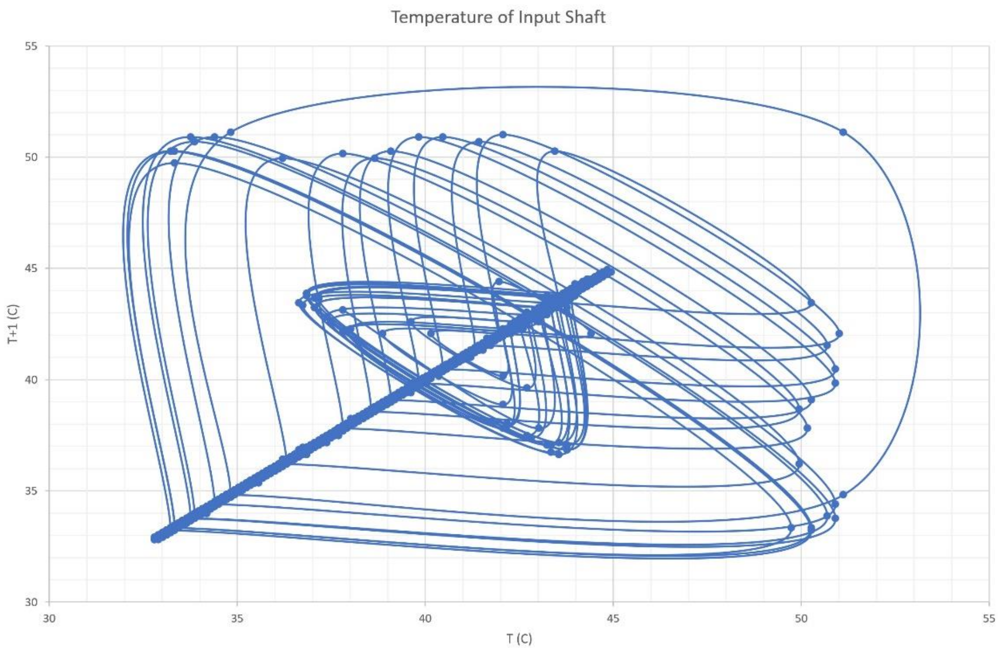

Figure 8b Shows the Poincare section for the input gearbox shaft between 4000-10000 seconds.

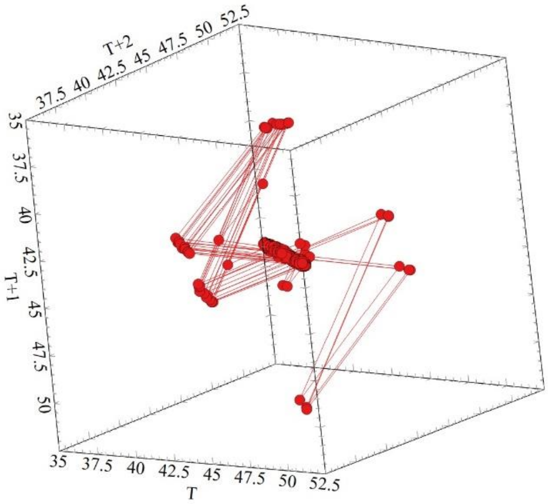

Figure 9a Shows the Phase Plan Map for the input gearbox shaft between 0.0-4000 seconds.

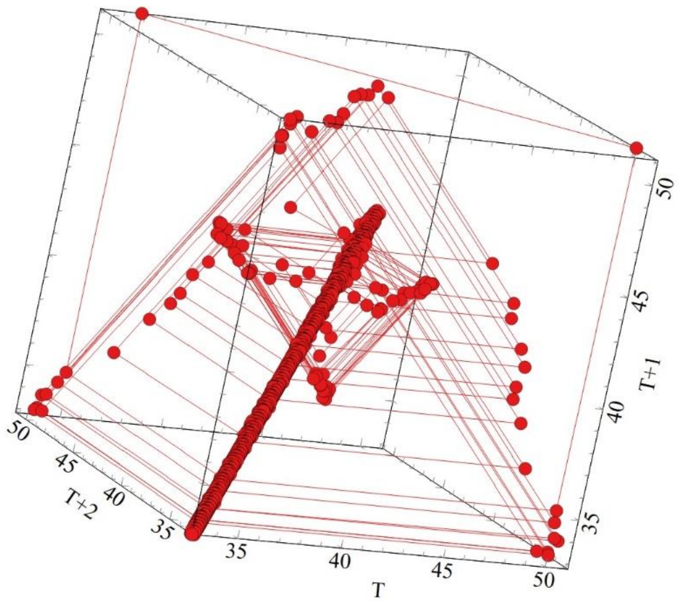

Figure 9a Shows the Phase Plan Map for the input gearbox shaft between 4000-10000 seconds.

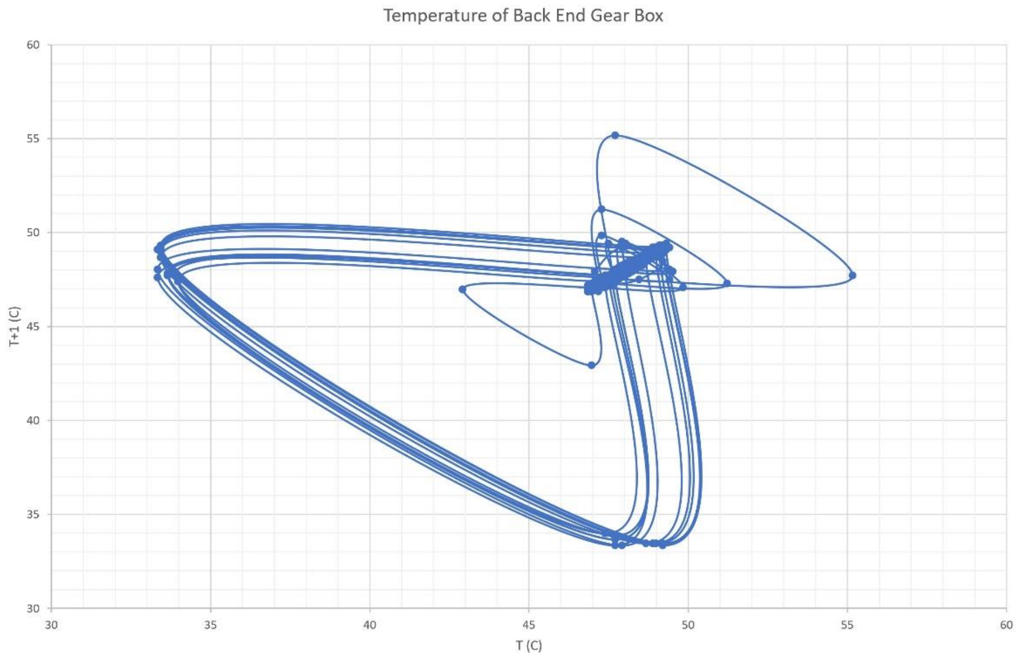

Figure 10a Shows the Poincare section for the back-end gearbox shaft between 0.0-4000 seconds.

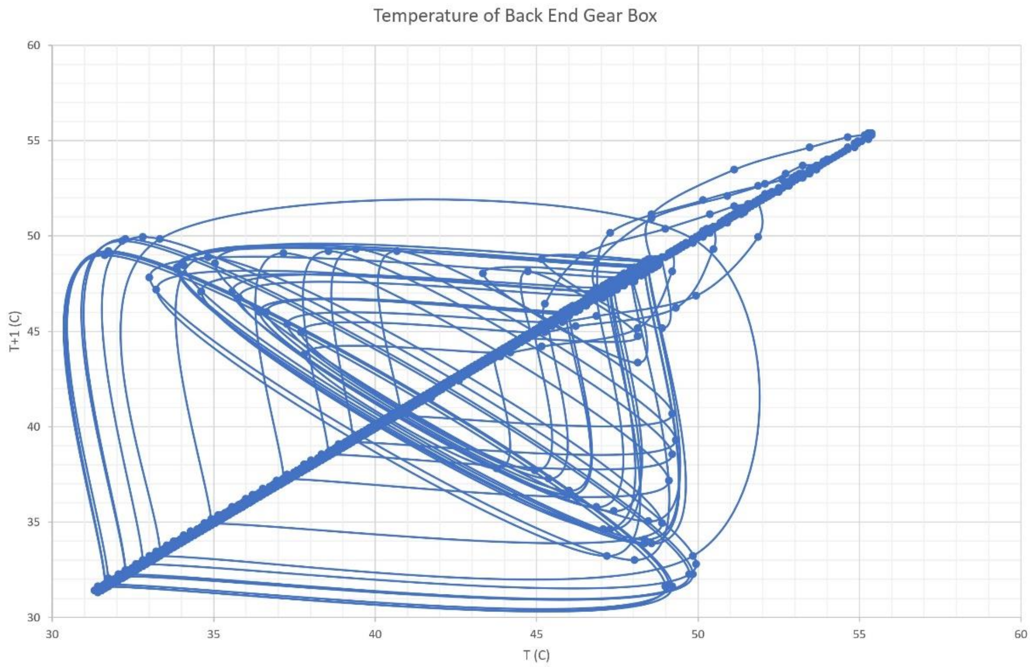

Figure 10b Shows the Poincare section for the back-end gearbox shaft between 4000-10000 seconds.

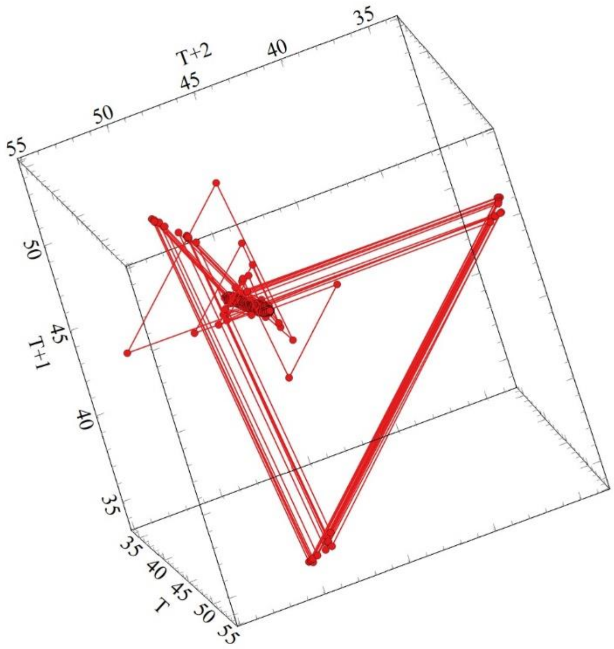

Figure 11a Shows the Phase Plan Map for the back-end gearbox shaft between 0.0-4000 seconds.

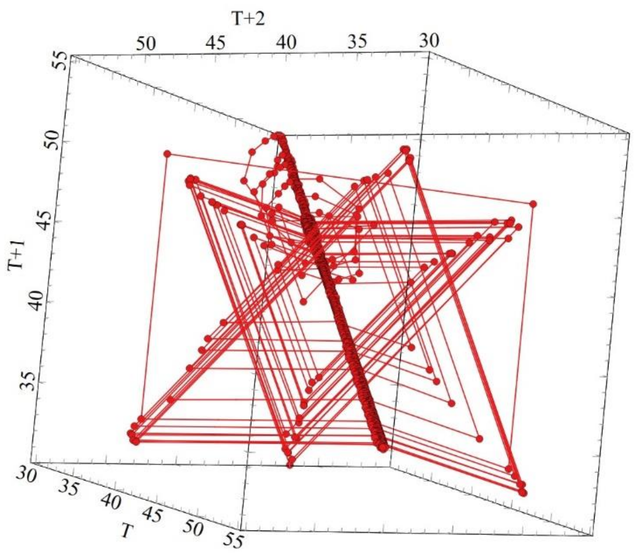

Figure 11a Shows the Phase Plan Map for the back-end gearbox shaft between 4000-10000 seconds.

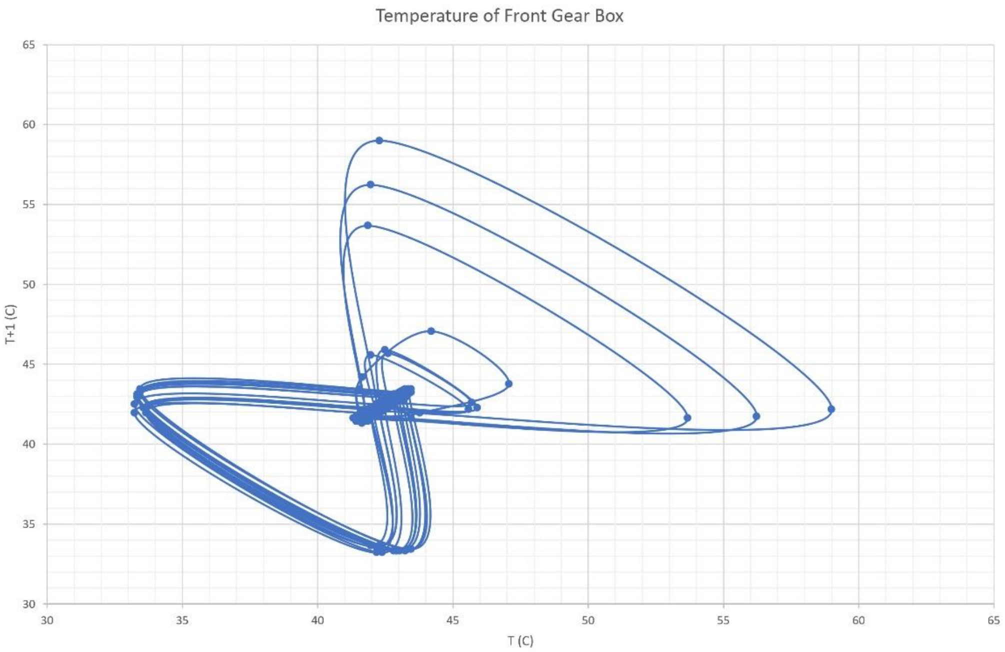

Figure 12a Shows the Poincare section for the front-end gearbox shaft between 0.0-4000 seconds.

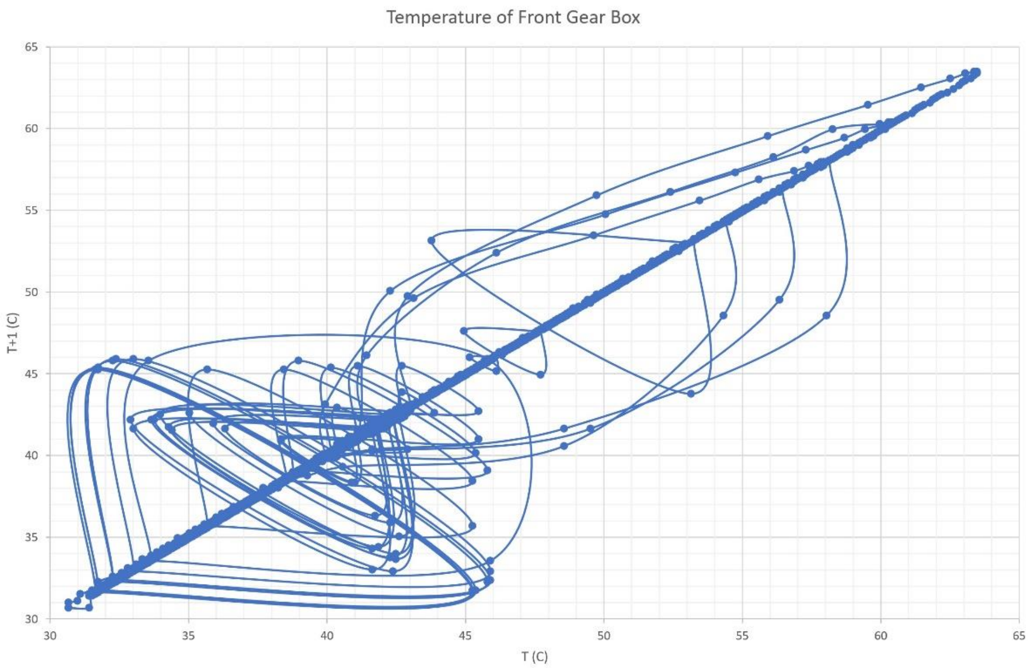

Figure 12b Shows the Poincare section for the front-end gearbox shaft between 4000-10000 seconds.

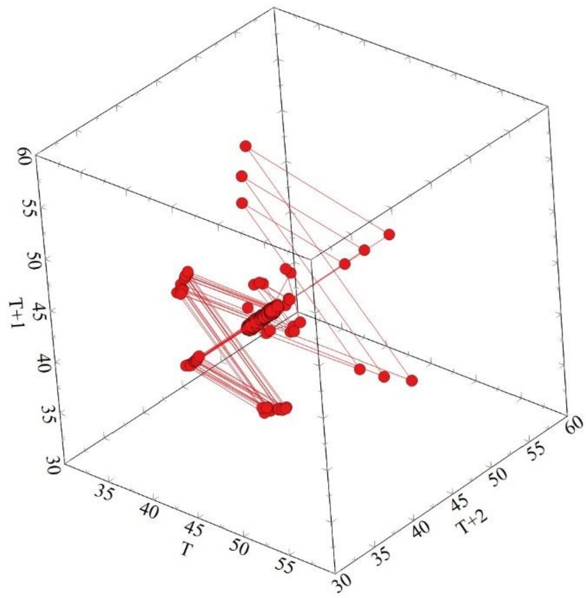

Figure 13a Shows the Phase Plan Map for the front-end gearbox shaft between 0.0-4000 seconds.

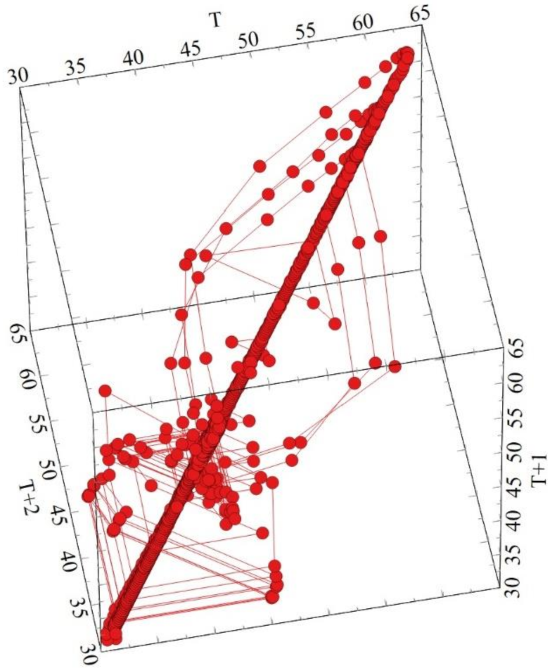

Figure 13a Shows the Phase Plan Map for the front-end gearbox shaft between 0.0-4000 seconds.

BIOGRAPHICAL DETAILS

Dr. Ali Albadri is a chief engineer at London Underground Ltd, Lifts and Escalators. He has a PhD and MPhil in Materials Science from the University of Manchester and the University of Sheffield, respectively, and two BSc degrees, one in Nuclear Engineering from Baghdad University and another in Mechanical Engineering from the Technology University. Prior to joining the vertical transportation industry, he worked for Manchester University, Brunel University and Oxford University, in the academic sector, then moved to industry to work for Cookson Group, ABB, Olympus and Hydronix Ltd. He owned various inventions such as the smart step, smart test rig and Titan for concrete solidification measurement. Albadri has published papers more than 45 papers in materials science, food & concrete industries, microwaves and design instruments as well as in escalators.

Enhancing the Inter-Linked Monte Carlo Simulation Method (iL-MCS) to Reflect Random Passenger Inter-Arrivals

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Keywords: Monte Carlo simulation, interlinked Monte Carlo simulation, passenger inter-arrival time, elevator, lift, round trip time, interval, elevator traffic engineering.

Abstract. The Monte Carlo Simulation method (MCS) has been successfully used to find the value of the lift round trip time under general traffic conditions, including cases such as multiple entrances, unequal floor heights, unequal floor populations, rated speed not attained in one floor journey, as well as the variation in group control algorithms (e.g., destination group control).

In conventional Monte Carlo Simulation, the various trials (or scenarios) are completely disconnected, where the end of one trial does not influence the following trial. Past research work presented the new extension of the Monte Carlo Simulation, by inter-linking each trial or scenario in the Monte Carlo Simulation with the next one, where it links the trials such that the end conditions of one trial become the initial conditions of the following trial. This “interlinking” allows the method to reflect the effect of the random passenger destinations on the value of the round-trip time.

The past research work examined in detail the effect of the first source of randomness in the lift system: the randomness of the origins and destination of passenger. It did not, however, examine the effect of the randomness caused by variable passenger inter-arrival time (following an exponential probability distribution).

This paper will also include the effect of bunching on the value of the round trip time as well as the queue length at the landing.

1. INTRODUCTION

The lift round trip time has for a long time formed the basis of sizing and selecting the number and speed of lifts in a building [1] following the assessment of demand [2]. Even with the advent of simulation, most designers still use the round-trip time as the basis for the initial phase of the design based on calculation and then follow it up with simulation runs to refine the final design.

The calculation of the value of the round-trip time has traditionally been based on using an equation that was developed and expanded in the 1980s [3] which relies on the lift kinematic equations ([4], [5]). The main drawback of this equation is that it is only applicable and correct in a special set of conditions such as incoming traffic, independent passenger decisions, rated speed attained in one floor jump, and a single entrance. Several researchers have attempted to extend the application of this equation to more general cases ([6], [7], [8]). An attempt was also made to extend the equation to accurately incorporate all these special conditions [9].

One of the most notable successes in this area was the application of the Monte Carlo simulation (MCS) method to find the value of the round-trip time under incoming traffic conditions [10] and then under general traffic conditions [11]. It was also used to find the value of the average travelling time [12]. In one of the latest papers, MCS was used to evaluate the round-trip time for destination group control [13].

In all these papers that used the Monte Carlo simulation to find the value of the round-trip time, the trials were completely independent. Each trial was kept separate from the preceding and the succeeding trials. An improvement was introduced by linking each of the trials to the following trial in [14]. It introduced the concept of interlinking the consecutive trials to better reflect the randomness in the lift traffic system. Specifically, it *interlinked* the trials to reflect the effect of the variability in the value of the round-trip time that is caused by the randomness of the passenger destination. It only considered one source of randomness: the randomness in the passenger destinations.

This paper extends this approach by taking into consideration the other source of randomness, which is the arrival times of the passengers (assumed to follow a Poisson distribution).

The conventional Monte Carlo simulation approach assumes that the number of passengers in each round trip is constant. By contrast, in the interlinked MCS approach, the number of passengers generated in each trial is not constant, but dependent on the previous value of the round-trip time.

The car capacity has been assumed to be limited, thus better reflecting the reality of the fluctuations in the value of the load in the lift car.

Another factor that has been taken into consideration is the phenomenon of bunching [15], [16]. The effect of bunching on the variability of the value of the round-trip time and the consequential variability of the number of passengers arriving has been taken into consideration.

The Monte Carlo Simulation method has also been successfully used in verifying the calculation of the round trip for more complex and larger buildings containing hypothetical two-dimensional buildings ([17] and [18]).

The next section identifies the two sources of randomness in the lift traffic system (from which all other manifestations of randomness arise). The third section identifies the two possible approaches that can be followed in generating random arrivals of passengers in time (based on either a Poisson probability distribution function for the number of passengers arriving in a period of time or based on an exponential distribution function for the inter-arrival time between consecutive passengers). Section four shows the results for the passenger queue length and the round-trip time. Section five shows the effect of "interlinking" on the handling capacity of the lift traffic system. Conclusions are drawn in the last section of the paper.

2. THE TWO SOURCES OF RANDOMNESS IN LIFT TRAFFIC SYSTEMS

The two sources of randomness in lift traffic systems are identified below:

1. The first source of randomness is the arrival time of the individual passengers. It has been suggested that the arrival of passengers for service follows a Poisson distribution (more precisely, the number of passengers arriving in a specified period follows a Poisson distribution, and this random variable is a discrete random variable). It is more common to model this process by examining the inter-arrival time between consecutive passengers, which follows an exponential distribution, whereby the random variable is a continuous random variable.

2. The second source of randomness in lift traffic systems is the randomness of the passenger origin and destination floors. In the general case, it is assumed that the passenger origin and destination selections are independent. When the building under consideration has a single entrance and the type of traffic is incoming only, the origin floor is the same for all passengers and the source of randomness is the passenger destination floors. Each passenger is assumed to select a destination based on the probability density function for the floor destinations, which is based on the number of occupants on each floor.

The randomness of passenger origins and destinations is introduced into the system by using the so-called Origin-Destination matrix (OD matrix) and applying random sampling. Full details can be found in [11].

These two sources are the source of all randomness in the lift traffic system, and any other display of randomness in the lift has its roots in one or both of these two sources. For example, the variability of the round trip is caused by the random passenger destinations (2nd source above), and the variability of the number of passengers boarding the lift car is caused by both the first and second sources above. A third possible source of randomness is the arrival of passengers in batches of more than one passenger (e.g., two or three).

It is also worth remembering that the variability of the round-trip time for each lift will lead to the time between the successive arrivals of the lifts at the landings being variable, a phenomenon known as bunching ([15], [16]). It is widely accepted that bunching can lead to the loss of handling capacity and an increase in passenger waiting time. It is also very common that bunching can lead to the reversal of the sequence of lift movements around the building (i.e., with four lifts in the group, and assuming they start in the sequence of A, B, C, and D, this could later become A, C, B, D).

The second source of randomness has been modelled in [14] (and more specifically, the passenger destinations only, as the building under consideration has only one entrance and the type of traffic is incoming only). Its effects on the variability in the value of the round-trip time, the number of passengers boarding the lift car, and the passengers left queuing behind at the landing were all explored.

This paper adds the other source of randomness, which is the random arrival time of passengers.

3. MODELLING THE RANDOM ARRIVAL TIME OF PASSENGERS.

In order to model the random passenger arrivals, there are two options:

1. Evaluate the number of passengers arriving in a period of time assuming a Poisson arrival process for the number of passengers arriving.

2. Evaluate the inter-arrival time between consecutive passengers assuming an exponential probability density function (pdf) for the inter-arrival time.

The decision was taken to follow the second approach in this case. A function has been created in MATLAB that generates the inter-arrival time between successive passengers using the exponential probability density function. It then keeps on repeating this process until the whole period has elapsed. By summing up all the passengers that have arrived in that period, it arrives at the total passengers arriving.

The inputs to this function are the average passenger arriving (λ) in units of passenger per second, and it assumes a Poisson arrival process.

4. RESULTS FOR ROUND TRIP TIME (RTT) AND QUEUE LENGTH

The modelling of the inter-linked Monte Carlo simulation has been implemented in MATLAB. The random passenger arrival has been implemented based on the exponential pdf for the inter-arrival time.

The same hypothetical building was used as that in [14]. By definition, the very nature of the interlinked MCS requires that more than one round trip be run. In the results that will be shown later in this paper, the number of consecutive round trips has been set to 100 (i.e., 100 interlinked round trips).

The number of MCS trials was set to 1000 (i.e., 1000 trials). The average of all 1000 trials was taken when reporting the results.

The results for the queue length (in passengers) and the round-trip time (in seconds) are shown in Figure 1 below. The results shown are the average of all the 1000 MCS trials. The length of the interlinked simulation is 100 round trips (as can be seen from the length of the x-axis, which has units of “round trips”).

As can be seen from the results, the following conclusions can be drawn:

1. The queue length continuously grows in length. The figure shows the two cases with random arrivals: Poisson and constant arrival, where both show a queue developing. Under the hypothetical case where the round-trip time is calculated using an equation, it assumes that all passengers are removed in each round trip (which is obviously not true in any of the two cases studied above).

2. The queue length is larger in the case of the Poisson arrival of passengers as opposed to the constant passenger arrival. This is expected, as the randomness of passenger arrivals makes it more difficult to clear the queue at the landing upon the arrival of the lift cars.

3. The value of the round-trip time for constant arrival seems to settle at a specific value and does not change any further. This shows that the system arrives at steady state conditions.

4. The steady state value of the round-trip time under Poisson passenger arrival conditions is slightly smaller than the value of the round-trip time under constant passenger arrival conditions. This is explained by the fact that the average passenger load inside the lift car is smaller under Poisson arrival conditions due to the random nature of the arrivals.

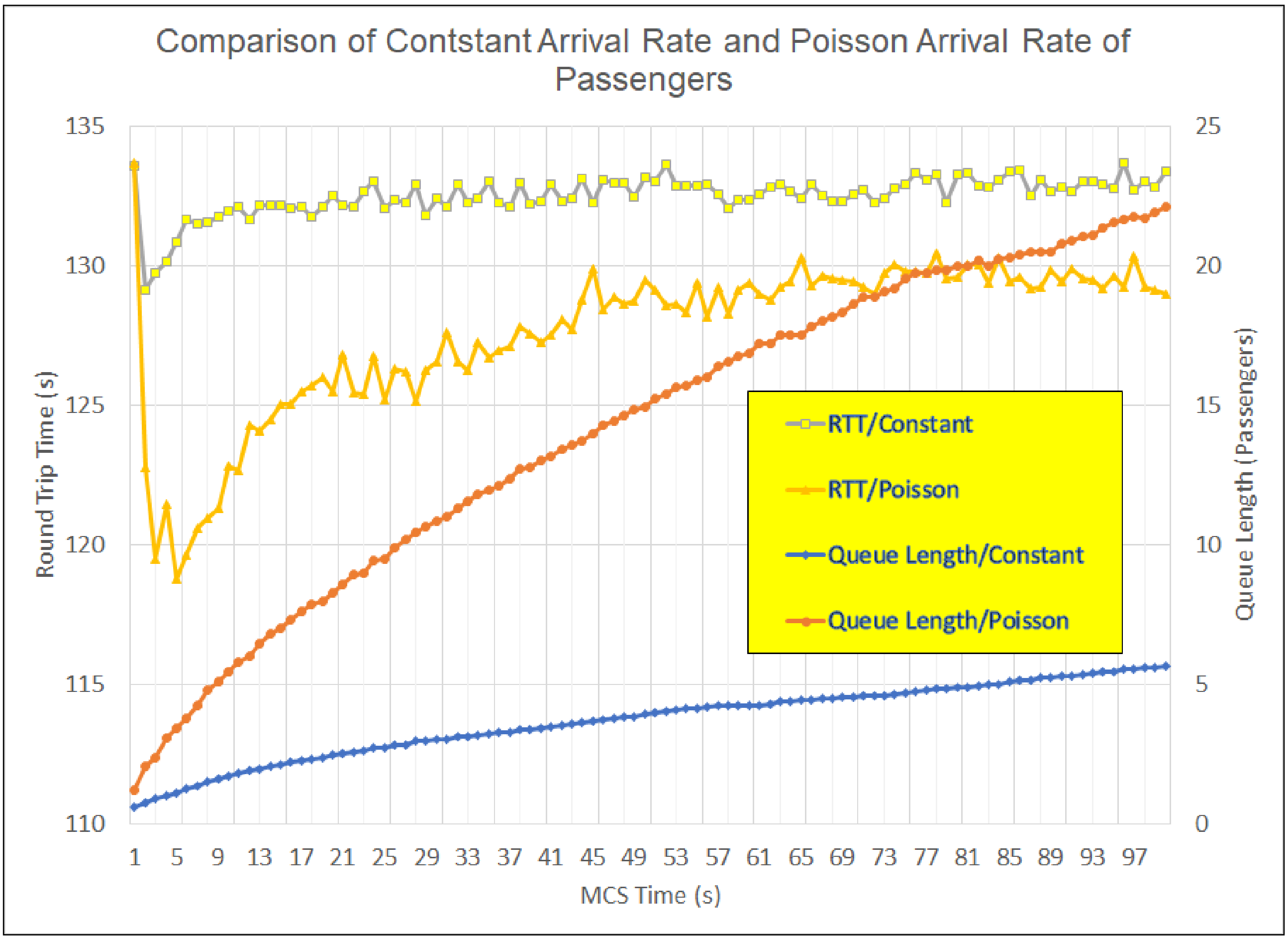

Figure 1 Comparison between the value of the Round-Trip Time (RTT) and the landing queue length under constant passenger arrivals and random passenger arrivals.

5. RESULTS FOR HANDLING CAPACITY

Following on from the results in the previous section, the question that would need to be answered is:

What is the overall effect on the handling capacity (HC%) of a smaller value of round-trip time and a smaller value of the number of passengers served in the lift car under random passenger arrivals?

In order to answer this question, the handling capacity of the lift system under random passenger arrivals in each round trip was calculated and compared to the calculated value of the handling capacity under constant passenger arrivals. The results are shown in Figure 2 below.

It is worth noting that the ideal handling capacity under the full absence of any random behaviour in the lift system is 12.5% (hypothetically 12.477%), based on the following parameters (assuming five lift cars in the group):

1. The number of passengers in the lift car in each round trip is 10 passengers.
2. The design value of the round-trip time under ideal conditions is 133.578 seconds.

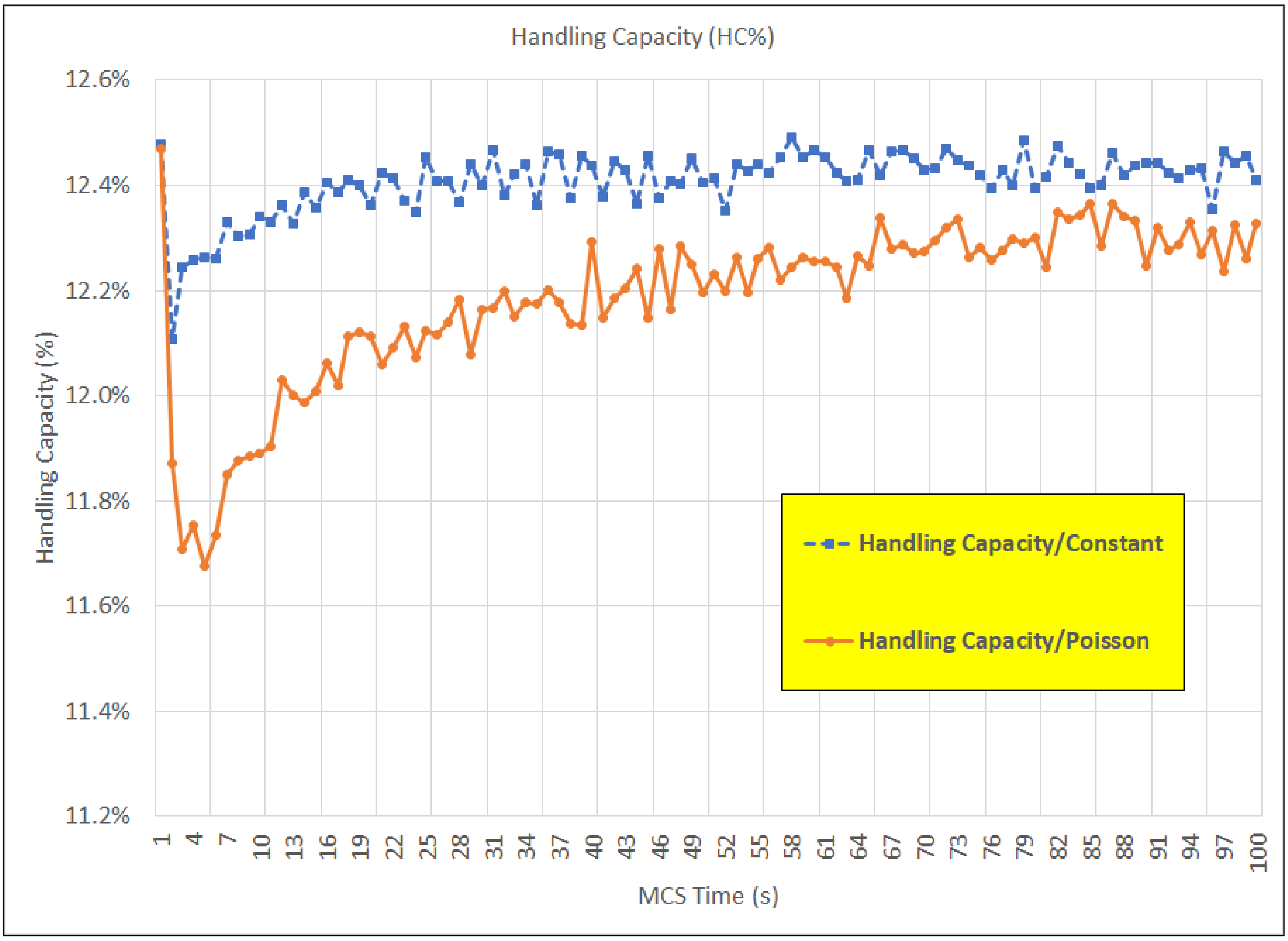

Figure 2 Comparison between the handling capacity (%) under constant passenger arrivals and random passenger arrivals.

Based on Figure 2 above, it can be seen that the handling capacity reaches a steady state value in both cases of constant passenger arrivals and random passenger arrivals. The following conclusions can be drawn:

1. The handling capacity in both cases is slightly smaller than the design handling capacity of 12.5% (hypothetical 12.477%).

2. There exists a slight loss in handling capacity when the randomness of passenger destinations under constant arrival conditions is introduced.

3. There is a further loss in handling capacity when random passenger arrivals are also taken into consideration.

6. CONCLUSIONS

The Monte Carlo simulation has been successfully used to find the value of the lift round trip time under general conditions, such as the multiple entrances, general traffic conditions, and rated speed not attained in one floor jump. It has also been used to find the value of the passenger transit time as well as the round-trip time under destination group control.

A previous paper has extended the use of the Monte Carlo simulation method to allow it to reflect the random nature of the passenger boarding the lift in each round trip and the random variations in the value of the round trip. This has been done by interlinking the consecutive trials by using the final value from one trial as the starting value for the next trial.

This paper has extended the case to include all the types of random variations expected in the lift system (namely: the variability in passenger destinations and the random passenger inter-arrival time).

The results show that the round-trip time is smaller when random passenger arrivals are assumed compared to constant passenger arrivals, and that the handling capacity is also smaller.

The practical significance of using the concept of "interlinking" is that it can provide the designer with more insights into the efficiency of the selected design. For example, the designer can observe how fast and how long queues will develop, and the consequential effect this would have on lobby sizes. This is particularly relevant when comparing destination control systems with conventional control systems. In addition, the result might help to better estimate waiting passenger times and transit passenger times.

Further work will be carried out in the future to identify the effects of enlarging the car capacity and how it impacts the queue length at the landing. It is expected that enlarging the car capacity sufficiently can be successfully employed to overcome both random effects of passenger destinations and the random passenger arrivals. This will be confirmed in future research to stipulate the exact increase in the rated car capacity required in order to fully restore the handling capacity of the lift traffic system and to reduce or eliminate the queue length at the landing.

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BIOGRAPHICAL DETAILS

Lutfi Al-Sharif received his Ph.D. in elevator traffic analysis in 1992 from the University of Manchester. He worked for 9 years for London Underground, London, United Kingdom in the area of lifts and escalators. In 2002, he formed Al-Sharif VTC Ltd, a vertical transportation consultancy based in London, United Kingdom. In 2006, he co-founded the Mechatronics Engineering Department at the University of Jordan, Amman Jordan, and progressed to full professor at the University of Jordan, where he spent 13 years as a faculty member, Mechatronics Engineering Department Head for six years and Vice Dean for Academic Affairs. Professor Al-Sharif is currently Vice President of Al Hussein Technical University in Amman, Jordan, and a part-time consultant for Peters Research Ltd. He is also a member of the management committee of the lift and escalator symposium.

Condition-based and Predictive Maintenance Strategy for Lift Installations using Big Data Analytics

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Keywords: Safety, Lifts, Big data analytics, Condition-based and predictive maintenance

Abstract. Safe and reliable lift services are essential for maintaining high accessibility and functional vertical transportation to help preserve the vitality of cities like Hong Kong which are renowned for its densely packed skyscrapers. This paper presents a proof-of-concept trial of a health monitoring platform for condition-based and predictive maintenance of lift installations using big data analytics. Implemented with various non-intrusive sensors, time series data of temperature, strain, acceleration, and displacement of lifts are collected and used to build predictive models with statistical and machine-learning techniques. The novel approach is capable of fault detection of brake malfunctions, lift car shaking, door malfunctions, and traction motor malfunctions and potentially enables prediction of the remaining useful life for the critical components.

1 INTRODUCTION

Lift installations play a crucial role in our daily lives, providing quick access to floors in buildings. However, lift systems are complex and require regular maintenance to upkeep their safe and reliable operation. Traditional maintenance approaches, such as time-based maintenance, can be inefficient and costly, leading to unnecessary downtime and repairs.

Condition-based and predictive maintenance strategies have emerged as promising alternatives to traditional approaches [1,2], leveraging big data analytics to monitor lifts and identify potential issues before they cause significant problems. These strategies rely on continuous monitoring of the lift installations. In recent years, they have been developed and implemented with various approaches. One approach is to monitor the traction sheave rope using computer vision [3]. Another approach is an automatic fault detection system using neural networks to monitor lift doors [4]. Besides, Li [5] proposed a vibration signal analysis to monitor the traction motor based on principal component analysis and Fourier methods. The exploration done in the field has enabled condition-based maintenance on specific critical components of lifts and advanced modern maintenance strategies.

In this paper, a condition-based and predictive maintenance strategy is implemented with non-intrusive sensors. Together with mathematical analysis and machine learning approaches, the detail of the methodology is established in Section 2. In Section 3, the results from four lifts at various locations in Hong Kong, namely Sir Ellis Kadoorie Secondary School Lift no.1, North Point Government Primary School Lift no.1, and Tai Po Government Office Lift no.1 and no.2 are discussed to evaluate the performance of this strategy. Finally, in Section 4, the findings are summarised, and the potential use in the future is discussed.

2 METHODOLOGY

To minimize any alteration of proprietary lift designs or interruption to the operation of different brands and models of lifts, non-intrusive electronic sensors were applied to monitor various physical parameters of interest. These sensors recorded the vibration of the traction motor, operation of the brake mechanism, and lift doors of the lift system. The sensor data is transferred to a cloud platform via a 4G LTE network periodically and analyzed to identify trends, anomalies, and potential failures.

In the following sessions, the lifts mentioned in Section 1 are mapped into Elevators 1, 2, 3, and 4 to enhance readability. Table 1 shows the name mapping of the lifts.

Table 1 Name mapping of lifts in the paper

Elevator 1	Tai Po Government Office Lift no.1
Elevator 2	Tai Po Government Office Lift no.2
Elevator 3	North Point Government Primary School Lift no.1
Elevator 4	Sir Ellis Kadoorie Secondary School Lift no.1

2.1 Traction Motor and Gear Box

Electrical accelerometers with a sampling rate of 1600 Hz installed on the outer edge of the lift car recorded its vibration signals. According to the industrial standards for lift safety in Hong Kong, the acceptable maximum peak-to-peak (P2P) lateral and vertical vibration is 0.25 m/s² for a lift speed of less than 6 m/s [6]. The measure is deployed as a shaking criterion, tagging any lift operation with P2P vibration above this level as a lift car shaking (LCS) incident. As the resonance frequencies of human body organs range from 2-50 Hz [7], a linear digital filter is applied to the vibration signals twice, once forward and once backwards, to preprocess the signals to [1, 50] Hz.

The same electrical accelerometers are installed on the traction motor to record its vibration signals. Assuming that the targeted components in the collected time series are sinusoidal, the Lomb method is suggested for the spectral analysis [8]. The Lomb-Scargle periodogram was first developed by Lomb [9] and formulated with a least-squares model fitting sinusoidal to data samples. It was proposed to analyze unequally spaced data of ground-based astronomical observation and further extended by Scargle [10] to search for periodic signals with low signal-to-noise ratios in unevenly sampled time series.

Given a set of n observations y_i, $i = 1,2,\ldots,n$ with zero mean and obtained at times t_i, the time series is described by

$$y_i + \varepsilon_i = a cos(2\pi f t_i) + b sin(2\pi f t_i), \quad (1)$$

where ε_i is the independent random measurement error at different times t_i and f is the frequency. To identify the dominant frequencies of a time series, the periodogram is used to estimate the spectral density of a signal. The classical periodogram definition $P(f)$ [11] is given by

$$P(f) = \frac{1}{N}[(\sum_n g_n cos(2\pi f t_n))^2 + (\sum_n g_n sin(2\pi f t_n))^2]. \quad (2)$$

After modifications on the denominators and adding a parameter τ to ensure time-shift invariance, the Lomb-Scargle periodogram P_{LS} in terms of frequency-domain representation [9, 10] is given by

$$P_{LS}(f) = \frac{1}{2}\left[\frac{(\sum_n g_n cos(2\pi f[t_n-\tau]))^2}{\sum_n cos^2(2\pi f[t_n-\tau])} + \frac{(\sum_n g_n sin(2\pi f[t_n-\tau]))^2}{\sum_n sin^2(2\pi f[t_n-\tau])}\right], \quad (3)$$

where τ is given by

$$\tau = \frac{1}{4\pi f} tan^{-1}\left(\frac{\sum_n sin(4\pi f t_n)}{\sum_n cos(4\pi f t_n)}\right). \quad (4)$$

In this study, the Lomb-Scargle periodogram is used as an instantaneous frequency estimator to generate spectrograms and visualize the frequency components of motor vibration signals.

2.2 Brake System

Electrical strain sensors installed on the braking arms collected 50 Hz time series data on the braking arm movement and contact when the brake is engaged. The time series is processed into braking cycles, where each cycle is the period from which the brake disengaged, then engaged. Given the information from the current transformer logger installed on the controller board, unexpected brake-arm movements are searched for in the entire dataset.

2.3 Door System

Proximity sensors installed in the car doors of the lifts recorded the distance between the car doors at a sampling rate of 9.1 Hz. The collected time series is processed into door cycles, where each cycle is the period from which a door starts to open from a fully closed state to a fully opened state, and then returns to its fully closed state. The period can include regular partial door re-openings.

According to the maintenance records, door malfunction (DM) incidents are identified in the processed door cycles. During a DM incident, the door attempted to operate but became either "stuck" for a prolonged period or moved roughly. DM can occur anywhere within a door cycle and be classified into door not closing (DNC) and door not opening (DNO) types. Based on a case study on a DNC incident in Elevator 3, shown in Fig. 1, two methods are developed to search for DM in the closing and opening stages.

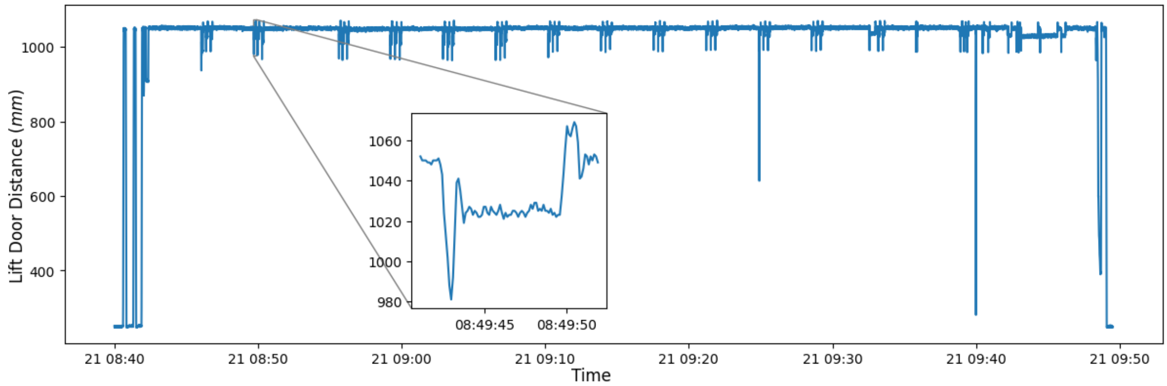


Figure 1 Lift door distance indicating a "door not closing" incident in Elevator 3, with zoom-in plot showing a door reopening waveform which is used in XGBoost training

Method 1: Threshold

In this method, door gap data is first normalized to [-1, 1] and abnormalities are detected using threshold(s). A door cycle is marked as suspected DM if the door gap stays within a prescribed high and low range for at least 4 seconds. The suspected DM is classified as DNC if found in the high gap and DNO if low. In Fig. 2, the DNC and DNO search areas are shaded in green and purple and correspond to the 0.75 to 0.9 and -0.75 to -0.9 levels. In the figure, a DNC spanned approximately 12 seconds was detected, highlighted in red. The method catches door movements indicating the door is "stuck" outside the fully opened and closed levels.

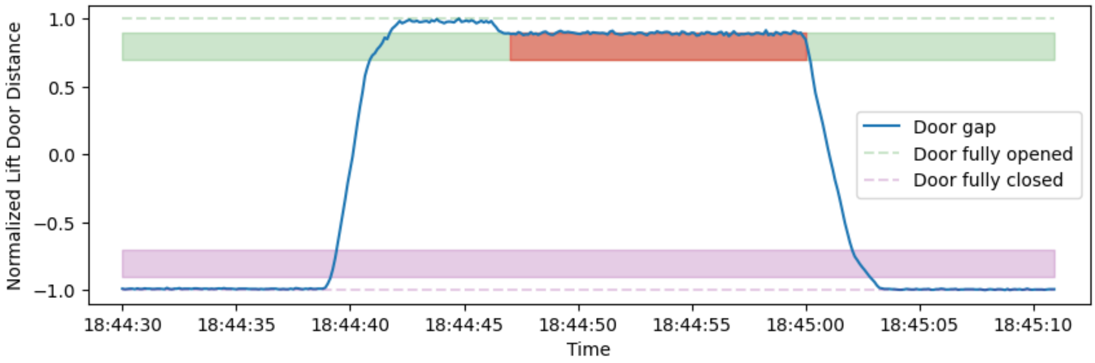


Figure 2 Door cycle with DNC failure (red region) found by threshold method

Method 2: XGBoost (eXtreme Gradient Boosting)

In this method, door gap data are sampled using a sliding window of 100 data points each, and a machine learning algorithm XGBoost [12] is trained to classify abnormal versus normal samples. The abnormal samples are taken from the "reopening" waveform in the DNC case illustrated in Fig.1, whereas the normal samples are taken from normal operating periods. An XGBoost classifier is trained and then applied to search for other unreported abnormalizes in the entire dataset.

2.4 Lift Levelling

Image sensors mounted on the lift car roof collected data on levelling deviation at each floor arrival by capturing the level code plate attached to each floor wall inside the lift shaft and computing the floor levelling. The daily spread of the levelling deviation of lift cars was studied by the standard deviation and interquartile range.

Given a set of n observations of levelling deviation y_i, $i = 1,2, \dots, n$, obtained at each floor arrival in one day, the standard deviation σ is given by

$$\sigma = \sqrt{\frac{\sum_{i=0}^{n}(y_i - \mu)^2}{n}}, \tag{5}$$

where μ is the mean levelling deviation. The interquartile range IQR is given by

$$IQR = Q_3 - Q_1, \tag{6}$$

where Q_1 and Q_3 are the lower and upper quartiles of levelling deviation data in one day. To prevent the daily interquartile range and standard deviation from being highly biased to a few travels, the number of operations per day is computed and used for filtering out highly biased data. The interquartile range and standard deviation are only calculated for days where the daily travel count exceeds half of the mean daily travel count for the entire year. Furthermore, the data is organized into clusters based on the destination floor of the operation cycles.

3 RESULTS

3.1 Traction Motor and Gear Box

Vibration signals of the lift car body in the horizontal (Ax) and vertical (Az) directions in an operational cycle, or travel, were retrieved from the vibration sensor and shown in Fig. 3. In Fig. 4, the results for daily lift car shaking (LCS) count for the study period in Elevator 1 and Elevator 2 are visualized. On a typical weekday, LCS occurred in Elevator 1 throughout the year in large numbers (up to 800 instances), while LCS rarely occurred in Elevator 2 (up to 4 instances).

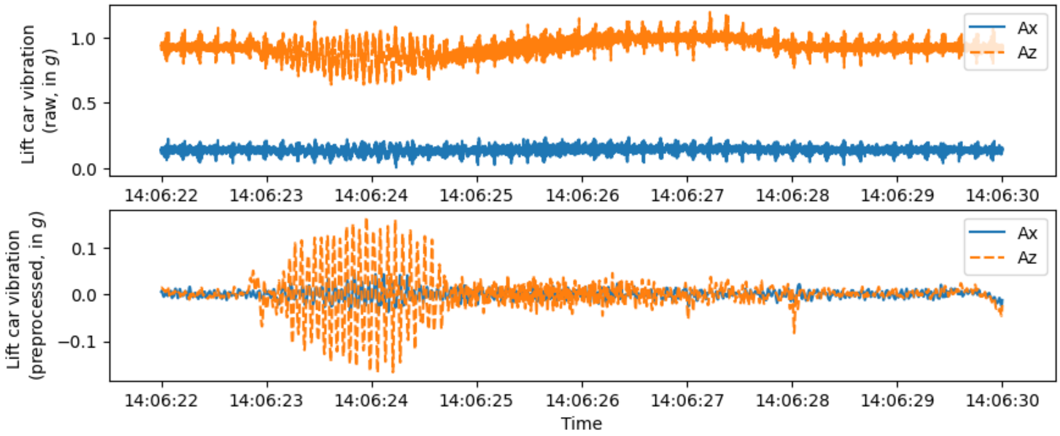


Figure 3 Time-domain signal of lift car vibration in an operational cycle

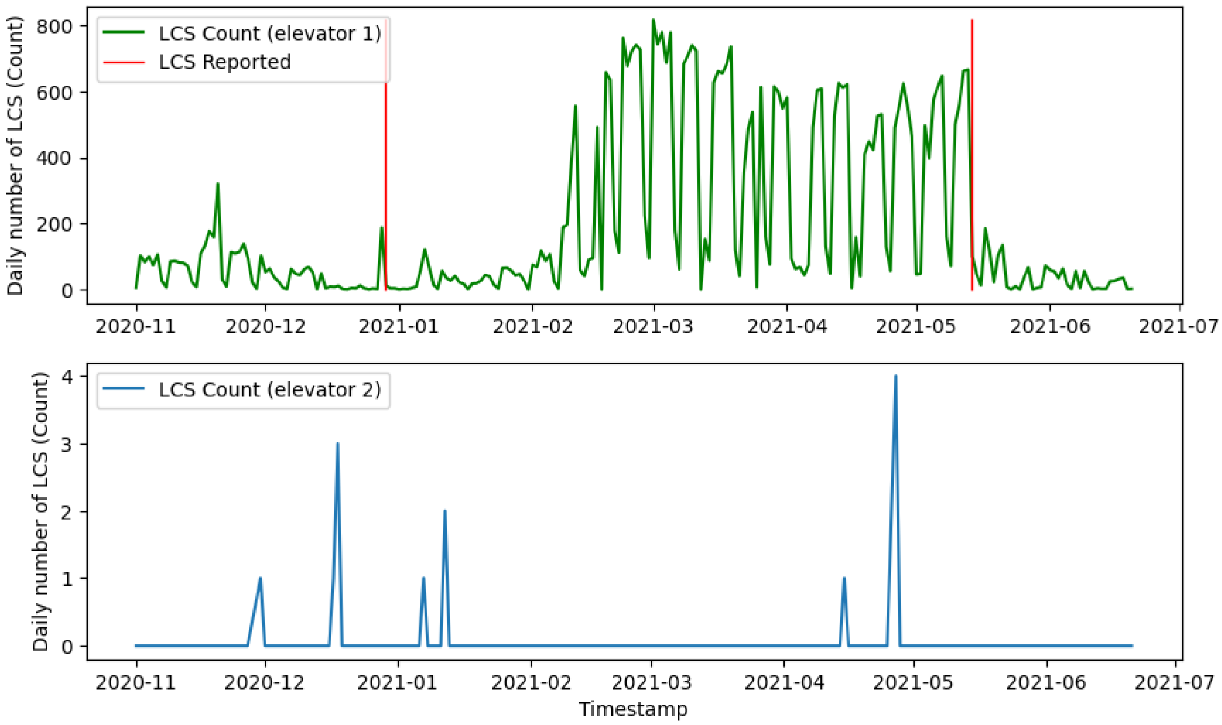
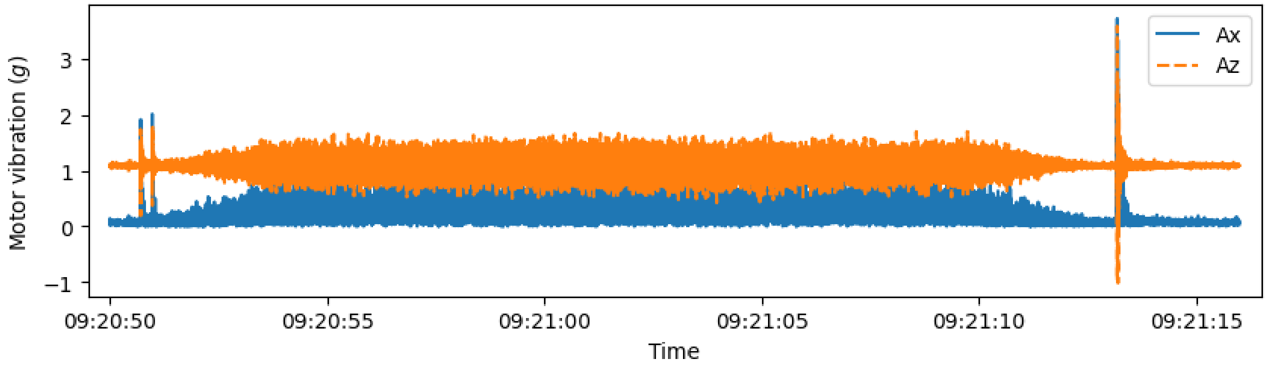


Figure 4 Number of lift car shaking found by our method (in green and blue) versus the actual lift car shaking events reported (the red lines) across the two lifts

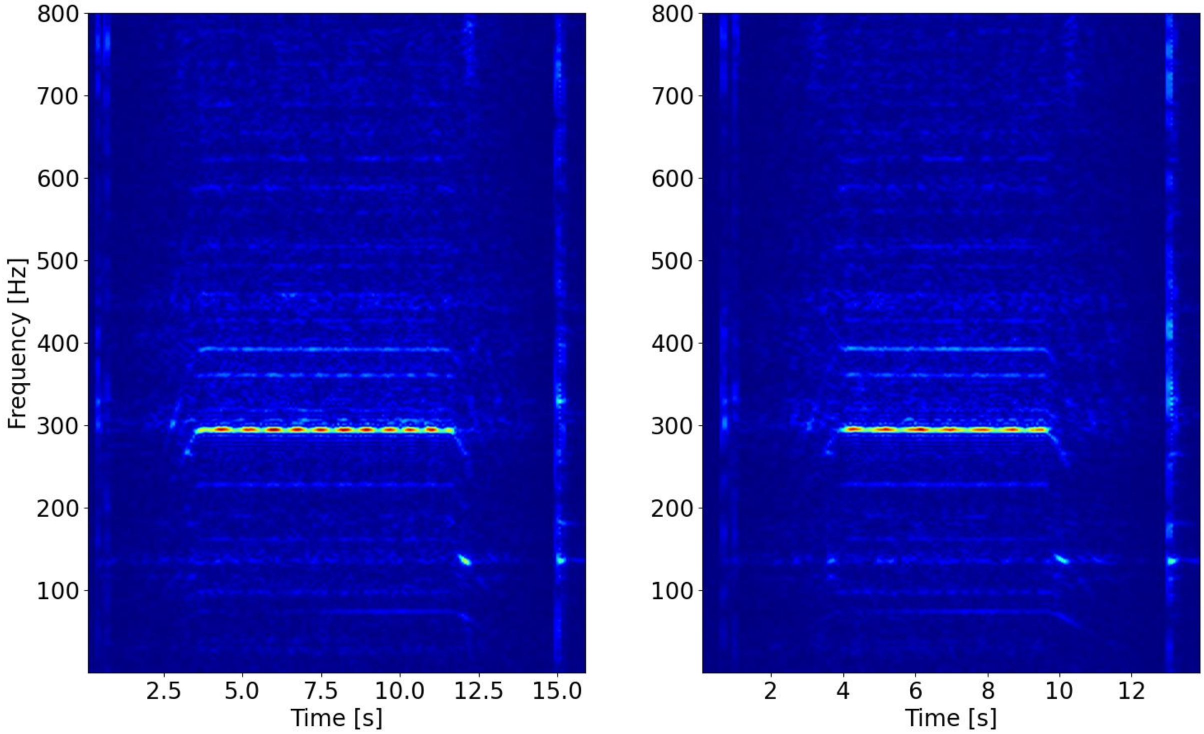
By analyzing the peak-to-peak (P2P) vibration amplitude exceeding a predefined threshold, our method suggests that Elevator 1 has a lot more potential LCS events compared to Elevator 2. This finding is consistent with the logbook records which logged two LCS incidents reported in Elevator 1, whereas Elevator 2 has none. So, we believe that P2P vibration amplitude is potentially a good metric for detecting lift car shaking events. However, due to the limited number of incidents, this hypothesis deserves further validation with more data in future studies.

In addition to lift car vibration, vibration signals of the traction motor in the Ax and Az directions in an operational cycle were retrieved from the vibration sensor and shown in Fig. 5. In Fig. 6, the typical signals of Elevator 1 and Elevator 4 are transformed into spectrograms computed with the Lomb method in Sec. 2.1. In Fig. 6(a) and 6(b), the time-frequency pattern is distinct throughout the lift journey for Elevator 4. The frequency, or motor rotation speed, gradually increased from the beginning of an operation cycle to a certain state and remained constant until near the end. It is consistent with Li's work [6]. However, the expected time-frequency pattern is insignificant in Elevator 1's signals in Fig. 6(c) and 6(d). The dispersed operational frequency pattern potentially relates to the deteriorating performance of the traction motor and gear box and causes the large LCS

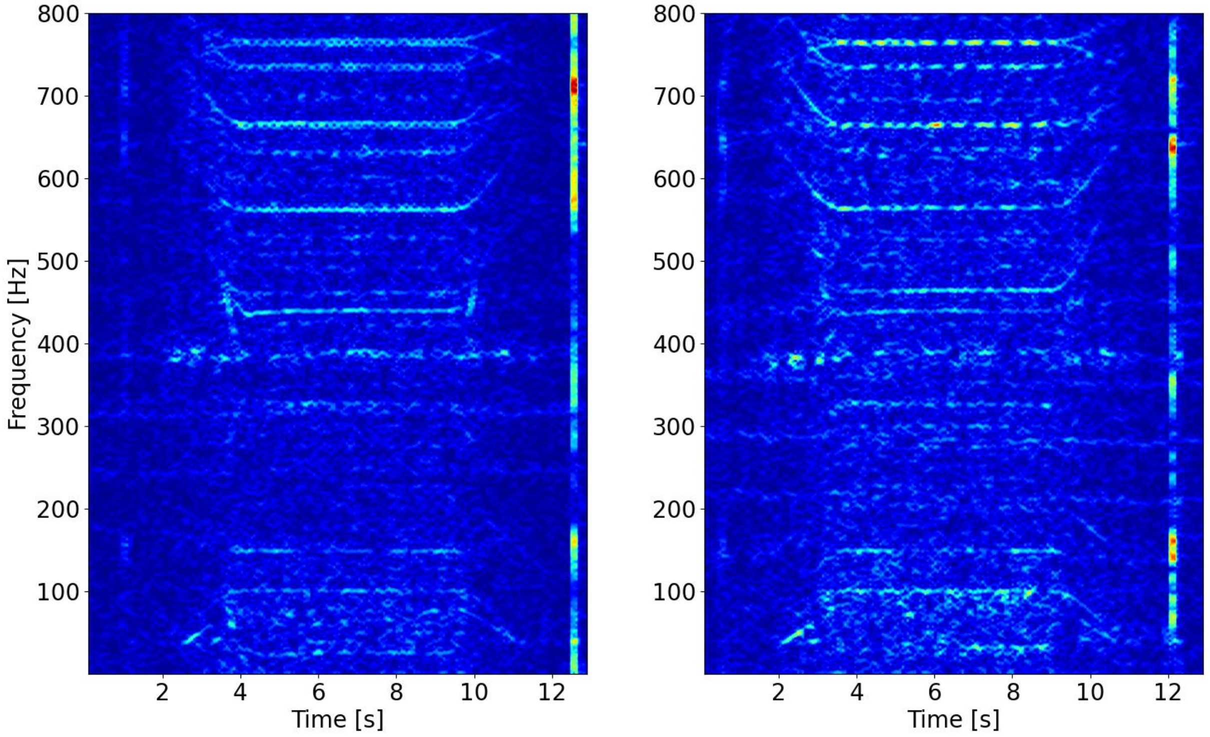


counts in Elevator 1 in Fig. 4.

Figure 5 Time-domain signal of traction motor vibration in an operational cycle



(a) up-drive condition, Elevator 4 **(b) down-drive condition, Elevator 4**



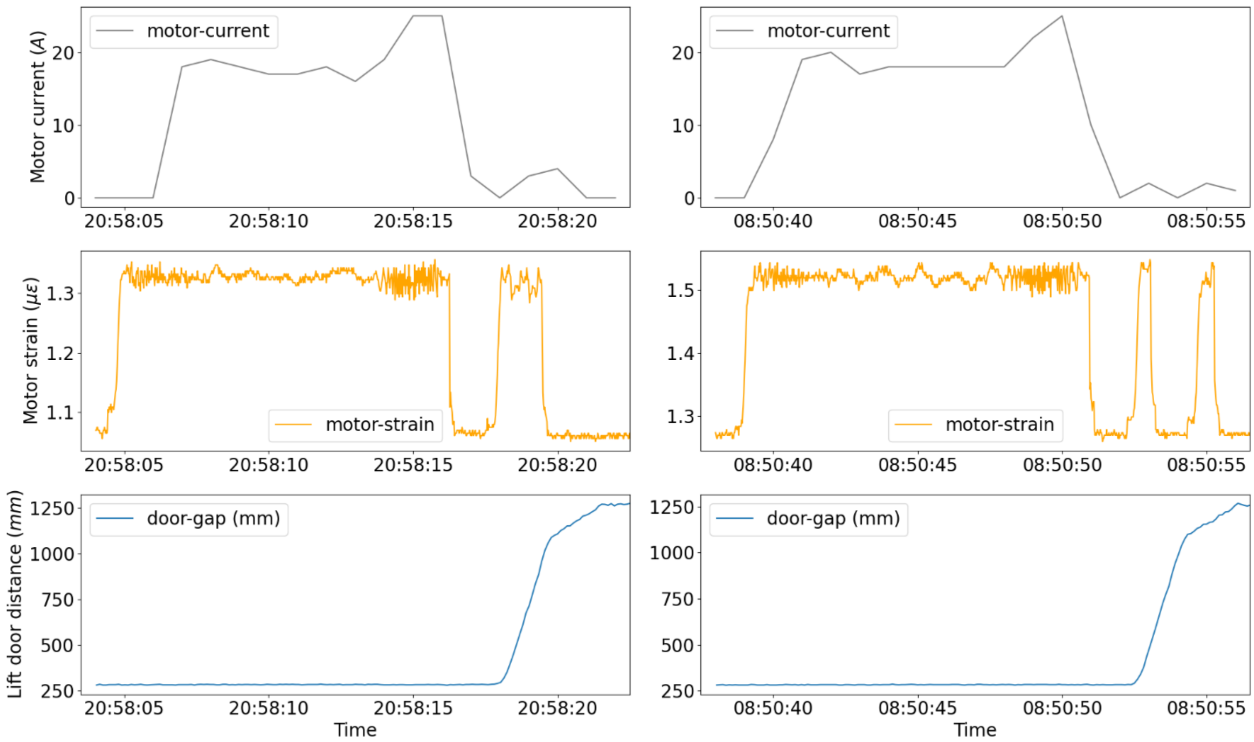
(c) up-drive condition, Elevator 1 **(d) down-drive condition, Elevator 1**

Figure 6 Spectrogram of traction motor vibration in different operating directions in lifts

3.2 Brake System

The strain sensor recorded the operation pattern of the brake system, in which the expected behaviour was to disengage once only when the lift car moved from one floor to another. However, in this study, unexpected behaviour of the brake system was discovered: multiple brake-arm engagements (MBE). In MBE incidents, the brake arm disengages and engages multiple times during and right after travel. In the study, the MBE incidents were classified into two groups: MBE-1 and MBE-2. In MBE-1, the extra brake cycle occurred just after the lift car travelled, while MBE-2 is within the lift car travelling period. There is no information regarding MBE incidents in the maintenance record.

MBE After Lift Travel (MBE-1) - In a typical MBE-1 travel visualized in Fig. 7(a), the additional brake cycle occurred as the lift car door opened. When the motor received the current supply, the brake arm disengaged, and the lift car moved to its destination floor. Once the lift car reached the designated floor, the brake arm engaged again, and the door opened. However, the brake arm operated again for about 1 to 2 seconds. Another typical type of MBE-1 travels, wherein the brake arm disengaged and engaged three times, has also been uncovered, comprising around 25% of all 20,000 MBE-1 in Elevator 1. A sample of this is illustrated in Fig. 7(b). MBE-1 is a potential risk for passengers and was not reported nor repaired. Furthermore, in Fig. 8, MBE-1 occurred in Elevator 1, Elevator 2, and Elevator 4 throughout the study period.



(a) MBE-1 (1 extra) **(b) MBE-1 (2 extra)**

Figure 7 Brake motor, brake arm, and car door operations during MBE-1 with extra brake operations (refer to the middle plot)

MBE During Lift Travel (MBE-2) - In Fig. 9, an MBE-2 travel is visualized. Brake engagements occurred during a lift operation. As seen in the middle subplot, the brake arm attempted to engage multiple times, which in turn caused large signal spikes highlighted by red points in motor vibration in Fig 9. Among the sites, 16 MBE-2 incidents were found in Elevator 2. The MBE-2 distribution throughout the study period is shown in Table 2.

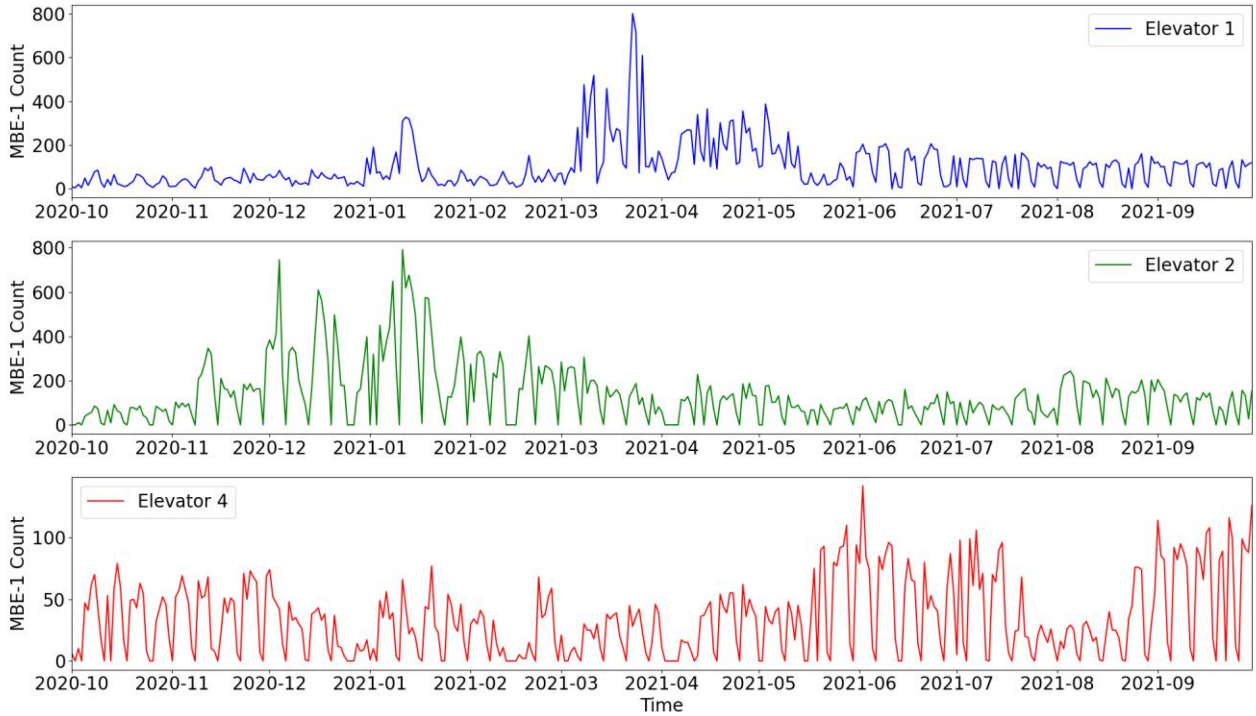


Figure 8 Daily count of MBE-1 in Elevators 1, 2, and 4

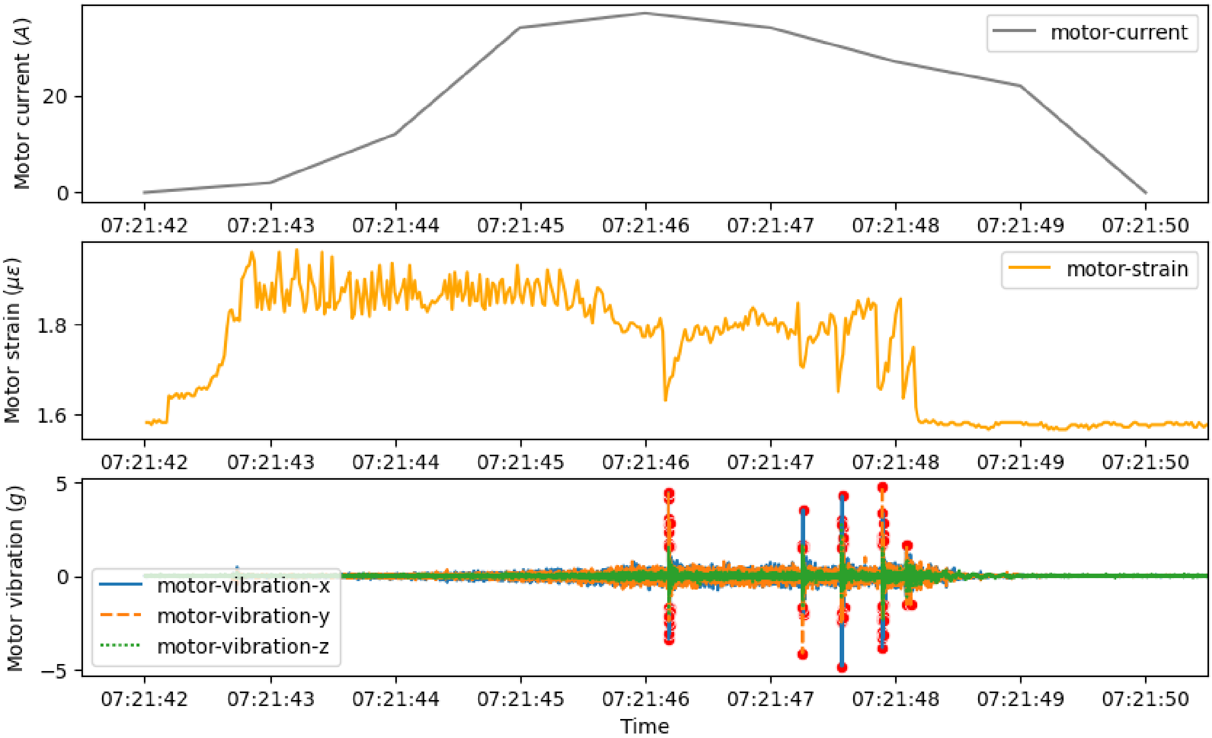


Figure 9 Motor current, brake strain, and motor vibration during MBE-2 incident. The red dots highlight the motor vibration spikes due to brake-arm engagement

Table 2 Distribution of Elevator 2 MBE-2 incidents in the study period

Month	Dec 2020	Jan 2021	Apr 2021
MBE-2 Count	2	1	13

3.3 Door System

In addition to the case study incident in Fig. 1, the methods captured other anomalous door movements. However, the DM discovered generally occurred within maintenance periods or post-incident repair works. A summary of DM incidents is given in Table 3. Plots of the three unrecorded failures found outside of maintenance and repair are included in Fig. 10 and Fig. 11 for the respective method. In Fig 10, the DM incident in the upper plot showed a door cycle where the door gap distance did not reach the fully opened door gap threshold, while the lower showed the door was moving roughly. In Fig. 11, the door gap distance largely fluctuated around the fully opened threshold.

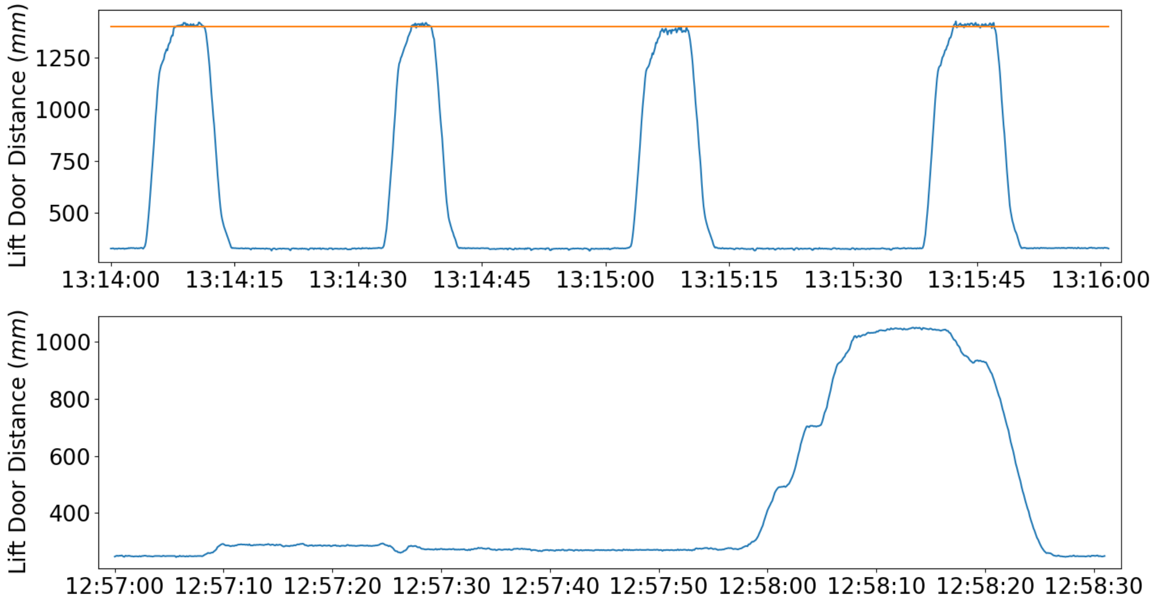


Figure 10 Unrecorded DM captured by the manual threshold method

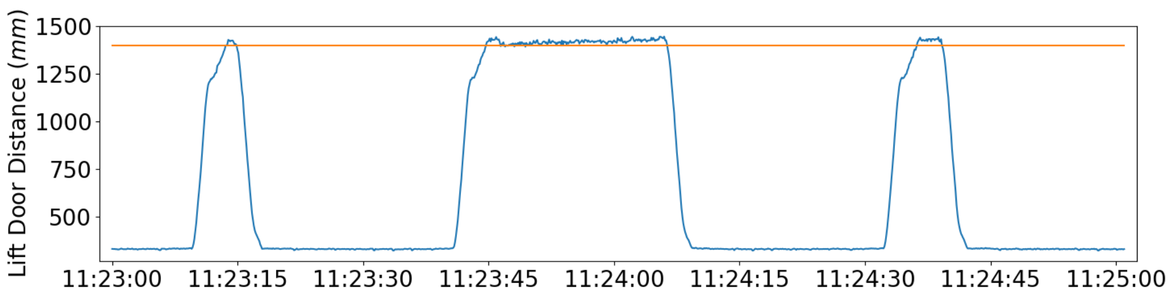


Figure 11 Unrecorded DM captured by XGBoost

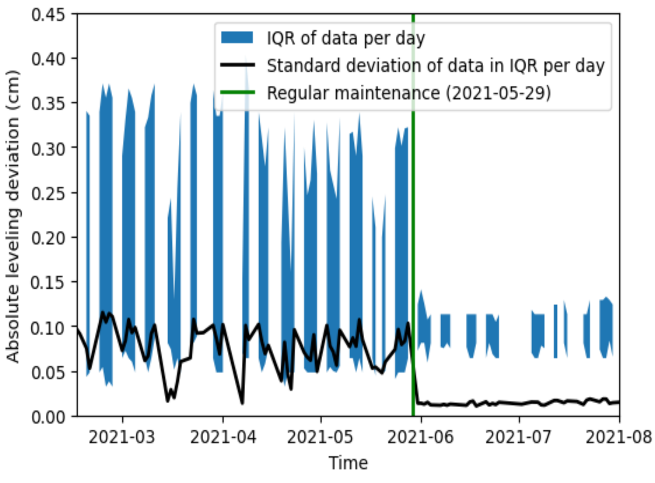
Table 3 Number of Days with DM by Threshold (Thr.) and XGBoost (XGB)

	Elevator 3		Elevator 4		Elevator 1		Elevator 2	
	Thr.	XGB	Thr.	XGB	Thr.	XGB	Thr.	XGB
Maintenance Period	1	1	2	0	6	1	5	0
Incident/Repair Period	2	1	0	0	1	0	1	0
Unrecorded Failure	1	0	0	2	0	0	0	0

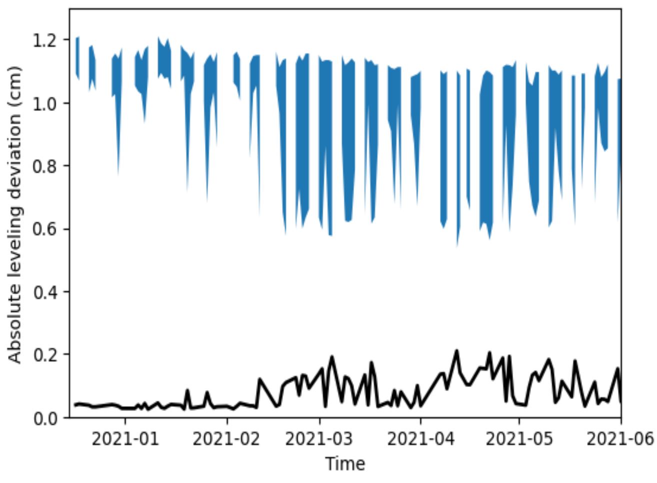
Although the threshold method captured more failures than XGBoost due to its generic nature, it only checks the door gap when the door is moving, while the XGBoost method detects abnormalities at any point in the door cycle. The threshold method is confined to searching only a portion of the opening or closing phase, but this can be rectified by widening or adding more search ranges. In contrast, due to the high specificity of the XGBoost method, it captures only the waveform or very similar patterns. Besides, some false alarms are detected, which include partial door re-openings and strong fluctuations in readings while the door is at rest, but the amount is negligibly small.

3.4 Lift Levelling

In Fig. 12(a), the interquartile range and standard deviation of the levelling deviation of Elevator 1, 3/F were visualized. The accuracy and precision increased significantly after the regular maintenance on 29 May 2021. The daily upper quantile was about 0.4 cm and dropped to less than 0.15 cm. Furthermore, the highly fluctuated standard deviation became stable at about 0.02. It indicates an enhanced performance of levelling due to scheduled maintenance. In contrast, in Fig. 12(b), the interquartile range and standard deviation of Elevator 2, 1/F increased over time, which implies a deteriorating condition of the traction motor or the door clutch on 1/F.



(a) Elevator 1, 3/F



(b) Elevator 2, 1/F

Figure 12 Interquartile range and standard deviation of levelling deviation per day.

4 CONCLUSION

This paper presents a proof-of-concept trial of a health monitoring platform for condition-based and predictive maintenance of lift installations using big data analytics. By using non-intrusive sensors, the critical components of the lift system are monitored and analyzed in various ways. The trial has been running for an entire year across four lifts and the data of all the sensors were collected and analyzed in order to construct various detection methods.

By using statistical methods and machine learning approaches, we developed methods that are capable of fault detection, brake malfunction, lift car shaking, door malfunction, and traction motor malfunction. And these methods can correctly identify the incidents reported by passengers during the study period. Additionally, these methods uncovered potentially unreported lift failures such as multiple brake arm engagements while the lift was moving, as well as unrecorded door malfunction incidents in two of the lifts.

Therefore, we believe that this health monitoring platform and the detection methods are useful tools for formulating condition-based and predictive maintenance strategy, could potentially be used to predict the remaining useful life for the critical components, and turns corrective maintenance into proactive maintenance.

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BIOGRAPHICAL DETAILS

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Change of the Dynamic Elongation in Steel Wire Rope Traction Systems over the Lifespan, Influencing Factors and Mitigation Measures

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Keywords: Steel Wire Rope, dynamic elongation, rope lifespan, total costs, elastic modulus.

Abstract. Essential characteristics of a Steel Wire Rope (SWR) Tractions System are the minimal breaking force, the permanent and dynamic elongation and the number of bending cycles projected prior to reaching the discard criteria. This paper focuses on the *change in the dynamic elongation of a SWR Traction System (SWRTS) over its lifespan*. It identifies, explains, and describes the impact of influencing factors. Since the cause of the change with the factors are identified, also corresponding mitigation measures are explained. Understanding and applying the mitigation measures is critical to ensure that the SWRTS can stay longer within the range of the required performance, extend its lifespan, lead to longer replacement intervals, and reduce therefore the overall operating costs of lifts.

1 INTRODUCTION

This paper examines the change in dynamic elongation over the lifespan of the SWRTS and identifies the factors that influence this change. The paper explains the impact of these factors and provides corresponding mitigation measures to ensure that the SWRTS can maintain its required performance, extend its lifespan, and reduce overall operating costs.

SWR constructions are commonly used in traction lifts due to their mechanical design, which is defined by the steel material and complex geometry. Mathematical models [1,10] can be used to calculate the deformation and elongation of wire rope under known tension, and the elastic modulus of a steel rod is well-defined. However, in practical use, imperfections and influencing factors can lead to a change in dynamic elongation.

The paper identifies these factors through observation and sample measurements in real lift installations. The impact of these factors is illustrated qualitatively. Corresponding mitigation measures are provided to ensure that SWRTS lifts sustain their overall performance over their lifespan.

2 PERMANENT AND DYNAMIC ELONGATION OF A SWRTS

We need to differentiate the terms “permanent” and “dynamic” elongation.

2.1 Permanent Elongation

Any new rope during the commencement of loading elongates permanently and in addition, dynamic elongation occurs, which will become evident after releasing the load. The permanent elongation is caused by the various components during the “*setting process*” with a corresponding reduction in overall rope diameter. The amount mainly depends on the type and construction of the rope and the range of loads. Most of the permanent elongation occurs early in the life of a “*running rope*”: around 4 to 6 weeks in operation and an equivalent number of bending cycles. Slight permanent elongation will occur throughout the lifespan of the rope. Fibre core ropes show significantly more permanent elongation than ropes with a steel core. The initial permanent elongation of a rope cannot be accurately determined by calculation and entirely depends on the rope manufacturer.

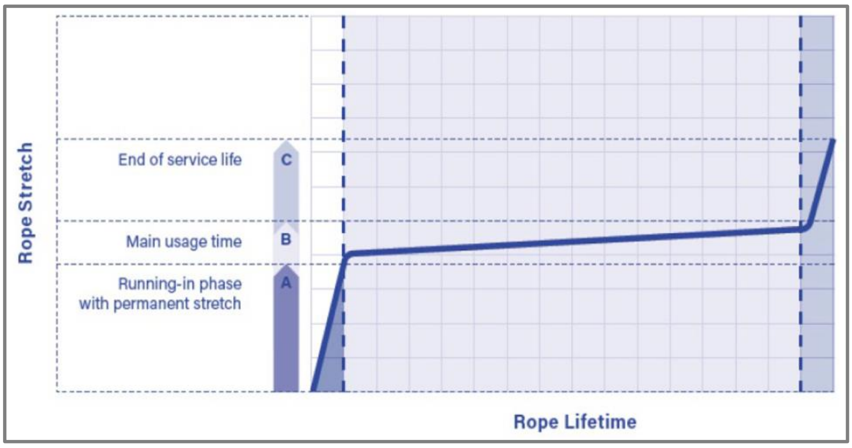


Figure 1: Permanent Elongation [2]

The "*setting process*" is also based on the rope manufacturer's process parameters. During the rope closing process, the strands are retarded in the machine baskets, therefore the closed rope must be pulled out of the spinning point. There are significant forces acting (see Figure 2) at the closing point, e.g., between 5% to 10% of the minimum breaking load of the wire rope. When the rope is spoiled onto the reels, the outer strands are without tension, hence, the diameter increases according to the tolerances of EN 12385-5 [3].

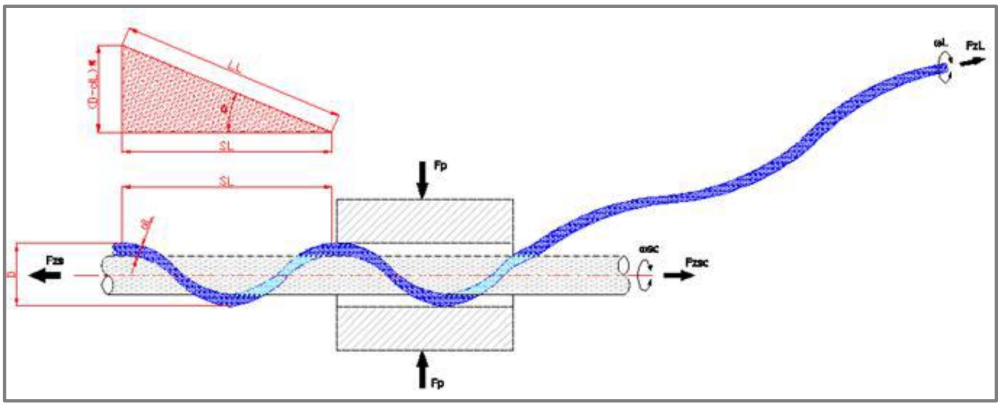


Figure 2: Forces of Spinning Point

2.2 Dynamic Elongation

Dynamic elongation is one of the most frequently misunderstood terms [5,6,11] for lifts, and the cause of much confusion. This is because there is no existing unequivocal elasticity module (E-Modulus) for SWR and SWRTS that can predict the elongation of the rope over its complete service life.

It is the main purpose of this paper to explain dynamic elongation better, with the identification of the many influencing factors as shown in chapter 3.

2.3 E-Modulus and Rope Modulus

The term E-Modulus (Elasticity Module) is only applicable in conjunction with the elasticity behaviour of materials. For SWR and SWRTS, the term elongation module (rope modulus) has been selected here due to the redundant arrangement of the supporting wires.

The elastic modulus is measured according to ISO 12076 [7], where the reference point is between the load of 10% Minimum Breaking Load (MBL) and 30% MBL. Between this range, ten cycles of loading and unloading are applied. At the same time, the degree of elongation is recorded. The elastic modulus recorded by the tensile machine already follows this regulation:

$$E_{10-30} = l_i \frac{F_{30\%} - F_{10\%}}{A_c(x_2 - x_1)} \tag{1}$$

The purpose of these loading cycles is to "*settle the ropes*", and they are not recorded.

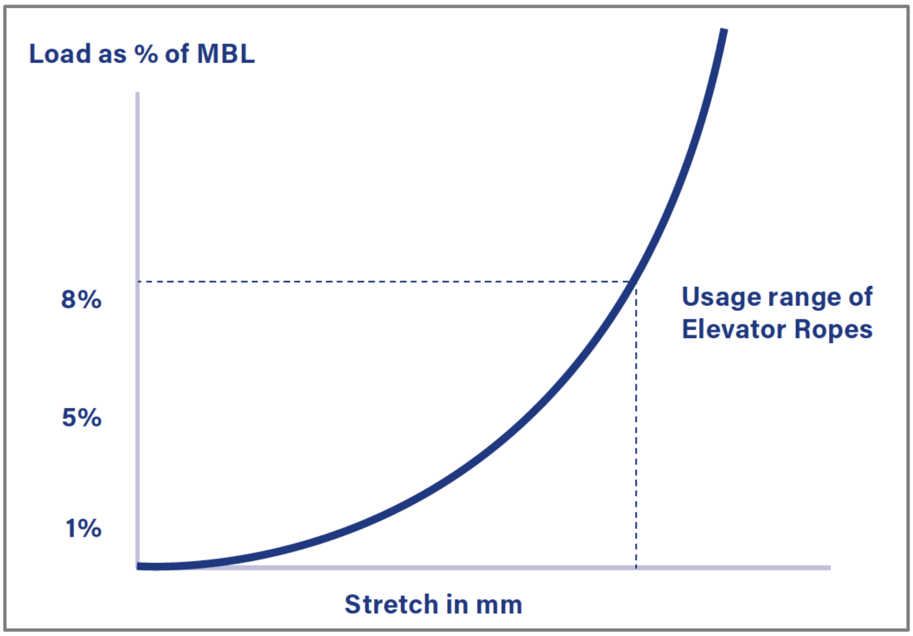


Figure 3: Nonlinear Dynamic Elongation (Stress-Strain Diagram) [2]

The required safety factor of lifts and generally not fully loaded cars, lead to operating the rope in a lower range of MBL.

As shown in Figure 3: At this working point the dynamic elongation is non-linear and therefore the rope modulus of a SWRTS has different values depending on the load.

2.4 Lay-Length Factor and Dynamic Elongation

The following considerations refer to the rope length as a single lay length of the rope. This makes the relationship more transparent. This approach is acceptable because the rope length can be interpreted as a multiple of the lay length. The standard ISO 4344 (2004) [4] indicates that the lay length shall not be greater than factor 6.75 of the nominal rope diameter. For instance, Ø16 [mm] x 6.75 = 108 mm lay length.

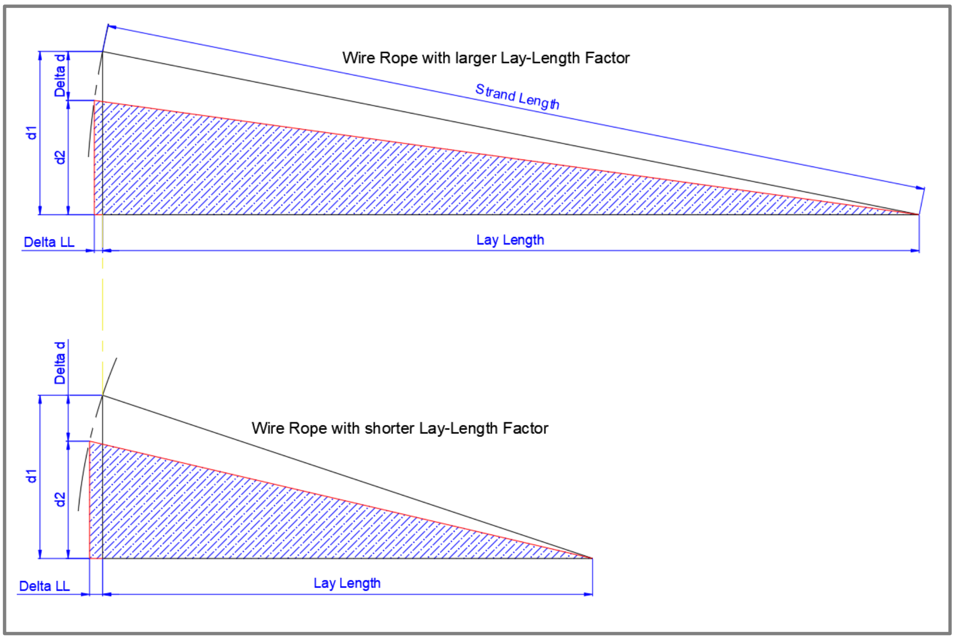


Figure 4: Elongation behaviour with different Lay-Length Factors

The resulting rope elongation in percentage due to diameter reduction is larger when the lay length is shorter. The calculation of the dynamic elongation is as follows:

$$\Delta L_E = \frac{S \cdot L}{A \cdot E_S} \tag{2}$$

where:

S	is the applied tensile load in N
L	is the overall rope length in mm
A	is the cross-section of the rope in mm²
E_S	is the Modulus of Elasticity in N/mm²

3 INFLUENCING FACTORS

The dynamic elongation of a SWRTS can be influenced by several factors. Each factor can cause a deviation in the rope's characteristics, mainly by changing its geometry suddenly or over time. This can result in an imperfect distribution of load to the individual wires within the steel wire rope, causing unequal stress on the wires.

Under ideal conditions, the elastic modulus of the SWRTS would be identical to a theoretical value calculated based on the elastic modulus of the original material and an individual wire.

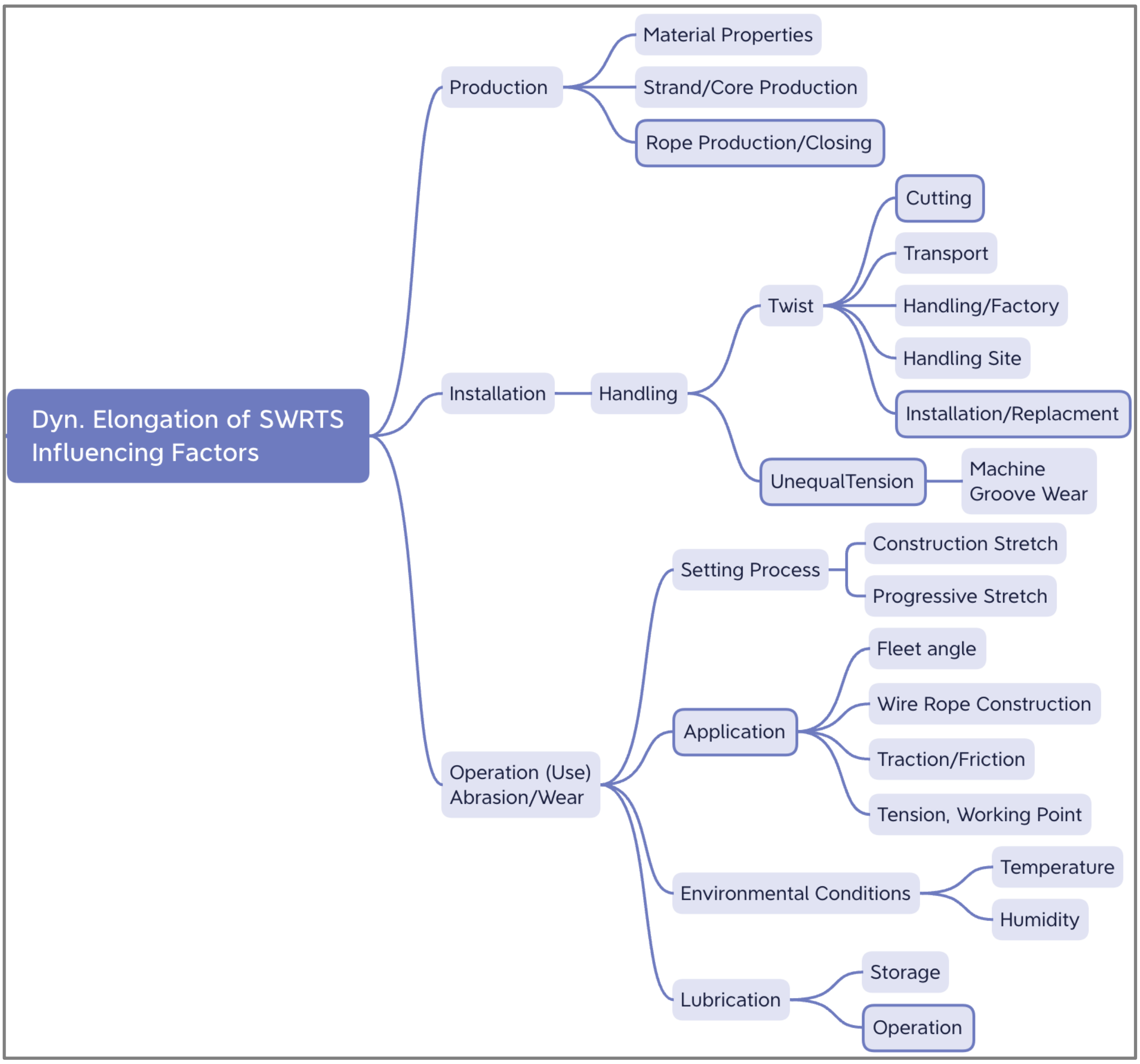


Figure 5: Influencing Factors to the dynamic elongation of an SWTS

As shown in the mind-map in Figure 5. We are dividing the factors into three stages of the rope's lifespan.

During *production*, the deviation of material properties of wires and core material is negligible if there is a basic quality control in material selection and production. More relevant is the impact of the stranding and closing process on rope elongation, which leads to construction stretch and uneven tension of strands and wires even within one production batch.

Construction and progressive stretch are compensated during the setting phase under load, either during production or after *installation* in lifts when load is applied. The setting process is indicated by a decrease of the rope diameter, permanent elongation, and decreasing dynamic elongation. During and after installation, it is essential to handle individual ropes carefully to avoid rope twist and therefore maintain the rope's geometry until load is applied.

During *operation***,** ropes are loaded only within a small part of the MBL (maximum 8.3% with full carload due to safety factor 12). Therefore, the overall setting process may take several months.

During this process, it is essential to distribute the load equally among the ropes. Failure to equalize tension and allowing rope twist can lead to uneven machine groove wear and further accelerate uneven rope tension and deterioration.

Matching the rope construction to the application is also relevant. Knowing the dynamic behaviour of the traction system over the lifespan is essential when designing the most economical lift configuration, particularly when considering the total cost of ownership. Environmental impacts, such as humidity, dust, and dry air in air-conditioned machine rooms, can change the lubrication effect [8], accelerate abrasion (e.g. rouge), increase elongation, and shorten the lifespan of the rope.

3.1 Attempt to Quantify the Factors

The factors explained above account for the deviation of calculated rope modulus from observed measured elongation values in a real lift system. As mentioned in the introduction, our focus is to provide a qualitative overview of the factors rather than compiling a set of quantitative measurements from real installations. A significant effort would be required to make a scientifically relevant statement on the extent of the phenomena. However, having such data is essential to accurately calculate and consider the impact of dynamic elongation over the lifespan and guarantee specified values when optimizing the total cost of a traction system.

Based on experience and sample measurements, some numbers can be shared to give a rough idea of the phenomena in real installations:

1. *Production*: The deviation of the rope modulus within a production batch can be as high as 5-20%. This can mainly originate from the production steps of producing and closing the strands. It is expected that this deviation will be reduced during the setting process once the ropes are installed. These values can be verified with a series of measurements after production and after installation.

2. *After Installation*: The difference between individual SWRTS (lifts) with the same configuration can be as much as -20% up to +25%, even after the setting process and before relevant wearing effects (see Figure 6).

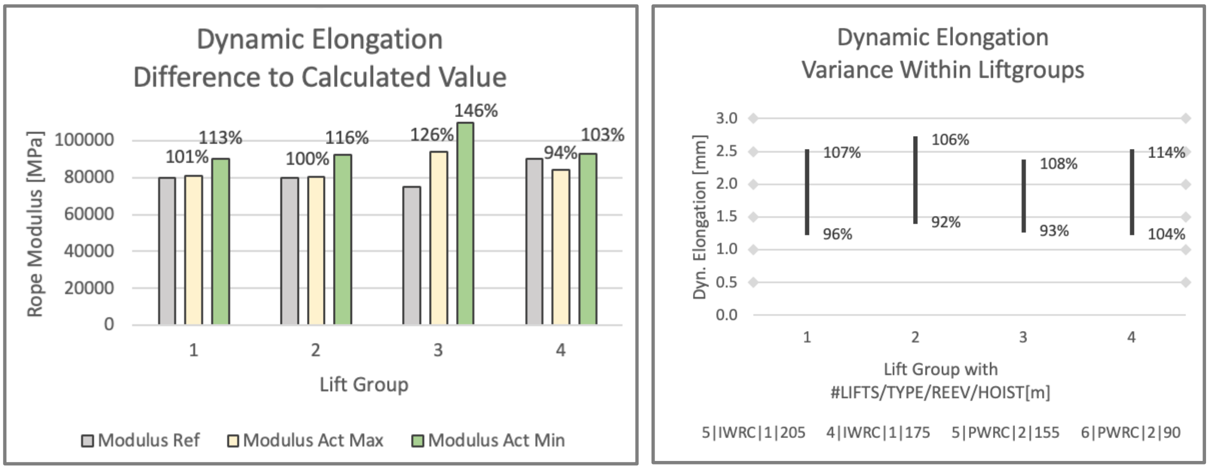


Figure 6: Dynamic Elongation: Variance within Lifts in the same Group

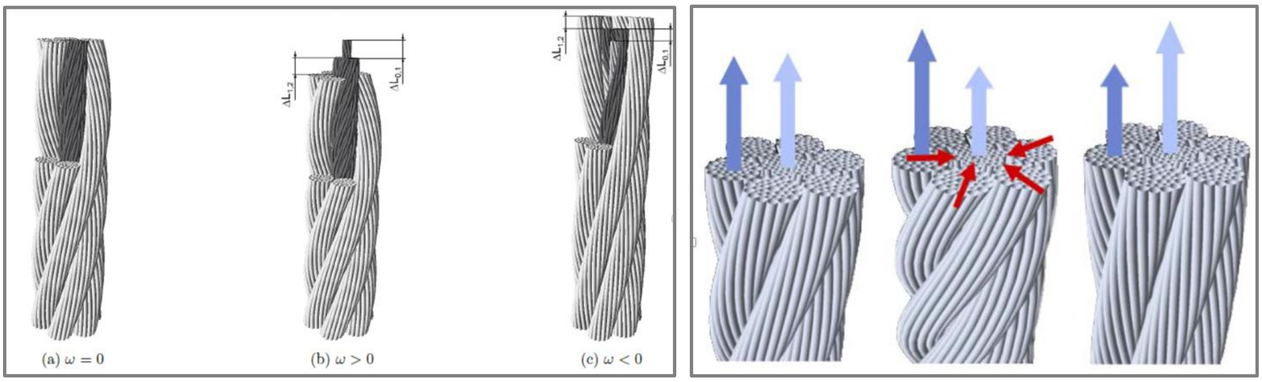


Figure 7: Influence of Twist to Elongation and Stress [9]

As visualized in Figure 7, a main part of the elongation difference after the installation can be explained by rope twist (ω>0 means twist in closing direction/shorter lay), which can lead to uneven and different lay lengths of the strands(ΔL), unequal tension, and stress between wires, strands, and ropes [9].

3. *In Use*: Measurements of an SWRTS with full steel IWRC ropes have shown an increase in elongation by factors (up to 4) when the diameter is still within the tolerated value of -10%. The deterioration can be explained by abrasion, internal wire breaks, and uneven tension. Other constructions with mixed and fibre cores show a longer increase in stiffness and a less dramatic decrease before reaching the discard criteria.

Figure 8 shows the core of an IWRC full steel rope after the elongation became excessive. Clear signs of wear to the individual wires are visible. This wear typically leads to steel powder and the well-known rouge/bleeding of the ropes. At the same time, not only the diameter decreases, but also the entire integrity of the rope is changed which can explain the rapid deterioration of the stiffness of the rope.

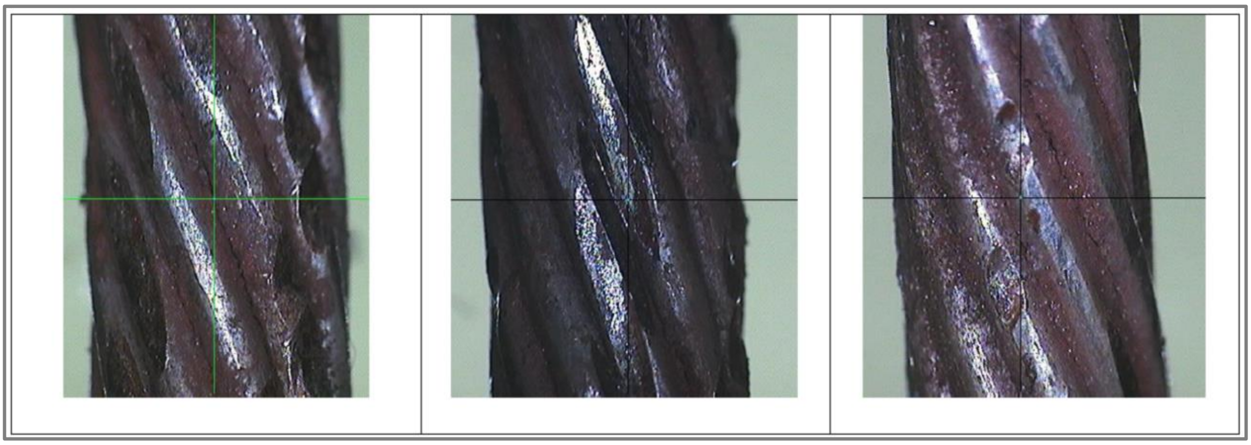


Figure 8 IWRC rope core: signs of wear

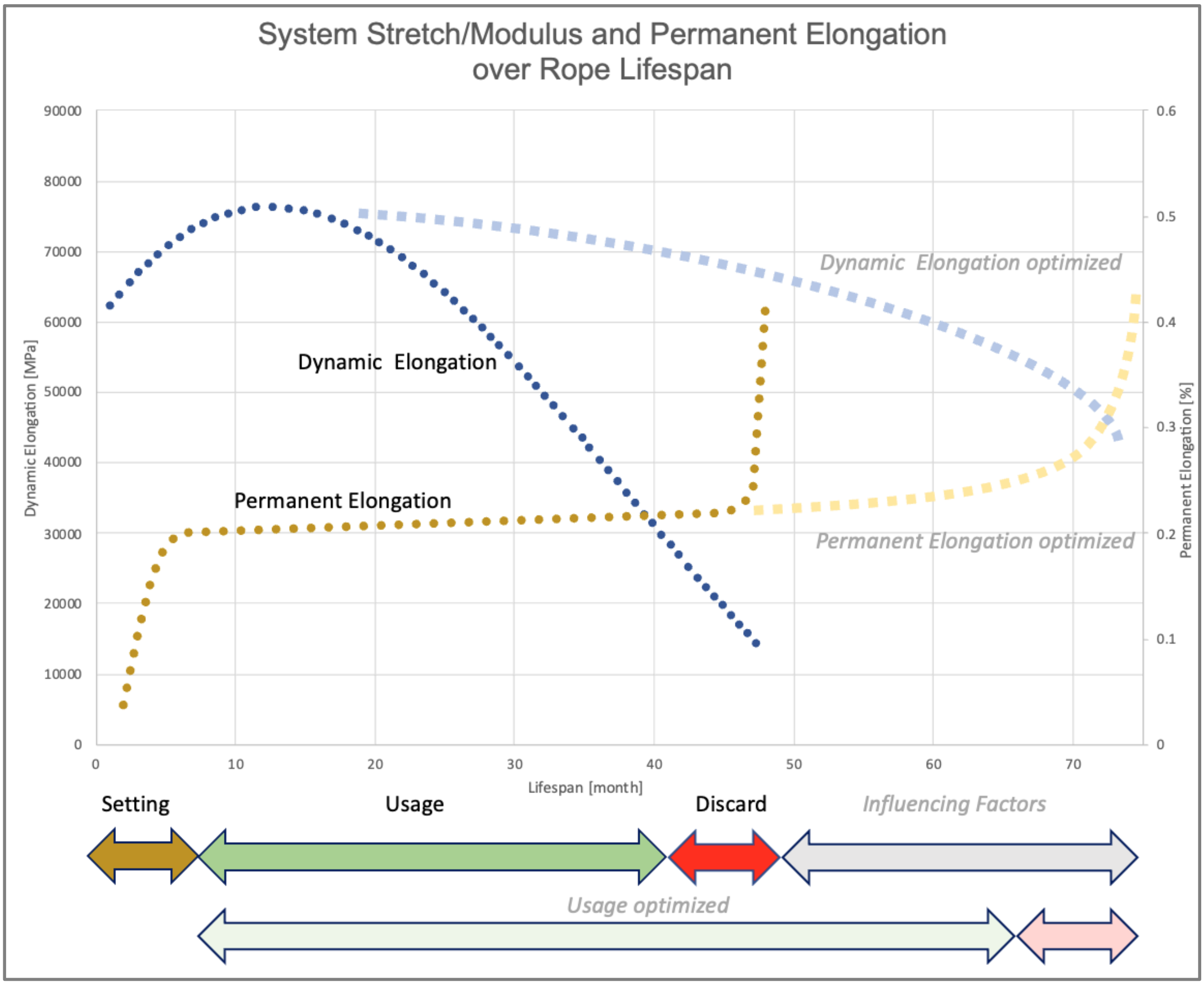


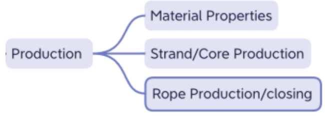
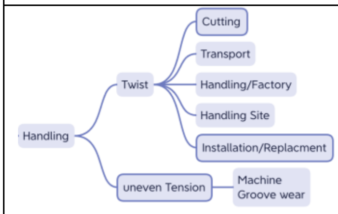
Figure 9: Dynamic Elongation Increase Over Time

Figure 9 shows how the dynamic elongation can increase due to wear in a non-optimized case and how this effect can be minimized when mitigating the influencing factors.

The setting process during the first weeks is indicated by a sharp increase in permanent elongation and stiffness of the ropes, while wear leads – depending on the configuration – to a decrease of the stiffness over time until the end of the rope life. The permanent elongation is rather stable until discard of the rope.

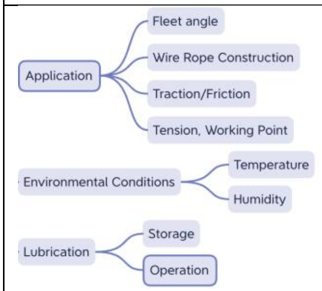
4 MITIGATION ACTIONS

With the given list of root causes that influence the dynamic elongation of an SWRTS, related mitigation actions can be derived. However, not all of these actions are directly applicable, so the most effective and tangible ones are marked with a bold border in Figure 5. While most of these actions are well described in manuals from rope suppliers and lift companies, we highlight the most important actions in the table below, to provide practical value to this paper.

<table>
<tr><th>Mitigation Action</th><th>Description</th><th>Impact</th></tr>
<tr><td>
</td><td>Rope producers' core skills include monitoring the strand production and rope closing process to ensure consistent batch production with minimal deviation from the theoretical value to the rope modulus</td><td>Medium impact. Consistent production with perfectly bedded wires in the strands and equal strand tension eases the setting process.</td></tr>
<tr><td>
</td><td>Any step in handling the rope, from transport and cutting to end finishing and installing, must focus on avoiding twist and changing the rope structure.[8]

Once installed, rope tension must be equalized over a longer period until the setting process is over. Automatic tension equalizers (hydraulic or mechanical) are available on the market and serve this purpose perfectly.

Highly recommended immediately after installation is a run-in program with maximum load, to accelerate the setting process and simplify maintenance of uneven tension.</td><td>Big impact. Avoiding twist and uneven rope tension is the most important task when installing and maintaining an SWRTS.

Equalizing rope tension is crucial to maintaining the overall performance of the SWRTS.
Failing to maintain equal tension may even lead to uneven traction sheave wear and drastically shorten the lifespan of both ropes and traction sheave.</td></tr>
<tr><td>
</td><td>To calculate and optimize a traction system, it is important to understand the dynamic behaviour of steel wire ropes. The goal is to balance lifespan, elongation over time, and traction system material to achieve the best total costs.

Lubrication is also important, and there is a lot of literature available on the topic. Re-lubrication during operation can compensate for the fading effect of factory lubrication. It is essential to maintain part of the rope within the most stressed bending section.</td><td>Big impact.

The construction of the rope can vary significantly in terms of performance, so it is crucial to match the application and the rope properties.

From experience, good lubrication can extend the rope's lifespan by up to 50% and slow down the effect of progressive stretch.</td></tr>
</table>

By implementing these mitigation actions, the overall performance of the SWRTS can be maintained, and its lifespan can be extended, leading to longer replacement intervals and reduced operating costs.

5 CONCLUSIONS

Understanding and predicting the value of elongation over time in steel wire ropes and traction systems is very difficult due to the complexity with many influencing factors.

This paper gives an overview of the factors, explains why it's difficult and provides practical tips to minimize some critical factors to maintain the expected performance.

To better understand these factors, lift companies and rope suppliers are advised to conduct *measurements over time* with different rope types. This research would help to understand the setting process and the impact of wear on SWRTS more accurately. This activity would also make economic sense, given the potential cost impact of a non-optimized SWRTS on lift maintenance.

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Vertical Transportation Consultant

Michael is an Austrian lift engineer who has held leading positions in global companies. He has been working in the field of lift technology for 20 years. Michael has expertise in planning, project management and installation as well as extensive international lift experience in Asia. In addition, he runs his own consulting office for lift technology, is a lift inspector and is a certified expert witness for lift technology. Michael graduated from the University of Northampton with a degree in Lift Engineering and has extensive experience in wire ropes.

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Senior Partner / Vertical Transportation Consultant

Erich is a Swiss Engineer with more than 25 years of experience in the E&E industry in Asia and Europe.

He was a development engineer and team leader with expertise in motor control technology and was Global Product Manager for electrical systems at a large OEM. Erich also completed an EMBA at the Western University (IVEY), London, Ontario.

He found his passion to tackle complex technical and commercial topics in High Rise buildings and offers independent vertical transportation consulting services in Asia and Europe.

Connected lifts. Value for Maintenance.

Julio Gil

MAC PUAR S.A. (MP Lifts), Spain.

Abstract. In the current era of communications, computing, data processing capacity and the Internet of Things, the industry in general and industrial equipment maintenance services are forced to change their operating processes to adopt and take advantage of this technology. All this represents a greater revolution than the one caused by the steam engine in the 19th century.

This revolution represents a huge technological leap whose use necessarily involves reinventing business processes and services.

In the elevation sector, there are different issues to solve:

1. Sensors: a combination between standard sensors (independent or not from lift working) and information from each controller.
2. Solving the way this information is captured within the lift, to be transmitted outside and the way to receive information to be "ordered" to the lift.
3. Communication level: specially focused on security (to avoid non-controlled traffic of information).
4. Platform to receive/analyse/send information to the lift.
5. Added value/services around the platform.

Nowadays, these are different technologies with few technological companies having the technical capacity for all of them, so the real technical value comes from the integration of all of them. The different ways of technical integration have an impact on the business model built around them and the type of services provided to the different stakeholders. From a technical point of view, the most important challenge has been the integration of all these levels that compose IoT for lifts and the capacity to act over different types of lifts.

An ecosystem was created with all these technical elements, with different technologies and partners to add value to this ecosystem.

1 TECHNOLOGY IN THE LIFT INDUSTRY

We are currently experiencing the consolidation of already known technologies, such as:

- IOT [1]
- Wifi
- LiFi [2]
- NB-OIT [3]
- 5G
- IA: Machine Learning, Deep Learning, Cognitive learning
- Computer Vision
- Augmented reality
- Services on Cloud
- Edge Computing [4]
- Virtualization
- Blockchain [5]
- Digital Twins [6]

These types of technologies are now available to small and medium-sized companies and are slowly making their way into the elevator sector, characterized by its traditional positioning.

At present, maintenance companies are beginning to connect elevators and collect data, but their use is limited and has little effect on maintenance processes.

In the future, these technologies are expected to change both maintenance itself (AI, Mixed Reality, Artificial Vision, etc.), as well as the relationship with the client (Cognitive learning, Machine Learning), from contracting services (Blockchain) to elevator design (Cloud services, Saas) and its manufacturing (digital twins). The tendency is to involve the customer in the lift's life cycle.

The main applications of IoT in elevators are:

- Predictive maintenance.
- Remote monitoring
- Fault diagnosis and prediction.
- Advanced reporting
- Connectivity management.
- Energy management.
- Smart advertising.
- Traffic management.
- Elevator access control.
- Elevator safety.
- Smarts contracts.

2 TECHNICAL CHALLENGES IN THE ELEVATION SECTOR

In the elevation sector, there are different technical challenges to be solved:

2.1 The existing fleet of lifts: high initial investments are needed in elevator modernization and IoT integrations.

Due to the enormous legacy of existing elevators, adapting them to achieve levels of connectivity for their management means carrying out total or partial modernization of the elevators.

2.2 Government support for Smart City [7] Development creating normative and standardized IoT connectivity.

Today there is no regulation for the standardization of connectivity for elevators or escalators. A standardized type of operations to be carried out through IoT on elevators does not exist, nor about the type of information to be reported by elevators. From a technical point of view, there is no regulation for standard protocols for communication with the lift.

At one extreme, the logical and physical communication protocol and even the structure and standardization of information could be regulated.

2.3 Sensors

The integration of standard sensors, whether independent or interconnected with the elevator's operation, is crucial. These sensors collect relevant data from the lift, providing valuable insights into its performance and maintenance needs. Sensors provide information. The main actuator on the lift is the lift controller.

Additionally, information from each lift controller may be collected to provide a comprehensive view of the elevator's functioning.

2.4 Connectivity IoT level [8]. Specially focused on security (to avoid non-controlled traffic of information).

Communication is a critical aspect of IoT systems, especially in terms of ensuring data security and preventing unauthorized access or tampering.

Leading industry security measures must be incorporated to protect against unauthorized access or data breaches. Utilizing encryption protocols, secure communication channels, and authentication mechanisms are essential to guarantee that the information transmitted to and from the elevator is protected from potential threats.

2.5 Platform to receive/analyse/send information to the lift.

An essential component of the IoT ecosystem is a powerful platform capable of receiving, analyzing, and transmitting data to and from the elevator.

It must serve as the central hub for managing the vast amount of data collected from elevators in real-time. It provides comprehensive data analysis, generating actionable insights for predictive maintenance, performance optimization, and operational efficiency. Additionally, the platform enables seamless communication with the elevator, allowing commands to be sent for maintenance requests, parameter adjustments, or any other necessary actions.

Another critical aspect of an IoT platform for lifts is its ability to scale and accommodate different types of elevators across various locations. The sheer volume of data generated by IoT-enabled lifts necessitates robust storage and advanced analytics capabilities.

Machine learning algorithms and predictive analytics models help identify patterns, detect anomalies, and forecast maintenance requirements. These insights empower facility managers and maintenance teams to make data-driven decisions, optimize operations, and enhance elevator performance.

2.6 Remote monitoring and control

With an IoT platform for lifts, remote monitoring and control capabilities can revolutionize the way elevators are managed and serviced.

Remote control functionality empowers technicians (and even owners) to perform certain maintenance tasks without physically accessing the elevator. For example, firmware updates, parameter adjustments, or software configurations can be remotely executed, minimizing service disruptions and optimizing maintenance operations.

2.7 Predictive maintenance and condition monitoring

One of the key advantages of an IoT-enabled lift system is the ability to implement predictive maintenance strategies and condition monitoring.

By continuously monitoring elevator performance, early warning signs of potential failures or deviations from normal operation can be detected early. Predictive maintenance algorithms analyse the collected data, identifying patterns and anomalies that indicate impending issues. This allows maintenance teams to intervene proactively, scheduling repairs or component replacements before failures occur. Predictive maintenance minimizes unplanned downtime, reduces repair costs, and extends the lifespan of elevator components.

Furthermore, condition monitoring capabilities enable real-time assessment of elevator health. By tracking parameters such as motor temperature, vibration levels, and door operations, the system can identify signs of wear and tear, enabling maintenance teams to address issues promptly and prevent major failures.

With collected data, predictive algorithms for machine learning can be trained to be integrated with an IoT platform as a separate piece of the global ecosystem.

2.8 Integration with Building Management Systems (BMS) [9]

A seamless integration between the IoT platform for lifts and the building's broader management systems enhances operational efficiency and streamlines facility management processes.

Integration with existing Building Management Systems (BMS) can enable centralized control and monitoring. Elevator data can be correlated with other building parameters, such as occupancy levels, energy usage, or HVAC [10] systems, providing a holistic view of facility operations. This integration facilitates intelligent decision-making, optimizing energy consumption, space utilization, and overall building performance.

This integration can be done through a global platform (Lift by IoT connected) with standard protocols (API REST [11] …) or locally in the building directly to the lift (SACADA [12], APIREST … proprietary protocols …)

3 CONCLUSION

The advent of IoT in the elevator industry represents a transformative opportunity to revolutionize maintenance services, optimize operations, and enhance the overall user experience. By addressing the challenges associated with sensors, data capture and transmission, communication security, platform capabilities, and value-added services, IoT solutions offer a scalable, secure, and efficient ecosystem for lifts.

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BIOGRAPHICAL DETAILS

Julio Gil Navarro is the Head of Digital Transformation for MACPUAR SA, responsible for IT systems.

He studied at the University of Seville, specialising in industrial engineering and organisation, and graduating in 1994. Before joining MACPUAR SA he worked in the energy and telecom sectors.

Classification and Recognition of Roller Bearing Damage in Lift Installations Using Supervised Machine Learning and Vibration Analysis

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Keywords: Machine Learning, Fault, Pattern Recognition, Maintenance, Damage, Roller Bearings.

Abstract. The resilience of rotating components, specifically traction sheaves and diverter pulleys in lift installations, is of paramount importance. However, these components frequently undergo fatigue failure due to their exposure to intense cyclic and dynamic loading conditions. Traditional methods for estimating bearing life, which show insufficiency in adapting to the dynamic operating conditions of lifts (such as variable load, speed, and direction), often fail to anticipate these breakdowns. An experimental laboratory rig comprising a rotating disk-shaft assembly with intentionally damaged components emulating real-world scenarios has been designed to address this challenge. Vibration data, representative of actual operational conditions, were systematically captured using accelerometers. This data was then leveraged to extract salient vibration features, which served as inputs to train artificial neural network (ANN) models within a supervised machine learning framework. The trained models have shown the capacity to identify and categorise damage patterns, thereby enabling a comprehensive understanding of fatigue failure mechanisms in these systems. The findings from this research demonstrate the potential for developing robust and efficient condition monitoring methodologies, which could significantly enhance both the longevity and safety of lift installations.

1 INTRODUCTION

The longevity and dependability of mechanical components within lift installations, particularly rotating elements such as traction sheaves and diverter pulleys, are paramount in maintaining the integrity of these systems (see Fig. 1). These components are subjected to vigorous cyclic and dynamic loading conditions, making them particularly vulnerable to fatigue failure – a prevailing challenge within the lift industry [1], [2]. Traditional prediction methods for bearing life have demonstrated limitations due to their inability to adjust to the diverse operating conditions that lifts typically experience [3]. As a result, these methods often fall short of effectively anticipating and preventing component failures. Given their direct implications on lift operations' safety and maintenance regimes' economic efficiency, the need for early identification and robust management of fatigue failure is critical.

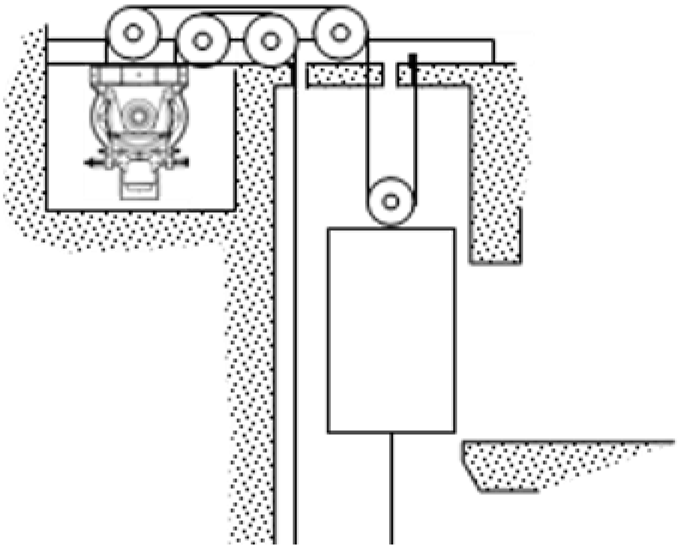


Figure 1 Inverted gearless lift machine arrangement.

Over the past decade, advancements in artificial intelligence (AI) have instigated significant transformations in maintenance procedures across various industries, with the lift industry no exception. AI technologies, particularly neural networks, have exhibited considerable potential in enhancing predictive maintenance strategies [4]. This capability to detect precursors of impending failure well in advance provides an opportunity for timely preventative action, thus offering substantial cost savings through minimising downtime and extending component lifespan.

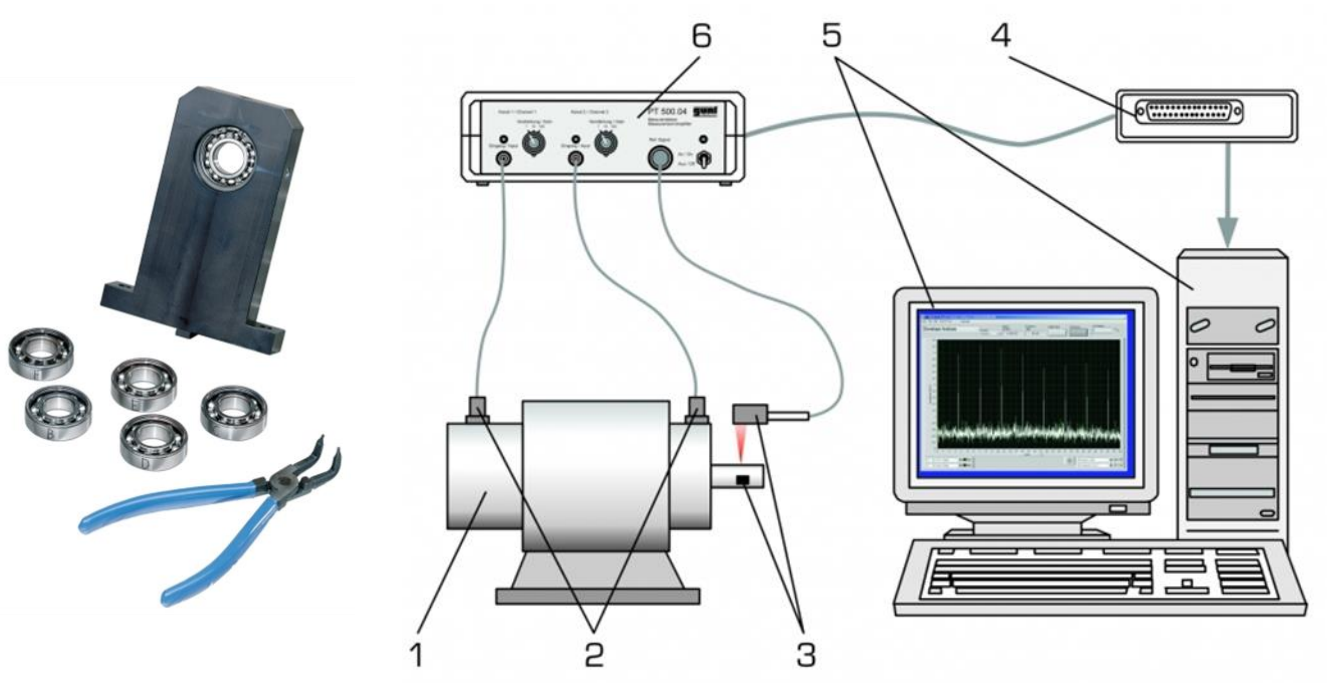
Figure 2 Experimental laboratory rig

To further investigate the potential of AI in combating component failure, the researchers developed a bespoke experimental rig (see Fig. 2). This rig encompasses a rotating shaft assembly held between two bearings and driven by a motor, mirroring real-world operating conditions. The shaft assembly was intentionally designed with both an undamaged state (Class "A") and various damaged states (Classes "B" through "F") to allow systematic analysis of different potential failure scenarios. These damage states were carefully modelled to include an unbalanced shaft, inner bearing ring damage, rolling element damage, compound damage (including outer ring roller damage), and severe bearing damage.

Equipped with accelerometers, the rig was utilised to gather vibration data, which was converted into wav files. The use of the MATLAB software platform for data processing facilitated the extraction of salient vibration features which correspond to different damage states. These features served as critical inputs for training an artificial neural network, forming the foundation of a comprehensive machine learning-based approach to condition monitoring.

Upon the training phase's completion, the neural network's performance was rigorously evaluated using new vibration data. The network's accuracy in damage classification is a crucial metric in assessing the effectiveness and reliability of this AI-based predictive maintenance strategy [5]. With a high degree of prediction accuracy, this methodology has the potential to significantly improve the way lift installations are maintained, markedly enhancing their lifespan and operational safety. Moreover, the wider implications of this research may provide a blueprint for AI-based maintenance strategies in other industries facing similar challenges related to fatigue failure and dynamic loading conditions.

2 EXPERIMENTAL APPARATUS AND DATA ACQUISITION



1 vibrating machinery, 2 acceleration sensors, 3 shaft with reference sensor, 4 USB box, 5 PC , 6 amplifier / filter

Figure 1 Experimental setup

The experiment was conducted using a bespoke testing rig, comprised of a driving motor, a shaft rotationally suspended by two roller bearings, and a flywheel (see Fig. 3). The analogue accelerometers were attached strategically on the shaft for precise vibrational acceleration measurements during operation.

The raw analogue data from the accelerometers were transduced into digital signals via a high-resolution analogue-to-digital converter (ADC). The integrity of the original signals was preserved by saving the digitised data in the .wav format, noted for its lossless properties.

Leveraging the bearings' interchangeability, seeded faults were introduced into the system to generate data for diverse damage classes. An unbalanced shaft state was induced by adding non-symmetric weight to the flywheel. In total, six damage classes were established and recorded for comprehensive analysis.

3 SIGNAL PROCESSING AND NEURAL NETWORK MODEL SELECTION

Upon examination of the data in MATLAB's Signal Analyzer [6], it was determined that all signals necessitated standardisation, smoothing, and centring. A notable peak appeared in the power spectrum around 4.1 kHz, likely attributed to the accelerometer's construction (see Fig. 4). To eliminate any influence on the subsequent results, a low-pass filter with a cut-off at 3.5 kHz was introduced.

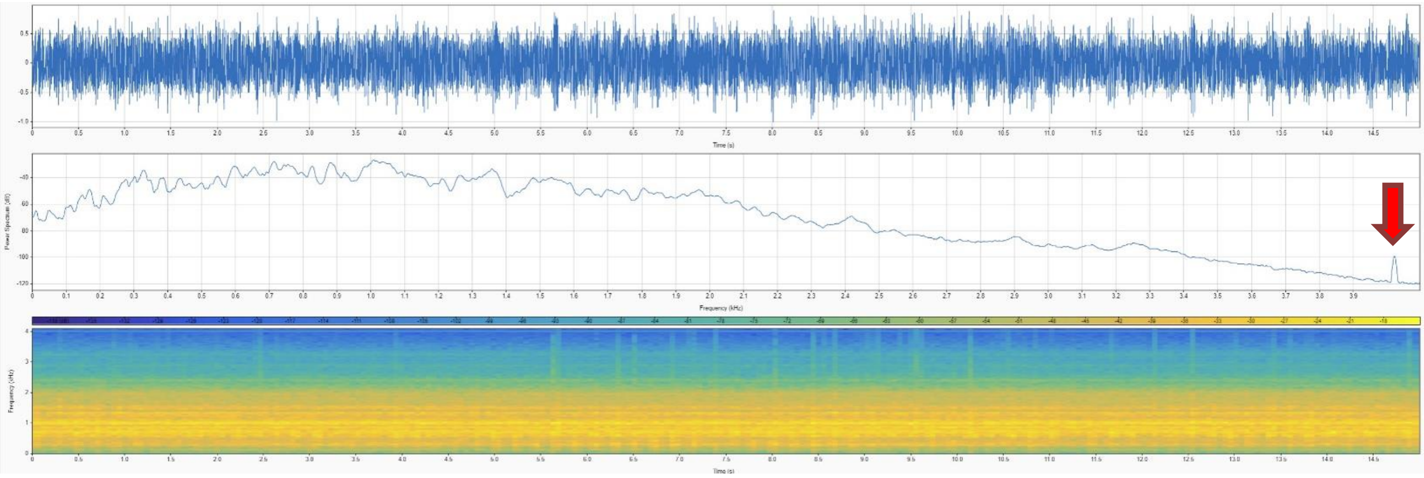


Figure 3 Signal Analyzer - Data Evaluation

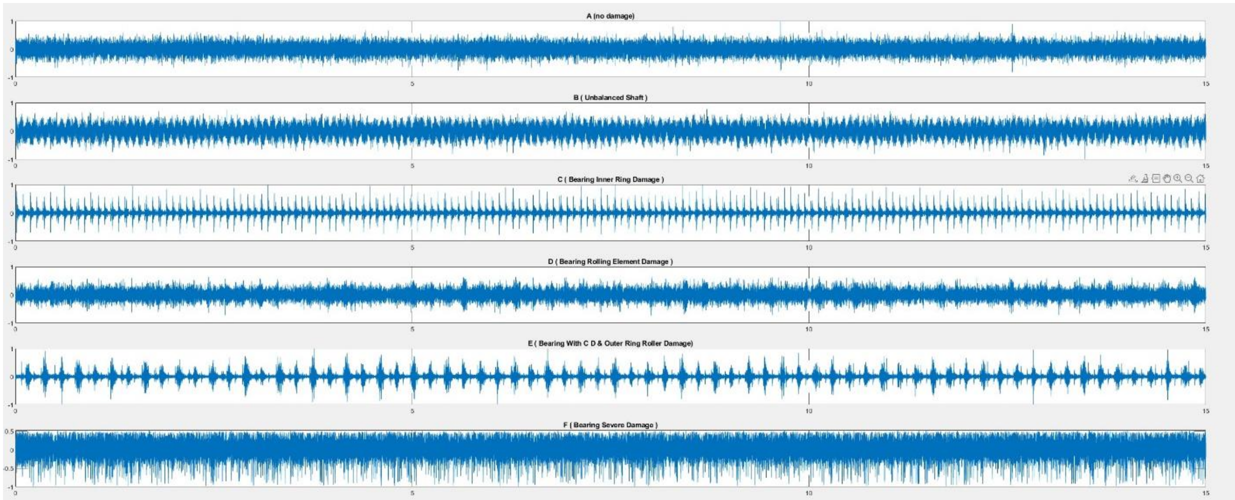


Figure 2 Six Damage Classes Signal

After pre-processing the entire collected signal data (see Fig. 5), the investigation turned towards selecting a suitable neural network model. Multiple models underwent rigorous testing, and their performance is summarised below:

- MATLAB's nnprtool app: The raw time datasets underwent pre-processing and normalisation, followed by post-processing to generate spectrograms. Subsequently, the cepstrogram's real coefficients were computed and employed as features for the Neural Network Pattern Recognition (NNPR) algorithm [7]. This process resulted in a uniquely processed Vibration Signature for each instance, contributing to the NNPR's intelligent pattern recognition capabilities. The analysis revealed that out of six classes, five were predicted with 100% accuracy. However, the 'no damage' class demonstrated a misclassification rate of 23.1% (see

Fig. 6). While these results were satisfactory, the team proceeded with the exploration of alternative models to enhance the classification accuracy further.

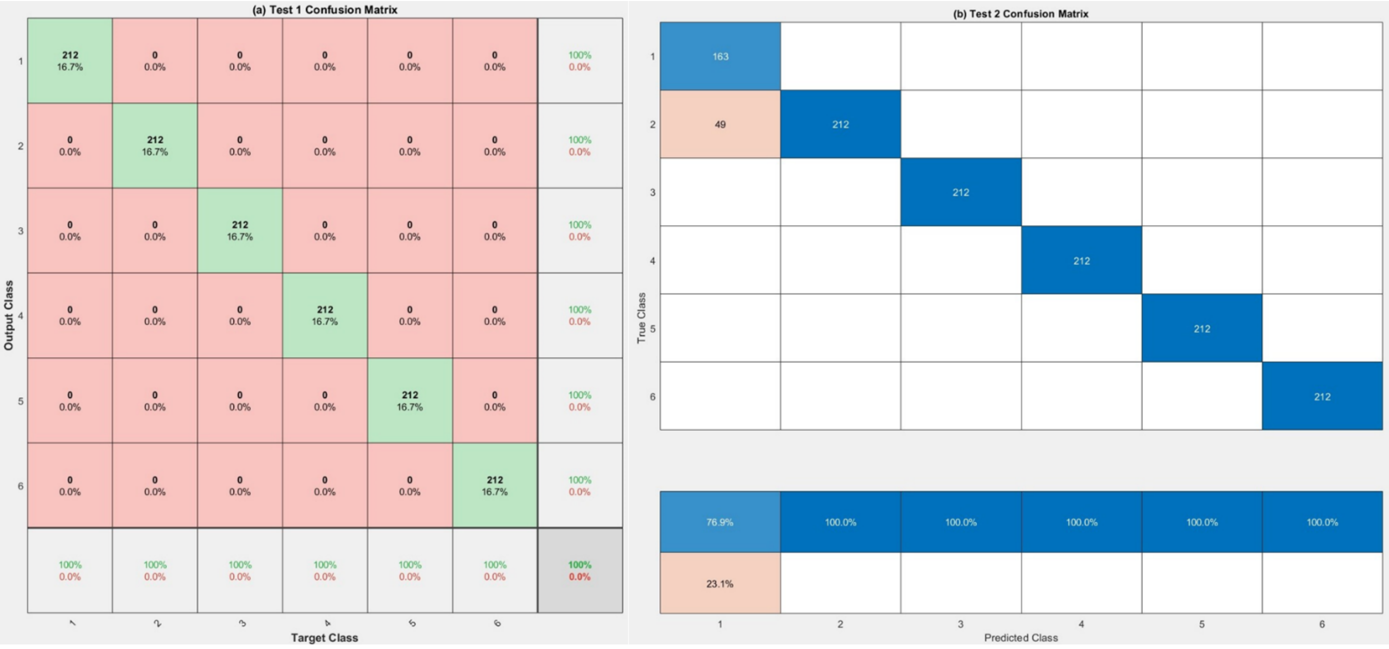


Figure 4 NNPR tool results: training and test confusion matrices

- MATLAB's feedforward network [8]: The identical set matrices as those used in nnprtool were employed. This model, however, facilitated the use of multiple neuron layers for training. Furthermore, retraining was undertaken to augment the classification accuracy of novel test data. For the feedforwardnet model, five out of six classes were correctly predicted. The 'no damage' class, though, had a misclassification rate of 35.8% initially and 31.6% after retraining (see Fig. 7). To improve these results, the team decided that more data work was needed.

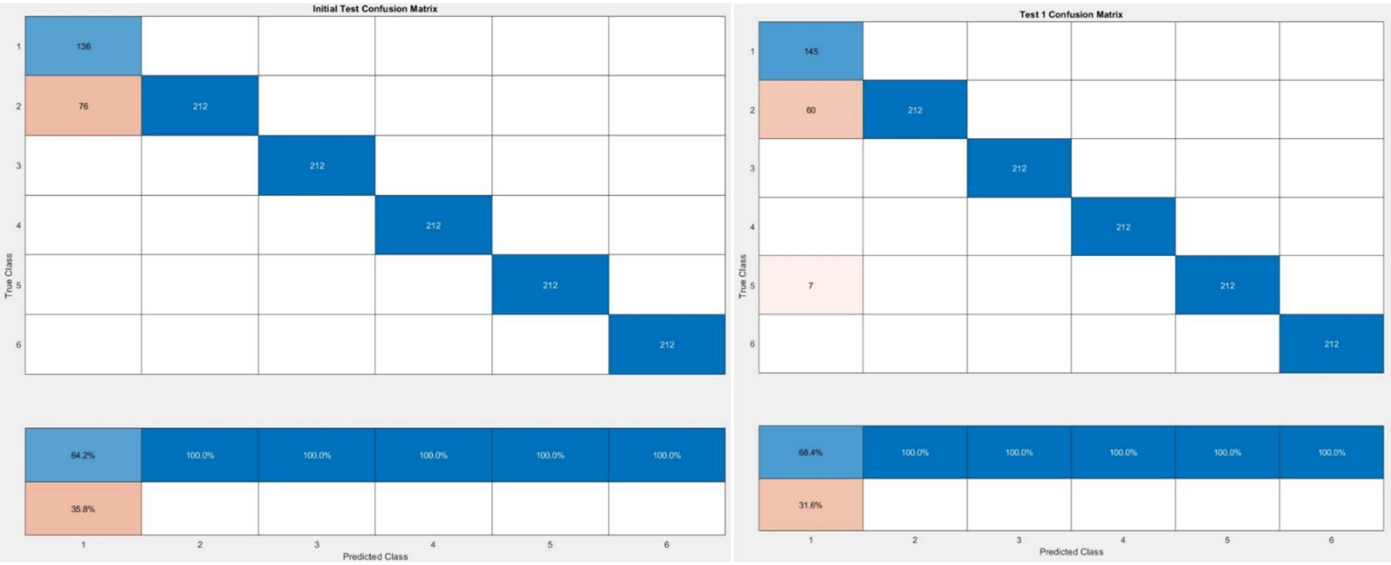


Figure 5 Feedforward net - Training and Retraining Test results

In pursuit of a more suitable model, the team initiated a new process, starting with the creation of a datastore that would be compatible with MATLAB's Feature Designer and Classification Learner app.

Signal data was initially pre-processed as in previous models and then segmented into one-second interval records. Given the motor's approximate speed of 700 RPM, each one-second data segment represented 11.6 rotations, providing a sufficient sample set for the data store.

Automated feature extraction was conducted to generate prevalent signal features after importing the datastore into the Feature Designer [9]. An Analysis of Variance (ANOVA) was subsequently performed to rank these features, with ten being classified as significant (see Fig. 8). Nevertheless, all features were exported to the Classification Learner app [10] for further analysis.

Figure 7 Feature Designer - Automated Feature extraction ANOVA ranking.

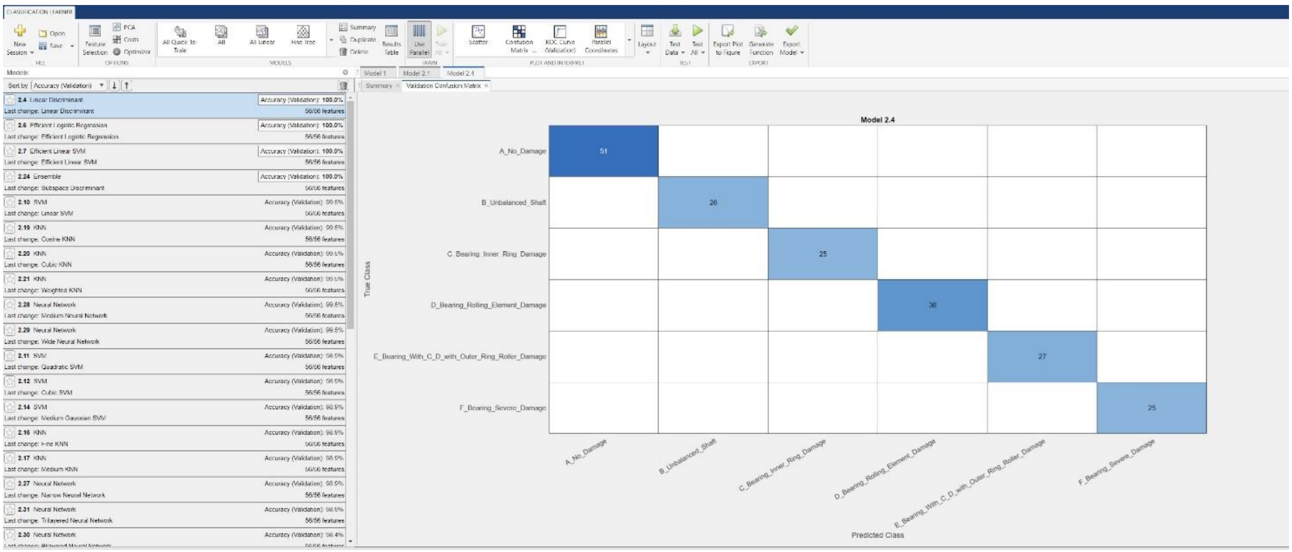


Figure 6 Classification Learner app - Training and Testing Results

Utilising the Classification Learner app, all accessible models were trained using the exported features from the Feature Designer. These models were then tested on 15% of the imported data for validation.

Remarkably, four models—Linear Discriminant, Efficient Logistic Regression, Efficient Linear SVM, and Subspace Discriminant—achieved 100% accuracy in predicting damage classification (see Fig. 9). Each of these models, exhibiting exceptional predictive performance, can hence be utilised for future measurements to anticipate damage classification reliably.

4 CONCLUSION

The research showcases the efficacy of artificial neural networks in detecting and predicting damage in crucial lift components, especially rotating shafts, pulleys and bearings. After training, the model consistently demonstrated high accuracy in damage classification, with values exceeding 80% and even reaching 100% in some cases.

The model requires additional development and broader data inputs from various lift systems for real-world applications. This strategy will likely enhance the model's predictive accuracy.

Integrating the model with MATLAB's Predictive Maintenance Toolbox can further improve its predictive capabilities. This software suite provides advanced tools for condition monitoring and failure prediction, leading to accurate failure time estimates and facilitating proactive maintenance.

In conclusion, the study presents a potential shift towards proactive maintenance strategies in the lift industry, focusing on rotating and other components. This move, aided by AI, promises more reliable and safer lift systems, marking a promising direction for future research and practical applications.

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BIOGRAPHICAL DETAILS

Mateusz Gizicki has a bachelor's degree in mechanical engineering from the University of Northampton and is currently working towards achieving his doctorate in the area of multi-physics and computational fluid dynamics. He is a member of the Institution of Mechanical Engineers. He has experience in research and development in the industry environment as well as academia. In addition, he has recently completed the Knowledge Transfer Partnership project, which combined management skills with complete product development as an associate.

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Dr Rory Smith has over 50 years of experience in all aspects of the lift industry including sales, installation, maintenance, manufacturing, engineering, research & development. He has worked for ThyssenKrupp Elevator for the last 24 years. Prior to becoming involved in ThyssenKrupp's Internet of Things, he was Operations Director at ThyssenKrupp Elevator Middle East. His scientific interests include: operations management, high rise–high speed technology, ride quality, traffic analysis, and dispatching. To date, he has been awarded numerous patents in these areas and has many pending patents.

Utilisation of VoIP in Lift Emergency Communications – A Case Study

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Keywords: Lift, emergency, communications, VoIP, evacuation, multimedia, video, voice, messaging, IoT, internet, connected cabin.

Abstract. The use of VoIP is set to become the predominant industry standard for emergency voice communications with lifts in this decade. Already networks are VoIP driven, with radio network backhauling, SIP (Session Initiation Protocol) trunked connections, and applications like Skype, Microsoft Teams and many others using this now as the proven SIP-based form of digital communication. The advantage of VoIP over analogue or even mobile operator-specific VoIP derivatives like VoLTE (Voice-over-LTE) is that end-to-end QoS protocols can be applied to lift call quality and associated media like DTMF signalling when using VoIP. This paper will introduce the topic of VoIP for lift emergency communications, give lift industry examples of utilization current or planned, and present a case study using the Cairo Monorail project currently being implemented as an example of such technology deployment and the benefits offered. Finally, there will be a brief discussion of the impact of EN81:28 in respect of VoIP utilisation and advice on how this topic can be supported at a national and European level with the ultimate goal of assisting industry stakeholders, particularly lift consultants specifying communication solutions and independent lift installers and maintainers who might be unaware of technological advances that can benefit themselves and their customers.

1 INTRODUCTION

The Cairo Monorail will be the longest driverless monorail system in the world. The Monorail's two lines will create the first public transport links from Cairo's metropolitan area to the New Administrative Capital – which, when completed, will become the new administrative and financial capital of Egypt – and the 6th of October City in the Greater Cairo Region. It will have the capacity to transport nearly 45,000 passengers an hour in each direction. Schindler was selected to deliver, install, and maintain 136 lifts for the Cairo Monorail project (along with 272 escalators). Safety and reliability were the principal commitments, and Schindler chose the IP-based 2N LiftIP to support the lift communication, with a unit in each of the project's lifts. The 2N LiftIP uses VoIP technology for transmitting calls from the lift cabin, with full duplex audio transmission facilitating high-quality, uninterrupted communication. The IP connectivity also allows continuous online monitoring and remote management.

IP-based connectivity supporting VoIP is a natural fit for these kinds of projects because of the quality of the audio communication, the ease of installation, configuration and the ease of possibilities for remote monitoring and integration with CCTV networks and BMS (building management systems).

The telco industry as a whole has completely switched to VoIP (using SIP protocol) in the network core. But this VoIP evolution has already spread from the core through access networks to the network edge and customers' premises. More and more customers replace old desk phones with VoIP and take advantage of modern IP voice networks.

It makes sense for the lift industry to follow the same path and get rid of legacy technologies of the past century and consider utilizing and leveraging the connected environments.

2 CAIRO MONORAIL SOLUTION – CASE STUDY

The lift communication solution proposed by 2N is all IP and utilises VoIP with SIP to facilitate high-quality voice calling which is unaffected by ambient electrical interference, as can be common with analogue (line-powered) phones. The solution utilises IP-based phone communicators in each lift cabin connected through ethernet in the travelling cables through a PoE (power over ethernet) switch to the rail station(s) local area network (LAN) and central PBX.

The following plan shows the scale and number of stations and most, if not all, will have lifts for passengers including mandated disabled access provisions.

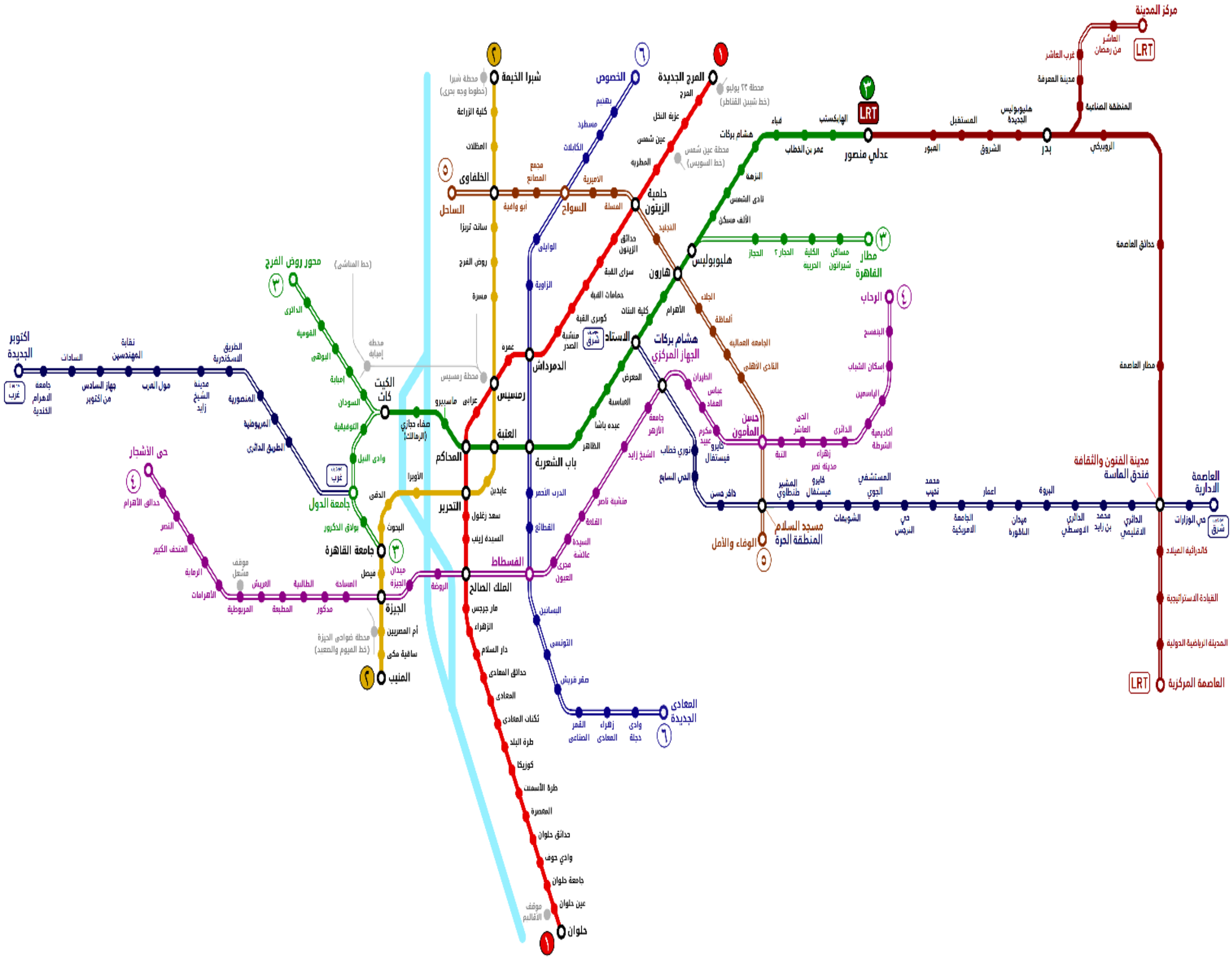

Figure 1 Cairo Monorail Layout (Source: Wikipedia)

Here is a typical schematic that will be replicated for each lift in every monorail station.

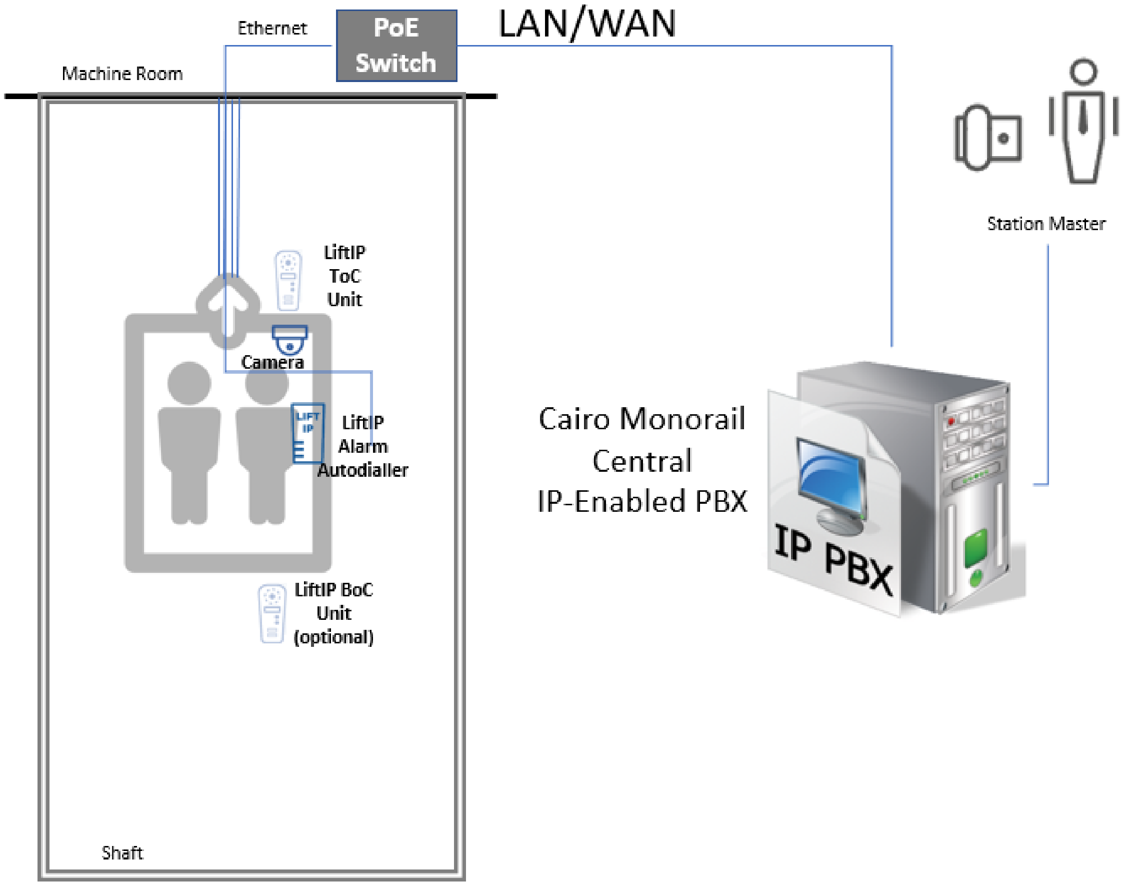

Figure 2 Lift Communication Solution Schematic (courtesy 2N)

3 IP TECHNOLOGY AS A FUTURE-PROOF SOLUTION

The whole telco industry has completely switched to VoIP (using SIP protocol) in the network core and this VoIP evolution has already spread from the core through access networks to the network edge and customers' premises. More and more customers replace old desk phones with VoIP and take advantage of modern IP voice networks. It makes sense for the lift industry to follow the same path and get rid of legacy technologies of the past century.

The concerns regarding VoIP infrastructure for use on lift emergency calls and the ability to guarantee connectivity are addressable in two ways. Firstly, mobile network gateways exist that have integrated analogue to VoIP converters which can work with any analogue autodialler and use the 4G data connection to connect the call through to the call centre, thereby providing direct connectivity without reliance on VoIP fixed networks. Those gateways are designed for EN 81-28 norm conformity, especially regarding the power backup. Secondly, a native IP emergency lift autodialler can be fitted with an I/O contact to deliver a notification if it is not possible for the IP autodialler to make a call regardless of network complexity from the lift to the call centre. The module monitors several key connection-related elements, including whether the IP phone is constantly registered to a SIP proxy server for call readiness, and can also ensure there are alarm number(s) programmed in the autodialler. This contact will also be triggered if the autodialler has no power.

4 SIP PROTOCOL AND MULTIMEDIA COMMUNICATION

SIP is a signalling protocol used for initiating, maintaining, and terminating real-time sessions. These real-time sessions (RTP - Real-Time Transport Protocol) can carry various types of data, it can be a traditional voice call, a video stream from IP cameras, or instant messaging from software applications. In essence, SIP uses the Internet as the medium for voice communication between two endpoints.

4.1 Voice communication

SIP supports VoIP and offers excellent end-to-end call conversation and DTMF quality.

4.2 Video communication

Installation of IP cameras in lifts is becoming a new trend for several reasons:

- Visual information helps to better understand an emergency situation
- One of the big benefits of video is false alarm elimination
- Call centre can monitor the cabin floor and check if the passenger has fainted
- IP cameras in lifts integrated as a part of the Building Management System (BMS)
- Visual information can serve for analytics about resource utilization
- Awareness of monitoring reduces the rate of vandalism

SIP allows you to easily merge voice from a VoIP auto-dialler and video stream from IP camera(s) and deliver it in a single video call to the call centre.

4.2 Text communication

So far, the regulations have not fully covered the needs of hearing-impaired passengers. This has changed with the latest release of ASME A17.1 [1] in the United States, where new or modernized lifts must also offer options to communicate via text messages. Cars and even the main landing or machine room must be equipped with displays. SIP protocol is very flexible and offers several extensions. For example, the one defined in RFC 3428 speaks about how to implement instant messaging functionality. If your call centre is “VoIP”-ready, the implementation of text communication in SIP will be much easier.

5 CLOUD AND IOT

Lift companies need to have a robust, secure, and scalable system which can take care of thousands or millions of lifts in real-time. Even if your company is not big enough to build such a system on your own, there will be vendors who will provide the cloud infrastructure as a service.

The key goals are obvious:

- remote access to reduce interventions on-site
- automatic deployment
- management of device fleet from a single point
- overcoming the knowledge gap of your workforce
- prevention of configuration mistakes
- constant supervision of device status
- easy integration with external systems
- preventive and predictive analysis

VoIP will play a key role as a central data connectivity hub for all technologies in lifts of the future. Even today there are 4G gateways that can also support VoIP and automatically translate even analogue calls from old, existing lift cabin phones to VoIP.

6 VOIP EMERGENCY COMMUNICATION SYSTEM ARCHITECTURES

Let me briefly comment on the three most common IP technology use cases that you might encounter on the market. The first one presumes a lift company has their own “IP ready” PBX (Private Branch Exchange). The lift company manages IP PBX licensing on their own, and because they do not want to use a 3rd party cloud, they set up each device individually. They save some money on cloud services but must spend extra time on configuration. Each problem on-site or configuration change means technicians will have to travel there to check out what is going on. It is harder to calculate operational costs. Figure 3 shows this stand-alone topology.

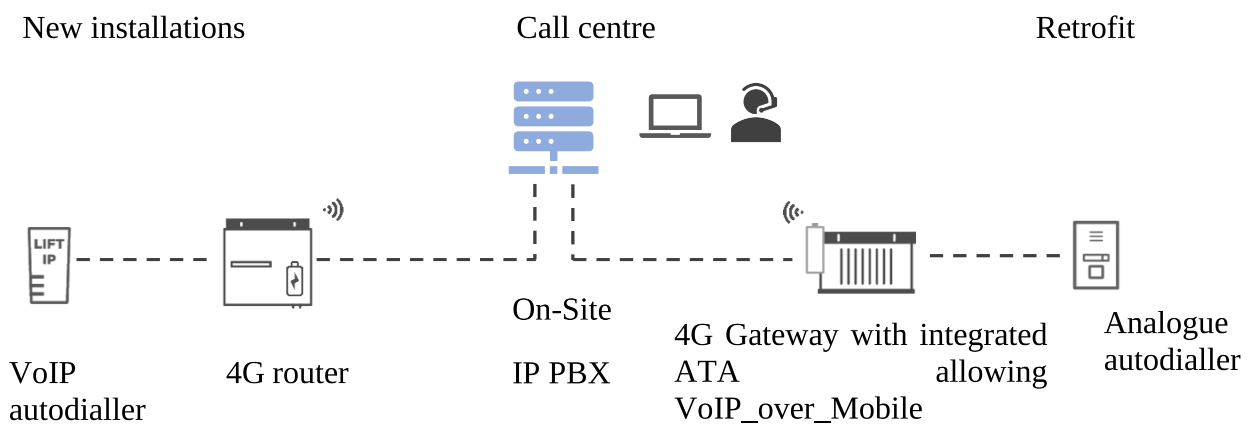

Figure 3 Stand-alone topology

The second use case is the opposite. The lift company has no experience with VoIP, and their PBX system does not support it. A complete emergency communication system will be delivered by a VoIP service provider in that market who offers both communication devices and cloud services. The lift company will pay a subscription fee, without any or with minimal investments into their own infrastructure. TCO (Total Cost of Ownership) and ROI (Return on Investment) are simple to evaluate. It is possible to perform remote troubleshooting to some extent. Upgrades, configuration changes and new features can be deployed centrally by clicking a “single button”. Figure 4 shows the Cloud topology.

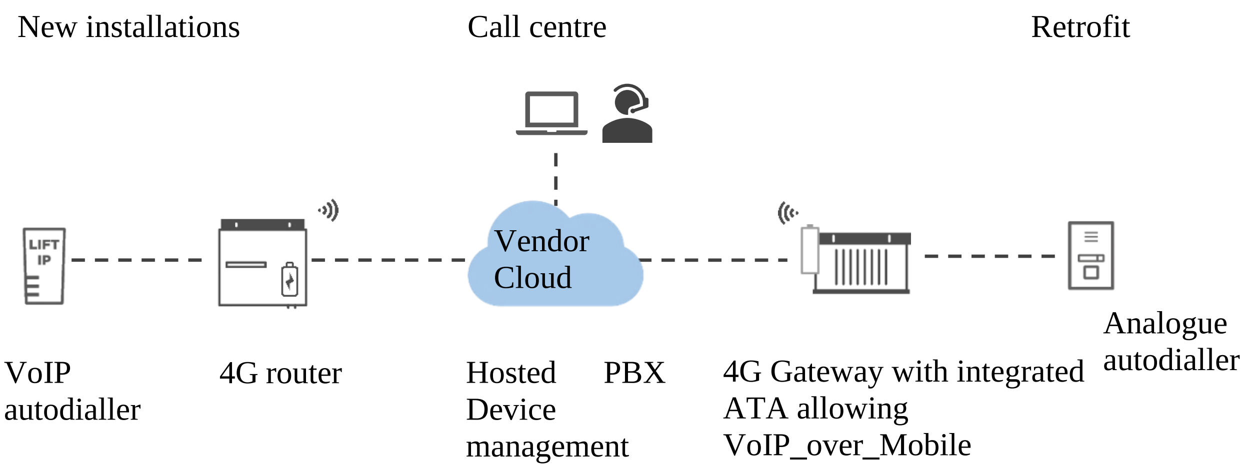

Figure 4 Cloud topology

The third scenario is a mix of the two previous. The lift company wants to keep their IP PBX for Call centre agents, but potentially tens of thousands of devices need to be registered at a national VoIP provider's hosted PBX due to cheaper prices. Both systems will be interconnected via SIP trunk. The lift company clearly sees the advantages of mass management and real-time monitoring and pays a small fee to get these value-added cloud services. Their emergency communication system is robust, secure, well-managed and without hidden costs. Figure 5 shows the Hybrid topology. Each architecture has its pros and cons and gives lift companies the option to choose the optimal solution.

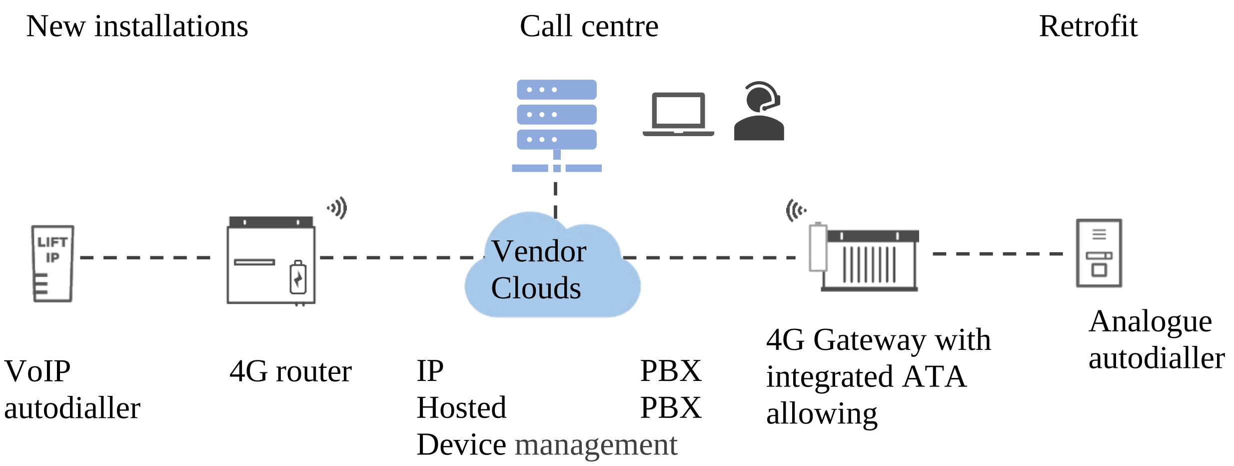

Figure 5 Hybrid topology

The following table shows a comparison of various architectures.

Table 1 Comparison of various architectures

	Stand-alone	Cloud	Hybrid
Lift VoIP auto-dialler registration	Customer's PBX	Hosted PBX	Both customer's and hosted PBX
Advanced cloud features	No	Yes	Yes
Simplicity of administration	Difficult	Easy	Medium difficult
Ease of integration with 3rd party systems	None	Easy	Medium
Cost	Low	Low	Medium

7 HOW TO GET READY FOR THE IP FUTURE?

Considering all mentioned factors forming today's and tomorrow's telco and IT world, the only way to the future goes hand in hand with transformation to full IP. Partnering with companies with strong competency in VoIP will save you time, money, and will help you to increase your reputation on the market. I believe there is a role for national lift associations LEIA and lift standards groups like CIBSE to assist with information, advice and guidance supporting and aligning with standards whilst encouraging the adoption of more modern, more robust technologies for lift communication.

8 CONCLUSIONS

We are standing at the beginning of changes that will define emergency communication for the next decade. The inevitable changes in communication network technologies will have a huge impact on all lift companies, and it is necessary to get ready for the VoIP shift as soon as possible.

Technologies allow video calls and easy management of a large number of communication devices, automatic configuration, and remote access without the need to educate and train your field technicians.

With IP technologies, you will save money, your workforce's time and number of on-site visits. Having an overview of devices in the field 24/7/365 puts your emergency communication under your control.

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BIOGRAPHICAL DETAILS

Jason Godwin is a Regional Sales Manager at 2N with responsibility for lift communication products across the UK, Australian and North American markets. He started work in the UK lift industry under his father, Mike Godwin before moving to Australia where he worked for Kone and Boral Lifts (OTIS) rising to senior management level on new lift sales and also modernisations. He then returned to Europe settling in Prague and, in the absence of lift industry opportunities there, decided to focus on telecommunications while also assisting his brother Adrian Godwin at Lerch Bates Europe from time to time. Jason holds an MBA from RMIT University in Melbourne, Australia.

Smarter Buildings: IoT-enhanced Traffic Analysis Embedded in Lift Sensors

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Keywords: smart buildings, people counting, traffic analysis, IoT.

Abstract. From manual people counters to 3D camera imaging, traffic analysis technology has come a long way in the last few decades. There are various technologies and commercial solutions available in the market today for people counting. Smart devices designed for other purposes, such as light curtains and time-of-flight camera sensors for lift door safeguarding, can have the people counting function embedded in them as well. Thanks to IoT, this sensor data can be computed and visualized for numerous applications, including lift usage optimization and predictive maintenance based on wear and tear. However, the potential of traffic data collected by lift sensors goes beyond the lift itself. It provides valuable insights on people flow in the building as a basis for informed maintenance and business decisions, energy saving, and building usage optimization. As a result, the lift is becoming an important part of the smart building ecosystem.

1 INTRODUCTION

There are several modern technologies that can be applied for people counting, including Wi-Fi tracking, ultrasonic sensors, infrared beams, thermal or time-of-flight cameras, and enhanced CCTV systems. Each technology has certain advantages and disadvantages. The latter include low accuracy (like ultrasonic or thermal sensors) or privacy issues (in case of Wi-Fi tracking and CCTV). This paper focuses on two people counting methods that can be successfully applied in lifts as well as entrance automation systems - light curtain infrared beams and 3D ToF (time-of-flight) camera sensors. First, the data acquisition process is discussed, followed by possible visualizations of processed information. In the last part, the value of this data for end users in the lift business as well as in the wider context of a smart building ecosystem is explored.

2 DATA ACQUISITION AND OUTPUT

2.1 Light curtain

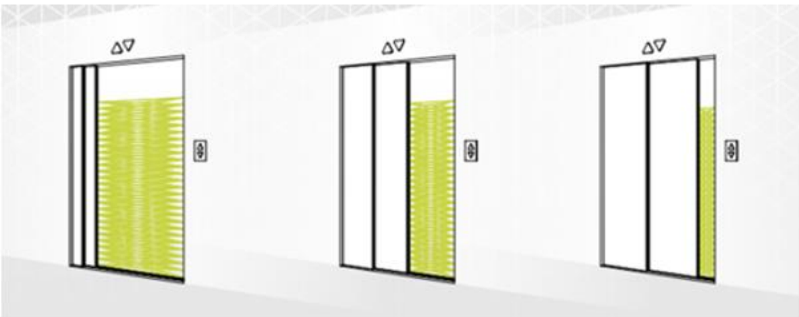
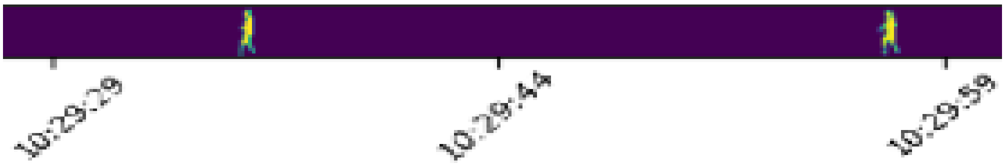
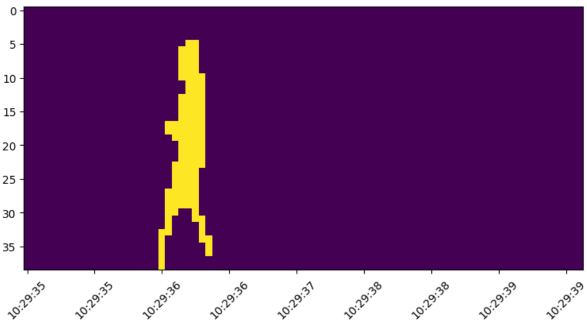


Figure 1 Image of a light curtain during an automatic door closing sequence

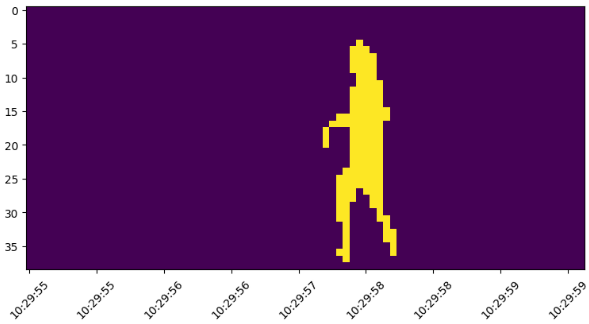
When a person passes through the beams of the light curtain, an image is captured. Below, we will analyse examples of one person and two people using a lift.



(a) Scanned image of one person entering and exiting a lift over time



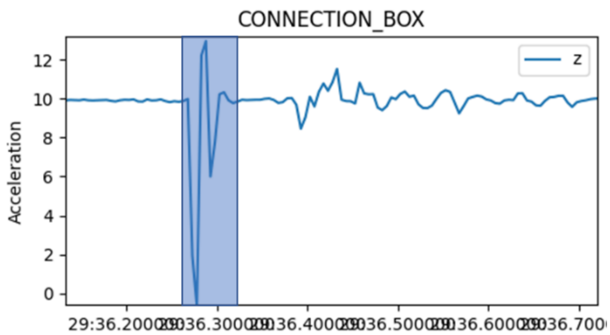
(b) Scanned image of entering



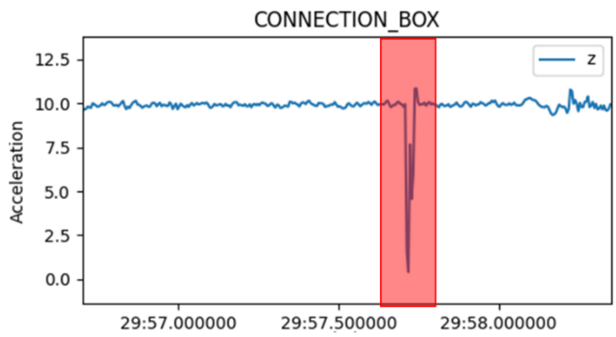
(c) Scanned image of exiting

Figure 2 Light curtain scanned image

As shown in Figure 2, the scanned image from the light curtain can describe the shape of a person but cannot indicate the walking direction, which makes it difficult to count people in the lift. Additional information (shown in Figure 3) is provided by an accelerometer, which is installed in the cabin. It indicates the cabin movement when people are entering and exiting the lift.



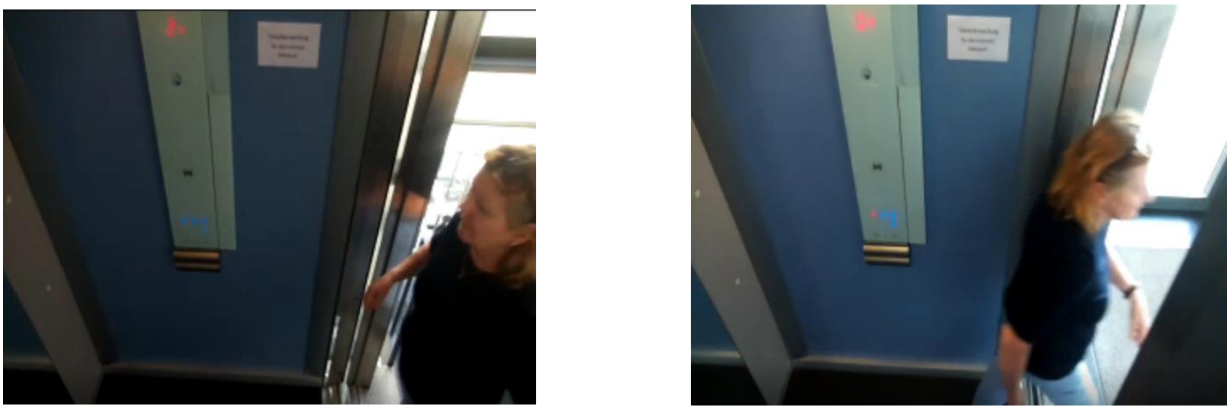
(a) Accelerometer during entering



(b) Accelerometer during exiting

Figure 3 Accelerometer data of the event showed in Figure 2

As shown in Figure 3, the cabin is quite stable before and during the ride. A significant movement is captured during entering and exiting the lift. Moreover, the behaviour of entering and exiting are different, which makes it possible to count people traffic with this solution.

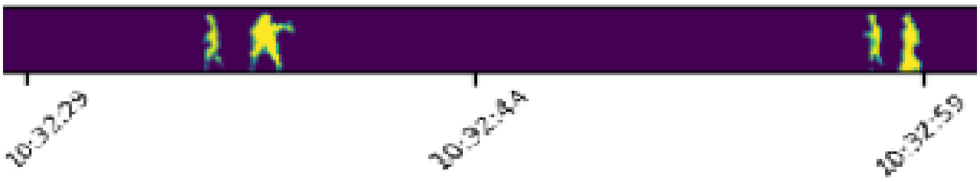


(a) Video frame during entering (b) Video frame during exiting

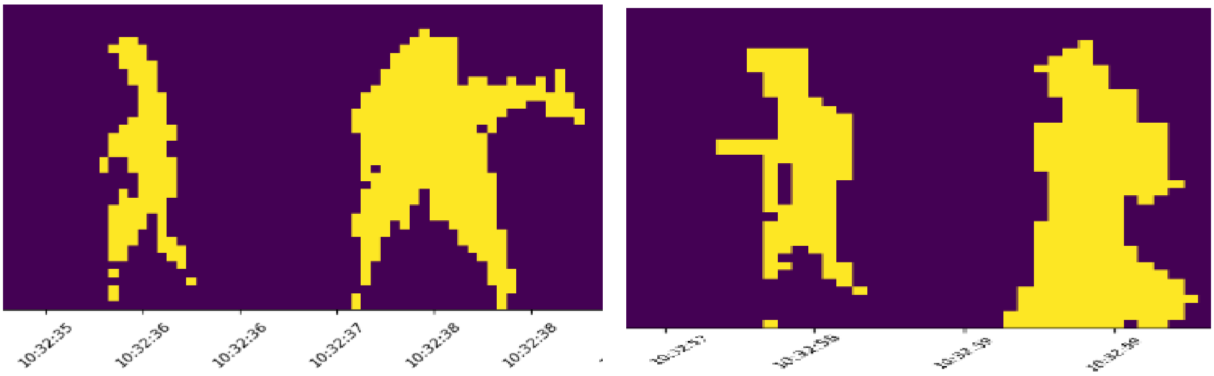
Figure 4 RGB video camera view of the event shown in Figure 2

Figure 4 shows an example frame of the mentioned entering and exiting event in Figures 2 and 3 from another RGB video camera, which is not included in this system.

In the second example, two people are using a lift.



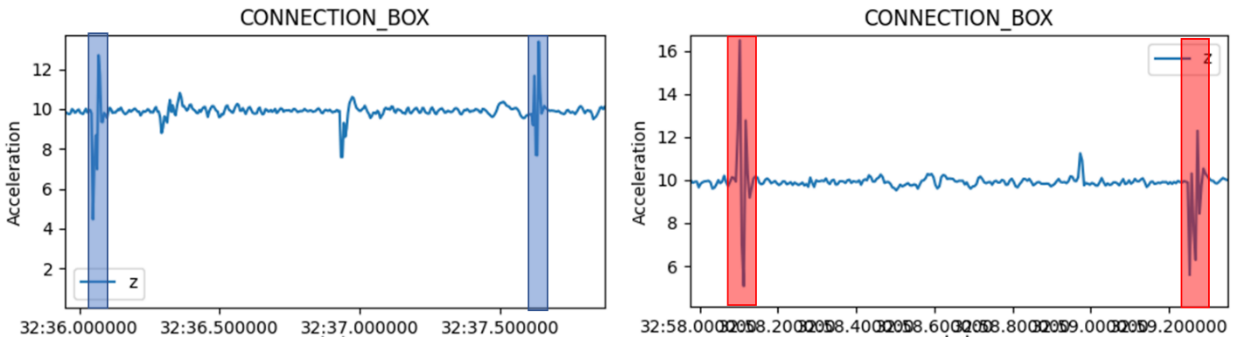
(a) Scanned image of two persons entering & exiting a lift over time



(b) Scanned image of entering **(c) Scanned image of exiting**

Figure 5 Light curtain scanned image

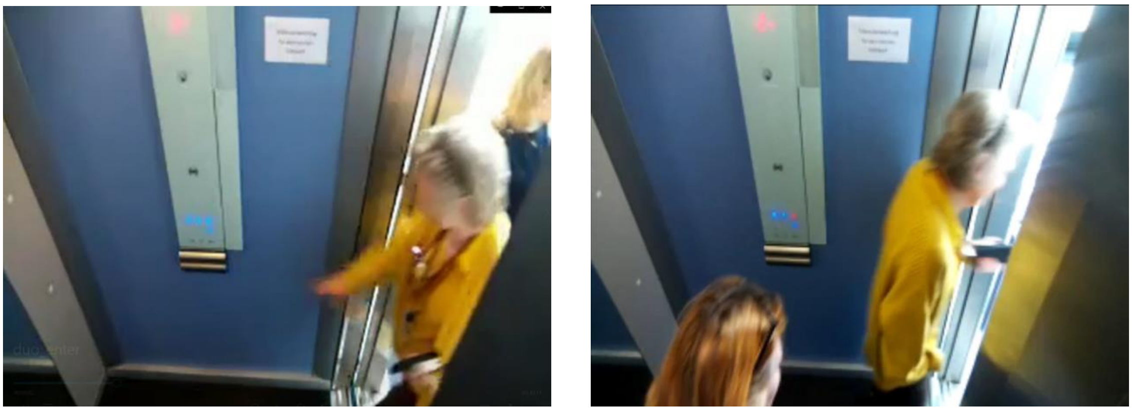
Figure 5 shows the scanned image from the light curtain of two persons entering and exiting the lift. Same as shown in Figure 2, the human shapes are clear, but the walking direction is difficult to tell.



(a) Accelerometer during entering **(b) Accelerometer during exiting**

Figure 6 Accelerometer data of the event showed in Figure 5

As shown in Figure 6, the cabin is quite stable before and during the ride. A significant movement was captured during the entering and exiting of the lift for each person separately.



(a) Video frame during entering **(b) Video frame during exiting**

Figure 7 RGB video camera view of the event shown in Figure 5

Figure 7 shows an example frame of mentioned entering and exiting events in Figures 5 and 6 from another RGB video camera.

2.2 3D image in front of the cabin

The 2019 North American Elevator Safety Code (ANSI A17.1-2019 / CSA B44-19) defines new requirements for the means of detecting persons or objects between the doors (2D) or approaching the lift (3D). A 2D light curtain combined with a 3D ToF (time-of-flight) sensor and a controller can fulfil all these code requirements (Fig. 4 and 5).

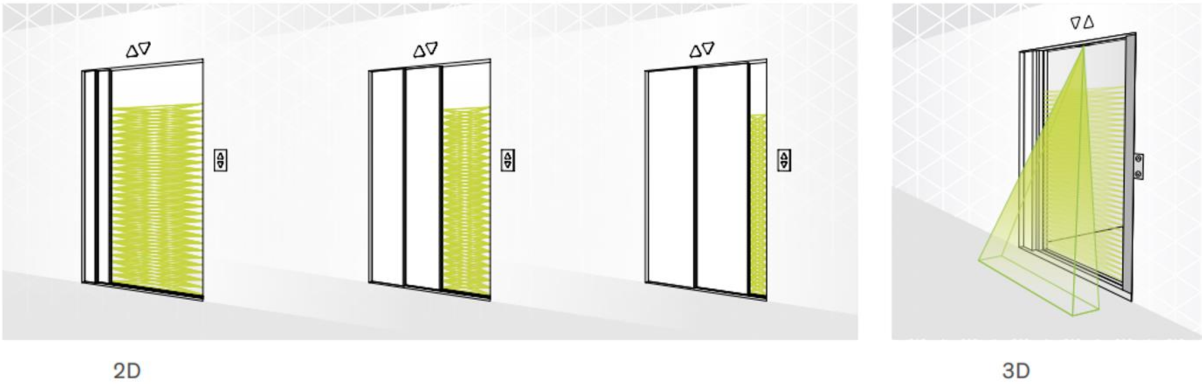


Figure 8 2D light curtain combined with a 3D time-of-flight sensor

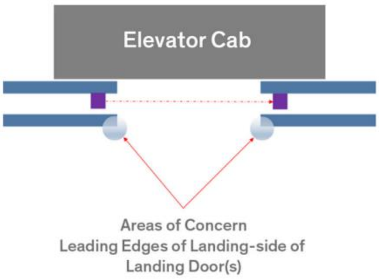


Figure 9 The detection areas of the system elements represented by red lines

When a person passes through the areas of concern, an intensity image is captured. Here is an example (shown in Figure 10) of a captured intensity image and its corresponding people detection results.

(a) No object detection

(b) One person is detected during entering the lift

(c) One person is detected during exiting the lift

Figure 10 Intensity image through a 3D ToF sensor and its object detection results

In Figure 10, the left side is an intensity map captured by a 3D ToF sensor, while the right side is an indicator of the object detection results. Blue indicates no detection of the object, and green indicates detection of the object. Compared to a light curtain solution, a 3D sensor can provide a clearer image. The walking directions are possible to calculate from its intensity images.

2.3 3D image in the lift cabin

There are also 3D ToF sensors that offer full door protection, without the need for an additional light curtain (Fig. 11). The figures below show an example with two people using the lift.

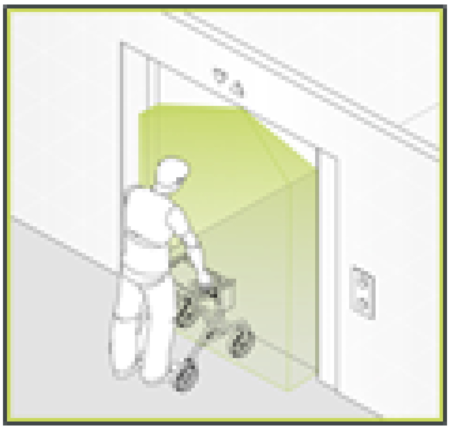


Figure 11 Full door area safeguarding with a 3D ToF sensor

Below, an example with two people using the lift is analysed.

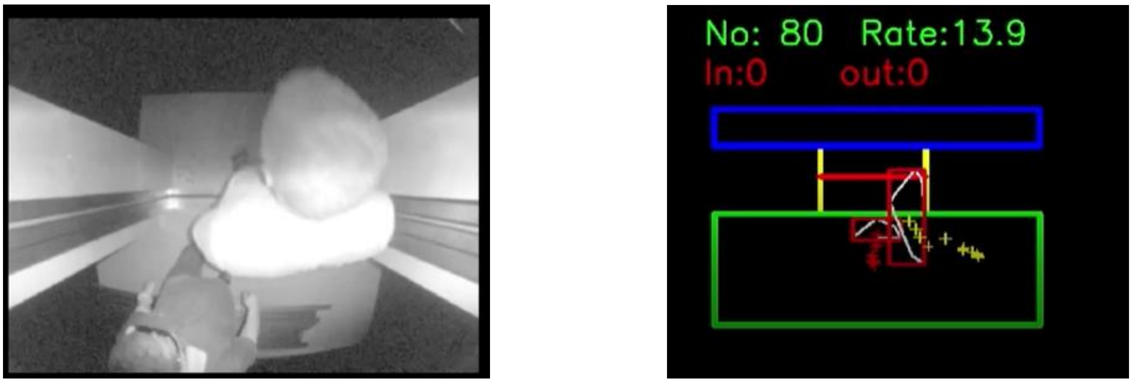


Figure 12 Two persons entering the lift

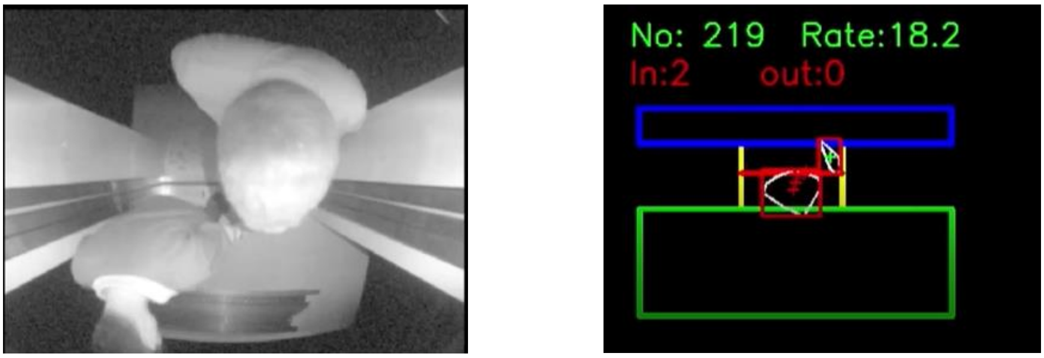


Figure 13 Two persons exiting the lift

Figure 12 shows an intensity image from a high-resolution 3D ToF sensor mounted in the transom on the left, and its related calculated results from input video frames on the right. The blue rectangle indicates the inside region of the lift, the yellow rectangle indicates the door region, and the green rectangle indicates the outside region of the lift. Additionally, red rectangles indicate detected objects and their tracking trajectories. The results show the detection of a person and tracking of a detected person. Counting entering and exiting people can be done in an accurate way.

2.4 Traffic visualization

This subsection illustrates some possible ways to visualize people counting and lift traffic overviews based on data acquired from technologies embedded in lift sensors.

Figure 14 Heatmap of the utilisation of a 20-storey lift over a 24-hour period

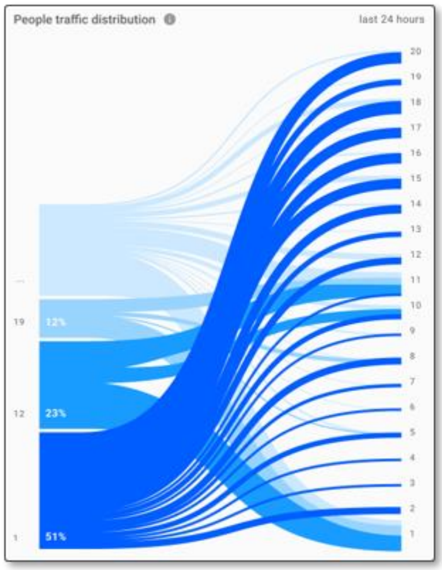


Figure 15 Distribution of passenger traffic in a 20-storey lift; on the left the departure floor, on the right the arrival floor

3 DATA VALUE FOR THE END USER

3.1 Data value in the lift business

People flow analysis has a significant impact on lift design. Peters, Smith and Evans point out that the design process is all too often based on historical data and assumptions, despite a visible change in traffic patterns in modern office buildings [1]. Real-time traffic data contributes to increasing dispatch algorithm efficiency and lift performance. This applies not only to new lift installations but also to lift modernization projects. People flow analysis helps to make informed decisions on the scope of modernization, such as replacing a conventional control system with a destination control system (DCS) to avoid long waiting times during peak times [2].

Ultimately, the main benefit lies in improving the individual experience of each lift passenger. In today's fast-moving world, sacrificing many minutes of a half-hour lunch break just to wait for a lift becomes a real nuisance, especially when it turns out to be overcrowded after it has finally arrived. Smart, data-driven lift traffic management increases end-user satisfaction by helping them save their most precious resource – time.

Moreover, the people counting function can serve to increase passenger safety where the number of passengers using the lift simultaneously needs to be controlled, for instance, to prevent lift overload. Another interesting potential use case came about during the COVID-19 pandemic, when, following the rules of social distancing, only one person at a time was allowed to use the lift. More importantly, a smart lift system knows that passengers are trapped inside a blocked lift before the passengers themselves do anything about it. Process improvements lead to faster rescue and might even save lives [3].

3.2 Data value in smart buildings

The potential of traffic data collected by lift sensors goes beyond the lift itself. Combined with data from other sources and visualised in reports and dashboards, this data turns into useful information for facility managers and building owners, improving the people flow and energy management in the building. The collected information becomes a piece of the smart building puzzle, contributing to a more complete picture of people flow.

Figure 16 Various sensors applied in a building (Source: CEDES [4])

Understanding modern building usage trends is crucial for optimization. Most recently, the COVID-19 pandemic has changed the way we work, shop, or eat out, and how much time we spend at home and in the office. According to a report published by Microsoft in 2021 [5], flexible working models such as remote or hybrid work are in high demand from the workforce. Consequently, building management needs to be adapted to this new reality, ensuring optimal use of resources such as energy and space. Rather than relying on past assumptions, building managers can base their decisions on near real-time people flow data.

Reducing building energy consumption while maintaining the comfort level of visitors and tenants remains a major challenge, especially since it depends on individual behaviour to a large extent. Data transparency on energy usage can lead to a change in behaviour towards conscious energy saving. In addition, many building-wide processes can be automated through occupancy-based control, i.e., determining the indoor environment settings based on the number of people in the room. Depending on the current number of occupants, the heating, ventilation, air conditioning (HVAC) and lighting systems can be regulated. This approach requires an efficient people-counting method. Zhang et al. (2022) compare various types of sensing technologies for this application [6].

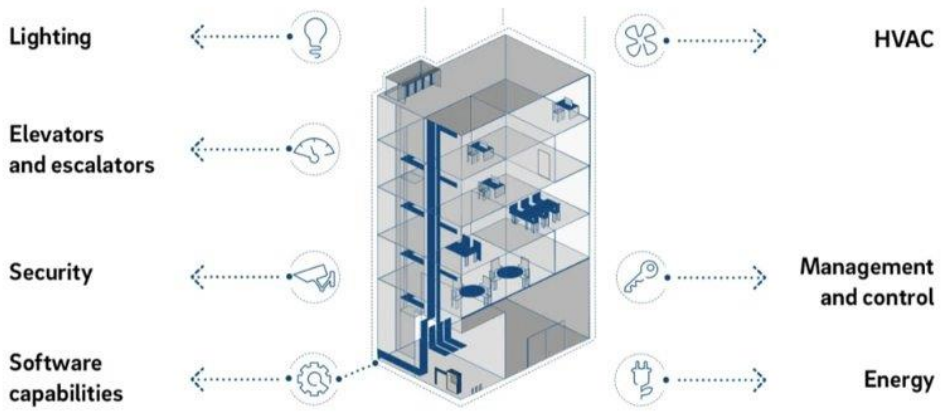


Figure 17 Key sectors in building automation (Source: Roland Berger, July 2020 [7])

Of course, precise occupancy information is relevant not only for comfort but also for safety. Similarly to the lift overload situation, maximum occupancy limits need to be observed in buildings, e.g. under fire safety regulations or social distancing rules [8]. Optimizing people flow with regard to safety is also of utmost importance in large event venues, during concerts, sporting events, etc.

Finally, people flow analysis is a basis for business decisions and can serve to prove the commercial value of real estate, justifying the rent or sales price of a particular property or a space within a property, such as store space in a shopping mall, in an area with particularly high traffic. Another good example is a convention centre, where organisers can share traffic data with exhibitors, for them to calculate their return on investment of a specific trade show booth.

4 CONCLUSION

Data is at the heart of any digital transformation. The more data sources on people flow that become available, the more applications for sustainable, safe, and life-enhancing buildings and cities can be discovered in the future. Vertical transportation is also an important part of this smart ecosystem. Lift sensors such as light curtains and 3D time-of-flight sensors already collect valuable data – feeding them into an IoT platform along with information obtained from other smart building systems provides a complete and transparent picture of how we use our buildings, as well as insights on how to optimise this usage.

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BIOGRAPHICAL DETAILS

Michele Guidotti – a graduate of ETH Zürich and the MIT Sloan School of Management, an IoT expert with extensive experience in the lift industry (Schindler Group), currently Senior Product Manager at CEDES working on an IoT business case.

Technology Redefining the Future of Elevator Installation Methods for High Rise Buildings

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Keywords: Installation, Scaffold & Scaffold-less, Climb lift, False Car, BIM, Robots,

Abstract. The installation of lift guiding systems is fundamental to the ride quality felt in the car. This paper will look at typical elevator installation methods and the technological journey of elevator installation in the construction business. Traditionally elevators were installed by fitters using scaffolds to access the hoistway, aligning the guide rails and adjusting the distance between them. The process was often quite challenging for the installation teams as safety was the main concern, along with the physical strain of working in a harsh environment. The process then progressed further to Scaffold-less installation methods with temporary suspended platforms, which offered improved safety standards according to the guidelines defined in EN 1808 & GB T 19155. At the same time climb elevators were developed as the building industry required elevators to be installed and operational whilst the buildings were progressing in the construction phase. Today new technology has allowed robots to become mobile, leaving the factories for robotic installation systems for lifts on construction sites. The repetitive tasks and harsh environments that challenged humans can now be done with the high quality and precision of robots.

1 INTRODUCTION

The correct installation and alignment of guide rails to form the lift's guiding path are fundamental to be able to achieve acceptable levels of ride quality in the lift system. Installation methods are continuously developing to fulfil today's challenging market requirements. Safety, manpower, labour shortages and installation time optimisation are key drivers for developing new installation methodologies of the future.

This paper will take a brief look at how installation methods have progressed from traditional scaffolding to breakthrough construction technologies for lift installations of today and the future.

The vertical transportation industry is a very special discipline within a building. Whilst most disciplines base their design and models on a floor-by-floor basis, the Vertical Transportation manufacture must inevitably cross more than one floor at a time.

As lift installation projects are complicated and time-consuming, proper onsite management and defined processes are mandatory for a successful project. This also includes better site coordination and on-site material logistics, as material storage is generally challenging on large projects.

2 LIFT INSTALLATION METHODS

2.1 Scaffold

Traditionally a scaffold was supplied by the main contractor in order to install the shaft material, and generally the scaffolds were a concern for the health and safety of the installation personnel. Additional work was required to bring the scaffolds up to the standard expected to ensure that employees can carry out the installation tasks. Scaffolding was often in the way of components being installed, like landing doors, and required continuous alteration to suit the lift system being installed and often safety procedures were compromised with people working above each other.

The scaffolds generally had quite a low installation efficiency as materials had to be transported to the individual floors and then hoisted into the shaft. Such methods also had no defined method statements or risk assessments to define the installation sequence with the appropriate tooling supplied. It was generally up to the subcontractor to decide how they would install the unit based on previous experience without training.

Although the fitters were wearing a fall protection safety harness connected to a rope in the shaft, the general working environment was quite dangerous and physically demanding, with the constant danger of debris falling down the shaft.

Furthermore, rental costs for scaffolds over longer periods were expensive for shaft heights of up to 500 meters. Also, the structural loading on scaffolds is quite questionable with excessive heights required for high rise lift installations.

Figure 1 High rise scaffold installation

2.2 Scaffold-less installation methodology

As safety standards were raised across the whole lift industry, building contractors were also pushing for safer installation methods with a clearly defined process. One major building contractor was pleased to have an installation method that mitigated risks based on sequential method statements for the entire installation process. This allows for a safe and independent installation methodology to be deployed over all product lines. The method also has a high degree of independence regarding the builder's readiness, allowing for greater flexibility to commence the installation work on the job site, as soon as the shafts can be handed over.

Scaffold-less installation methods (SLIM) were developed and certified, to create safe working environments for the installation teams, with the highest safety standards according to [1] EN1808:2015 Safety requirements for suspended access equipment - Design calculations, stability criteria, construction - Examination and tests.

SLIM is adjustable for all shaft dimensions and travel heights. Thanks to the pre-engineered material, it can be reused numerous times. The suspended platform, or false car [2] as it's called, has three independent safety redundancies. Primary rope with hoist, secondary rope with fall arrest device and independent free fall safety gear acting on the guide rails. The safety gear is automatically activated with spring force the instant that no suspension members are detected.

One of the main advantages of the methodology is that the installation can start whilst the building is still under construction with only temporary power supplies available. The so-called "staged installation process" is applied, where the installation teams can work under the safety of a crash deck, temporarily installed in the shaft. With a staged installation, a shaft platform is installed along with suspension beams for the hoisting ropes to suspend the false car. The whole installation kit rises with the construction of the building, once the final building height has been reached and the machine rooms handed over, the lifts can be finished.

SLIM offers flexible, safe and tailor-made solutions to meet the project specifications, allowing the customer to have the lifts ready for handover at an earlier stage or to be further utilised as builders' lifts throughout the construction phase.

Scaffold-less installation methods still require a guide rail installation kit (GRIK) to be installed as a reference to plumb the shaft for the accurate positioning of the rail brackets and guide rails. The GRIK enables the guide rails to be positioned within a tolerance of 0.5 mm to be able to achieve superior ride quality at 10 m/s^2.

Generally, the advantages for the installation fitters are:

- Clean, safe, and bright working environment.
- Being able to move the false car into position at the optimal height for drilling.
- Stable platform working area instead of open scaffolds.
- Optimal room for hoisting and positioning rails in the shaft.

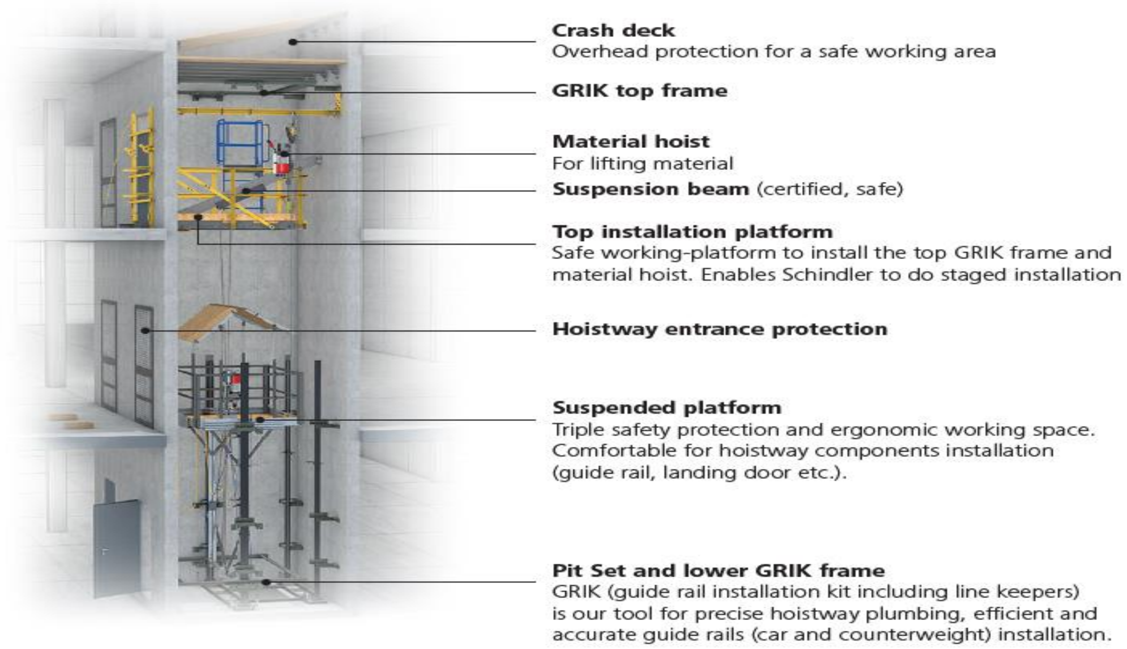

Figure 2 Scaffold-less Installation Method

Customers are often confronted with different on-site situations; solutions need to be optimised and tailored depending on the construction site requirements and progress.

A. SLIM, topped-out installation.

The machine room with a concrete slab and machine beams already exists for the suspension of the false car.

B. SLIM, staged installation.

The complete shaft platform is installed with a Lean2Beam for suspension points and the templates for the plumbing of the shaft.

This option allows for fast execution since it can be continuously moved in line with the construction of the building.

Figure 3 Scaffold-less installation method options

2.3 Digital quality assurance

During the installation process, it is important to do quality checks (QC) at each hold point to ensure the equipment is installed at the expected precision. Once the car is installed and the lift system is operational, it is too difficult to make the necessary adjustments and rail realignment.

QC1: Guide rail alignment

QC2: Landing door alignment

QC3: System Check

These checks are done fully automatically with the QC-APP which allows the quality inspector to execute the 3 checks in a paperless way, using his/her mobile phone – measurements, photos and reports will be uploaded to a cloud where they can be analysed via a power BI (Business Intelligence) solution, transparent to all stakeholders.

2.4 Climb lifts

Climb lifts are basically fully operational lift systems that utilise the permanent shaft, generally located central to the core of the building. They have a temporary machine room that moves upwards ("Climbs") in the shaft as the construction of the building progresses.

The main advantages of a climb lift are:

- The faster construction process, enabled by lifts being able to travel at higher speeds compared to the conventional rack and pinion Alimak lifts on the outside of the building.
- They are self-climbing using dedicated suspension points at the crash deck or slip from and therefore can be independent from the building site crane if required.
- Increased safety, security and comfort, especially during severe weather conditions, when generally an Alimak would be out of service. Also, the added advantage of 24-hour operation with no noise disturbance because of the central location.
- Much earlier availability of permeant lifts in the building and the fact that the façade of the building can be progressively closed to allow the customer to rent out the building on lower floors while the construction above continues.
- The methodology requires pockets at the rear wall of the lift shaft to allow the retractable support beams of the machine platform to be inserted and the front beams to remain securely on the floor slab.

The general installation method of Climb Lifts is following the same methodology as Scaffold-less installation with a false car as a suspended platform. The installation fitters can work safely from the platform of the false car, moving up and down to install the guide rails in the section above the climb lift.

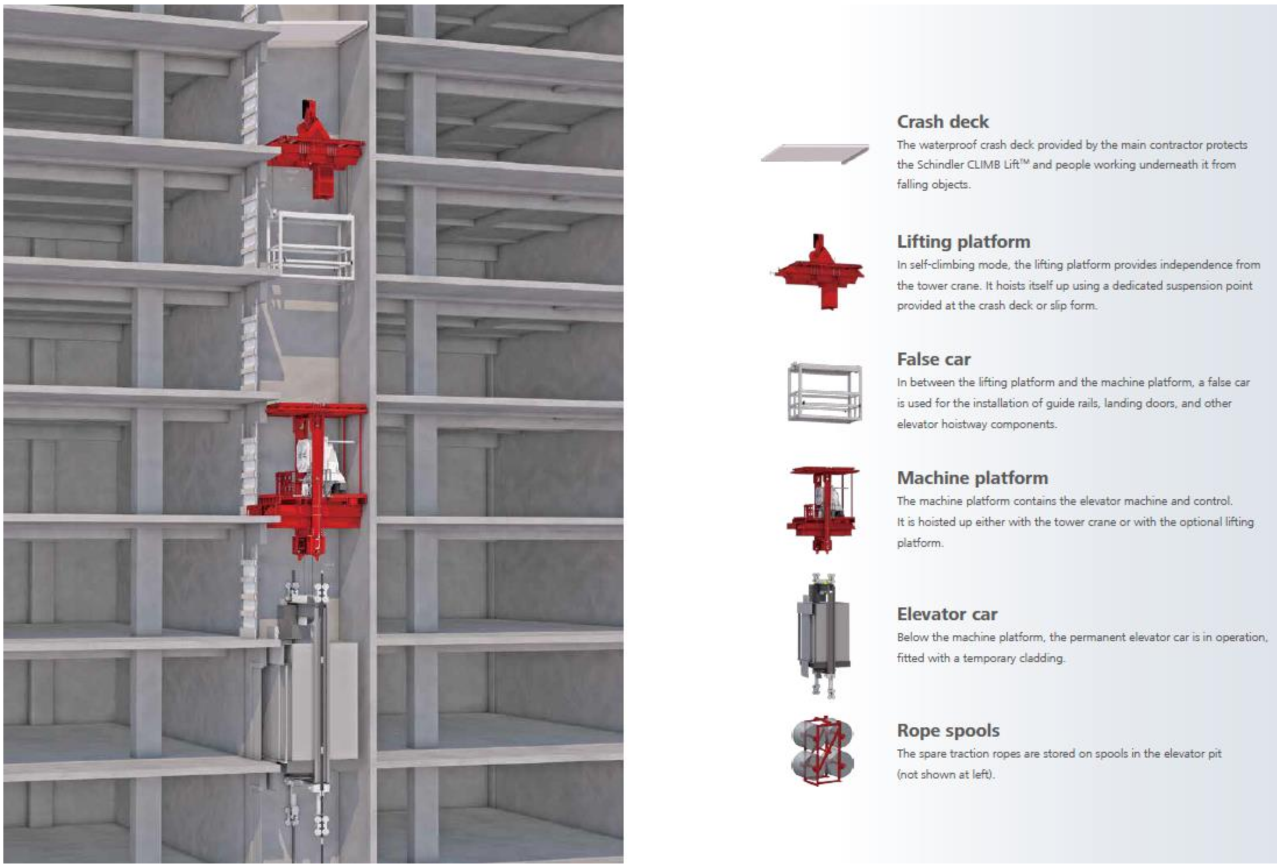

Figure 4 Climb lift installation method

2.5 Benefits of using building information modelling during installation

Building Information Modelling (BIM)[3] is defined as a collaborative way of working using digital technologies that allows all parties in a construction project to work more efficiently throughout the project life cycle (from concept design to operation). Previously pre-created families of products were supplied to clients, now this can be done by fully-coordinated BIM models with individual components that form the elevator or escalator system and contain all the relevant information used throughout the life cycle of the asset. Each of the elevators and escalators provided are tailor-made for each individual project. The uniqueness of this approach guarantees a higher level of integration and collaboration within the projects and creates personal relationships and trust in the quality of the work performed, which is positively valued by the customers, especially in large and complex jobs.

The installation of Climb Lifts is not only a technical challenge but also a fine-tuning exercise where all parties must work in unison. To assist in this process, BIM offers the possibility to time-phase the models to coordinate material installation, transportation of material within the construction site, crane operations, temporary works and more importantly, the jumps.

The use of BIM allows you to leverage the data available in traditional project management tools such as Gantt Charts (data source) and link it to specific components in the BIM models. By linking this data, the site team will get a visual overview of the project and tasks can be assigned to components, groups of components, etc. (granularity will depend on each specific scenario and the tasks to be performed). Once the model setup is finished, the site team will amend the data source when necessary and the simulation will be automatically updated to reflect the current installation status.

3 ROBOTIC INSTALLATION METHODS

As we are entering the new era of digitalization in the building industry, the question arises of how technology can support us in shaping the future of smart high-rise buildings. One answer was to look at what applications exist for robots in the construction industry and more specifically at lift installations, that require repetitive and physically demanding tasks with a high level of accuracy.

Robotic installation system for elevators (R.I.S.E), combines artificial intelligence with lift technology to make lift installations safer and more efficient with automated accuracy.

Schindler R.I.S.E consists of an industrial robot that is mounted to a moveable platform, the power supply requirements are 400 volt / 50 hertz, 30 amp, three phase + neutral + earth. The platform is winched up the shaft to the next defined drilling position, where the platform bracing system is released, locking it into position. The robot obtains the positioning data automatically from the BIM models to identify the position for drilling the holes.

The robotic arm then selects the rebar scanner to scan the shaft wall, identifying the position of the rebar under the concrete. With the information on the location of the rebar, the hole position for the rail brackets can be compared with the uploaded digital data and adjusted accordingly to avoid drilling in the rebar.

Then the robotic arm returns to the tooling station where the impact drill is selected to drill all holes at the pre-determined position. Once the holes are drilled the anchor bolts are set and pre-tightened ready for the bracket installation.

With all the holes drilled and anchor bolts set, the installation team can quickly install the rail and brackets from an installation platform like the lift car or false car.

The Schindler R.I.S.E fleet has already been successfully deployed on 4 continents, delighting our customers, main builders [4], supervisors and fitters on dozens of Schindler's large projects.

The benefits of Schindler R.I.S.E are:

- Health and safety of personnel are not compromised by being subjected to work in the shaft.
- Significant time reduction in the measuring, drilling process and anchor bolt setting.
- High precision and quality of repetitive tasks.
- Automatic documentation with installation protocol.
- Attractive job profile for the Schindler R. I.S.E operator.

Figure 5 Safe moving of Schindler R.I.S.E into hoistway

Figure 6 Automatic vertical positioning, bracing, and getting ready to operate the robot arm.

Figure 7 Wall surface scanning and obstacle avoidance.

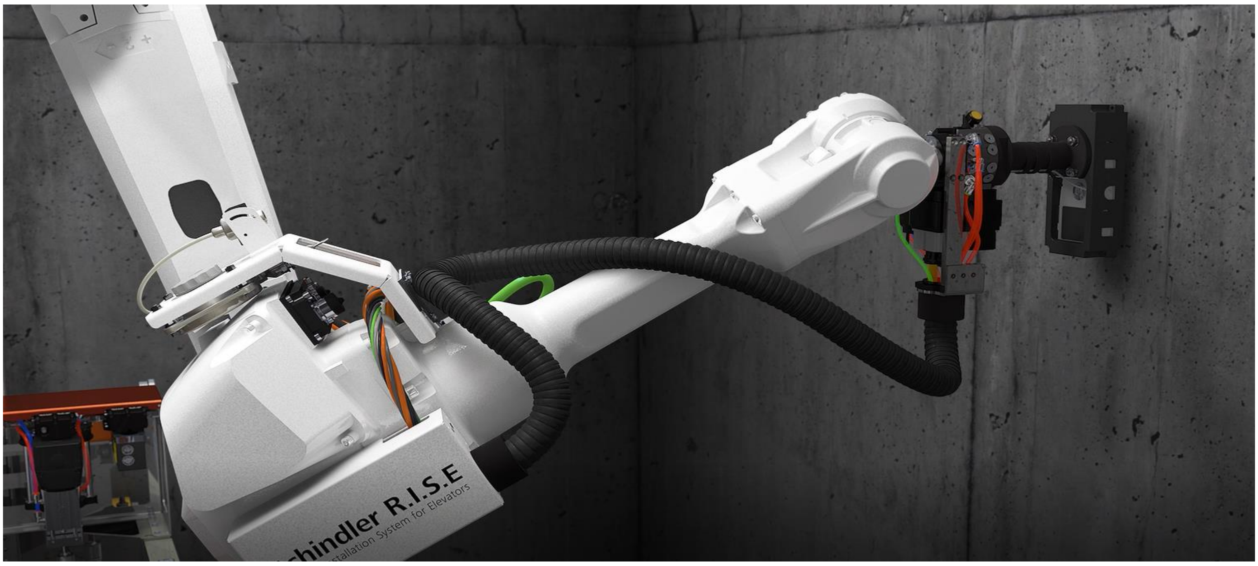

Figure 8 Drilling position calculation based on rebar/wall scan.

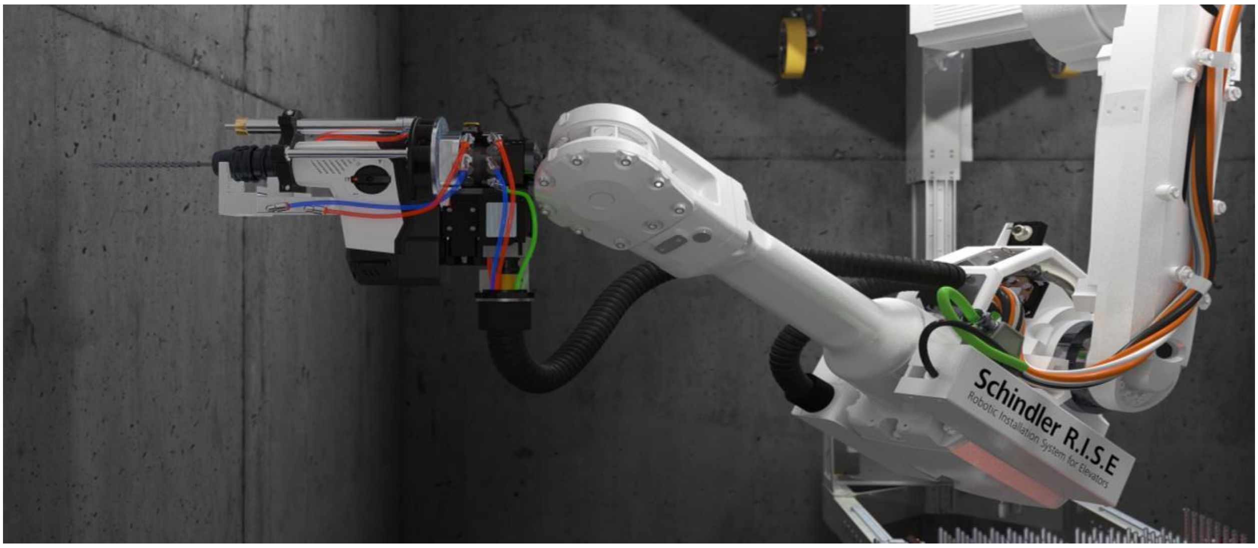

Figure 9 Drilling the holes.

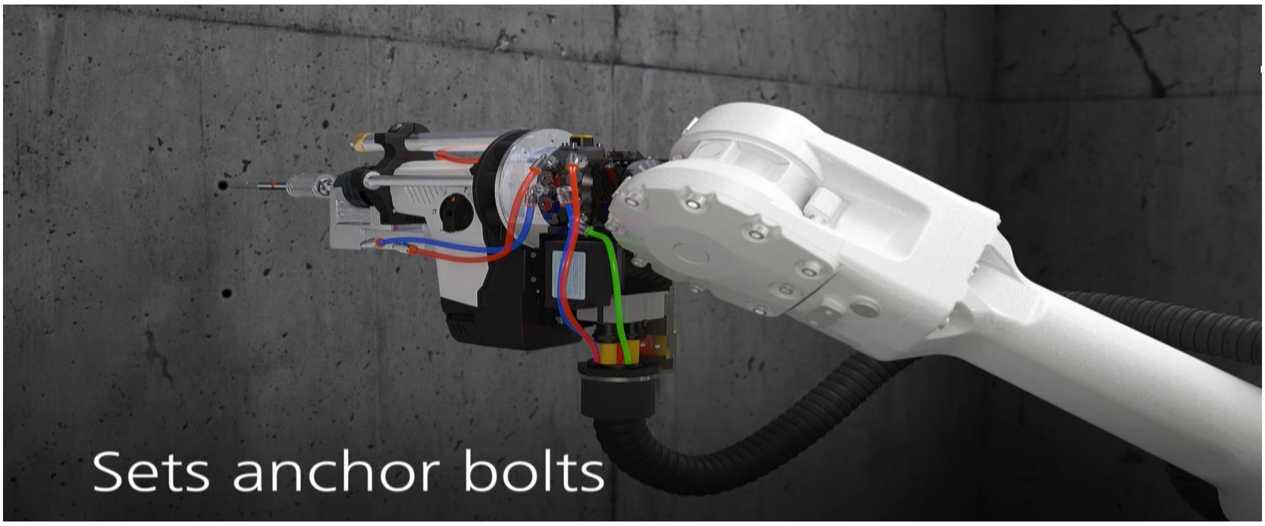

Figure 10 Setting the anchor bolt.

3.1 Schindler R.I.S.E. – Bidirectional communication

Intelligent BIM models can transfer the coordinates of the anchor bolts to Schindler R.I.S.E. This process is meant to be seamless and bi-directional, or in other words, the robot will pick up the coordinates from the BIM models and once the anchor bolt installation has concluded, Schindler R.I.S.E. will send the information of the coordinates back to the BIM models to obtain a level of accuracy of the as-built information as never seen before.

The accuracy of the information provided by the robot is made possible thanks to the state-of-the-art technology the robot incorporates. In addition to the anchor bolt setting, the robot also incorporates a laser that measures the shaft dimensions at each bracket height, as well as a rebar scanner which can detect the position reinforcement bars embedded in the concrete and reposition the anchor bolts accordingly in case of a clash, and send this information back to the BIM models once the anchor bolt setting has finished.

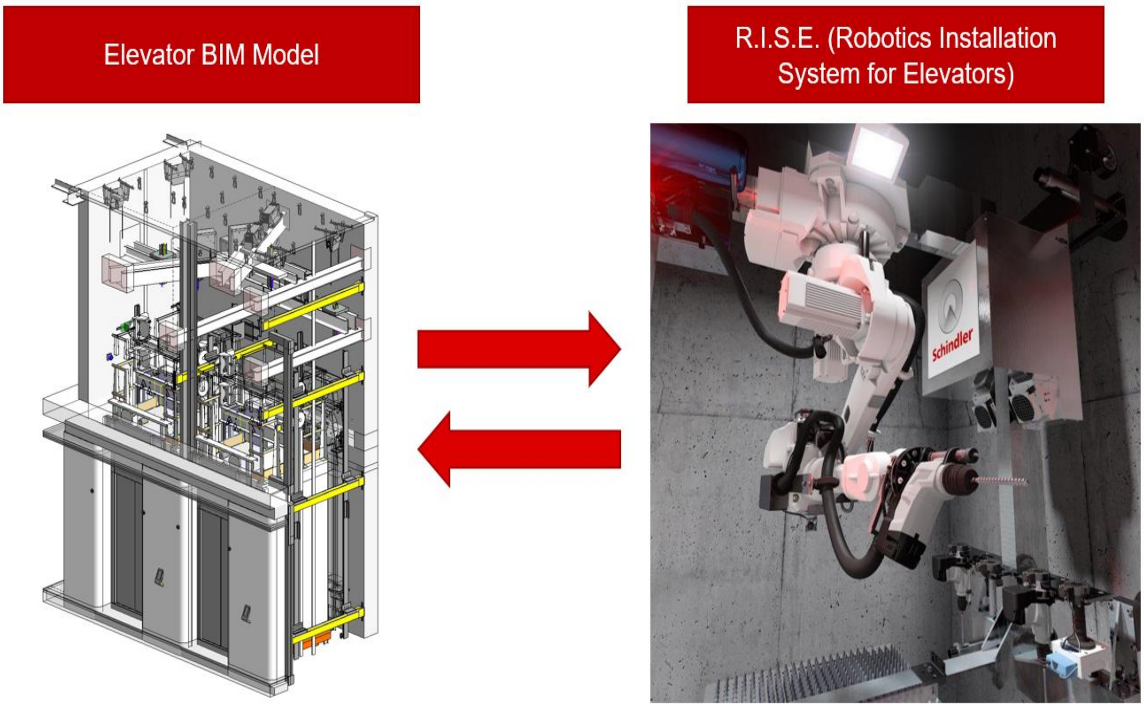

Figure 11 Bidirectional communication with BIM & Schindler R.I.S.E.

4 CONCLUSION

The vertical transportation industry has come a long way from traditional scaffold installations, with risk assessment-based installation processes. Lift shafts are harsh environments with humid and damp conditions, where the safety of employees is the main priority with any installation method. For lift systems to operate optimally, they must be installed with a high level of accuracy for the buildings that they were designed for.

The use of digital engineering, new technologies and artificial intelligence is changing the lift installation process. According to Oetterli [5], the vast range of new technologies and opportunities may also lead to a re-thinking across the construction industry about incorporating technology providers earlier into the design process for buildings, to deliver best-in-class holistic solutions for customers.

Digital innovation and state-of-the-art technologies have enhanced processes across the industry, not only in the way that internal processes and projects are delivered but also in the way that architects, developers, builders, and consultants receive information throughout the project cycle.

The future of lift installation will also see an increase in prefabricated and modular construction, where pre-assembled components can be assembled into a complete lift system.

New and future engineering development will not only benefit the customers, but the innovative technologies will also help to motivate and develop employees.

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BIOGRAPHICAL DETAILS

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Urs Püntener holds a bachelor's degree in electrical engineering and a master's degree in business management. He has 25 years of experience in the elevator & escalator business, currently in the role as the global head of Schindler's fulfilment business. He is responsible for methods, processes &

tools including digitalisation & automation for Schindler's new installation & modernisation business.

Miguel Castro is an enthusiastic young leader with 10 years of experience in a multinational and multicultural environment, fascinated by technology. He has a broad knowledge of operational processes and the application of modern digital technologies to the construction site.

Discussion on Destination Control System for Up-Peak Traffic with Non-Uniform Distribution of Passenger's Destination

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Keywords: Destination control, Sectoring, Up-peak traffic, Traffic calculation.

Abstract. Various policies are used by lift group control systems to provide good services to passengers on the main floor during up-peak traffic. One of those is the so-called destination control system, in which the destination floors covered by each car are dynamically decided based on the destination information entered by passengers at a lift hall. The destination control system is expected to improve round trip time and handling capacity. The degree of improvement depends on the distribution of passengers' destinations because the distribution affects sectoring which is the division of the building floors into groups of floors. In lift traffic design, designers usually evaluate the destination control system on only the uniform distribution. This paper shows the up-peak equations for the destination control system for non-uniform distribution. In the numerical experiments, the probability distribution is expressed as the cumulative distribution function of the truncated normal distribution with mean μ and standard deviation σ. Numerical results show that one method of sectoring is effective for uniform distributions but less effective for non-uniform distributions, and we discuss the implications of these result.

1 INTRODUCTION

Handling up-peak traffic has been a significant issue for group lift scheduling systems for a long time. This is because the passengers gather at the main floor such as an entrance floor at the same time, and queue in front of the lift in some cases. To solve this issue, the lift traffic designer uses an up-peak traffic calculation to design a lift whose handling capacity, which is the number of passengers transported by the lift, is more than the number of passengers occurring at the main floor. The handling capacity is calculated on the assumption that every car carries CAP passengers per round trip. CAP is usually the maximum number of passengers boarding a car. Thus, we can assume that $K \times CAP$ passengers occur per the round trip time, where K is the number of cars. Recently, the destination control system has been attracting attention as an advanced lift. The formulation for the destination control system is based on the conventional system and assumes to know the destination of the $K \times CAP$ passengers prior to them registering their destinations [1][2][3]. Hence, if the destination information changes, the handling capacity and round trip time for the destination control system will be affected. In practice, the probability distribution is not always uniform and changes over time due to tenants, flexes, etc. However, designers usually design based on a uniform distribution. This paper shows up-peak traffic equations for the destination control system for non-uniform distribution which is discussed based on numerical results.

2 FORMULATION FOR TRAFFIC CALCULATION

This section shows the up-peak traffic equations on the assumption that $K \times CAP$ passengers occur per the round trip time and the distribution of passengers' destinations is non-uniform.

2.1 Conventional system for arbitrary probability distribution

Barney and Al-Sharif introduce the round trip time and the handling capacity for the conventional collective control system for non-uniform distribution [2].

Let us assume that served floors above the main entrance are $\Phi = \{1,2, \dots, N\}$, and the probability of getting off on the n-th floor is expressed as $P(n)$. The probability that nobody gets off on the n-th floor is $(1 - P(n))^{CAP}$, where CAP is the number of passengers boarding one car. Since the probability that somebody gets off on the n-th floor is $1 - (1 - P(n))^{CAP}$, the expected number of stops S is calculated as follows:

$$S = \sum_{n\in\Phi}\left(1 - \left(1 - P(n)\right)^{CAP}\right) \tag{1}$$

The probability that one passenger will get off on the 1-th, 2 -th, …, n-th floors is $\sum_{m\in\Phi(n)} P(m)$, where $\Phi(n) = \{m \in \Phi \mid m \leq n\}$. If there are CAP passengers in a car who will get off on the 1-th, 2 -th, …, n-th floors, the car travels no higher than n-th floor. The probability of the car travelling no higher than n-th is shown by:

$$Q(n) = \left(\sum_{m\in\Phi(n)} P(m)\right)^{CAP}, \quad n \in \Phi. \tag{2}$$

The probability that the i-th floor is the reversal floor is $\big(Q(n) - Q(n-1)\big)$. The expected reversal floor (H) is calculated as follows:

$$H = \sum_{n\in\Phi} n\big(Q(n) - Q(n-1)\big),\ \ \mathrm{Q}(0) := 0 \tag{3}$$

According to Barney and Al-Sharif [2], round trip time RTT and HC based on (1) and (3) are expressed as follows:

$$RTT = 2 \times H \times t_v + (S+1) \times t_s + 2 \times CAP \times t_p$$

(4)1

$$HC = \frac{K \times CAP \times 300}{RTT} \tag{5}$$

2.2 Destination control system

The destination control system is dynamic sectoring and dynamic allocation [1]. The sectoring is division of building floors into groups of floors, which are called sectors. The dynamic sectoring means that the size and composition of sectors change per lift round trip. Dynamic allocation refers to the lifts being allocated to different sectors in different round trips. There are several methods of sectoring, which affects the performance of the destination control system [1][3]. In this section, we formulate equations for the destination control system on i-th round trip after sectoring.

Let us assume that the destination group control system knows in advance the destination floor probability distribution $P(n)$ for $K \times CAP$ passengers on the i-th round trip, where $i = 1,2, \dots$. The destination control can perform sectoring based on the prior information before the passengers register. Here, we set $\Omega_k^{(i)}$ as the sector allocated to car k on i-th round trip, noting the number of sectors is equal to the number of cars. Then, car k only carries passengers destined for floors included in the sector $\Omega_k^{(i)}$. Thus, the probability distribution of one passenger in the car k will get off on n-th floor is expressed by

$$\hat{P}_k^{(i)}(n) = \frac{\alpha_k^{(i)}(n)\, P(n)}{\sum_{m\in\Omega_k^{(i)}} \alpha_k^{(i)}(m) P(m)}, \tag{6}$$

where $\alpha_k^{(i)}(n)$ is a parameter for cases where one or more floors overlap, and satisfying $0 < \alpha_k^{(i)}(n) \leq 1$ and $\sum_{k=1}^{K} \alpha_k^{(i)}(n) = 1$. If only one car stops on the n-th floor, $\alpha_k^{(i)}(n) = 1$. When multiple cars stop on the n-th floor, the sum of $\alpha_k^{(i)}(n)$ for these multiple cars becomes 1.

The expected number of stops $\hat{S}_k^{(i)}$ and the expected reversal floor $\widehat{H}_k^{(i)}$ is derived from using $\hat{P}_k^{(i)}(n)$ for the process similar to Section 2.1.

$$\hat{S}_k^{(i)} = \sum_{n \in \Omega_k^{(i)}} \left(1 - \left(1 - \hat{P}_k^{(i)}(n)\right)^{CAP_k^{(i)}}\right) \tag{7}$$

$$Q_k^{(i)}(n) = \left(\sum_{m \in \Omega_k^{(i)}(n)} \hat{P}_k^{(i)}(m)\right)^{CAP_k^{(i)}} \tag{8}$$

$$\widehat{H}_k^{(i)} = \sum_{n \in \Omega_k^{(i)}} n\left(Q_k^{(i)}(n) - Q_k^{(i)}(n-1)\right) \tag{9}$$

where $\Omega_k^{(i)}(n) = \left\{m \in \Omega_k^{(i)} \,\middle|\, m \leq n\right\}$. Please note here that if $K \times CAP$ passengers hope to use the lift on the i-th round trip and $\sum_{n \in \Omega_k^{(i)}} \alpha_k^{(i)}(n)P(n) > 1/K$, $K \times CAP \times \sum_{n \in \Omega_k^{(i)}} \alpha_k^{(i)}(n)P(n)$ passengers greater than CAP hope to ride on the car k however, the car is only capable of transporting CAP passengers. On the other hand, if $\sum_{n \in \Omega_k^{(i)}} \alpha_k^{(i)}(n)P(n) \leq 1/K$, the car transports only $K \times CAP \times \sum_{n \in \Omega_k^{(i)}} \alpha_k^{(i)}(n)P(n)$ passengers lower or equal to CAP. Therefore, the number of passengers boarding the car k on i-th round trip is calculated as follows:

$$CAP_k^{(i)} = \min\left(K \times CAP \times \sum_{i \in \Omega_k^{(i)}} \alpha_k^{(i)}(n)P(i), CAP\right) \tag{10}$$

The round trip time for the destination system with respect to the car k and i-th round trip is obtained by substituting (7) and (9) for S and H in (4), respectively.

$$\widehat{RTT}_k^{(i)} = 2 \times \widehat{H}_k^{(i)} \times t_v + \left(\hat{S}_k^{(i)} + 1\right) \times t_s + 2 \times CAP_k^{(i)} \times t_p \tag{11}$$

Since the destination control system is dynamic allocation, the average round trip time for the lift on i-th round trip is written by

$$\widehat{RTT}^{(i)} = \frac{\sum_{k=1}^{K} \widehat{RTT}_k^{(i)}}{K} \tag{12}$$

K cars per one round trip carry $\sum_{k=1}^{K} CAP_k^{(i)}$ passengers during $\widehat{RTT}^{(i)}$. Here, let us define that I is the number of rounds within 5 min, which is satisfying $\sum_{i=0}^{I} \widehat{RTT}^{(i)} \leq 300$, $\widehat{RTT}^{(0)} := 0$. Then, the lift carries $I \times \sum_{k=1}^{K} CAP_k$ passengers by I round trips, and as many passengers as it can carry during $300 - \sum_{i=0}^{I} \widehat{RTT}^{(i)}$ on $I + 1$ -th round trip. Therefore, the handling capacity for the destination control system is follows as:

$$\widehat{HC} = \sum_{k=1}^{K} CAP_k^{(i)} \times \left(I + \frac{\left(300 - \sum_{i=0}^{I} \widehat{RTT}^{(i)}\right)}{\widehat{RTT}^{(I+1)}}\right) \tag{13}$$

3 NUMERICAL EVALUATION

In this section, we calculate the round trip time and the handling capacity while changing the standard deviation for the probability distribution. Firstly, we set an example of calculated building information and the probability distribution given by the truncated density function. Next, we simplify numerical evaluation. By regarding the destination control system as static sectoring and dynamic allocation, we rewrite (12) and (13). In a numerical experiment, we calculate the conventional system and the destination control system with two types of sectors.

3.1 Example of building information

We set each car as $\mathrm{K} = \{1,2,3,4\}$ and floors above the main floor as $\Phi = \{2,3, \dots ,17\}$. Table 1 is the required parameters for the calculations not yet shown above.

Table 1 Definition of parameter

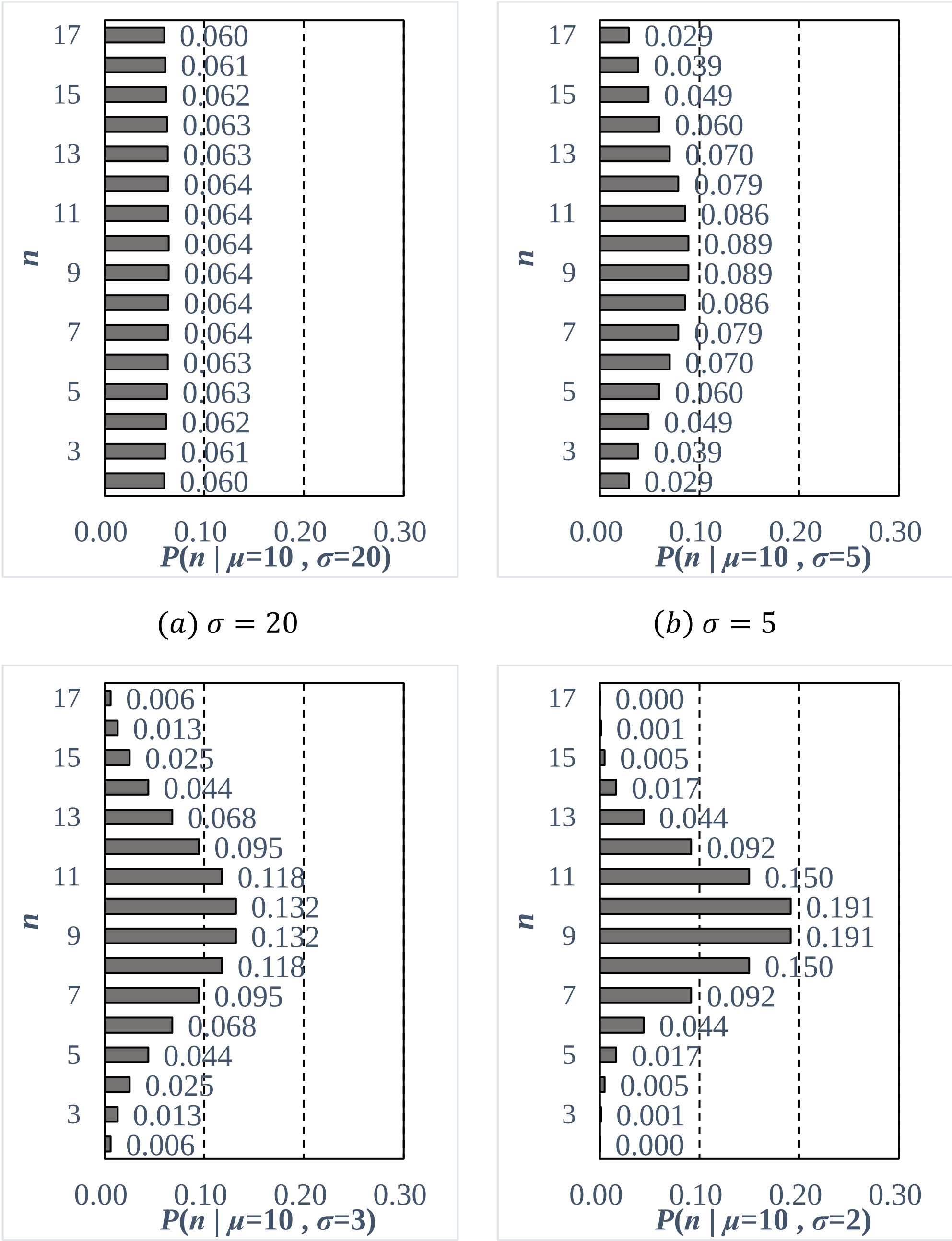
Parameter	Symbol	Value
Average interfloor distance	D_f	4000mm
Maximum number of passengers in car	CAP	20
Rated velocity	V	1.5m/sec.
Acceleration and deceleration	acc	0.8m/sec^2
Door opening time + Door closing time	t_{door}	4.3sec.
Average one-way passenger transfer time	t_p	1.0sec.

3.2 Distribution of destination floor

If the cumulative distribution function of the truncated normal distribution with mean μ and standard deviation σ is defined as $F(n|\mu, \sigma, 1 \leq n \leq N)$, the probability $P(n)$ of getting off on the n-th floor is expected to be as follows:

$$P(n|n \in \mathbb{Z}, 2 \leq n \leq N) = F(n) - F(n-1) \tag{14}$$

Figure 1 shows the distribution of the destination for $\mu = 10$ and $\sigma = 20, 5, 3, 2$. It can be seen that the lower the standard deviation σ is, the more the destination floor is clustered around the mean μ.



$(a)\ \sigma = 20$ $(b)\ \sigma = 5$

$(c)\ \sigma = 3$ $(d)\ \sigma = 2$

Figure 1 Distribution of destination floor

3.3 Destination control system for static sectoring

In lift traffic design, the handling capacity and the round trip time for the destination control system are usually calculated on the assumption that sectoring is static. Static sectoring refers to the composition of the sector as fixed on every round trip.

By static sectoring, where all sectors on the first round trip are equal to the sectors on subsequent round trips, we obtain relationships (15)

$$\Omega_k^{(i)} = \Omega_\ell^{(1)}, \quad k, \ell \in \{1,2, \dots, K\} \tag{15}$$

From (15), (12) is rewritten as follows:

$$\widehat{RTT} = \frac{\sum_{k=1}^{K} \widehat{RTT}_k^{(1)}}{K} \tag{16}$$

, where $\widehat{RTT} = \widehat{RTT}^{(i)}$. Substituting (12) as (14), we obtain

$$\widehat{HC} = \frac{\sum_{k=1}^{K} CAP_k^{(1)} \times 300}{\widehat{RTT}} \tag{17}$$

In this numerical experiment, we set two types of sectors as follows:

$$\Omega_1^{(1)} = \{2,6,10,14\}, \Omega_2^{(1)} = \{3,7,11,15\}, \Omega_3^{(1)} = \{4,8,12,16\}, \Omega_4^{(1)} = \{5,9,13,17\} \tag{18}$$

$$\Omega_1^{(1)} = \{2,3,4,5\}, \Omega_2^{(1)} = \{6,7,8,9\}, \Omega_3^{(1)} = \{10,11,12,13\}, \Omega_4^{(1)} = \{14,15,16,17\} \tag{19}$$

3.4 Numerical result

The round trip time and the handling capacity for the conventional system and destination control system with the two types of sectors are calculated based on sections 3.1, 3.2 and 3.3.

Tables 2 and 3 show the round trip time and handling capacity, respectively, when there are $K \times CAP$ passengers per each round trip. With the uniform probability distribution $\sigma = 20$, the destination control system with (19) has the best round trip time and the best handling capacity. However, as σ becomes smaller, the handling capacity becomes smaller even though the round trip time of the destination control system with (19) becomes smaller. The reason is that the round trip time and the handling capacity are calculated for the cars allocated $\Omega_1^{(1)} = \{2,3,4,5\}$ and $\Omega_4^{(1)} = \{14,15,16,17\}$ running with less than CAP passengers because of $\sum_{n \in \Omega_k^{(1)}} P(n) < 1/K, k = 1,4$. On the other hand, there are more than CAP passengers who hope to board the cars allocated $\Omega_2^{(1)} = \{6,7,8,9\}$ or $\Omega_3^{(1)} = \{10,11,12,13\}$ because of $\sum_{n \in \Omega_k^{(1)}} P(n) \geq 1/K, k = 2,3$. Thus, left-behind passengers occur.

Table 2 Round trip time

	RTT (sec.)			
	20.00	5.00	3.00	2.00
Conventional system	218.97	213.13	195.36	172.24
Destination control system with (18)	158.35	157.31	148.68	132.91
Destination control system with (19)	134.03	133.93	116.66	102.75

Table 3 Handling Capacity

	HC (persons/5min.)			
	20.00	5.00	3.00	2.00
Conventional system	109.60	112.61	122.85	139.34
Destination control system with (18)	151.48	151.96	161.20	179.75
Destination control system with (19)	177.28	152.82	139.09	127.40

The round trip time and the handling capacity of the destination control system with (18) improve as σ is small. The improvement in the round trip time is due to the lower reversal floor. Moreover, the destination control system with (18) satisfies $\sum_{n\in\Omega_k^{(1)}} P(n) \approx 1/K, k = 1,2,3,4$, for $\sigma = 20, 5, 3, 2$ so that the cars carry about CAP when they leave the main floor. Therefore, the handling capacity of the destination control system with (18) increases as σ is small.

In general, the distribution of the destination floor $P(n)$ can be calculated from the population on each floor. The population on each floor is roughly estimated on the basis of the floor space at a design time of a new building. Since the same number of people are supposed to live in the equivalent floor space, the distribution of the destination floor often looks uniform. However, in practice, the distribution is not always uniform. There is a possibility that the distribution changes with tenant replacement. Even if the distribution calculated from the population is uniform, the distribution of the passengers transported in the round trip is not always uniform, and $P(n)$ will be defined as a function of time. Furthermore, tenants often introduce flexible working time, which affects the distribution.

Although the destination control system is robust to handle the change in the distribution, if the handling capacity is insufficient, there is a possibility that a change of sectoring might reduce the line of passengers. On the other hand, if the lift traffic has been designed on the assumption of the one type of sectoring with uniform distribution in the first place, it is difficult to reduce the waiting line later, when it includes more than the expected number of passengers and the unexpected distribution of the destination floor.

In this paper, we assume that passenger destinations are known prior to the passengers registering for the lift, although in reality their destination is unknown until they register. Even if the destination control system (19) is actually applied by predicting in real time that the distribution of passenger destination is uniform, if the prediction is wrong, the performance will be degraded as well as the numerical result.

In lift traffic design, it is important to totally evaluate calculations for several types of sectors and for several probability distributions.

4 CONCLUSION

In this paper, we formulate up-peak traffic equations for the destination control system on the non-uniform distribution of passenger destination. In a numerical experiment, we calculate the round trip time and the handling capacity using the formulation on the assumption that the probability distribution $P(n)$ is the cumulative distribution function of a truncated normal distribution with mean μ and standard deviation σ and the destination control system is static sectoring. Numerical results show that even for the one type of sector with the best handling capacity in uniform distribution, it deteriorates in non-uniform distribution. This suggests that the lift traffic design with the destination control system which can be applied to several types of sectors is more robust.

5 ACKNOWLEDGEMENTS

We would like to thank Dr. Daniel Nikovski, Mitsubishi Electric Research Laboratories, U.S. for his support in preparing this paper.

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On the Mechanical Interactions in Suspension Rope – Sheave / Pulley Systems

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Keywords: suspension rope, bending stress, tensile stress, Euler-Bernoulli beam.

Abstract. Steel wire ropes employed as suspension means in lift systems are subjected to bending when passing around rigid traction sheaves/pulleys. In this paper, a suspension rope is represented as a moving Euler-Bernoulli beam and its global mechanical behaviour and interactions at the contact area are described by a nonlinear Boundary Value Problem with an unknown boundary. The problem is solved numerically for a lift system with the car suspension in a 2:1 roping configuration. The solution yields the curvature values, slope angles and the distribution of tensile and bending stresses along the rope span. It is demonstrated that the boundary angles vary during the lift travel and the distribution of stresses over the transition arc is nonuniform.

1 INTRODUCTION

Steel wire ropes (SWRs) and coated steel belts are used as suspension means in lift systems. The traction between the sheave and the suspension ropes is the fundamental consideration in the design of a traction lift installation [1]. Wire ropes have a finite life and are subject to the continual process of degradation associated with their operational conditions and stress fluctuations [2]. One of the primary mechanisms responsible for stress fluctuations is bending when the rope passes over the sheaves and pulleys. Consider the diagram shown in Fig. 1. The curvature of the suspension rope/belt increases along the rope from the point of application of tension T to the point of contact C where the curvature of the rope matches the curvature 1/R of the sheave/pulley surface. To meet the safety code requirements of BS EN81-20 the design must ensure that the ratio between the pitch diameter of sheaves and pulleys (or drums) and the nominal diameter of the suspension ropes shall be at least 40, regardless of the number of strands of the suspension ropes [3]. The suspension ropes must also meet BS EN 12385 – 5 [4] tensile strength grade requirements.

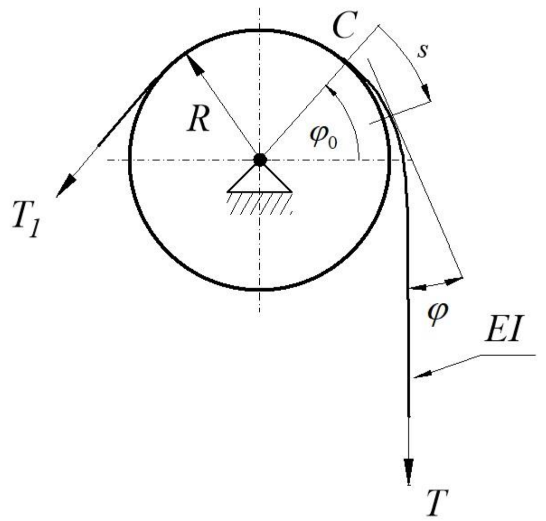

Figure 1 Rope passing over a sheave/pulley

2 EULER-BERNOULLI BEAM FORMULATION AND GLOBAL ROPE STRESSES

To determine the bending curvature, the rope can be considered as an elastic continuum and represented by a tensioned Euler-Bernoulli beam model [5]. The relationship between the bending moment M at the cross-section defined by the arc length s and the curvature κ is given by Eq. 1.

$$\kappa = \frac{M}{EI} \tag{1}$$

where EI is the bending stiffness of the rope. The curvature is equal to the reciprocal of the radius of curvature ρ and can be expressed as the rate of change of the slope angle φ along the rope arc as

$$\kappa = \frac{1}{\rho} = \frac{d\varphi}{ds} \tag{2}$$

Considering Eq. 1 and Eq. 2 the slope angle φ can be determined by solving the Boundary Value Problem (BVP) represented by the differential equation and boundary conditions defined by Eq. 3.

$$\begin{aligned} &\varphi'' - \beta^2 \sin\varphi = 0 \\ &\varphi'(0) = \kappa_0,\ \varphi'(\widehat{L}) = \kappa_{\widehat{L}} \end{aligned} \tag{3}$$

where $\beta^2 = \dfrac{T}{EI}$ and $(\ )'$ denotes differentiation with respect to s, $0 \le s \le \widehat{L}$, with $\widehat{L}$ representing the overall arc length of the rope. For small slope angles, the approximation $\sin\varphi \approx \varphi$ can be applied. Eq. 3 is then solved exactly to give the slope angle and the curvature as

$$\begin{aligned} &\varphi = C_1 e^{\beta s} + C_2 e^{-\beta s} \\ &\kappa = \varphi' = C_1 \beta e^{\beta s} - C_2 \beta e^{-\beta s} \end{aligned} \tag{4}$$

where C_1 and C_2 are constants to be determined from the boundary conditions at $s = 0,\ s = \widehat{L}$, respectively. It should be noted that the solution of Eq. 4 assumes that bending stiffness EI of the rope is constant. Once the Boundary Value Problem (3) is solved, the global bending stress in a wire of diameter d_w in the rope can be calculated by the following equation

$$\sigma_b = E\kappa \frac{d_w}{2} \tag{5}$$

where E represents the modulus of elasticity of the wire. It should be noted that this calculation provides an estimated global stress value (as first proposed by Reuleaux [6]) and assumes that the wire in the rope does not have a helix form. For a constant strand lay angle the real bending stresses in wires can be assumed to be the same as those given by Eq. 5 [6].

On the other hand, the global tensile stress in the wire rope can be calculated as

$$\sigma_t = \frac{T}{A} \tag{6}$$

where A is the global metallic cross-section area, determined as the sum of the cross-sections of all wires in the rope. While the real wire tensile stresses are larger than the global stress [6], Eq. 6 presents a useful practical estimation of the rope tensile stress conditions.

3 MOVING ROPE MODEL

For a rope–sheave/pulley system in motion the BVP (3) needs to be developed further. Fig. 2 shows a free body diagram of the rope segment of length ds. The equilibrium of forces in the normal direction and the tangential direction, respectively, yields the following equations of motion [5]

$$\begin{aligned} &\kappa'' - \frac{1}{EI}\left(T - mv^2\right)\kappa + \frac{mg}{EI}\sin\varphi = 0 \\ &T' - mvv' + EI\kappa\kappa' + mg\cos\varphi = 0 \end{aligned} \tag{7}$$

where g is the acceleration of gravity, v is the axial speed and m is the mass per unit length of the rope.

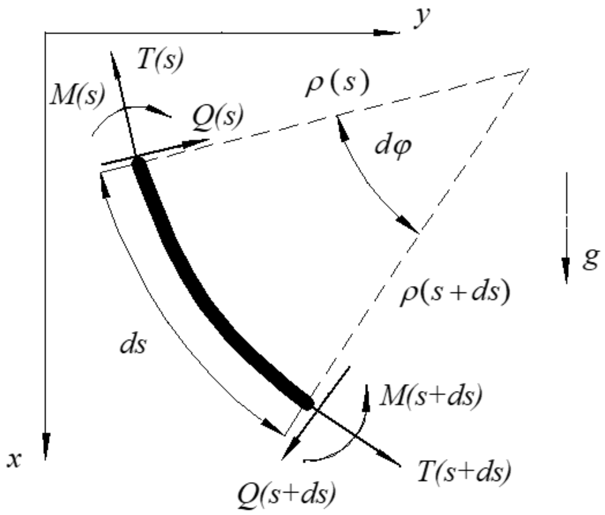

Figure 2 Free body diagram of the rope segment

By considering that the Cartesian coordinates of rope sections are expressed as

$$\frac{dx}{ds} = \cos\varphi$$
$$\frac{dy}{ds} = \sin\varphi$$
(8)

The model given in terms of Eq. 7 and Eq. 8 can be formulated as a 1st order system defined by

$$\mathbf{y}' = \mathbf{f}\left(s, \mathbf{y}; t\right), \quad 0 \le s \le \widehat{L}(t) \tag{9}$$

where t denotes time and

$$\begin{aligned} &\mathbf{y} = \left[\kappa, \kappa', T, \widehat{L}, \varphi, x, y\right]^T \\ &\mathbf{f} = \left[\kappa', \quad \frac{1}{EI}\left(T - mv^2\right)\kappa - \frac{mg}{EI}\sin\varphi, \quad mvv' - EI\kappa\kappa' - mg\cos\varphi, \quad 0, \quad \kappa, \quad \cos\varphi, \quad \sin\varphi\right]^T \end{aligned} \tag{10}$$

It should be noted that vector **y** represents unknown quantities and includes the arc length $\widehat{L}(t)$ which is an unknown boundary.

4 THE SOLUTION STRATEGY AND A LIFT SYSTEM EXAMPLE

To solve the equation system (9) the boundary conditions need to be defined. For example, consider a lift system with the suspension ropes at the car side in a 2:1 roping configuration (see Fig. 3). By taking into account the suspension rope span between points A and B, the boundary conditions are defined in Eq. 11.

$$\begin{gathered}\kappa(0)=-\frac{1}{R},\ \kappa(\widehat{L})=-\frac{1}{r},\ T(\widehat{L})=\frac{Mg}{2n_{SR}\cos\varphi(\widehat{L})},\ x(0)=-R\sin\varphi(0),\ y(0)=R\cos\varphi(0),\\ x(\widehat{L})=L-r\sin\varphi(\widehat{L}),\ y(\widehat{L})=R-r\left[1-\cos\varphi(\widehat{L})\right]\end{gathered} \tag{11}$$

where n_{SR} is the number of ropes. The solution strategy for the BVP (9-11) with the unknown time-varying boundary $\widehat{L}(t)$ involves reformulation into the 'standard' form defined over a fixed interval [7]. This is accomplished by introducing nondimensional variables defined by Eq. 12.

$$\tilde{s}=\frac{s}{\widehat{L}},\quad \tilde{x}=\frac{x}{\widehat{L}},\quad \tilde{y}=\frac{y}{\widehat{L}},\quad \tilde{\kappa}=\widehat{L}\kappa,\quad \tilde{T}=\frac{T\widehat{L}^2}{EI},\ \tilde{v}=\frac{v}{c_0} \tag{12}$$

where $c_0=\sqrt{\dfrac{Mg}{n_{SR}m}}$. The system (9-11) can then be expressed in terms of variables (12) (see Appendix) and solved numerically by the application of a collocation method for BVPs. The solution procedure involves providing the initial solution guess. For the guess, the estimations given by Eq. (4) are used and the problem is solved in MATLAB with the **bvp4c** function [8].

Table 1 Fundamental parameters

Parameter	Value	Unit
M	1800	kg
n_{SR}	4	
m	0.407	kg/m
A	42.5	mm^2
d_w	1	mm
EI	1.6	Nm^2
V	1.5	m/s
$L(0)$	2	m
R	0.28	m
r	0.25	m

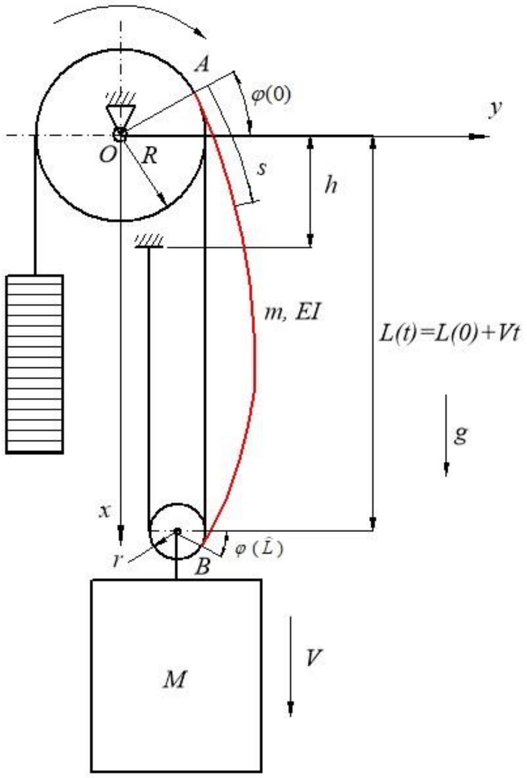

Figure 3 Lift system

5 NUMERICAL RESULTS

The system parameters used in the numerical simulations are presented in Table 1. The suspension rope is an 11 mm 8×19 S - FC rope [9], and the *EI* value is determined by laboratory vibration tests. The simulation is carried out for the lift moving down at constant speed over the time interval 0 – 5 s. Fig. 4 shows the variation of slope angles during the lift travel, determined at the contact points at $s=0$ and at $s=\widehat{L}$, respectively. The variation is small, and the plots demonstrate slightly larger values at the car pulley. The curvature changes and global bending stresses (calculated from Eq. 5) over the rope span length are illustrated in Fig. 5(a) and Fig. 5(b), respectively. Fig. 6 shows the variation of global tensile stresses (determined from Eq. 6).

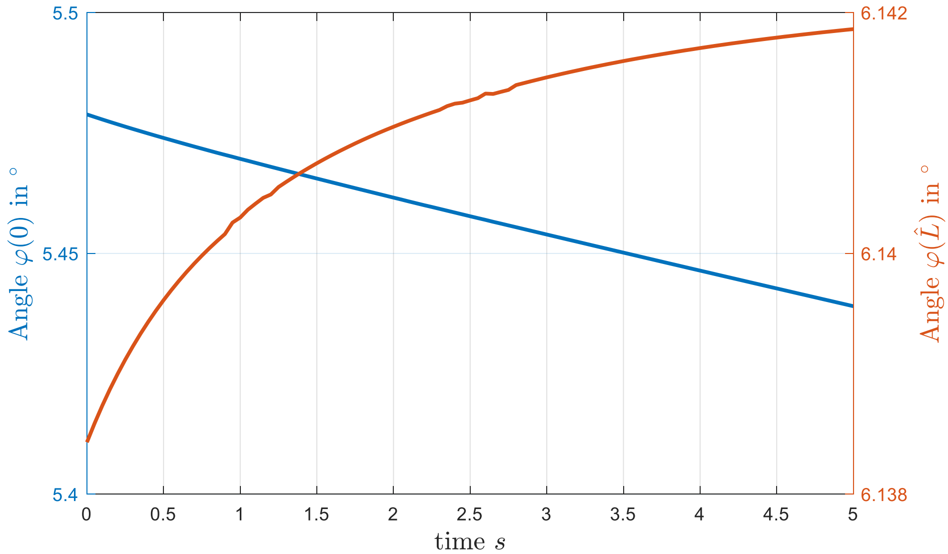

Figure 4 The slope angle at the boundary points: $s=0$ and $s=\widehat{L}$

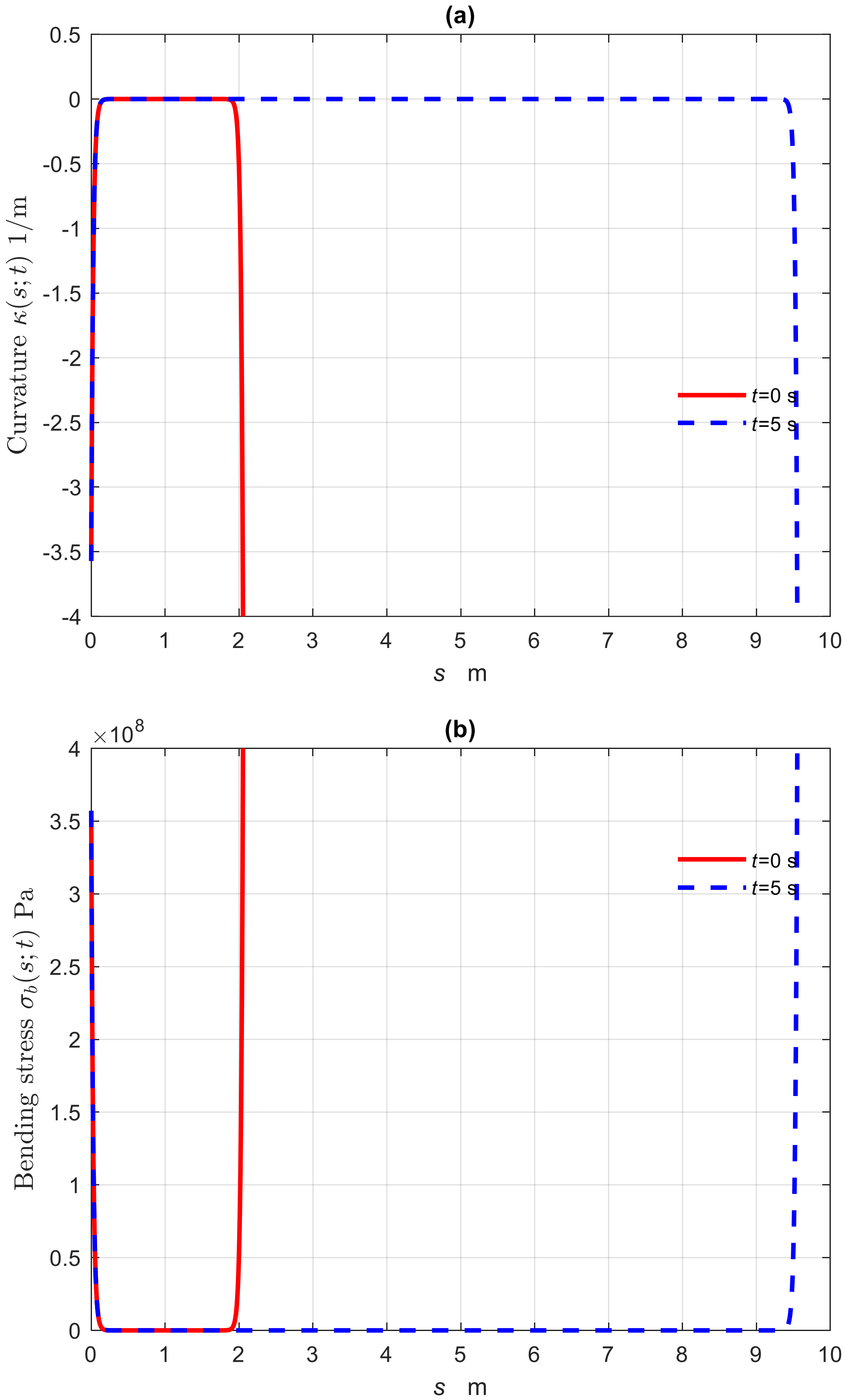

Figure 5 (a) curvatures and (b) bending stresses

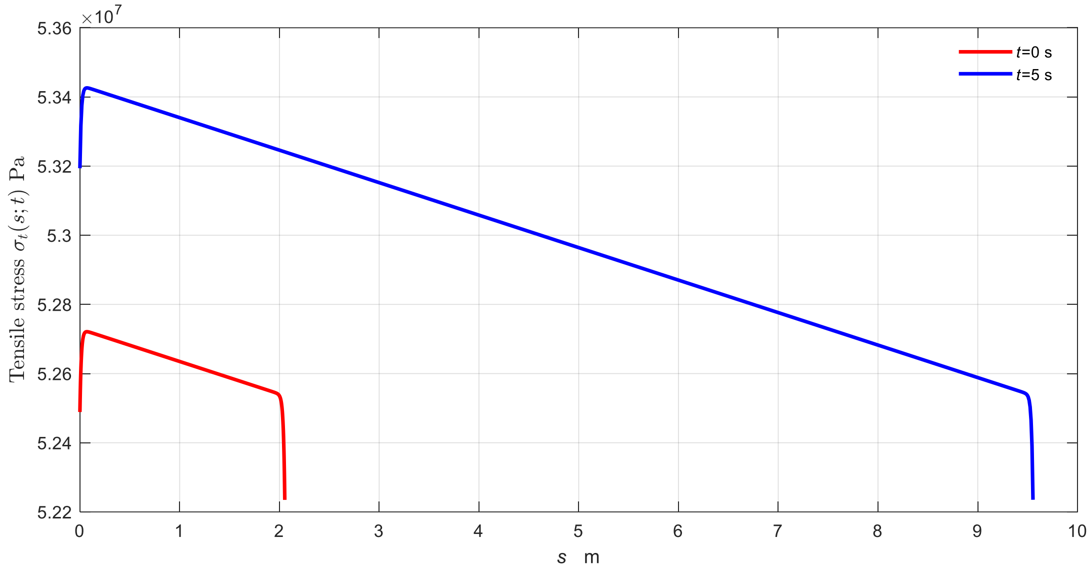

Figure 6 Tensile stresses

6 SUMMARY AND CONCLUSIONS

The work presented in this paper demonstrates a simplified model to analyse the global behaviour of lift SWR suspension ropes passing over a traction sheave/pulley system. The model is used to calculate fundamental parameters describing the performance of the ropes subjected to bending and tensile stresses. The method is based on the application of a tensioned Euler-Bernoulli beam which results in a nonlinear BVP problem. The problem can be treated by standard ODE solvers. The results show estimated bending and tensile stresses that vary along the rope length. The bending stresses can be reduced by using smaller diameter ratios between the pitch diameter of sheaves/pulleys and the nominal diameter of the suspension ropes. The lifetime/endurance of SWRs running over sheaves/pulleys can then be estimated in terms of the number of bending cycles until breakage [10].

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APPENDIX

Substituting the nondimensional parameters Eq. 12 into Eq. 7 yields [5]

$$\begin{aligned} &\tilde{\kappa}'' - \left(\tilde{T} - \beta^2 \widehat{L}^2 \tilde{v}^2\right)\tilde{\kappa} + \frac{mg}{EI}\widehat{L}^3 \sin\varphi = 0 \\ &\tilde{T}' - \beta^2 \widehat{L}^2 \tilde{v}\tilde{v}' + \tilde{\kappa}\tilde{\kappa}' + \frac{mg}{EI}\widehat{L}^3 \cos\varphi = 0 \end{aligned} \tag{A1}$$

where $\beta = \sqrt{\dfrac{Mg}{n_{SR}EI}}$ and $(\ )'$ denotes now differentiation with respect to the nondimensional variable $\tilde{s}$ defined over the fixed interval $0 \le \tilde{s} \le 1$. Eq. 10 assumes then the following form:

$$\begin{aligned} &\mathbf{y} = \left[\tilde{\kappa}, \tilde{\kappa}', \tilde{T}, \widehat{L}, \varphi, \tilde{x}, \tilde{y}\right]^T \\ &\mathbf{f} = \left[\tilde{\kappa}', \quad \left(\tilde{T} - \beta^2 \widehat{L}^2 \tilde{v}^2\right)\tilde{\kappa} - \frac{mg}{EI}\widehat{L}^3 \sin\varphi, \quad \beta^2 \widehat{L}^2 \tilde{v}\tilde{v}' + \tilde{\kappa}\tilde{\kappa}' - \frac{mg}{EI}\widehat{L}^3 \cos\varphi, \quad 0, \quad \tilde{\kappa}, \quad \cos\varphi, \quad \sin\varphi\right]^T \end{aligned} \tag{A2}$$

BIOGRAPHICAL DETAILS

Dr Stefan Kaczmarczyk is Professor of Applied Mechanics and Postgraduate Programme Leader for Lift Engineering at the University of Northampton, UK. His expertise is in applied dynamics and vibration, computer modelling and simulation with applications to vertical transportation and material handling systems. He has published over 100 journal and international conference papers in this field. He is a Chartered Engineer, elected Fellow of the Institution of Mechanical Engineers and a Fellow of the Higher Education Academy.

Vertical Transportation Design Deliverance to Iconic Buildings

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Keywords: Design deliverance, Sustainable built environment, Efficient traffic flow, Energy efficient products, IoT Deployment.

Abstract. *Objective:* "Delivering safe, healthy and sustainable built environment buildings that perform" comprehensively captures the essence of a highly efficient building. This paper showcases, from a vertical transportation point of view, one of the most prominent projects in India – 'Central Vista' – located in the heart of the national capital, which is a modern centre of national governance.

Methodology: In any VIP building, the horizontal and vertical transportation environment becomes increasingly more important and needs to be designed in the most efficient and effective way to ensure the right balance.

Main results: In this context, the paper addresses opportunities to apply new state of art technologies within a multi-disciplinary and multi-cultural environment to improve the efficiency and effectiveness of the building. The planning is done with scope for future expansion, exploring the new built typologies.

Conclusions: This paper finally provides a comprehensive outlook on presenting an in-depth analysis of state-of-the-art methodologies deployed for safe and smooth vertical transportation in terms of passenger comfort, code compliant, energy-efficient products, sustainable maintenance procedures, IoT deployment to maximise the built potential and yet be modern and Iconic.

1 BIRTH OF THE CENTRAL VISTA

During the colonial era, leading British architects Edwin Lutyens and Herbert Baker envisaged the Central Vista complex as the centre of administration in India to house all facilities needed for the efficient functioning of the Government. It was inaugurated in 1931 and comprised the buildings, Rashtrapati Bhawan, Parliament House, North and South Blocks and the Record Office (later named The National Archives), along with the India Gate monument and the civic gardens on either side of the Rajpath. The plan was designed using traditional urban planning instruments, featuring a strong axis, an emphasised focal point, the formation of important nodes, and a definitive termination point. At the time, it was one of the largest projects of its kind in the world, conceived and designed to reflect the spirit, progress and global importance of India.

Figure 1 Architect Herbert Baker **Figure 2 Architect Edwin Lutyens**

Indian influences marked the overall design of the Central Vista. It comprised the use of red and beige sandstone, which had been used for the monumental architecture of Delhi since the 13th century; the modelling of the dome of Viceroy’s House on the Great Stupa at Sanchi; ancient Indian bell capitals for the Pillars of Dominion placed between the Secretariat Blocks; and countless features of Indian architecture – jalis (pierced stone screens), chhajas (projecting overhangs), chhatris (pillared cupolas), and more.

1.1 Rashtrapati Bhavan - The Emblem of the World's Largest Democracy

The Rashtrapati Bhavan, home to the President of the world’s largest democracy, epitomizes India’s strength, its democratic traditions and secular character. Lutyens and Baker conceptualized the H-shaped building, covering an area of 5 acres on a 330-acre estate. It has a total of 340 rooms spread over four floors, 2.5 kilometres of corridors and 190 acres of garden area. Joint efforts of thousands of labourers including masons, carpenters, artists, carvers, and cutters saw the completion of this masterwork in the year 1929. Originally built as the residence of the Viceroy of India, Viceroy's House as it was then called, has metamorphosed into today’s Rashtrapati Bhavan. It is emblematic of Indian democracy and its secular, plural and inclusive traditions.

1.2 The Parliament Building - Icon of India’s Democratic Ethos

A 93-year-old Heritage-I grade building, functioning as the legislative and parliamentary hub for one of the world’s biggest democracies. An icon of India’s democratic spirit, the Parliament Building sits at the heart of the Central Vista and houses the Rajya Sabha (Council of States) and Lok Sabha (House of the People) in separate chambers in the Parliament Building. In 2006, the Parliament Museum was also added in the Parliament Library Building to showcase the 2,500 years of rich democratic heritage to the citizens.

Figure 3 Old Parliament Building

The Parliament building has, over the years, become an enduring symbol of India's thriving democracy and was notified as a Grade I heritage structure by the Heritage Conservation Committee in 2009.

The objective of the Central Vista Development/Redevelopment Master Plan is to improve the productivity and efficiency of administration by providing it with highly functional and purpose-designed office infrastructure. Some of the emergent governance benefits shall be as follows:

Combining all 51 Central Government Ministries in 10 Common Central Secretariat buildings will allow for easy movement of personnel, documents and goods, thereby increasing administrative efficiency. The proximity and ease of inter-departmental movement, along with flexible and modular floor plans will enable the government to function in a more efficient and productive manner.

The major increase in office spaces will offset the huge gap in present and future demand and existing availability. It will create modern workspaces with the latest technology for better productivity and efficient utilization of human resources. The infrastructure and facilities will be built at par with global standards. The redevelopment project will augment efforts towards sustainable development, with the construction of green buildings and clean transportation. Overall, the redevelopment will trigger efficiency and synergy in the Government's functioning.

The Prime Minister's Office, Residence and Vice President Residence are proposed to be built near the South Block and North Block respectively, in proximity to the Parliament and Common Central Secretariat, which would help in addressing security and logistic arrangements in a comprehensive manner, without interfering with the regular movement of traffic.

Public spaces shall be improved in the Central Vista, including the National Museum, IGNCA, reformed Central Vista Avenue, and India Gate plaza and lawns, which shall be accessible to the public. Around 80,000 sq. m. of government space in the North and South Blocks will open as public space due to their conversion to the National Museum complex.

An underpass within the Central Vista Avenue is also being constructed to ensure the road safety of people visiting the iconic spot while reducing traffic congestion.

People can reach the Central Vista Avenue through public transport or park their vehicles at the dedicated parking space made available at the site. Further, dedicated spaces for social gatherings in the refurbished avenue will provide opportunities to tourists for leisure and recreation.

1.3 Environmental Sustainability

Environmental Sustainability is at the core of the Central Vista Development/Redevelopment Master Plan, with a comprehensive approach to use centralised systems and infrastructure, promote the use of public transport and have upgradeable technology, systems and services. Strict measures are also being undertaken simultaneously to minimise the environmental effects of the Central Vista project during the construction phase. Steps are being taken to minimise on-site air emissions, noise, wastewater discharge, soil erosion as well as construction waste.

The projects will result in an overall increase in green cover. No trees will be cut in any project in the Central Vista. Trees will be transplanted in Eco-Park being developed by NTPC at Badarpur after due permission from competent authorities.

Figure 4 New Central Vista – Aerial view

2 GUIDING PRINCIPLES OF CENTRAL VISTA DEVELOPMENT/REDEVELOPMENT OF MASTER PLAN

2.1 Restoring the Original Symmetry and Layout of the Central Vista

The Central Vista was originally designed with strong underpinning geometry, splendid symmetry and a carefully choreographed processional route (axis, focal, point, nodes and termination). The Master Plan aims to restore the original symmetry and order while respecting the Heritage of the building and spaces.

2.2 Strengthening the Functioning of Legislature

The Master Plan proposes the first purpose-designed Parliament for independent India, equipped with state-of-the-art infrastructure to meet all the needs of an expanded Parliament. After the present building is retrofitted and refurbished, the two will be used in conjunction. In addition, a separate building to house the offices of Members of Parliament is also planned. The present Parliament building, Library and Annexe, along with the new Parliament Building and Chambers for Members of Parliament, will form an integrated Legislative Enclave.

2.3 Improving Productivity and Efficiency of Administration

The planned Common Central Secretariat (CCS) will include 10 office buildings and a Central Conference Centre. At present 39 Ministries are housed in the Central Vista, whereas 12 Ministries have offices outside the Central Vista. All 51 Ministries are envisioned to be located in 10 CCS buildings to improve coordination, collaboration and administrative synergies. The office spaces are being planned with modern technological features and adequate space with amenities. The present buildings of the Central Vista shall be replaced with modern office buildings with the capacity to hold about 54,000 personnel, which will meet the present and future needs of the Ministries/ Departments. All these offices are planned to be connected through a loop of automated underground people-mover, over-ground shuttles and walkways. These buildings will come up through the redevelopment of existing Central Secretariat Offices like Udyog Bhawan, Nirman Bhawan, Krishi Bhawan, Shastri Bhawan, etc. located on either side of Rajpath. Further, the Defence Enclave has been planned in order to consolidate the multiple Departments and attached offices of the Ministry of Defence, including the Defence Research and Development Organisation (DRDO), Department of Defence Production and Offices of the Indian Armed Forces i.e. Indian Army, Indian Navy and Indian Air Force. Overall, the Secretariat will house modern offices, and conferencing facilities for all Ministries of the Government of India.

2.4 Conservation and Rejuvenation of Cultural and Heritage Facilities

The Central Vista Avenue will be refurbished, its infrastructure upgraded, and new social amenities will be provided, while retaining its essential character, to make it more comfortable to use and of a befitting quality, with adequate infrastructure for national events. The magnificent North and South Blocks will be refurbished to house the National Museum. They will house exhibits of 'India up to 1857' and 'India since 1857' respectively. The IGNCA will continue its important cultural agenda, at a new location opposite Hyderabad House on the Hexagon, in expanded, purpose-designed, world-class facilities. Further, a purpose-designed facility is also envisioned beside the historic building of the National Archives of India (NAI) for creating state-of-the-art facilities.

2.5 Providing Adequate and Secure Infrastructure for Executive Offices

A modern, secure and appropriately-equipped Executive Enclave is planned to house executive offices and facilities for the Prime Minister's Office, the Cabinet Secretariat and the National Security Council Secretariat. Secure residential facilities for the Vice President and the Prime Minister are planned behind the North and South Blocks, with all necessary amenities for their day-to-day functioning.

2.6 Ensuring Environmental Sustainability, Expanding Public Space and Extending the Central Vista Axis

The overall objective of works planned on the Central Vista is to ensure environmental sustainability, expand and improve public space, and to extend its axis. The New India Garden is being planned near the River Yamuna. thereby extending the present Central Vista axis by 2.24 km to realise the vision of 'Ridge to River'. Further, a publicly-accessible National Biodiversity

Arboretum is planned to the west of the President's estate, to showcase endangered plants of India in high-tech greenhouses set amidst indigenous forestation.

Figure 5 Ensuring environmental sustainability

2.7 Providing Adequate and Secure Facilities for the Vice President and the Prime Minister

Modern, adequate and secure residential facilities for the Vice President and the Prime Minister are planned to the north of North Block and south of South Block respectively. These new residential facilities will be highly functional and equipped with all the necessary amenities. Locating offices and residences of all dignitaries in a single location will reduce redundancies of infrastructure and improve city traffic management.

2.8 Promoting Transit Oriented Development

The Central Vista Development/Redevelopment project has been envisaged by integrating the principles of transit-oriented development. An Automated People Mover of approximately 3.1 km in length will be constructed underground to connect and integrate all the buildings of the Common Central Secretariat. It will run in a close loop to satisfy the transportation requirement of Government employees working in these buildings. It will provide connectivity to the existing Metro Network at Udyog Bhawan and Central Secretariat Stations at the Yellow and Purple lines of the Delhi metro which has onward connectivity to the National Capital Region (NCR) and that will reduce the need to commute to the office using private vehicles. All the buildings of the Central Secretariat will be connected to each other and to Delhi's metro network via a secure underground people mover and with the city's bus network via a grade shuttle. As a result of the uptake of shared transit facilities, overall emission and air pollution level from personal vehicles is expected to reduce, resulting in the improvement in the overall air quality of the capital city.

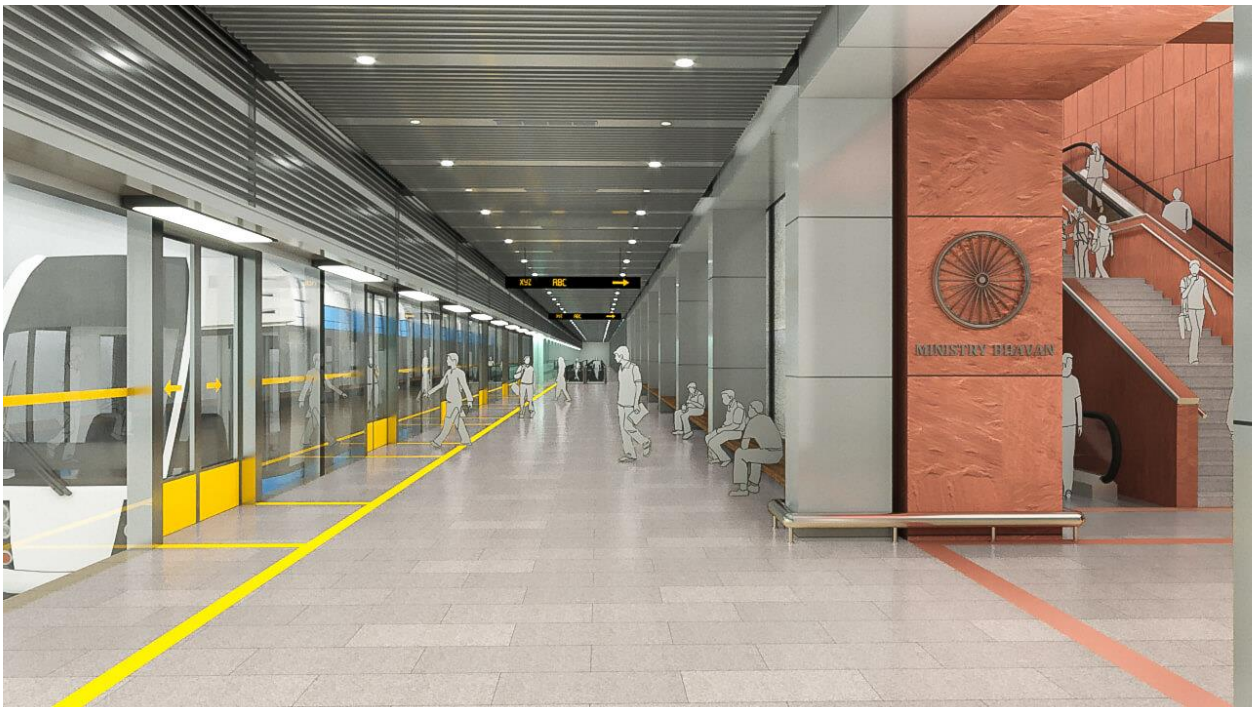

Figure 6 Transit Oriented development

3 HORIZONTAL AND VERTICAL TRANSPORTATION PLANNING -CASE STUDY - CENTRAL SECRETARIAT

Central Vista, located in the heart of the national capital, is a modern centre of national governance, consisting of new secretariat buildings located in four clusters along the Rajpath. The first Cluster of 3 Central Secretariat Buildings is a G+6 storied building with 2 basement levels connecting three individual towers and is designed to house a population of 5750 people in each tower.

3.1 Scope

This report covers input data, assumptions, design criteria for simulation and recommendations for lifts and escalators for the cluster of 3 central secretariats.

3.2 Inputs data and assumptions

i. Area Statement and population of the building
ii. Architectural Floor plans and sections
iii. Lift design data:

a. Project Traffic Study Data

Name of building:	Central Secretariat
No. of floors:	2 Basements, Ground +6 floors
Occupancy type:	Office / Business
Design with or without Machine Room:	Machine Room Less (MRL)
Building construction status:	Scheme/design stage

Lifts serving terrace: No

b. Lift Floor Height Details:

	OVER HEAD	
6	4575	OFFICE
5	4575	OFFICE
4	4575	OFFICE
3	4575	OFFICE
2	4575	OFFICE
1	4575	OFFICE
G	4575	MAIN ENTRY
B1	6900	BASEMENT-1 PARKING
B2	4500	BASEMENT-2 PARKING
FLOOR		

c. Population Details for Each CS Building:

Population : 5750

Floating population (Visitors considered at 20% of population) : 1150

Total Population considered : 6900

Total users during peak : 90%

Total no. of users in peak : 6210

population considered per zone (4 zones): 1553

FLOOR WISE POPULATION	
6	1000
5	1000
4	950
3	950
2	950
1	450
G	450

d. Assumptions:

Parameters	Variables
Tenancy	Multi Tenancy as Floors Would Be For Different Departments
Total Population Given	6900 - including floating population
Population Consideration For Traffic Study	90% Occupancy
Door Open Time	Variable
Door Closing Time	Variable
Passenger Entry/Exit Time	Variable
Avg. Highest Floor Reached	Variable
Avg. No. of Stops Made	Variable

e. Assessment of Peak Demand:

Parameters	Variables	Assumptions
Occupancy of the building	5750	
Staff arriving from metro	2875	Assumed 50%
Staff arriving from car	1438	Assumed 25%
Staff arriving by bus	575	Assumed 10%
Staff using APM	3163	Staff from metro & 50% from Bus are assumed using APM
Staff using basement car parks	719	50% of car park staff from basement are assumed
Total staff from basements to the ground floor	3881	

f. Arrival Rates Assumptions in Peak Hour on the Ground floor

Parameters	Variables
Staff from basements to the ground floor	3881
Staff arriving directly on the ground floor	1869
TOTAL POPULATION	5750
Consider floating population	1150
Total Population consideration	6900
90% Occupancy	6210
Population arrival per zone	1553
Peak burst arrival assumed in 5 minutes during morning up peak (Considering rapid APM arrivals)	311
Arrival rate demand% considered during peak burst arrival in morning up peak	20.0%

4 MORNING UP PEAK

- People using the metro shall use the APMs to arrive at the basement floors.
- People using their own transportation shall park on the basement floors.
- From basements, people shall reach the ground floor using escalators and basement parking lifts provided to travel from the basement floors to the ground floor. They shall then take the main passenger lifts in their respective zones to reach their destination floor.
- Main passenger lifts are not accessible in the morning hours for use. They shall be accessed from the ground floor only.
- The people arriving by other means of public transport shall directly enter the ground floor and take the main passenger lifts to their destination floor.

5 CONCEPT DESIGN RELATED INFORMATION

5.1 Passenger Lifts:

The design has 4 passenger lifts (2+2) with 4 zones of lifts in 4 corners of the building. Traffic study results are based on a per-zone basis.

5.2 Fireman’s Lifts:

On all 4 corner zones of the buildings, there are 2 independent lifts per zone. These 2 lifts shall be specified/designated as Fireman’s lifts but can be used as service lifts regularly.

5.3 Basement Parking Lifts

These 4 lifts (2 North wing & 2 South wing) shall be in addition to escalators.

5.4 Cafeteria Lift

This lift shall be used to carry cooked food from B1 to the ground and first-floor cafeteria.

5.5 Escalators

Escalators are provided for rapid passenger movement from basements to the ground floor.

6 BIOGRAPHICAL DETAILS

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With over 29 years of experience, Kumar is heading one of India's leading vertical transportation consulting firms, L'Avenir lift consultancy associated with various landmark projects in India with vertical transportation consulting services and 6000+ units under consulting base currently. Chairman, ISHRAE Vertical transportation sub-committee for preparing Energy performance standards for Buildings in India. Member of IGBC (Indian Green Building Council) core committee, Bangalore. Publisher and Managing Editor of premium elevator magazine L'Avenir Elevator Digest. L'Avenir Elevator Digest is a premier digital magazine on the latest in technology in the field of vertical transportation.

Activities and Results of the Rope Vibration Analysis Working Group in the Japan Society of Mechanical Engineers

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Keywords: Wire rope, Vibration, Simulation, Seismic response, Earthquake

Abstract. Resonance of wire ropes or cables in a lift due to earthquakes and strong winds is a critical event for the safe operation of the lift, because if the ropes catch equipment in a shaft by the resonance, the passengers will be trapped and it will take a long time to rescue them. To prevent damage caused by rope vibration or resonance, it is important to estimate the vibration of ropes by simulation analysis in advance. However, the simulation method of rope vibration is complicated because it consists of various eigenmodes, the tension is not constant due to its own weight, and it is influenced by various factors, resulting in nonlinear vibration. Therefore, the Panel of Elevator Safety and Reassurance of the Japan Society of Mechanical Engineers (JSME) established the Rope Vibration Simulation Working Group. The working group studied simulation methods for rope vibration. This paper reports on the activities and results of the working group.

1 INTRODUCTION

Lifts are an important facility for high-rise buildings. However, lift ropes such as hoist ropes for suspending cages and counterweights and governor ropes for detecting overspeed have become longer, causing vibration-related problems. For example, in the Great East Japan Earthquake, rope snagging is one of the main causes of earthquake damage, and 24% of the damage to lifts was caused by rope snagging [1]. In addition, lift ropes in skyscrapers in Osaka Prefecture, 700 km from the epicentre, resonated, causing damage such as trapping of passengers [2].

When buildings resonate due to earthquakes or strong winds, the rope ends are forced to vibrate, and if the natural period of the building is close to that of the rope, there is a risk of resonance, which can cause snagging of ropes on rail brackets or other equipment in the hoistway. In addition, the early earthquake warning for long-period seismic motion has been put into operation in Japan since February 2023 [3], and lift control is one of the examples of its use, so resonance of the long ropes in lifts by earthquake is one of the important phenomena at present. The first step in preventing such damage is to properly estimate the response of the rope. Given the size and variety of buildings and lifts, simulation analysis is suitable for estimation of the rope vibration.

When performing simulation analysis, lift ropes can be represented by a string with time-varying length and location-varying tension, so partial differential equations have to be solved numerically, which requires a high level of expertise. As a result, vibration response analysis of ropes in lifts is carried out using each company's own methods or special calculation tools, and no generic, simplified method has been established that can be used throughout the industry.

From this background, the Panel of Elevator Safety and Reassurance of the Japan Society of Mechanical Engineers (JSME) established the Rope Vibration Analysis Working Group to investigate analytical methods for rope transverse vibration, to publish for various manufacturers and researchers, and to share and develop knowledge regarding rope vibration analysis. Firstly, the working group investigated vibration analysis methods and techniques related to wire rope vibration that have already been proposed. Then damping ratio of the wire rope, which is an important factor in determining the vibration amplitude, was investigated from the literature. Then seismic response analysis was carried out. This paper describes an overview of the activities and results of the Rope Vibration Analysis Working Group in the Japan Society of Mechanical Engineers.

2 ABOUT THE ROPE VIBRATION ANALYSIS WORKING GROUP

The Rope Vibration Simulation Working Group is a part of the Panel of Elevator Safety and Reassurance in the Transportation and Logistics Division, in the Japan Society of Mechanical Engineers (JSME).

The JSME, founded in 1897, is a Japanese society for mechanical engineering with more than 30,000 members, including researchers, engineers, teachers, students and so on. The JSME aims to improve and exchange the academic knowledge of the members and to return technological outcomes to society by publishing journals, bulletins, and textbooks, or by organising conferences, workshops, lectures, and international cooperation. The JSME has 22 technical divisions such as fluids engineering, thermal engineering, dynamics and so on, where more specialised discussions and activities are conducted.

The Transportation and Logistics Division is one of the technical divisions in the JSME and deals with technologies and research related to railways, automobiles, aerospace, ships, lifts, escalators and other vehicles. The Transportation and Logistics Division has 5 panels for further specialised and detailed discussions.

The Panel of Elevator Safety and Reassurance was established in 2011 to investigate and analyse issues related to lift and escalator technology. The Rope Vibration Analysis Working Group was established as a part of the Panel of Elevator Safety and Reassurance to investigate analytical methods and techniques related to wire rope vibration from 2015 to 2021. About 10 members, who are engineers or researchers from lift manufacturers and universities, participated.

3 INVESTIGATION OF ROPE VIBRATION ANALYSIS

3.1 Investigation of Analytical Methods

Firstly, the working group investigated the methods of rope vibration analysis that have already been proposed. According to the literature survey, the following 4 methods have been mainly proposed.

The first one is a method that expresses the rope vibration in the wave equation with time-varying length [4, 5]. The wave equation is calculated numerically by using the finite difference method. The second is a method that uses a single-degree-of-freedom model derived from the wave equation [6]. The vibration modal shape is assumed to be a sinusoidal wave, and the equation of motion is calculated numerically using the Newmark β method. Recently, an improved method of this one using the single-degree-of-freedom model has been proposed, which takes into account the coupling with the vertical motion of the cage [7]. The third one is a method using a multi-body dynamics model [8], which expresses a rope in many rigid elements connected with rotational springs and dampers. The fourth is a method using a finite element method [9].

Table 1 shows the comparison of the above methods for rope vibration analysis. The accuracy of the methods based on the wave equation, multi-body dynamics and finite element method is very good because they can represent the motion of each part of the rope, tension distribution, and interaction between vertical motion in detail. However, the method replaced with a single-degree-of-freedom model has a slightly lower accuracy compared with other methods, because the tension distribution and higher-order modes cannot be considered in exchange for the simplicity of the model. Methods based on multi-body dynamics and a finite element method require special software or computer programs to solve the vibration response. In addition, it is necessary to set the spring constants and the damping coefficients of a rope, which are difficult to determine from the rope specifications prior to numerical analysis. On the other hand, methods based on the wave equation and the single-degree-of-freedom model are easy to apply to vibration response analysis and have sufficient accuracy. Therefore, the working group specially focused on the methods based on the wave equation and the single-degree-of-freedom model.

Table 1 Comparison of rope vibration analytical methods

	Wave Equation	Single Degree of Freedom	Multi-body Dynamics	Finite Element Method
Accuracy	Very good	Good	Very good	Very good
Difficulty	Easy, but relatively difficult if car movement and tension distribution are considered	Easy	Difficult, calculation of spring constant and so on are required	Difficult, calculation of spring constant and so on are required
Generality	High	High	Special software is required	Special software is required

3.2 Investigation of Damping Ratio

The damping ratio of ropes is a very important parameter that directly determines the response amplitude. For example, if the damping ratio doubles, the response amplitude at resonance is halved. Therefore, the damping ratio of the transverse vibration of the rope was investigated in a literature survey.

Kimura et al. conducted free vibration experiments on full-scale hoist ropes to determine the damping ratio of the ropes [10]. The results showed that the damping ratio was generally 0.2%, although there were differences depending on the length and diameter. Kaneko et al. also conducted free vibration experiments on full-scale hoist ropes and the damping ratio of the ropes was 0.38% [8]. Crespo et al. used 0.3% of the modal damping ratio for their simulation analysis [11].

In addition, Utsuno [12] found that the damping of ropes obtained by experiment was smaller than the actual damping and investigated the effect of air resistance on rope vibration.

4 VIBRATION RESPONSE ANALYSIS

4.1 Analytical Procedure

Based on the above investigations, a transverse vibration response analysis was carried out in the working group. The working group adopted the following wave equation method, which is accurate and does not require special software.

$$\rho A\left(\frac{\partial^2 u}{\partial t^2} - 2V\frac{\partial u}{\partial t\partial z} + V^2\frac{\partial^2 u}{\partial z^2}\right) + C\left(\frac{\partial}{\partial t} - V\frac{\partial}{\partial z}\right)u - \frac{\partial}{\partial z}\left[T(z,t)\frac{\partial u}{\partial z}\right] = 0 \tag{1}$$

Where t is time, z is a spatial coordinate whose origin is the top of the building, $u(z,t)$ is the transverse displacement of the rope, ρA is a linear density of the rope, V is the velocity of the cage and C is the damping coefficient of the rope. As shown in Fig. 1, the tension $T(z,t)$ takes into account not only the distribution due to the weight of the rope itself, but also the variation due to the vertical motion of the car. The parameters shown in Table 2 were used. Theoretical natural frequencies f_n in Table 2 were calculated using the following formula for natural frequency of simple string vibration that takes into account the average tension due to the rope's own weight.

$$f_n = \frac{n}{2l}\sqrt{\frac{T_0 + \rho A g \frac{l}{2}}{\rho A}} \tag{2}$$

Where n is an order of vibration, l is the length of the rope, T_0 is the vertical load by weight of the car and g is the gravitational acceleration. The numerical analysis was carried out using the finite difference method.

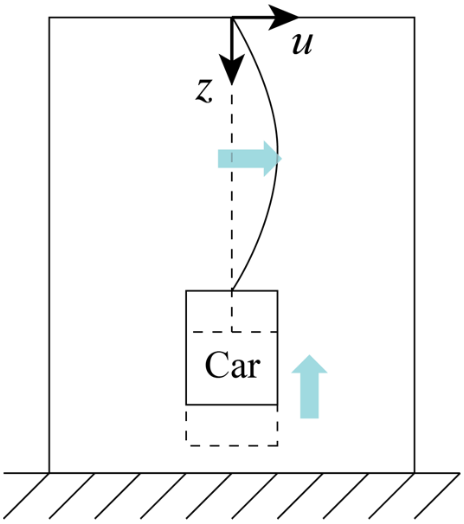

Figure 1 Comparison of resonance curve with the single-degree-of-freedom model

Table 2 Parameters of rope

Vertical load by car T_0 [N]	1960
Length l [m]	50
Linear density ρA[kg/m]	0.494
Damping ratio ζ [%]	0.2
Theoretical natural frequency f_n [Hz]	0.65, 1.30, …

4.2 Comparison with Single Degree of Freedom Model

To verify the accuracy of the simple method using the single-degree-of-freedom model, a comparison with the wave equation method was conducted. The single-degree-of-freedom model has the same natural frequency and damping ratio as the rope, namely 0.65Hz and 0.2%, respectively. Figure 2 shows the resonance curves for each method when a sinusoidal waveform is input. The result of the modal analysis, which extended the single-degree-of-freedom model to 5th order mode, is also shown in Fig. 2. The maximum response displacement of the rope decreases as the vibration mode increases for the same input acceleration, so vibration modes should be considered up to 4th or 5th order modes. Note that the vertical motion of the car is not taken into account here, because nonlinear vibration occurs if it is taken into account as described below.

As shown in Fig. 2, the result by the single-degree-of-freedom model for the first-order mode around 0.65 Hz is in agreement with the result by the wave equation and is sufficiently accurate. The result by the modal analysis also accurately represents the second-order mode around 1.30 Hz, although the amplitude is smaller than the result by the wave equation because the tension distribution is not considered. As discussed below, the response of the ropes becomes smaller when the vertical motion of the car is taken into account, so the single degree of freedom method estimates a larger response than the actual response, because the single degree of freedom model does not take into account the vertical motion of the car.

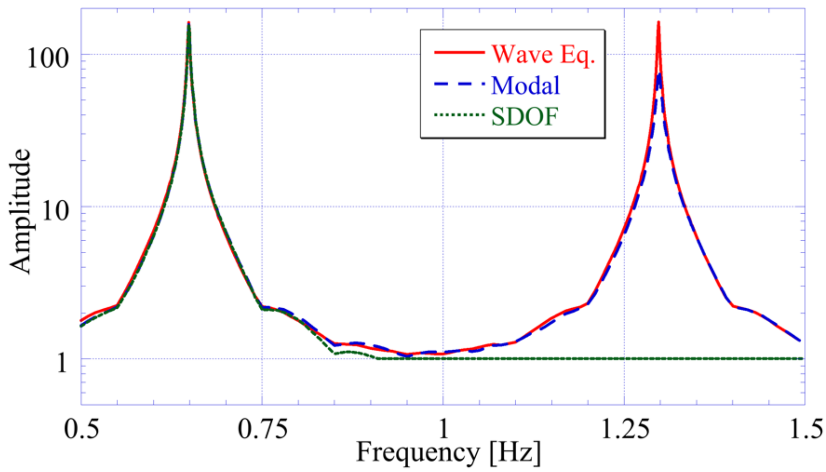

Figure 2 Comparison of resonance curve with the single-degree-of-freedom model

4.3 Influence of Vertical Motion of Car

In the vibration analysis of ropes, the amplitude at resonance is particularly important. Generally, the amplitude of a vibration system strongly depends on the damping ratio of the system, but according to experiments in the past, the actual response amplitude tends to be smaller than that estimated by the damping ratio obtained from free vibration tests. Assuming that the elongation of the rope is very small, the car moves upwards by the transverse vibration of the rope. The inertia force based on such a cage movement should cause variation in the rope tension. Therefore, the vertical motion of the car was taken into account in this section, and the effect of the vertical motion of the car on the response was investigated.

In this section, the vertical elongation of the rope and its attachment was ignored. This means that the displacement of the car z_{car} is calculated geometrically using the following equation.

$$z_{car} = l - \sum_{i=1}^{N-1} \sqrt{\Delta z^2 - (u_{i+1} - u_i)^2} \tag{3}$$

Where l is the length of the rope, Δz is the length of each element of the rope in the finite difference method, N is the number of the rope elements and u_i is the transverse displacement of the ith element of the rope. Then the vertical acceleration of the car $\ddot{z}_{car}$ was calculated from the second time derivative of the displacement z_{car}, and the inertia force by the vertical acceleration $\ddot{z}_{car}$ was considered in the tension of the rope at each step.

Figure 3 shows the influence of the vertical motion of the car on the resonance curve. As shown in Fig. 3, the amplitude and frequency at resonance decrease as the input displacement increases. This tendency is similar to that of nonlinear vibration, and the variation of tension caused by the vertical movement of the cage acts as a soft spring.

Figures 4 and 5 show the influence of the vertical motion of the car on the maximum amplitude and resonance frequency. As shown in Fig. 4, the maximum amplitude decreases rapidly and then converges as the input displacement increases. As shown in Fig. 5, the resonance frequency slightly decreases as the input displacement increases.

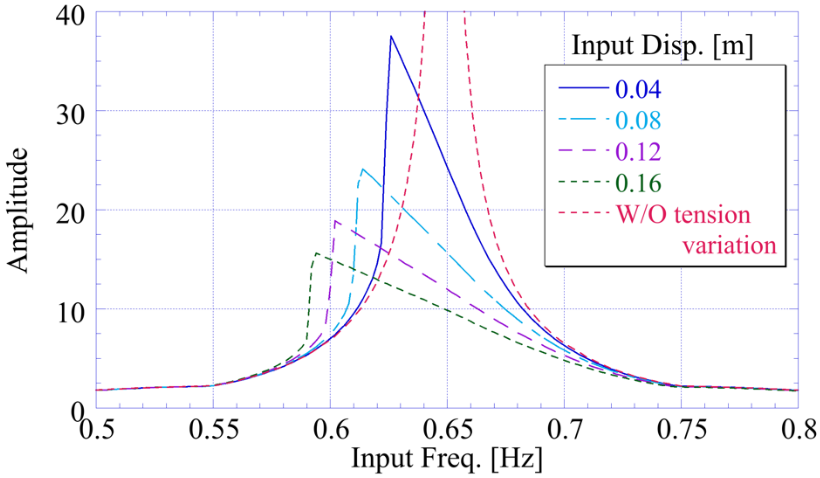

Figure 3 Influence of vertical motion of car on resonance curve

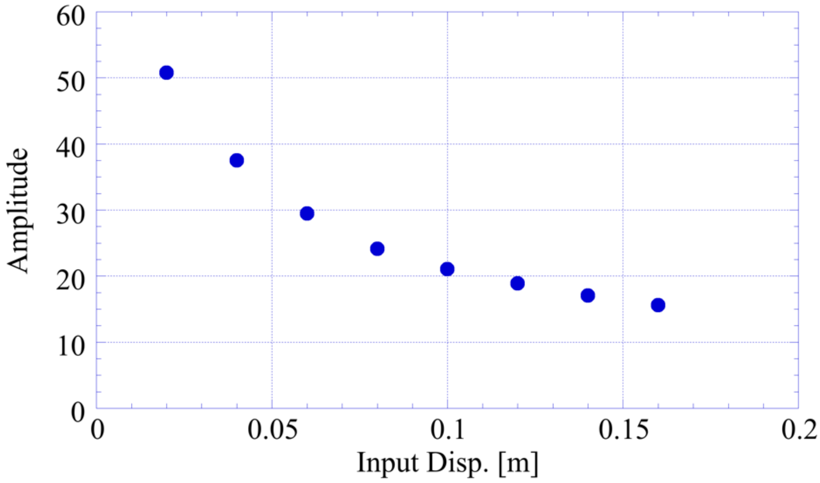

Figure 4 Influence of vertical motion of car on the maximum amplitude

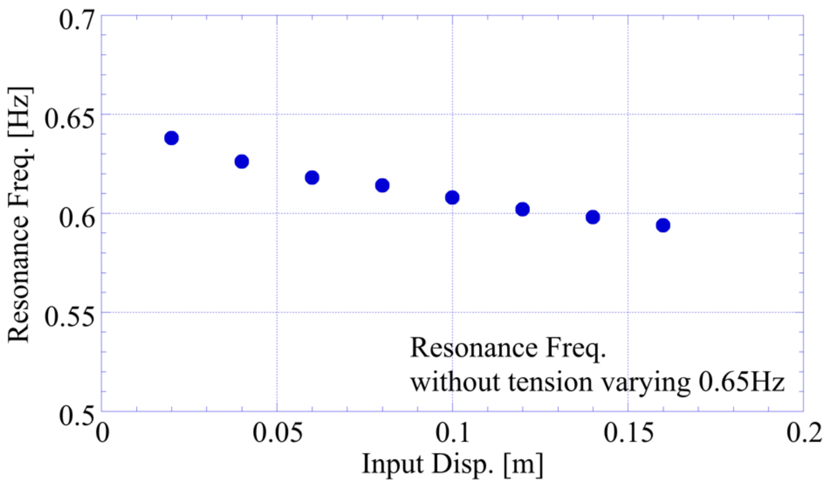

Figure 5 Influence of vertical motion of car on resonance frequency

4.4 Seismic Response Analysis

The seismic response analysis of the rope was carried out in this section. A response analysis using sinusoidal input waves was also performed to compare the seismic response with the response at resonance. Firstly, the seismic response of a building with a height equal to the rope length was analysed using a single degree of freedom model, and the resulting response was used as input to the rope. The input seismic waves to the building were El Centro NS waves, JMA Kobe NS waves and Hachinohe EW waves with maximum velocities of 0.25 and 0.50 m/s. The height of the building, i.e. the length of the rope, was 20, 40, 60, and 80m. The natural period of the building was 0.025 times the building height and the damping ratio was 2%. For the sinusoidal analysis, the top of the rope was vibrated with a sinusoidal wave.

The relationship between input and response displacement is shown in Fig. 6. The horizontal axis is the ratio of the maximum input displacement to the rope length, and the vertical axis is the ratio of the maximum response displacement to the input. As shown in the legend on the right-hand side of Fig. 6, each plot represents analytical results for the seismic response. The solid plots are results that take into account the tension fluctuations caused by the vertical movement of the car, and the open plots do not consider this. For comparison, the analytical results for the sinusoidal wave response are shown as lines.

From Fig. 6, the maximum response displacement is generally the same regardless of the rope length when a sinusoidal wave is input, and the maximum response displacement decreases as the input displacement increases. This is because the response displacement of the rope increases as the input displacement increases, and the vertical vibration of the cage also increases, so the nonlinearity of the vibration consequently increases.

Even when seismic waves were input, the maximum response displacement decreased as the input displacement increased. In addition, the maximum response displacement was smaller than that of a sinusoidal wave input because the time of excitation at the resonant frequency was short and the response did not grow. Therefore, the response due to seismic waves is on the safe side if the resonant response in sinusoidal waves is evaluated.

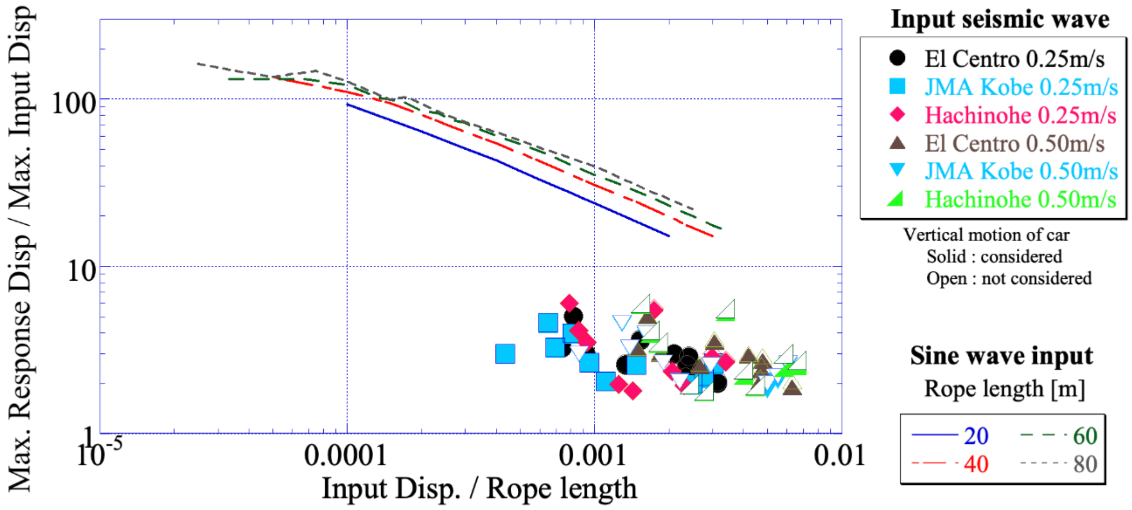

Figure 6 Maximum response displacement of seismic response

5 CONCLUSION

This paper described the activities and results of the Rope Vibration Analysis Working Group of the Japan Society of Mechanical Engineers. In the working group, previously proposed rope vibration analysis methods and rope damping were investigated through a literature review and vibration response analysis was performed. As a result of the working group's discussion, analytical methods based on the wave equation and the single-degree-of-freedom model are suitable for rope vibration analysis. The damping ratio of lift ropes is generally small, i.e. about 0.2%, but the amplitude will be small due to the non-linear vibration caused by the vertical motion of the car. It is expected that the analysis methods of the rope vibration will be further improved in the future based on the results of the working group.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to the members of the Rope Vibration Analysis Working Group, i.e. Ms. R. Tamashiro of Tokyo Denki Univ., Mr. T. Abe, Mr. Y. Sekiya, Mr. T. Watanabe of Hitachi Building systems, Mr. K. Tanaka, Mr. Y. Ogawa, Mr. T. Shiki of Toshiba Elevator, Mr. R. Onoda, Mr. K. Kiyomoto, Mr. K. Izawa of Otis Elevator, Mr. M. Harada, Mr. K. Ueda of Fujitec, Mr. S. Watanabe, Mr. D. Nakazawa of Mitsubishi Electric and Mr. M. Shinomiya of Schindler Elevator, for their valuable advice and devoted assistance to conduct the working group.

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Dr. Keisuke Minagawa is an associate professor at the Saitama Institute of Technology and is a chair of the Panel of Elevator Safety and Reassurance held in JSME (Japan Society of Mechanical Engineers). He has been an evaluator of lift systems and mechanical car parking systems in Japan since 2015. He is also an expert in seismic isolation and vibration control.

Prof. Satoshi Fujita, a JSME (Japan Society of Mechanical Engineers) Fellow, has ten years of management experience as a director, a dean of the school of engineering and a vice-president of Tokyo Denki University. He has been engaged in engineering research and development of seismic isolation systems and vibration control systems for buildings or key industrial facilities for over 35 years at both the University of Tokyo and Tokyo Denki University. In recent ten years, he has been a committee member of the Panel on Infrastructure Development of the Japanese Ministry of Land, Infrastructure and Transport (MLIT), and a chair of the Special Committee on Analysis and

Evaluation of Lifts, Escalators and Amusement Facilities Accidents and Failures held in MLIT. In addition, he has been a chair of the ISO TC178 Japanese committee.

Study on the Concept of Using Lifts and Escalators in Evacuation Routes Using Fragility Assessment

(Damage Analysis and Pedestrian Simulation)

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Keywords: Safety Evacuation, Escalator, Fragility assessment, Seismic response analysis

Abstract. In Japan, seismic safety design has been used for buildings on the ground surface and for important facilities and equipment. However, few studies have been conducted on maintaining system functionality during earthquakes, considering buildings and equipment within buildings as a single system. Lifts and escalators, which are normally used as flow lines, cannot be used in evacuation routes in the event of fire or disaster. In this study, a pedestrian simulation is carried out on the assumption of escalators after the revision of seismic standards reported in a previous paper, taking into account damage occurring to equipment related to the selection of evacuation routes, and the concept of an appropriate evacuation route is examined. This paper analyses the effectiveness of the use of escalators and elevators for rapid evacuation using pedestrian simulation in a high-rise building. As a result, it was confirmed that, in the analyzed building model used in this study, the use of escalators and elevators is effective in reducing the evacuation time by about 70 seconds for every 10 stories, compared to the time when evacuating by staircases.

1 INTRODUCTION

In Japan, seismic design has been adopted for buildings on the ground surface and important mechanical structures [1]. However, few studies have examined the maintenance of system functionality during earthquakes by considering the building and machinery within the building as a single system. For example, during strong earthquakes, not only the building itself is damaged, but also various piping, electrical cables, air conditioning equipment, elevators, and other mechanical elements within the building that maintain the function of the building system are often damaged, resulting in the failure of the building's function [2]. In addition, the impact of such damage on evacuation routes can be significant. Elevators and escalators, which are always used for human flow, cannot be used in evacuation routes. In the event of a disaster, lifts and escalators are designed to quickly move to the nearest floor and unload passengers, and escalators may stop suddenly when an abnormality is detected, such as in the event of an earthquake. In any case, the escalators are not yet ready to be utilized as evacuation routes.

This study examines the concept of appropriate evacuation routes based on pedestrian simulations considering damage events to mechanical structures related to the selection of evacuation routes, assuming the escalators after the revision of the seismic design standards reported in the previous paper [3]. In this paper, pedestrian simulations in a 40-story high-rise building are conducted to quantitatively evaluate the time required to complete evacuation and to analyse the effectiveness of using escalators and elevators for rapid evacuation.

2 DAMAGE PROBABILITY FROM FRAGILITY ASSESSMENT OF MECHANICAL STRUCTURES

2.1 Fragility assessment

In this study, the fragility assessment of equipment and machinery is carried out using an assessment method based on the realistic bearing capacity and realistic response of the object [4], [5]. The target equipment is modelled and the fragility evaluation indices are selected to produce a fragility curve that represents the damage probability of the equipment. The fragility curve is obtained using the probability density function of the capacity and response [6]. The probability density function is a normal distribution that includes uncertainty and can be expressed as follows, where μ is the mean of the data and σ is the standard deviation.

$$f_c(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{\left[\frac{(x-\mu)^2}{2\sigma^2}\right]} \tag{1}$$

$$f_{Ra}(x_R) = \frac{1}{\sqrt{2\pi\sigma}} e^{\left[\frac{(x_R-\mu')^2}{2\sigma^2}\right]} \tag{2}$$

The fragility for an optional value of H due to the response of the rating index is a cumulative distribution function that represents the conditional damage probability that the probability density function $f_c(x)$ of the realistic capacity exceeds the probability density function $f_{Ra}(x_R)$ of the realistic response. It is expressed as follows.

$$F(\alpha) = \int_0^\infty f_{R\alpha}(H, x_R)\left(\int_0^{x_R} f_c(x)dx\right)dx_R \tag{3}$$

2.2 Damage mode

The fragility curve derived from the probability density function represents the probability of the occurrence of one damage mode. In real mechanical structures, damage occurs continuously in response to external inputs. If the occurrence or non-occurrence of only one damage state is analyzed, the hazards caused by other damage states and damage caused by other factors are not taken into account sufficiently. Therefore, this study focuses on damage modes, which divide the damage modes of mechanical structures into different phases. The damage mode is a classification of a specific damage mode in the response, and the damage probability represents the corresponding conditional probability.

2.3 Examples of fragility curves

In this example, suspended ceilings are considered [7], [8]. Suspended ceilings have a large installation area, so damage such as falling off may cause serious damage. In past major earthquakes, extremely critical situations due to falling ceiling panels have frequently been observed. Because of this risk, damage assessment is carried out under the stresses generated by the seismic response. Here, a ceiling with a mass of more than 2 kg/m2 is considered, as shown in Fig. 1. The suspension structure of a ceiling basically consists of suspension bolts with embedded inserts, bracing material between the pitches of the suspension bolts, and clips fixing the lower frame and ceiling plate. In the analysis, the mass part of the suspended ceiling is modelled as a one-degree-of-freedom vibration system. The capacity of the ceiling plate support clips is then investigated from the response of the mass section of the suspended ceiling. The damage mode settings for suspended ceilings are shown in Table 1. Mode 2 is set in consideration of the plastic deformation of the member due to the load test of the clip. Mode 3 is based on the acceleration at which rupture of the suspended ceiling is confirmed, and

Mode 4 is based on the capacity of the member. The calculated fragility curve is shown in Fig. 2. Based on the fragility curves, the damage probability of a suspended ceiling with a suspension length of 800 mm, a pitch of 900 mm between suspension bolts and a unit mass of 22 kg can be summarized for each clip, as an example, from the time history response of the building using one degree of freedom model due to each seismic wave. Table 2 summarizes the damage probabilities for each clip. Other fragility assessment factors considered in the study include suspension bolts and suspended equipment such as air-conditioning.

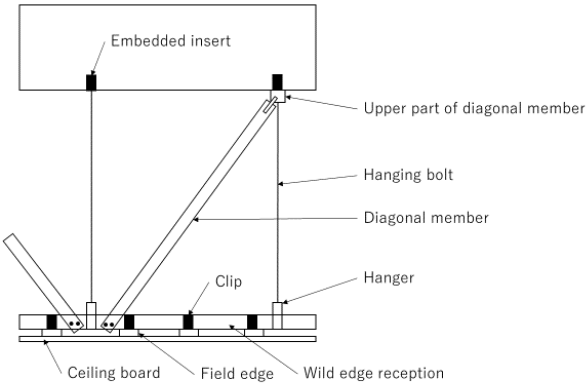


Figure 1 Typical suspended ceiling configurations

Table 1 Damage mode of suspended ceiling

Damage mode	Damaged condition
Mode1	No damage
Mode2	Plastic deformation of metal clips
Mode3	Partially dropped out
Mode4	All dropped out

Table 2 Seismic wave and Clip damage mode

Seismic wave	Max resp. Acc. [m/s^2]	Max resp disp [m]	Stress [N]	Damage mode value	Damage probability [%]
El Centro NS	3.84	0.0395	485	2.51	75.0
JMA Kobe NS	7.86	0.121	994	3.02	96.3

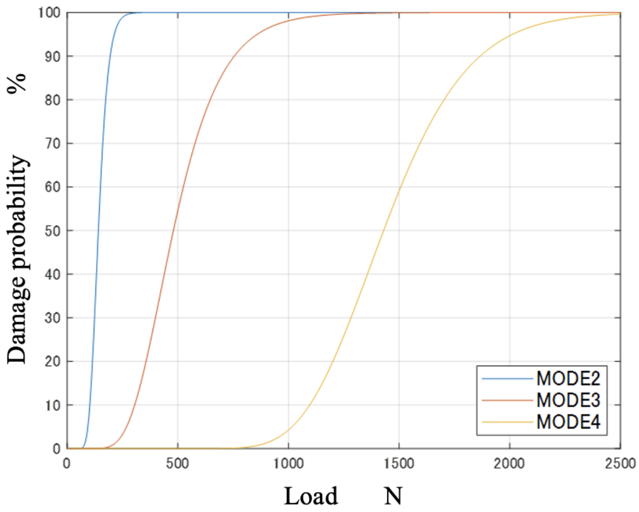


Figure 2 Fragility curve of clip

4 INFLUENCE COEFFICIENT AND SIMULATION OF A PEDESTRIAN

4.1 Influence coefficient from pedestrian simulation

In general, public facilities and buildings used by many people have defined evacuation routes, but not all of them may be passable in a disaster. Various damaged or dropped equipment in buildings may cause the evacuation route to be blocked. Generalizing the detour routes for evacuating pedestrians to obstacles and understanding the trends of detours according to the size of the obstacle and the degree of path occupancy can contribute to improving evacuation safety from the stage of designing the layout of equipment.

In this study, diversion routes against obstacles are considered from pedestrian simulations, and the influence of obstacles on evacuation routes is calculated as an influence coefficient. In the simulation, one pedestrian is assumed to proceed along the evacuation route while bypassing obstacles. Obstacles are placed on the evacuation routes divided into a grid with different occupancy rates for different degrees of damage. Basically, pedestrians go straight ahead, and if there is an obstacle in their path, they bypass it to the left or right. The distance from the start point to the end point is calculated. In this simulation, a 1/6th scaled evacuation route with a passageway of 2.5m wide and 10m long, divided into 15 × 60 cells, is used. The diversion behaviour of the pedestrian is assumed to be to a greater extent than the actual size to avoid the obstacle. A weight of 50 % passability is added around the proximity of the obstacle. The influence coefficient is determined from the simulation results and the ratio of straight-ahead time without obstacles.

$$e = 1 - \frac{v_e}{v_0} = 1 - \frac{x/t_e}{x/t_0} = 1 - \frac{t_0}{t_e} \qquad (4)$$

In here, v_e: walking speed in each damage mode, v_0: walking speed without obstacles, t_e: required evacuation time for each damage mode, t_0: required evacuation time without obstacles. An obstacle is defined as e=0, and no passage at all is defined as e=1. For the walking speed during evacuation, the average walking speed of all generations of men and women, 1.18 [m/s] [9], is used from the average walking speed of men and women by age group. In this paper, it is assumed that healthy persons evacuate by walking.

4.2 Simulation with a suspended ceiling as an obstacle

The evacuation routes for each damage mode assuming a ceiling fall are shown in Fig.3. The ceiling panel is 1.8×0.9 m. Several patterns of evacuation routes are derived from the simulation. Four examples are shown here. From the simulation results, the bypass patterns for each damage mode are shown in Fig. 4. The walking times and calculated impact coefficients for each damage mode are summarized in Table 3.

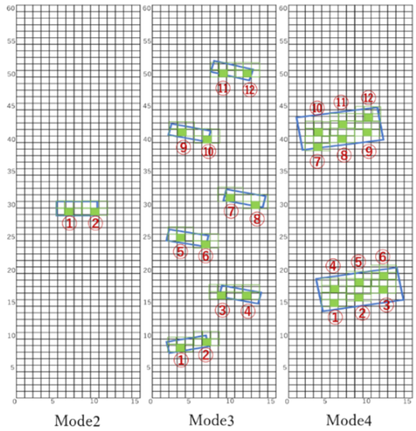
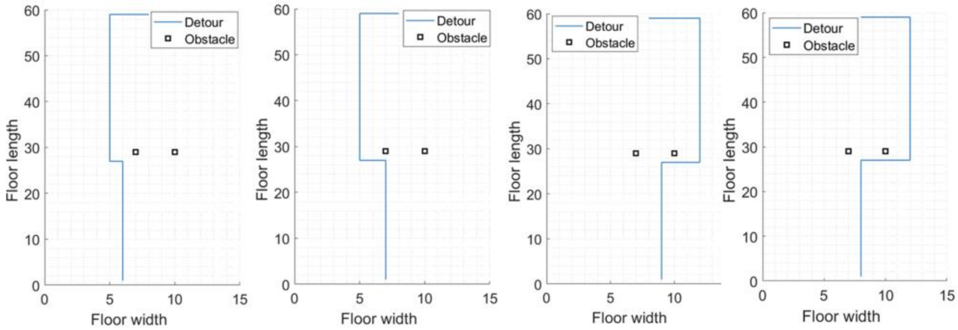
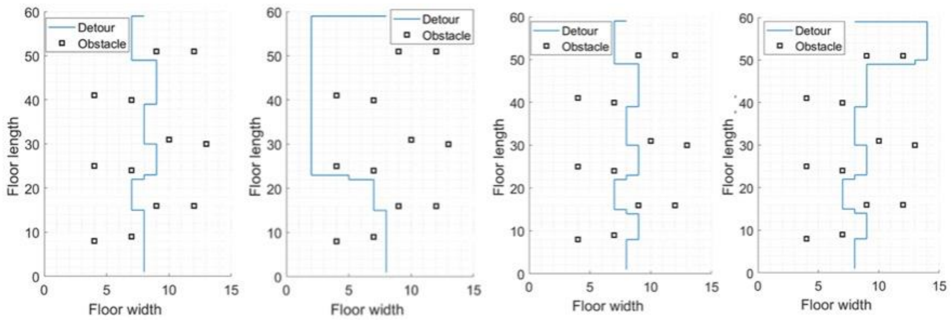


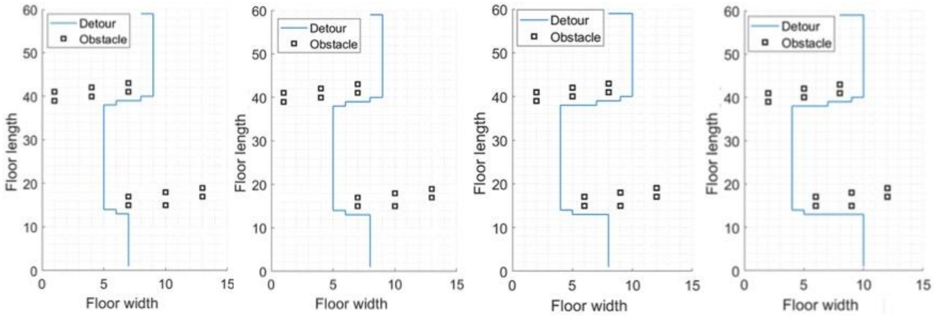
Figure 3 Example of a study of falling ceiling panels into an escape route.



(a) Mode2 simulation results of ceiling



(b) Mode3 simulation results of ceiling



(c) Mode4 simulation results of ceiling

Figure 4 Simulation of evacuation with falling ceiling panels

Table 3 Walking time and Influence coefficient

Damage mode	Min. walking time [s]	Max. walking time [s]	Min. Influence coefficient	Max. Influence coefficient
Mode2	8.47	8.89	0.231	0.267
Mode3	9.32	9.83	0.301	0.337
Mode4	9.15	10.17	0.288	0.359

5 PEDESTRIAN SIMULATION IN A HIGH-RISE BUILDING

5.1 High-rise building for simulation

In high-rise buildings, the seismic response differs between the low-rise, mid-rise and high-rise floors, which may result in various types of damage to the installed equipment. Therefore, a comprehensive understanding of the effects of the seismic response is required. In addition, evacuation simulation in high-rise buildings makes it possible to ascertain evacuation assumptions for different building heights and structures.

In this study, the evacuation situation is simulated by pedestrian simulation on each floor of a high-rise building, and the time required for evacuation is investigated from the results. A 40-storey office building is assumed as a high-rise building. The building model is shown in Fig. 5. The height of the target building is assumed to be 160 [m] and 4 [m] per storey. The dimensions of each floor are set to 40 x 40 [m].

The floor map for each floor is the same for each of the 10 floors as shown in Fig. 6. As the diagram shows, each floor has two staircases, an escalator, and an elevator. A total of 100 evacuees are assumed for each floor and a total of 4000 evacuees are considered in the building for the pedestrian simulation.

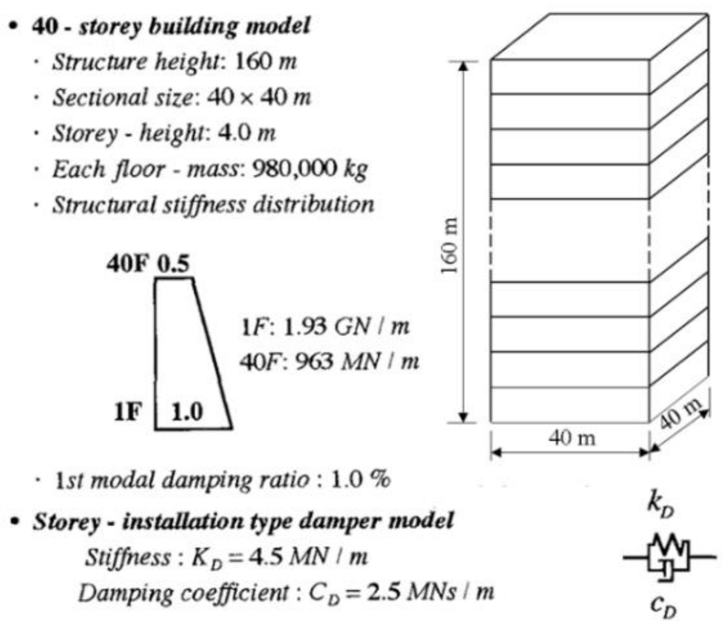


Figure 5 High-rise building model used for Pedestrian simulation

Figure 6 Floor map for each of the 10 floors

The equations of motion of the building model are expressed by the following equations:

$$\boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{C}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} = -\boldsymbol{M}\ddot{\boldsymbol{Z}}_H. \tag{5}$$

Here, the mass matrix, damping matrix and stiffness matrix are as follows:

$$\boldsymbol{M} = \begin{bmatrix} m_1 & 0 & \cdots & \cdots & 0 \\ & m_2 & 0 & \cdots & 0 \\ & & \ddots & & \vdots \\ & & & m_{39} & 0 \\ & & & & m_{40} \end{bmatrix} \qquad \boldsymbol{C} = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & \cdots & 0 \\ & c_2 + c_3 & -c_3 & \cdots & 0 \\ & & \ddots & & \vdots \\ & & & c_{39} + c_{40} & -c_{40} \\ & & & & c_{40} \end{bmatrix}$$

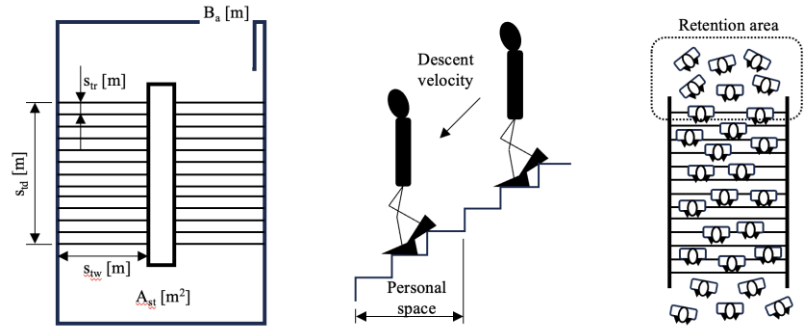
$$\boldsymbol{K} = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & \cdots & 0 \\ & k_2 + k_3 & -k_3 & \cdots & 0 \\ & & \ddots & & \vdots \\ & & & k_{39} + k_{40} & -k_{40} \\ & & & & k_{N40} \end{bmatrix}$$

5.2 Pedestrian simulation method using a high-rise building

5.2.1 Examination of evacuation method by staircase

In this pedestrian simulation, the cells divided into a floor map grid are numbered, and the simulation is performed by moving to a cell with a smaller number than the current cell. If there is a person or obstacle in the cell to be moved to, the algorithm waits, or acquires the number of the diagonal cell and can move if the number is smaller than the current cell and there is no person in the cell. The walking speed is 1.0 m/s and the time is calculated from the number of steps required for evacuation. The evacuation of a high-rise building involves a large percentage of time for staircase evacuation, including escalators if available. Therefore, the staircase movements shown in Fig. 7(a) are considered in detail and the time required for evacuation is calculated. In the case of stair descent by evacuees, the number of persons who can be evacuated within a certain time is calculated. Furthermore, the delay time due to stagnation propagation is assigned as a variation of the evacuation time using a model for the occurrence of stagnation phenomena as shown in Fig. 7(c) caused by human congestion at staircase entrances and in staircase rooms.

In order to establish these calculation models and to obtain the stair specifications and the behaviour of pedestrians when descending stairs, field measurements are carried out and a realistic evacuation time is calculated based on the measured data [10]. The calculation model outputting the throughput for evacuation from the staircase is calculated on the basis of references [11]. Here, the specifications of the staircase (stair width and length, door width, landing area, etc.), pedestrian specifications (step height, walking speed, number of parallels, etc.) and the retention specifications that occur near the entrance (retention area, retention density, etc.) are set. Based on the setting of the various parameters, the occurrence time and the transition (flow rate) of the number of people in the three states of stagnation, start of stair descent and end of stair descent are calculated.



(a) (b) (c)

Figure 7 Analytical parameters for the use of stairs during evacuation

The performance of the staircases used in the simulation in a given time period is considered. As an example, the performance of staircases and people, and the resulting evacuation time model cases are shown in Table 4. For the generation of delay times due to stagnant propagation in stairwells in high-rise buildings, the walking conditions in the stairwells are differentiated between flow and stagnant conditions. The parameters of the stagnation in stairwells are based on statistics: the density of the flow state is 1.66 /m^2, the stagnation density is about 4.0/m^2, and 5.5/m^2 is a complete stop. The confluence ratio of the passage and staircase descent communities is 0.66~0.69. The example dimensions of the staircase landing are a landing length of 4.5m, landing width of 2.1m, and landing area of 9.45m^2. The calculated results are shown in Table 5.

The results show that the maximum floor evacuation time without stairwell stagnation is 52s, the maximum delay time due to stagnation propagation is 52s and the maximum floor evacuation time due to delay time is approximately 85s. These results show that the floor evacuation time is approximately in the range of 58-100s when stairwell retention

Table 4 Stairs and walker specs

Target	Measured value
Stairs entrance width [B_a]	1.2 [m]
Stair width [s_{tw}]	2.22[m]
Stairs walking distance [s_{td}]	13.91 [m]
Length of one staircase [s_{tr}]	0.294 [m]
Stairs travel time [Est]	19.3[s]
Max. number of people in parallel [Pmax]	3
Congestion end time [N]	67.3 [s]
Width space [Cs]	0.6~0.9[m]
Vertical space [Cv]	3[step]

Table 5 Delay time by retention

Max. delay time [s]	Min. floor evacuation time[s]	Max. floor evacuation time [s]
52.1	51.9	84.7

5.2.2 Examination of evacuation method by escalators

In Japan, the use of elevators for evacuation and escalators during disasters has not yet been authorized, but this paper examines the possibility of improving the efficiency of evacuation routes by using escalators and stairs together when evacuating a large number of people from upper floors during an earthquake [12]. In many commercial buildings, escalators are located in the centre of the floor and evacuation stairways are located at the end of the floor, far from the centre. In such structures, the use of escalators for evacuation could greatly improve safety and evacuation time efficiency. Escalator travel during evacuation is assumed to be accompanied by walking. In this case, the speed of the escalator is 0.5 m/s and the speed of movement during stair walking is 0.6 m/s, which together are treated as 1.1 m/s. The length of the escalator is assumed to be 8 m. As the building in question is a 40-storey building, the number of escalators is 39 x 2. The calculation of the time required to complete the evacuation by escalator can be expressed by the following equation.

$$\frac{l \times n}{v} + t_t \times 2 \times (c - 1) \tag{6}$$

In here, l: escalator length, n: number of escalators, v: travel speed, t_t: time per step, c: number of people in line.

5.2.3 Examination of evacuation method by lifts

In high-rise buildings, few elevators move through all levels, and the floors on which they operate are often defined [13]. In this study, the elevators are set up so that they stop every ten floors and the doors open and close. The specifications of the elevator handled in this study are shown in Table 6. This elevator specification is commonly used for general purposes.

Table 6 Elevator specifications

Service floor	1 to 40	
Capacity [people]	22	
Rated speed [m/s]	5.0	
Acceleration and deceleration [m/s^2]	±0.7	
Door width [m]	1.1	
Door opening and closing time [s]	1.5	
Flow coefficient [people/m/s]	【Ride】1.07	【Alighting】1.22

5.2.4 Pedestrian simulation result in a high-rise building

Using the above condition set-up, an evacuation simulation is carried out for a 40-storey high-rise building. The results are shown in Fig.8. The figure graphically shows the time to complete evacuation for each evacuation method used, in relation to the inputs to the building in question. The results show that as the seismic input increases, the time to complete the evacuation increases due to the progression of damaged equipment and the increase in obstacles to the evacuation route. It can also be confirmed that the use of multiple means of evacuation allows for a faster and safer evacuation. The time saved by using only the staircase versus using all evacuation routes is about 300 seconds. It can also be confirmed that escalators contribute to faster evacuation than elevators.

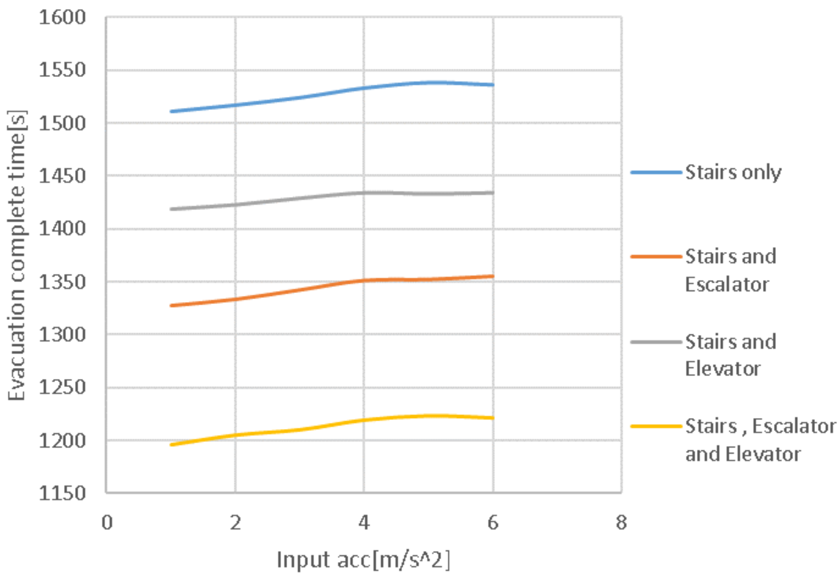


Figure 8 Pedestrian simulation result in high-rise building

6 CONCLUSIONS

Damage to equipment in buildings during an earthquake under seismic loads due to building response was investigated, and evacuation routes were evaluated, taking into account the probability of damage. In this paper, impact coefficients representing the degree of impact on the pathway at the time of damage were calculated from pedestrian simulations, from each damage mode defined for the damage state of the mechanical structures. An analytical model was also developed to calculate the evacuation capacity of stairways, focusing on stairways as an existing means of evacuation. Furthermore, pedestrian simulation in multi-storey buildings in a time history response analysis of a high-rise building was carried out to quantitatively confirm the time required to complete evacuation in relation to the input earthquake level. Furthermore, pedestrian simulation in multi-storey buildings in a time history response analysis of a high-rise building was carried out to quantitatively confirm the time required to complete evacuation in relation to the input earthquake level. The effectiveness of using escalators and elevators together as evacuation means to speed up evacuation was confirmed. As a result, it was confirmed that a time reduction of about 300 seconds was achieved compared to a staircase evacuation. Based on the concept of using escalators and elevators in combination with stairs, it was confirmed that a time reduction effect of about 70 seconds could be achieved for every 10 levels. The pedestrian simulation constructed to determine evacuation times can be set up for group travel, but does not apply psychological states and interactions between people, so reflecting these effects in the simulation would contribute to improving the accuracy of actual evacuation route time estimation.

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BIOGRAPHICAL DETAILS

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The Global Dispatcher

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Keywords: traffic control, dispatching, global, universal, conventional control, destination control, single deck, double deck.

Abstract. A modern lift traffic control system, often known as a dispatcher, can collect passenger calls in several ways. Conventional dispatching uses up-and-down buttons on the landing with additional buttons for each floor in the car. Destination control dispatching uses destination input devices on the landings so that passengers can select their required floor when the lift is first called. Hybrid dispatching systems use a combination of landing call buttons, car call buttons and destination input devices. Aside from a range of input devices, advanced dispatchers may manage single and double-deck lifts, multiple lifts in the same shaft, and a combination of these lift types within a lift group. This paper describes how the same dispatching software can manage all input devices and lift types by applying a unified approach to lift dispatching. The core software is built on a lift controller software model, which can manage all lift and call types. Unknown information, for example, future car calls once a landing call is answered, is predicted. The choice of which lift serves which call is made by applying a simulation model, which assesses the outcome of alternative allocations the dispatcher could make. The Global Dispatcher applies the Global Dispatcher Interface.

1 INTRODUCTION

Lift dispatching describes managing and coordinating the movement of lifts within a vertical transportation system to transport passengers and goods efficiently between different floors. Lift dispatching plays a pivotal role in managing the efficient movement of passengers within multi-story buildings.

Conventional dispatching uses up-and-down buttons on the landings with additional buttons for each floor in the car. Destination control dispatching uses destination input devices on the landings so that passengers can select their required floor when the lift is first called. Hybrid dispatching systems use a combination of landing call buttons, car call buttons and destination input devices. Aside from a range of input devices, advanced dispatchers may manage single and double-deck lifts, multiple lifts in the same shaft, and realistic combinations of these lift types within a lift group.

The objective of the Global Dispatcher is to provide a unified framework so that all realistic options can be addressed within a single set of dispatcher software. This paper sets out an approach to solving this problem.

2 THE CONTROLLER

2.1 About the lift controller

Lift controllers are responsible for managing the movement and behaviour of lifts in a building. There is one lift controller per lift. The primary purpose of a lift controller is to ensure safe, efficient, and smooth transportation of passengers or goods between different floors.

The lift controller monitors various inputs, such as button presses inside the elevator car and on the floors, door status, and car position. Based on these inputs and the pre-programmed logic, the controller determines the appropriate actions, such as opening or closing the doors, stopping at a floor, and travelling to the desired destination.

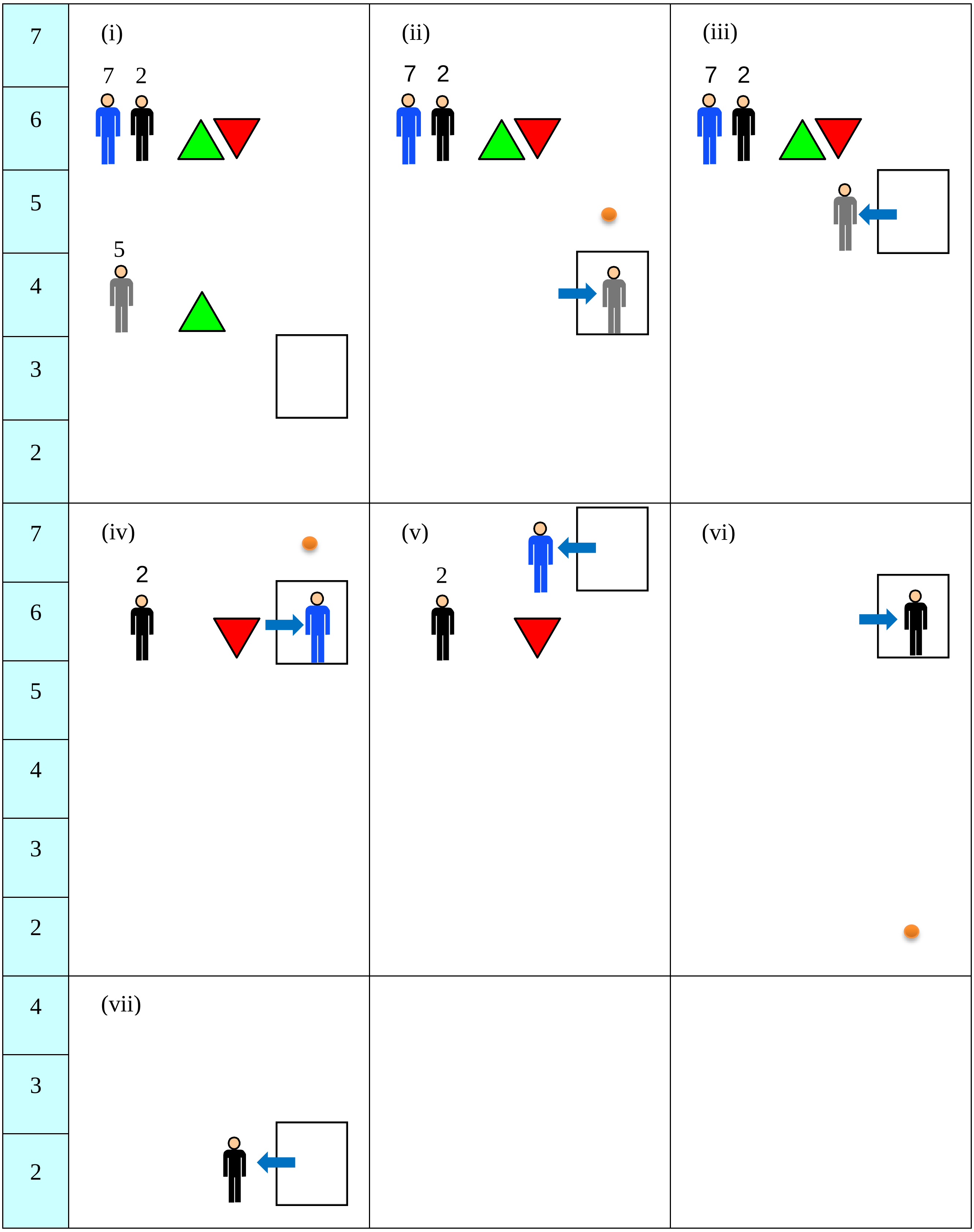

Figure 1 Collective operation (passenger destinations shown above heads)

2.2 Collective control

A single (simplex) lift does not need a dispatcher; its controller includes software enabling it to serve its calls logically. Most modern lifts answer calls collectively, as illustrated in Figure 1. All landing calls and the resulting car calls in one direction are served; then, the car reverses and serves calls in the opposite direction.

For lift groups, a simple approach to dispatching is to have separate dispatching software to decide which lift will serve which call. The inputs are the status of the lifts and the calls registered. The outputs are which lifts should serve which landing and/or destination call. The dispatcher software must also understand collective control to assess how long each lift would take to answer a call. Once the allocation is made, the call can be passed from the dispatcher to the selected lift, adding it to its schedule according to collective control rules.

The problem with this approach is that all lift controllers implement collective control slightly differently, and the assumptions of the dispatcher and controller can conflict. For example, consider the scenario illustrated in Figure 2 (i) where a lift is travelling to serve a down call. While the lift is travelling to the down call, a new call is registered travelling up from the same landing; see Figure 2 (ii). The dispatcher cannot, with confidence, predict whether the controller will serve the up or down call first.

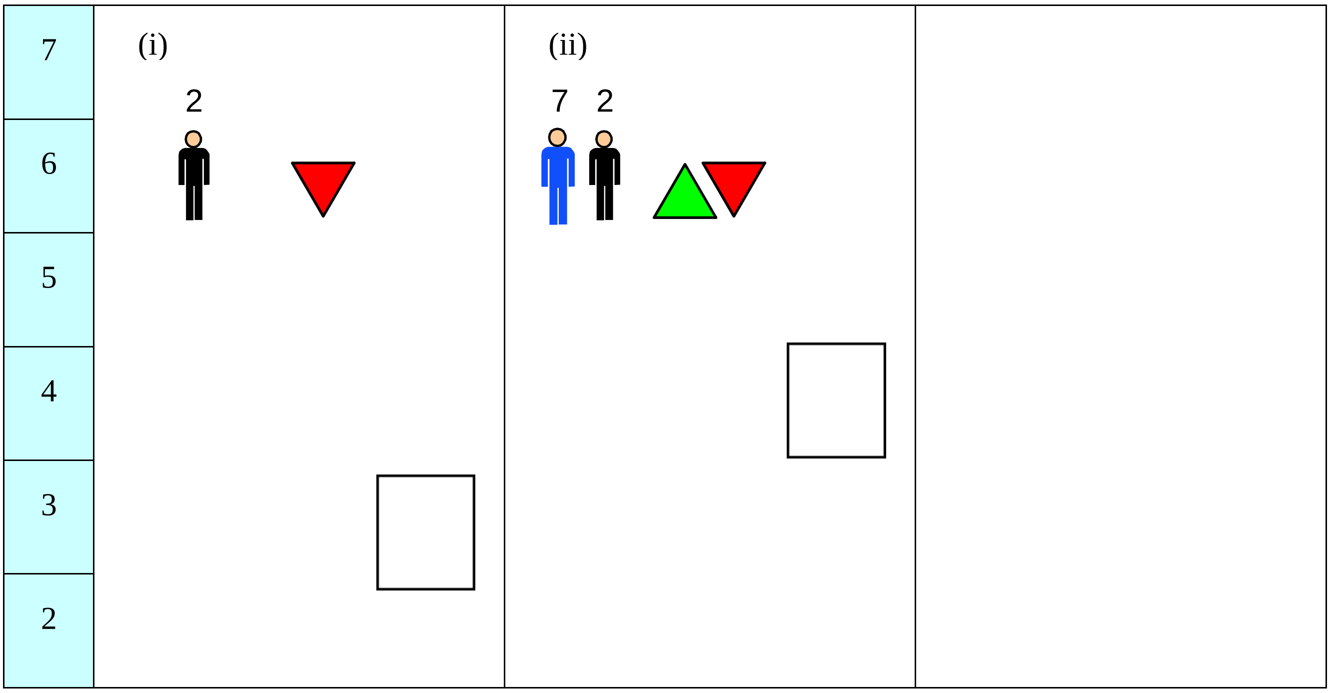

Figure 2 Collective control operational inconsistencies – which call will be served first?

There are also scenarios where the dispatcher might not want to be restricted by the controller's logic. For example, if both passengers had loaded in Figure 1 step (iv), the stop at step (vi) could have been avoided, saving time. A passenger would be taken in the "wrong direction" at first, which is considered unacceptable [1]. Nevertheless, with destination control, these so-called "reverse journeys" can be advantageous [2] and may be a dispatcher option.

Thus, for a Global Dispatcher capable of working with a range of lift controllers, the collective control logic is best removed from the lift controller and implemented solely as part of the dispatcher function; the Global Dispatcher is then responsible for instructing the lift on its destination floors, one at a time, rather than allocating calls to the lift controller implementing its own version of collective control.

2.3 Door operation

As for the collective control logic, the lift controller has historically managed door operation. This limits the system's overall efficiency as the dispatcher has additional information, which can save time. For example, in some instances, the dispatcher knows that just one person is loading or unloading the car. Once the door beams have been broken and reestablished, an intelligent dispatcher will know the doors can be closed immediately rather than waiting for a lift controller's dwell time to expire. For safety reasons, the lift controller must remain in charge of opening and closing the doors, but the Global Dispatcher can provide the logic to send door open and close requests. To do this, the dispatcher must be provided (by the controller) with door beam status so it knows when passenger transfer begins and ends.

3 COLLECTIVE CONTROL WITHIN THE GLOBAL DISPATCHER

3.1 Managing call types

The collective control function within the Global Dispatcher needs to manage collective control for both destination calls and conventional calls generated by passengers, see section 7. The mixture of call types is possible as a destination call is equivalent to a landing call with a car call [3]. When a landing call is registered, it can be treated as a destination call with an inferred car call. Once a landing call is answered and any new car calls have been registered, the destination call can be updated. For example, a down call from level 7 may initially be treated as a destination call from level 7 → ground floor. When the down call is answered, and a car call to level 1 is registered, that destination call may be updated from level 7 → ground to level 7 → level 1. In some instances, for example, using load weighing and when multiple car calls are registered, one landing call may be assumed to spawn multiple destination calls; for example, a down landing call from level 7 may initially be treated as a single destination call from level 7 → ground floor. If the load weighing demonstrates two extra passengers load at level 7, and then car calls to levels 3 and 4 are registered, the single destination call level 7 → ground may be replaced by two destination calls, level 7 → level 4 and level 7 → level 3. Aside from enabling call types to be mixed, this approach brings passenger-centric dispatching to conventional control, see section 4.1.

3.2 Lift types

The collective control function is designed to manage double-deck lifts; a single-deck lift is treated as a double-deck lift but with a block on any allocations to the (non-existent) upper deck. Two lifts per shaft are implemented based on single-deck lifts with an additional rule set, see section 6.

3.3 Application of the collective control function

The collective control function is applied within the Global Dispatcher in two different contexts:

1. To model the movements of the lift, determining the probable outcome if a call is allocated to a lift. This helps the dispatcher to choose the "best" lift to allocate a call to.
2. To determine where to send the lift to and door operation once calls have been allocated to lifts.

In the second context, controlling the actual lift, the real system provides the door and door beam status, which changes due to real passengers loading and unloading a lift. In the first context, an internal simulation, the simulation code provides the door and door beam status, mimicking the effect of passengers based on its knowledge of the registered calls.

4 OPTIMISATION GOALS AND ALLOCATING LIFTS

4.1 System versus passenger-centric objectives

There are many approaches to allocating calls to lifts. A common strategy for conventional control is to assess the Estimated Time of Arrival (ETA), i.e., how long would it take lift A, lift B, and lift C to answer a new landing call. The lift with the lowest ETA is allocated the call. There may be other considerations; for example, a "co-incident call bonus" may be applied to reduce the ETA and make it more likely that lifts already stopping at the landing call floor receive the allocation [4].

Many dispatchers use these and other system-based measures to choose the "best lift". A more sophisticated approach is to make the assessment passenger-centric. This is the basis of most destination control algorithms [1] [3], which consider every passenger's waiting and transit time. Passenger-centric optimisation goals can also be applied to conventional and hybrid control if conventional calls are translated to destination calls (see section 3.1) before the allocation process. The internal simulation of the Global Dispatcher only needs to recognise destination calls.

By making the objectives passenger-centric, any practical combination of destination and conventional landing calls can be allocated for any lift type (single-deck, double-deck, two cars per shaft).

4.2 Optimisation algorithms

The objectives are implemented in an optimisation algorithm which translates each "passenger experience", as determined by the internal simulation, into a cost. The increase in total cost arising from an allocation of a call to a lift can be determined, and the lift with the lowest cost is allocated.

An optimisation algorithm based on minimising the total time to destination is widely applied. Still, research into the psychology of waiting suggests that different parts of the journey may be more frustrating than others [5] [6].

To address this, the optimisation algorithm can account for a range of human factors. Indeed, it is possible to optimise on anything that can be modelled, including energy consumption [7].

Specific to double-deck lifts and systems with two lifts per shaft, a passenger's journey may be delayed by unseen activity in another lift or cabin delaying a passenger's journey. This can be addressed by breaking up the lift journey into more phases, including departure delay and blind departure delay [8]. If the relative frustration of each phase of the lift journey can be qualified, this can also be part of the optimisation algorithm.

The disproportionate "pain" of long waits can be accounted for if each extra second is weighted more than the previous [7].

The application of Artificial Intelligence is beyond the scope of this paper, but for an introduction, refer to [4].

5 DOUBLE-DECK LIFTS

Double-deck lifts have two cabs in one unit, serving adjacent floors together. Escalators connect the lower and upper ground floors. The technology is available from most major suppliers.

Double-deck lifts are most efficient if, during peaks, lower cabs serve odd floors and upper cabs serve even floors. With destination control, this restriction is easy to avoid in the software, although it can significantly impact handling capacity and the overall quality of service.

The Global Dispatcher implementation is based on applying the collective control function. There are restrictions aside from the lower cab not being able to serve the top floor and vice-versa; some allocations must be banned.

5.1 Banned allocations due to passenger loading the wrong car

In Figure 3, a passenger is loaded into the upper cab travelling to level 6. There is a passenger at level 6 wanting to travel to level 8. The dispatcher must consider both lower and upper cab allocation possibilities. If the lower cab is allocated, the upper cab will stop at level 6 first and the lower cab second. The person will get into the upper cab instead of the lower cab by mistake. So, the allocation of the passenger to the lower cab must be banned.

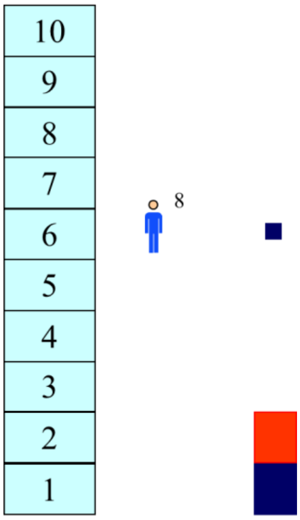

Figure 3 Scenario where person loads the wrong car

6 TWO CARS PER SHAFT

6.1 General

Installations with two cars per shaft are currently only available from one supplier [9]. Their handling capacity limit is comparable to double-deck lifts, which is apparent if you consider them as a double-deck lift with an additional degree of freedom, i.e., the two cabins are not attached to each other [10].

Managing two lifts in one shaft introduces unique dispatching challenges as follows. The core Global Dispatcher group collective algorithm must be supplemented by additional logic to avoid collision, impasse scenarios, and passengers getting into the wrong car.

6.2 Collision avoidance

The first step required is to have a collision avoidance strategy; for example, see Figure 4 from [7]. This involves holding back one car where the next destination cannot be completed without collision and inserting additional calls to move an obstructing car out of the way.

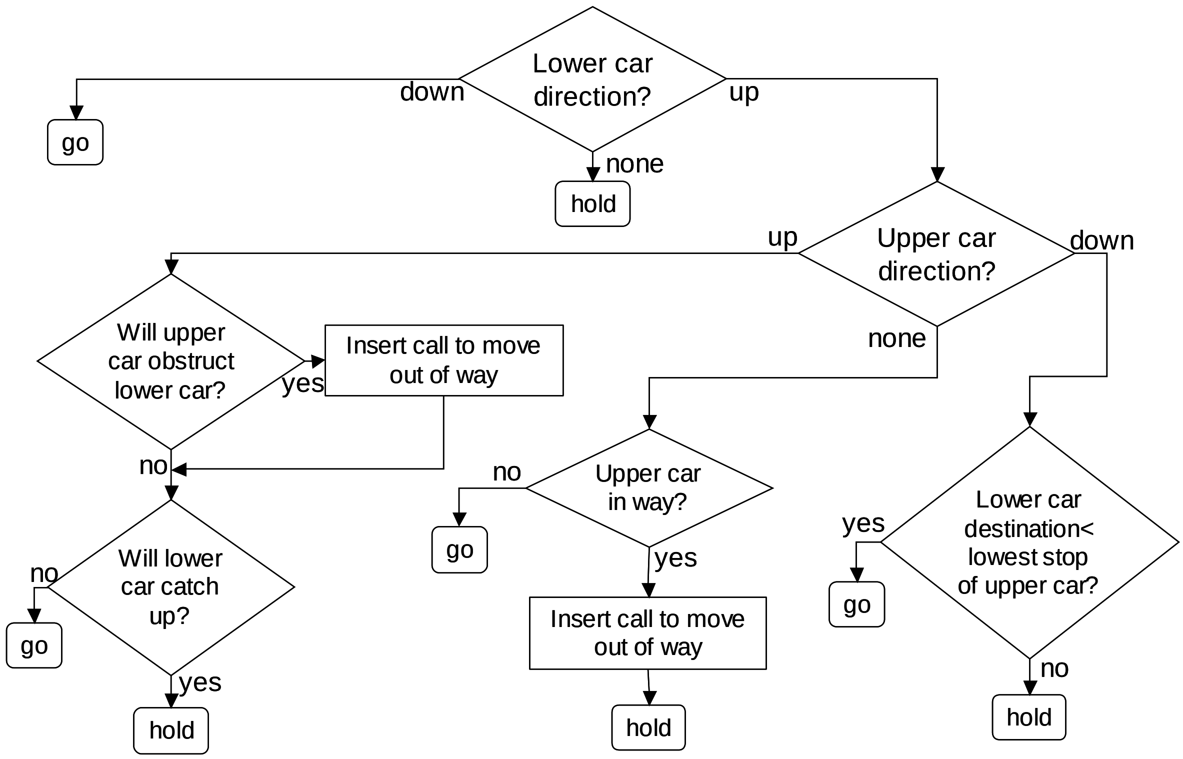

Figure 4 Collision avoidance strategy

6.3 Banned allocations due to impasse scenarios

Another issue is that some combinations of calls result in an impasse; this occurs when to complete the allocated calls, we must reverse a car which already has a passenger in it, see Figure 5.

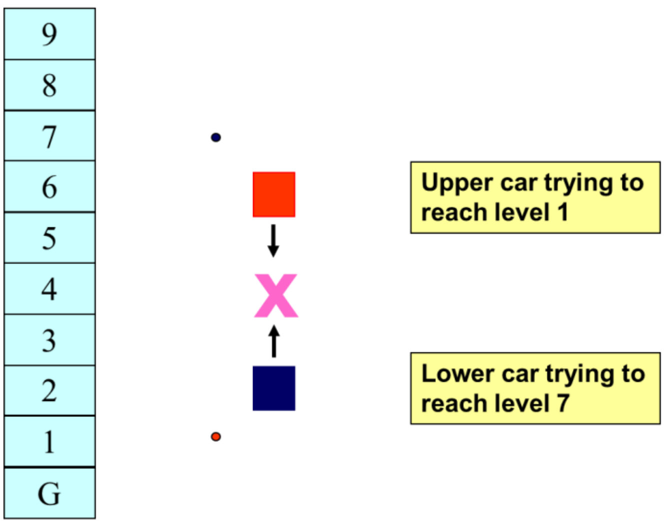

Figure 5 Impasse scenario

6.4 Banned allocations due to passenger loading the wrong car

Like double-deck lifts, there is a risk that a passenger will get into the wrong car. In the example represented in Figure 6, the dispatcher wants to consider allocating a call from level 7 to the lower car. However, the upper car is already scheduled to stop at level 7. As the two cars are both loaded from the same landing doors, the passenger that the dispatcher wants to load the lower car is likely to load the upper car by mistake.

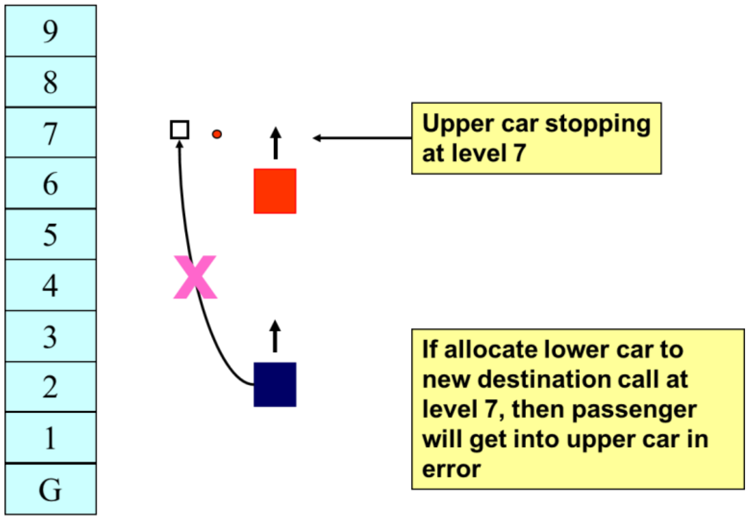

Figure 6 Scenario where person loads the wrong car

7 IMPLEMENTATION

The Global Dispatcher applies the Global Dispatcher Interface [11]. Messages are communicated over TCP/IP applying Protocol buffers, which is a language-neutral, platform-neutral, extensible mechanism for serializing structured data.

All the dispatching calculations are implemented in a single software module (a self-contained and reusable unit of code). In simulation [12] this software module runs in parallel to the simulation software on the user's computer. The same software module is run in buildings on an Industrial IoT Edge Gateway device [13] to direct lift controllers [14].

The Global Dispatcher applies central (rather than distributed) control as part of the group controller, see Figure 7. All the dispatching calculations take place in the group controller, which is required to achieve the benefit of a modular, controller-independent dispatcher. In the alternative, a distributed system, each lift controller is responsible for calculating a "bid" for the new call and any one of the lift controllers can act as a master to review the bids and make the allocation. This distributed approach is inherently robust, something central control relies on a backup device to achieve.

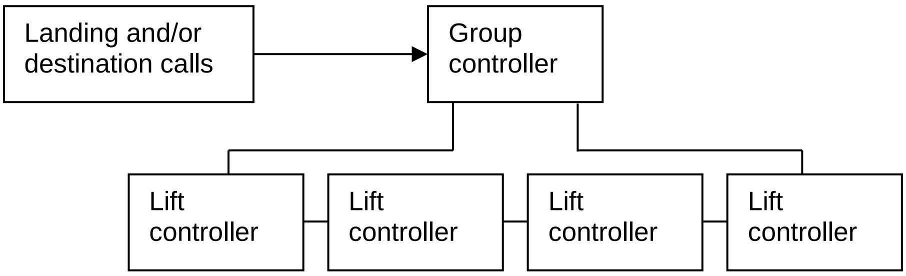

Figure 7 Centralised control (from Figure 9.3 CIBSE Guide D: 2020 [15])

Destination input devices are off-the-shelf Android kiosk tablets with Power-over-Ethernet [16], running a non-proprietary kiosk browser [17]. Conventional landing and car calls require additional hardware to convert button presses to messages on the same network. All software updates and configuration options can be applied remotely from off-site.

8 CONCLUSIONS

The conception of the Global Dispatcher and its evolution emerged from a culmination of thirty-six years engaged in the design and subsequent deployment of dispatcher algorithms.

In that time, the complexity of dispatching has grown with the introduction of diverse input devices and lift configurations. Within our proprietary simulation software [12], we have developed and continue to manage fourteen such dispatchers. While retaining the need to employ legacy dispatchers for assessing modernisation projects, there also exists a requirement for a more optimised resolution to this challenge.

Another challenge encountered has been the necessity of formulating distinct dispatchers for varying controllers. By transferring certain decisions typically made by the controller to the dispatcher, a singular dispatcher software module can be universally applied across all lift controllers.

Furthermore, by applying passenger-centric optimisation objectives and treating conventional landing calls as destination calls with inferred destinations, the Global Dispatcher can evaluate all feasible allocations across different lift configurations under a uniform criterion. This capability empowers the dispatcher to impartially juxtapose calls from diverse input devices against potential assignments to various lift types. While the simultaneous deployment of single-deck, double-deck, and two-cars-per-shaft solutions within the same group is improbable, this capability facilitates evaluating and deploying all conceivable combinations of such.

The Global Dispatcher remains an ongoing undertaking. While not all functions have been fully realised and deployed, the foundational framework and concepts have been substantiated. Preliminary iterations are operational both in simulation and real-world building scenarios.

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ACKNOWLEDGEMENTS

The author would like to acknowledge Dr Mike Pentney of Peters Research Ltd and Mr Brendan Johnson of Lester Controls Ltd without whom the Global Dispatcher and the Global Dispatcher Interface would have remained a theoretical concept.

BIOGRAPHICAL DETAILS

Richard Peters has a degree in Electrical Engineering and a Doctorate for research in Vertical Transportation. He is a director of Peters Research Ltd and a Visiting Professor at the University of Northampton. He has been awarded Fellowship of the Institution of Engineering and Technology, and of the Chartered Institution of Building Services Engineers. Dr Peters is the principal author of Elevate, elevator traffic analysis and simulation software.

The Need for Standardized Metrics and KPI's for AI Performance

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Keywords: Artificial Intelligence, Metrics, Maintenance.

Abstract. The use of Artificial Intelligence (AI) in the lift industry is becoming commonplace. It, along with remote monitoring, is being applied to lift and escalator maintenance.

Some governments who require monthly or twice monthly maintenance now only require quarterly maintenance if remote monitoring and AI are utilized.

The benefits of AI-augmented maintenance such as increased up time, improved first time fix rate and fewer running on arrival (ROA) calls are being touted by governments and lift companies alike. However, no standardized set of metrics exists for these benefits.

A set of metrics for lift and escalator maintenance is proposed and discussed.

1 INTRODUCTION

In this paper, existing service metrics for lifts and escalators will be reviewed. The meanings of these metrics and how these metrics are used to evaluate service performance when using Artificial Intelligence (AI), as well as how these metrics can be misinterpreted or even manipulated, will be reviewed.

2 METRICS

2.1 False Positives, False Negatives

Machine Learning based on Pattern Recognition is one form of AI that is being used for lifts [1]. One of the goals of Machine Learning (ML) is to be able to predict that a lift will fail in the near future and send a technician to the site to fix the lift before it fails.

Vibration patterns of many lift components can be captured by accelerometers. The vibration of a new component will be different from an older or damaged component. The remaining life of these components can be monitored and these components can be replaced before they fail.

When a prediction is made that a lift WILL fail there are two possible outcomes as follows:

1. True Positive (TP). It was predicted that the lift would fail, and it fails.
2. False Positive (FP). It was predicted that the lift would fail, and it does NOT fail.

When it is predicted that a lift will NOT fail there are also two outcomes:

1. True Negative (TN). It was predicted that the lift would not fail, and it did not fail.

2. False Negative (FN). The lift was predicted not to fail, and it failed.

The following example is used to explain the terms False Positives and False Negatives as well as True Positives and True Negatives [2].

Example 1. A Building Complex with 100 lifts equipped with IOT remote monitoring devices are connected to a cloud-based predictive analytics system. This system has predicted that 10 of the 100 lifts will fail in the next 2 weeks. This also means that the other 90 lifts will not fail.

A technician is sent to each of the 10 units that are predicted to fail and finds 8 lifts that have a condition that if not repaired will definitely cause the lift to fail in 2 weeks. He fixes the 8 lifts.

During the next two weeks, the 2 lifts that were predicted to fail do NOT fail. However, 3 other lifts do fail.

Of the 10 predictions, there were 8 True Positive predictions and 2 False Positives.

Additionally, there were 3 False Negative predictions.

One method of visualizing these results is a Confusion Matrix [3]. Figure 1 is a confusion matrix of these results.

		Predicted	
		Failure 10	No Failure 90
Actual	Failure 11	TP 8	FN 3
	No Failure 89	FP 2	TN 87

Figure 1 Confusion Matrix

These results will be viewed differently by the building complex manager than by the Lift Company's branch manager.

Building Complex manager's perspective:

> Prior to adding the IOT equipment the complex would have experienced 11 breakdowns. The IOT system prevented 8 breakdowns. The complex manager is satisfied with the improvement.

Branch manager's perspective:

> With or without IOT, 11 lifts would need to be repaired. With IOT, 2 additional service visits to the lifts that did not fail were required. The branch manager is unhappy because the two visits to lifts that did not fail will reduce the branch profitability and his bonus.

False Positives are an important metric. The lower the occurrence rate of False Positives, the happier both the Building Manager and the Branch Manager will be.

Prior to installing IOT equipment, all breakdowns were False Negatives. Fixing a lift before it fails should come at a lower cost, particularly if it can be repaired during normal working hours.

Eliminating False Negatives should improve both customer satisfaction and operational efficiency. False Negatives can also be labelled *Unpredicted Failures*.

Unpredicted failures, particularly the reduction of unpredicted failures, is a significant metric.

2.2 Precision and Recall

Statisticians use the metrics of Precision and Recall in evaluating predictions [4].

Precision represents the accuracy of the predictions that were made. It is defined by the following formula:

$$Precision = \frac{Tp}{(Tp+Fp)} \tag{1}$$

Where: Tp represents True Positives

Fp represents False Positives

In Example 1, ten predictions were made. There were 8 True Positives and 2 False Positives. The Precision of these predictions was 0.8.

Recall represents the number of True Positives that were predicted compared to the number of True Positives that could have been predicted. Recall is defined by the following formula:

$$Recall = \frac{Tp}{(Tp+Fn)} \tag{2}$$

Where: Tp represents True Positives

Fn represents False Negative

Ideal Values of both Precision and Recall are 1.0.

In Example 1, Eight True Positives were predicted. However, there were a total of Eleven Positives. Since there were 3 Failures that were not predicted, there were 3 False Negatives. The Recall value of these predictions was 0.73.

Recall and Precision are not metrics of the Predictive Maintenance system but rather are metrics of the Machine Learning system that is a part of the Predictive Maintenance system. If the ML system has Recall and Precision values of 1.0 but they are ignored and no actions are taken to fix the lift before it fails, then the Predictive Maintenance system has no value to either the building or the lift maintenance provider.

It should also be noted that if the ML algorithm is conservative, then there can be high Precision levels because there will be no false positives. However, Recall values will be low because false negatives will be high.

2.3 Lift Failures

What is the definition of a Lift Failure or the more commonly used term, Breakdown?

One definition proposed is, "The lift is unable to move the users up and down in a building" [5]. This seems to be a simple definition. However, consider the three following examples:

1. There are some failures that appear for a period of time and then the lift returns to service without any human intervention. These failures often go unreported.

2. Buildings report a lift is out of service, but when the technician arrives, the lift is functioning properly. This type of failure is often reported as Running on Arrival or ROA.

3. A Machine Learning system connected to a lift determines the lift is out of service and initiates a remote reset of the controller. After the reset, the lift functions normally. The building did not detect that the lift was out of service.

Should any of these three examples be considered failures? What is good for a brochure might not be so good for the building operator. All failures should be reported so the AI system can be properly evaluated.

2.4 MTBF

MTBF, Mean Time Between Failures is a standard metric used for years in industrial applications [6]. Since one of the benefits of AI is the ability to fix things before they fail, AI should result in longer MTBF values. MTBF can be calculated as follows:

$$MTBF = \frac{\sum(start\ of\ downtime - start\ of\ uptime)}{number\ of\ failures} \tag{3}$$

2.5 MTTR

MTTR, Mean Time to Repair is a metric that simply calculates the average time required to return a lift to service that has failed. AI should shorten the time to repair because simple repairs can be performed before the failure becomes more serious and additionally reduces diagnostic times.

$$MTTR = \frac{\sum(start\ of\ uptime - start\ of\ downtime)}{number\ of\ failures} \tag{4}$$

2.6 Failures per Unit

Failures per Unit are usually expressed as failures per unit for a time period such as a year. The average number of failures or breakdowns per year is difficult to determine from published literature. One source stated that breakdowns per unit per year of well-maintained lifts varies from 0.5 to 2 per year [7]. Another source states that the average lift has 4 breakdowns per year [8]. A major manufacturer claims to have less than 1 breakdown per unit per year on the lifts that they maintain [9].

The ability of AI to predict impending failures before they occur and permit lifts to be fixed before they fail should reduce the failures per unit per year.

2.7 First Time Fix Rate

First Time Fix Rate (FTFR) is a metric used to determine the efficacy of an unscheduled service visit [10]. How is a First Time Fix defined? One definition is that the fault does not reoccur for 30 days [5]. The following are two examples that could make the reported FTFR appear better than the true FTFR.

Example 1.

Sequence of Events:

Technician A is dispatched to the site of a breakdown. The lift is not running, and he can find no apparent reason for it being out of service. He cycles the isolator switch, and the lift starts to run. On his service ticket he reports “Found lift out of service, adjusted door locks on floors 1, 2, and 3. Car returned to service”.

Two weeks later the lift has a second breakdown. Technician B is dispatched to the same site, and he also cannot find the cause of the problem. He cycles the isolator switch, and the lift starts to run. On his service ticket he reports "Found lift out of service, adjusted Gate Switch and cleaned car door tracks. Car returned to service".

Three weeks after the first breakdown, Technician C was dispatched to the site to upgrade the controller software. The lift has not been reported out of service and Technician C finds the lift running properly. The technician installs the new software, and the lift is still functioning properly after 90 days.

Impact on FTFR:

Although the two breakdowns occurred within 30 days, because the problem resolutions were different, both breakdowns were reported as being Fixed the First Time. Because a software upgrade prevented further breakdowns, the root cause of the breakdowns was a software bug. The two breakdowns were not Fixed the First Time. However, they were reported as being Fixed the FirstTime.

Example 2

Sequence of Events:

A hydraulic lift is serviced quarterly. When the piston leaves the cylinder as the lift travels in the up direction, a film of oil is deposited on the piston. As the piston returns into the cylinder, the film of oil is wiped off the piston and into a collector ring. A small hose is connected to the collector ring which transports the oil into a 19-litre container.

A technician is dispatched to the hydraulic lift site because the lift is reported out of service. The technician finds the lift shut down due to a lack of oil. He empties the oil from the overflowing 19-litre oil container into the oil tank and adds 10 additional litres of oil to the tank. The lift is returned to service.

Six weeks later the lift is shut down again, and again the problem is a lack of oil. This time a repair crew is sent to replace packing gland seals and add 20 litres of oil. With new seals, the lift will deposit a smaller film of oil on the piston. The lift can now run without shutting down due to low oil between the quarterly services.

Impact on FTFR:

Because the shutdowns occurred more than 30 days apart, the first breakdown was reported as being Fixed the First Time. However, the lift was not fixed until the packing was replaced after the second low-oil event.

In both of these two examples, the lift was reported as Fixed the First Time, making the FTFR metric look good. However, the breakdowns per unit per year metric will look worse than if the problems were fixed the first time.

2.8 Running on Arrival Incident Rate

When a service technician is dispatched to repair an out-of-service lift, it is very common to find the lift Running on Arrival. There is the assumption that there was never anything wrong with the lift and that the building management company failed to verify that the lift was truly out of service.

One lift company will invoice the customer for ROA calls unless they have an IOT-based remote monitoring system [11].

Those with experience in service operations have found that ROA calls usually involve a real problem that is intermittent, or condition based.

For example, a door lock may be misadjusted. The lift will function properly most of the time. However, if passengers are distributed in the lift car in a particular way, the car may tilt slightly and cause the door to not properly lock. In this case, the car will not run until the passengers exit and the car balance changes. With the change in car balance, the car then runs. This creates an ROA event.

Are ROA calls considered a breakdown? In many cases, they are not counted and the customer is invoiced for a nuisance call.

The number of ROA calls could be a performance metric. A large number of ROA incidents indicates there are unresolved intermittent problems.

3 CONCLUSIONS

There are metrics available that can effectively be used to evaluate the efficacy of the application of AI in lifts and escalators. However, the definitions of what is a breakdown, what is a First Time Fix, or the significance of an ROA call can have an impact on the meaningfulness of these metrics.

A set of standardized metrics would be helpful for consultants and building management when considering an investment in AI and for evaluating the efficacy of an installed AI system. Additionally, standardised metrics would help the lift companies better understand the efficacy of their AI systems and how to improve those systems.

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Market Feedback and Additional Guidance on ISO 8100-32

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Keywords: lift, traffic, calculation, simulation, standard.

Abstract. ISO 8100 Part 32 is a new international standard published in 2020, addressing the planning and selection of passenger lifts for installation in offices, hotels, and residential buildings. The standard describes two methods to determine an appropriate lift installation: traffic calculation and simulation. Guidance is given on inputs to the analysis and how to review its results. A Technical Report is being prepared to support the application of the standard. In preparation for this work, a survey was undertaken to help understand the application of the standard and how the authors could best support its use. The survey results provide insights into how people engage with the standard and what additional guidance needs to be provided. This paper summarises the feedback and the scope of the additional guidance which will be included in the Technical Report.

1 INTRODUCTION

The ISO 8100-32:2020 standard, titled “Planning and Selection of Passenger Lifts to be Installed in Office, Hotel and Residential Buildings”, was the culmination of seven years of work by ISO Working Group 6, Subgroup 5 to create an international standard on that topic under the aegis of the International Standards Organization [1]. The work started from ISO Technical Committee 178 resolution in 2013 to revise ISO 4190-6:1984 and extend its scope to buildings other than residential buildings [2]. Note that other planning and selection guides are developed in certain geographic regions, such as CIBSE Guide D from the Chartered Institution of Building Services Engineers [3].

The planning and selection of lifts has historically been a mix of art and science with varied practices that depend on training, experience, functional background, geographic region and building application. The process is typically partially based on industry-standard analysis methods but also interpreted by subjective factors. In light of a wide range of differing approaches, a primary objective of the 2020 standard was to define a core process in terms of inputs (e.g., data requirements) and outputs (e.g., reported metrics), to establish a common terminology, to specify a set of basic design criteria, and to endorse and briefly describe two industry-standard analysis methods. Recognizing the complexity of the subject matter and the difficulty in achieving consensus on more subjective guidance, the standard focused on the core analysis and terminology that would be applicable by those already skilled in the planning and selection process but also provided several simplified charts under a few scenarios for those less inclined to implement a detailed analysis method.

In 2022, the ISO working group proposed a new work item assigned to the same subgroup that created the original standard to supplement the standard with a separate Technical Report that provides additional guidance and discussion on some of the more complex topics. As a first step, the working group felt that Market Feedback from the user base on the standard was essential to make sure that the Technical Report addressed the most fruitful areas for guidance. Accordingly, the subgroup prepared a questionnaire and solicited feedback through a variety of associations, forums and publications intended to reach the main audience for the standard. The survey itself was made publicly available via a web-based survey tool from the end of November 2022 to the end of January 2023.

This article intends to describe: (1) the goal of the questionnaire, the survey design and how it was reviewed, advertised, and implemented; (2) the key findings from the survey; and (3) a conclusion on the results and how they will impact the Technical Report. This feedback will inform the subgroup as it prepares the Technical Report expected to be published in 2025. Section 2 of this article discusses the survey methodology and design, sections 3-5 summarize the key results from the responses to the survey and section 6 discusses the conclusion of the Market Feedback.

2 METHODOLOGY

The survey questions, logic, and target distribution list were discussed and agreed upon by the working group responsible for ISO 8100-32. The survey was implemented using popular online survey software, which could easily be circulated electronically. The survey software provided some logic to ensure follow-up questions were only presented when relevant. It also used cookies to make it difficult for people to complete the survey more than once. No personal information was collected, avoiding General Data Protection Regulation (GDPR) issues.

The survey was sent to 21 organisations representing engineering societies, associations, the press, and standards bodies related to the international lift industry. The survey was open for three months from the end of November 2022 and received 427 responses. The questions asked are shown in Table 1.

Table 1 Survey questions

#	Question
Q1	In what country do you live?
Q2	For what regions do you work professionally?
Q3	What is your profession/job title?
Q4	What type of organization do you work for?
Q5	Have you used ISO 8100-32?
Q6	How often have you referred to or used ISO 8100-32?
Q7	For office buildings, how frequently do you use ISO 8100-32?
Q8	For hotel buildings, how frequently do you use ISO 8100-32?
Q9	For residential buildings, how frequently do you use ISO 8100-32?
Q10	How frequently do you use the calculation method from ISO 8100-32?
Q11	How frequently do you use the simulation method from ISO 8100-32?
Q12	Which parts of ISO 8100-32 have you used?
Q13	Are there any specific reasons why you have not used ISO 8100-32?
Q14	Which other guidance documents have you found useful for your work?
Q15	What additional guidance on ISO 8100-32 would you consider helpful?
Q16	Please specify in more detail where additional guidance should be provided.

The introduction to the survey explained that the first edition of ISO 8100-32 was published in 2020 and that it addressed the planning and selection of passenger lifts to be installed in offices, hotels, and residential buildings. The purpose of the survey was to assist the working group responsible for ISO 8100-32 in preparing a guidance document in the form of a Technical Report. Feedback on using the standard was invited so that this Technical Report could be provided.

For ease of analysis, most questions asked the respondent for a selection of one or more options, with an “other” option to capture unanticipated answers. Questions 7 to 11 used a scale of 1 (Never) to 5 (Always). Question 14 invited freeform text to help determine other guidance documents people find helpful.

The responses are summarized in the following sections. Responses to some of the questions are further categorized by responses to a background question such as Question 1 and Question 4. It is worth noticing that the sample size in some of the resulting categories is too small for statistical significance. For such categories, the data is included in the analysis, but further conclusions are not made.

3 BACKGROUND OF THE RESPONDENTS

As the survey was distributed to organisations around the world, it is not surprising to find responses from 68 countries in total including every geographical region of the globe. 75% of the respondents were living in European and Asian countries where there are relatively large lift markets. The United Kingdom and Australia dominate as the respondents’ country of residence with more than 15% of the respondents living in those. Table 2 lists the top-ten countries in which the respondents were living along with the number of respondents in each according to the responses to Question 1. One respondent did not reveal their country of residence.

Table 2 Top-ten countries in which the respondents live

Country	Respondents	Country	Respondents
United Kingdom	67	United States	16
Australia	65	Poland	12
Switzerland	23	Hong Kong	12
China	18	Spain	11
Germany	18	India	10
Unknown	1	Other (58)	174

By combining responses to Questions 1 and 2, the geographical region in which the respondents were living can be tabulated with the region for which they were professionally working. Table 3 relates the respondents living in each region to the regions they worked for. Since Question 2 allowed multiple choices, the total number of respondents working for different regions exceeds the number of respondents living in that particular region. Generally, more than 95% of the respondents worked for the same region as they were living. Oceania makes an exception to this rule as only 84% of the respondents living in the region also worked for the region. The European respondents stand out from the others since a significant portion of them, circa 15%, also work in each of the other regions.

Table 3 The regions in which the respondents live and for which they work

Region of living	Respondents living in the region	Respondents working for a region				
		Africa	Americas	Asia	Europe	Oceania
Africa	6	6		1	1	
Americas	36	1	35	2	4	1
Asia	103	5	3	99	11	4
Europe	212	25	35	39	206	27
Oceania	69		2	15	5	58
Total[1]	426	37	75	156	227	90

Table 4 explores the relationship between the responses to Questions 3 and 4, i.e., the role in which a respondent was working and the type of organisation for which they were working. More than half of the respondents, 231 in total, worked for lift suppliers. Significant numbers of them worked in engineering and sales roles. Lift consultancies and engineering firms were the only other types of organizations, from which a significant number of responses originated. The low number of responses from architectural firms and construction companies may result from two reasons: either the survey distribution channels did not have many representatives from such organisations or ISO 8100-32 was not known well enough to raise interest to respond to the survey.

Table 4 The role and type of organization of the respondents

Type of organization	The role of the respondents						Total
	Architect	Consultant	Engineer	R & D	Sales	Other	
Architectural firm	1	4					5
Construction		1	6	1	5	2	15
Engineering		15	26	2	1		44
Government		2	1			3	6
Lift consultancy		56	9			2	67
Lift supplier		7	101	14	88	21	231
Regulatory org.		1	6			2	9
Other			11	2		13	26
Total	1	86	160	19	94	43	403

4 THE USE OF ISO 8100-32

"Yes" responses to Question 5 of the survey guided the respondents to more detailed questions about their use in Questions 6 to 12. By choosing "No", a respondent was allowed to continue directly from Question 13. In total, 214 respondents (50% of them) had used the standard, 170 respondents (40% of them) confirmed having not used the standard, and 43 (10%) had skipped the question. Table 5 summarizes the number of respondents for each choice of Question 5. Since Question 5 allowed

[1] Table 3 data does not the respondent who did not reveal his/her country of residence. As a results, the total number of respondents is 426 instead of 427.

multiple choices for a respondent, the shown values add up to higher values than the simple Yes/No categorisation. Of those who had not used ISO 8100-32, 44% were not aware of it while 34% did not have access to a copy of it. On the other hand, 34% of the respondents had a copy of it but either had not read it or just not used it.

Table 5 The number of respondents categorised by the use of ISO 8100-32

Used or not	Response	Respondents
No	I was not aware of it	74
	I do not have access to a copy	58
	I have access to a copy but have not read it	12
	I have read it but have not used it	46
Yes	I have referred to it in a specification of a lift installation	141
	I have applied it to the planning and selection of lifts for a project	165
	I have used it for another purpose	36

The remaining analysis in this section concentrates on the 214 users of ISO 8100-32. Those using the standard for its intended use based on Question 6 responses were further categorized by the type of organisation for which they work as shown in Table 6. Generally, 77% of the users had applied it to planning and selection while 66% had referred to it in a specification. This pattern repeats across the different types of organisations, where sample size allows meaningful conclusions, i.e., in the cases of engineering firms, lift consultancies and lift suppliers.

Table 6 The uses of ISO 8100-32 categorised by the type of organization

Type of organization	Used ISO 8100-32	Referred to ISO 8100-32 in a specification	Applied ISO 8100-32 to the planning and selection of lifts
Architectural firm	3	2	1
Construction	9	9	8
Engineering	18	11	14
Government	1		
Lift consultancy	27	18	21
Lift supplier	144	96	113
Regulatory org.	3	1	
Other	9	4	7
Total	214	141	164

Question 6 concerned the frequency of using ISO 8100-32 and allowed a respondent a single choice from daily to annual use. Table 7 explores the responses categorised according to the type of organization, where four respondents working for a lift supplier had skipped this question. Here, a frequent user is defined as using the standard either daily or weekly. Accordingly, 37% of all users had used the standard frequently. A slightly greater percentage, 40%, of the users working for lift suppliers were frequent users. The number of frequent users in lift consultancies and engineering firms was too low for a reliable conclusion, although the portion of frequent users in such organisations ranged from 26% to 33%.

Table 7 Frequency of using ISO 8100-32 per the type of organisation

Type of organization	Daily	Weekly	Monthly	Annually	Total
Architectural firm		2	1		3
Construction	1	2	6		9
Engineering	1	5	6	6	18
Government			1		1
Lift consultancy	1	6	16	4	27
Lift supplier	8	49	59	24	140
Regulatory org.			1	2	3
Other	3		5	1	9
Total	14	64	95	37	210

Questions 7 to 9 asked about the frequency of using ISO 8100-32, for example, when a respondent is working on an office building. The respondents were given a range of choices from one to five, where a value of one corresponds to never and five corresponds to always. In comparison to Question 6, which charted the frequency of use in time, Questions 7 to 9 consider the frequency of using the standard for a particular purpose. In the following, a respondent is interpreted as a frequent user if they responded either "four" or "five" as the frequency. Figure 1 shows the number of frequent users categorised by the type of organisation for different building types along with their percentage shares. According to the figure, frequent use of ISO 8100-32 is independent of the building type. On the other hand, more than 80% of the users working for a lift supplier use the standard frequently while 40-50% of the users working for lift consultancies and engineering firms belong to the frequent users.

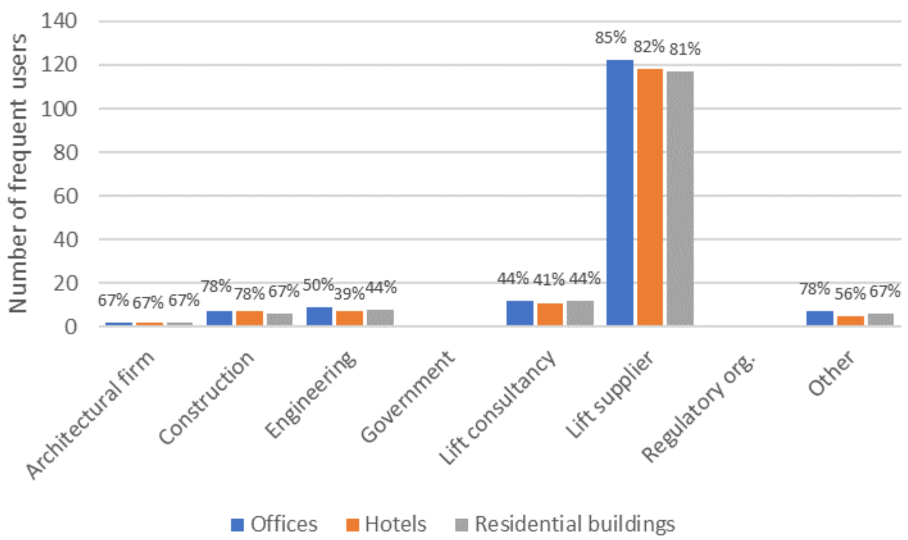

Figure 1 Frequent users of ISO 8100-32 for offices, hotels, and residential buildings

Questions 10 and 11 asked about the frequency of using the calculation method and the simulation method, respectively, in the range from one to five. Figure 2 depicts the number of frequent users categorised by the type of organisation. The difference in using the different methods is the clearest for the users working for lift suppliers, where 85% of the users frequently use the simulation method but less than 10% use the calculation method. The responses from lift consultancies and engineering firms resembled each other as about 50% of the frequent users had used the simulation method but about 30% the calculation method. Nevertheless, the results show that the simulation method defined in ISO 8100-32 is used significantly more often than the defined calculation method.

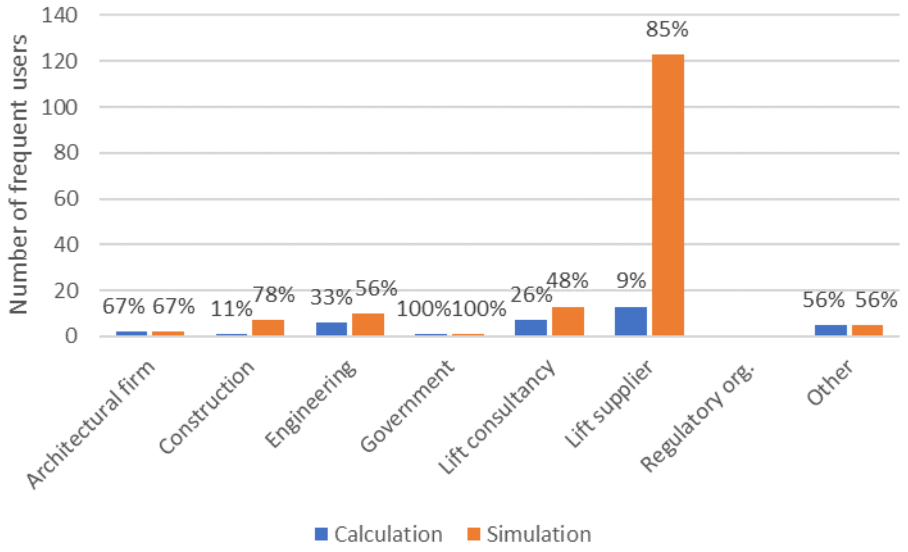

Figure 2 Frequent users of ISO 8100-32 for the calculation and the simulation method

Question 12 allowed a respondent to choose from all the top-level clauses of ISO 8100-32 that they had used. Figure 3 depicts the number of users having used each clause along with a percentage of all users. Clause 8, which sets requirements for the simulation method, is clearly the most referred to part of the standard as almost 80% of the users had used it. The other parts of the standard attracted less than 30% of the users. However, of those, “Terms and definitions”, “Reporting”, as well as Annexes A, B, and C attracted more than 25% of the users.

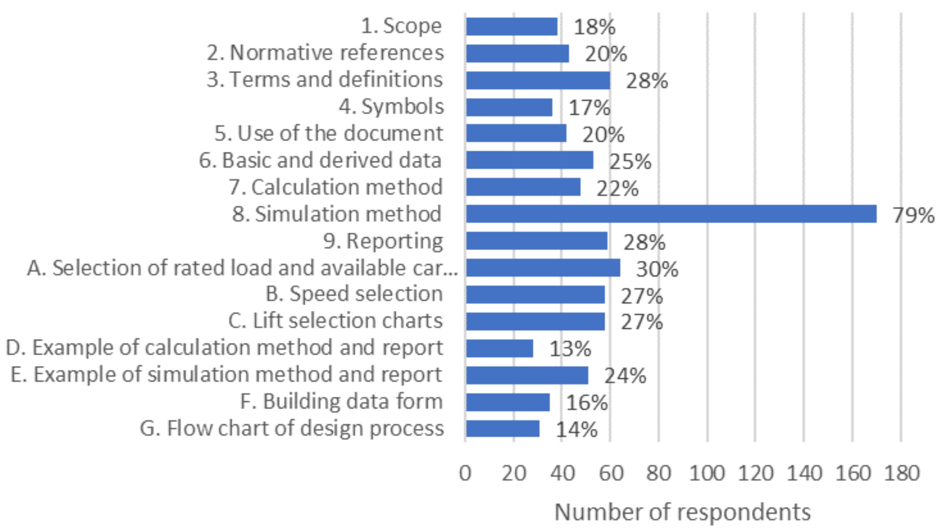

Figure 3 The use of the top-level clauses of ISO 8100-32

5 THE NEED FOR ADDITIONAL GUIDANCE

Questions 13 to 16 aimed at gathering a further understanding of why the respondents had not used the standard and what kind of guidance need they had. These results were assumed to give concrete ideas about topics that could be covered in the new Technical Report under preparation. First, Table 8 summarizes responses to Question 13 about reasons for not using ISO 8100-32. More than half of the respondents indicated that there are no specific reasons not to use the standard. However, 35 respondents either did not know of or were not confident of how to use the standard, so could benefit from the additional guidance.

Table 8 The reasons for not using ISO 8100-32

Any reason not to use?	Response	Respondents
No	There are no reasons for not using ISO 8100-32	235
Yes	I do not know how to use it	15
	I am not confident how to use it	20
	I prefer other design procedures	27
	I am required to use other design procedures	25
	Other	48

Freeform responses to Question 13 along with the option "Other" gave additional yet hard-to-summarise feedback, although some recurring reasons could be identified:

1) some respondents or their customers were not aware of the standard;
2) some respondents' work did not include planning and selection of lifts;
3) some respondents did not have access to the standard;
4) some respondents prefer other methodologies and/or guidance documents.

In Question 14, respondents were asked to list other guidance documents that they have been using. As the responses were given as freeform text, they contained a wide variety of document references. Table 9 summarizes the number of respondents based on the guidance documents that they used.

Internationally known CIBSE, BCO, and PCA guidelines provide guidance within the scope of ISO 8100-32 and are, therefore, the most relevant other guidance documents for this survey [3,4,5]. CIBSE Guide D was the most referred to document as 62 (15%) of the respondents named it. The users of CIBSE Guide D split interestingly into different kinds of organisations: 28 of them (45%) worked for a lift consultancy, 14 (23%) for a lift supplier and 9 (15%) for an engineering firm. On the other hand, about half of those having used CIBSE Guide D had not used ISO 8100-32 while another half of them had used ISO 8100-32.

BCO and PCA guidelines were mentioned by more than 10 respondents, however, this represents less than 5% of the respondents. The respondents also mentioned other local codes and guidelines as well as their own or proprietary documents. Some of the responses also listed other standards.

Table 9 Other guidance documents the respondents had used

Type of organization	CIBSE Guide D	BCO	PCA	Other local codes and guidelines	Own or proprietary
Architectural firm	2				1
Construction					
Engineering	9	4	5	1	2
Government	1				1
Lift consultancy	28	11	2	9	1
Lift supplier	14	1	8	12	8
Regulatory org.				2	
Other	8	2		5	1
Total	62	18	15	29	14

The last part of the survey concentrated on collecting needs for additional guidance on ISO 8100-32. Figure 4 shows the percentage of respondents needing guidance on a specific part of the standard based on Question 15. The simulation method specified in Clause 8 was ticked by more than 30% of the respondents while more than 25% would need more guidance on lift selection charts in Annex C. The respondents were given an additional choice, which was not directly linked to any particular parts of the standard. More than 25% of the respondents indicated their need for additional examples in applying the standard.

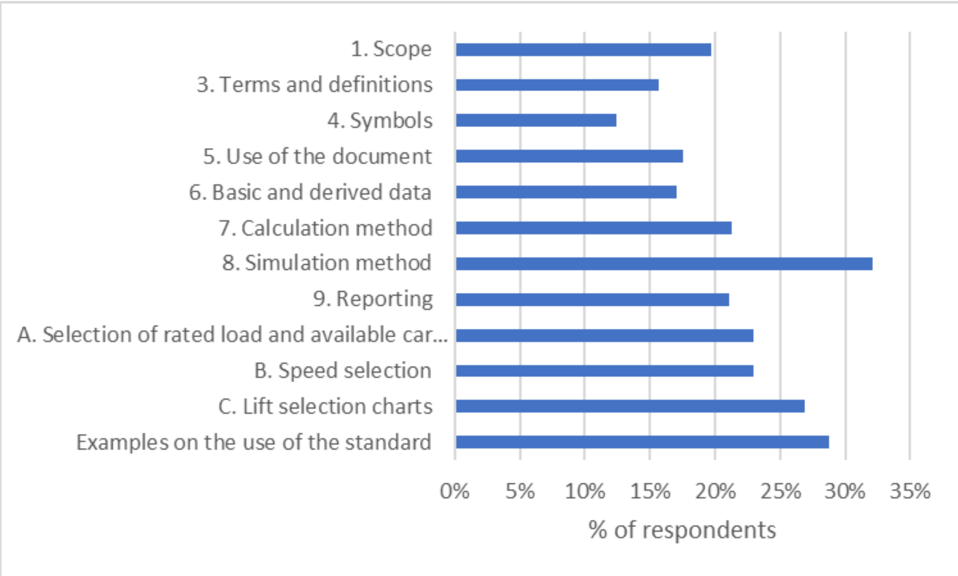

Figure 4 Percentage of respondents needing additional guidance in different parts of ISO 8100-32

Quite naturally, the high-level responses to Question 15 only indicate parts of the standard that are challenging for its users to understand and can direct the efforts to create additional guidance. However, they cannot tell what guidance is actually needed. Therefore, the purpose of Question 16 was to collect more detailed descriptions, specifically what kind of guidance could benefit the users of the standard. In total, there were more than 100 non-empty responses to this question. Some of them meant “no comments” expressed in one way or another. Some of them gave a rather vague idea of what kind of guidance is really needed. Some of them indicated change proposals to the standard, which is not in the scope of the Technical Report under preparation.

About 20% of the comments were related to the application of ISO 8100-32 in general: how or when should it be used, how to use it for the replacement/modernisation of lifts in existing buildings, or what are its legal requirements. These needs could be covered by describing in more detail how lift planning and selection integrates with the building design process. Some comments asked for an explanation of how ISO 8100-32 is related to other guidance documents, e.g., CIBSE Guide D, and how to establish their equivalence. Guidance on design criteria and other parameter values for building types or lift uses other than in the scope of the standard, e.g., hospitals and goods lifts were requested in about 10% of the comments. However, the analysis methods of the standard require well-established data definitions and design criteria for each type of building within its scope. In addition, many comments were related to the data, such as building occupancy and typical lift performance parameters. About 10% of the comments further confirm the observation related to Question 15 that additional practical examples showing the use of the standard in steps would help in understanding it and how to apply it in practice.

Two respondents raised detailed questions about the value of lunch traffic required handling capacity in ISO 8100-32 design criteria for offices. The value is assumed to accommodate standard designs. In other words, peak passenger demands in a typical office building are not expected to exceed the required handling capacity defined for the full population, i.e., with no allowance for absenteeism or stair usage.

Generally, peak demands during lunch traffic have been found to be higher than during morning uppeak traffic although also the contrary occurs [6,7]. As well, lunch traffic demands higher than ISO 8100-32 required handling capacity were observed especially in buildings with one (major) tenant and in certain geographic areas. Thus, in addition to internationally accepted minimum values, lift planning and selection should carefully consider local conditions and the targeted use of the building.

To allow more future-proof and flexible designs, higher handling capacity than given in ISO 8100-32 can be required as implied by a note:

> “Other values [than the ones shown in Table 3 of ISO 8100-32] can be used provided they are documented with reasons. The values given can change depending on national and cultural norms, building usage, etc.”

For example, CIBSE Guide D requires a higher handling capacity for lunch traffic than ISO 8100-32.

It is also worth noticing that the ISO 8100-32 simulation method requires consideration of passenger demands higher than the required handling capacity. The method does not impose any strict limits for passenger service quality under higher demands but helps in understanding the sensitivity of a lift installation to such demands.

6 CONCLUSION

ISO 8100-32 has now been public since June 2020. The survey organized by ISO/TC 178/WG 6/SG 5 aimed at collecting market feedback on the standard and needs for additional guidance. The survey invitation was sent to 21 organisations and attracted 427 responses from around the world. More than half of the respondents worked for lift suppliers while significant proportions worked for lift consultancies and engineering firms. Approximately half of the respondents had used the standard, of whom about 80% had used the simulation method as specified in Clause 8. In open questions, the respondents also indicated other guidance documents that they had used as well as details of what kind of guidance should be provided.

The responses to the survey indicate clear needs for additional guidance and raise items that could be considered for adding to the scope in the next periodic review of the standard. The additional guidance, to be given in the form of a Technical Report, should, to say the least, encourage those who do not know or are not confident about how to use the standard to start using it. SG 5 is currently drafting the Technical Report, tentatively titled "Guidance on ISO 8100-32:2020 – Planning and selection of passenger lifts to be installed in office, hotel and residential buildings". All comments and feedback are being considered as part of the drafting process.

The group is targeting to submit the first complete draft for WG 6 review later this year and expects the Technical Report to be published at the latest in 2025.

Initially, the scope of the Technical Report has been defined as follows:

> "This Technical Report consists of clarifications and additional examples of selected topics pertaining to the planning and selection of passenger lifts as covered by the ISO 8100-32:2020 standard as well as giving further explanations and background information on why specific items are out of the scope of the standard. This document also responds to feedback received from the market."

While being a high-level description of the work in progress, it readily contains elements that the survey revealed, such as clarifications, examples, and background information. The Technical Report will *not* become another book on lift traffic planning but is intended to gather key information in a concise form and cite other guidance documents and books for further information. Since the simulation method is the most frequently used part of the standard and probably the least known for industry practitioners, it may deserve more additional guidance than the other parts of the standard.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Lukas Finschi and Dr. Gina Barney for supporting the data analysis of this paper. ISO/TC 178/WG 6/SG 5 would like to thank all the survey respondents for their feedback that will help the group provide relevant guidance on ISO 8100-32 and further improve it.

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BIOGRAPHICAL DETAILS

Janne Sorsa, D.Sc. (Tech.) in operations research, joined the lift industry and KONE in 2001. He has published more than 30 articles on people flow planning, optimization, and simulation. He acts as the convenor of ISO/TC 178/WG 6/SG 5 and the project lead for the ISO 8100-32 standard on planning and selection of passenger lifts.

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Design, Manufacture, and Installation of The Great Glass Lift, Lift 109 at Battersea Power Station

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Keywords: Battersea, chimney, Lift 109, panoramic, viewing platform, rescue, Machinery Directive, The Great Glass Lift.

Abstract. This paper describes the unique engineering challenge posed by putting a panoramic lift into a chimney of the redeveloped Battersea Power Station. The engineering solution is discussed with a particular focus on how passengers would be rescued from the lift and how the conformity assessment of the whole system is in accordance with relevant new equipment regulations. This paper will describe how the following challenges were met.

1 INTRODUCTION

1.1 The concept

Eight years ago, as part of the overall redevelopment of the Battersea Power Station site, the lift industry was challenged through a design competition, to develop a unique, one-of-a-kind attraction. This would be a bespoke lift that could travel to the top of one of the iconic chimneys and provide an unobstructed, 360-degree panoramic view at a height of 109m (hence the name Lift 109) of the London skyline. The system also had to ensure that visitors could return to the ground safely in the unlikely event of power failure or another emergency.

Otis proposed a unique ‘three lifts in one’, comprising a double-deck lift (panorama lift), a platform lift and a rescue lift (MIP lift).

The panorama lift contains a top cabin and acts as the panoramic platform that protrudes out the top of the chimney and a lower cabin that contains plant equipment and a docking area, with the platform lift linking the two cabins together in case of rescue. Finally, the MIP lift, a dual-purpose lift that could travel within the same chimney and to wherever the panorama lift may have stopped.

Due to the entire lift system needing to be contained within the chimney, the only position for the controls and machines was at the base of the chimney. Environmental conditions required extra protection of the electrical and mechanical systems. The need for the car to have a greater travel distance than the counterweight meant an elaborate special roping arrangement.

The panorama lift is rated for 40 people and travels at 1 m/s which allows passengers to enjoy an eye-catching light show and immersive sound experience as they approach the rim of the chimney.

1.2 The challenge

- How to design, manufacture, install and commission a 40-person London experience that provides 360° panoramic views, travelling within one of Battersea Power Station’s iconic chimneys (see Figure 1).
- How to safely evacuate passengers from the viewing platform at potentially any point within the chimney, above the entry floor where there is no alternative exit level.
- Combining 3 independent units (Panorama Lift, Access Platform within Panorama Lift and Mobility Impaired Passenger (MIP)/Rescue Lift) into a single unified machine.

- Having a lift with only one defined landing level and therefore not fully meeting the scope of BS EN 81-20 [1], and the subsequent complexities of certifying a unique, one-of-a-kind machine through a Type Examination process via Otis UK's Approved Body.
- The design required the panorama lift to emerge from the top of the chimney and therefore become fully exposed to the external environment. Whilst the MIP lift remained within the structure of the chimney, some elements still needed to be considered. In addition to the inevitable rain, sleet and snow that will enter the chimney there are also other factors such as high winds, lightning, pollution and the proximity to salt water from the river. During cold periods there is the risk of ice build-up within the chimney. All of these factors had to be considered in the design process.

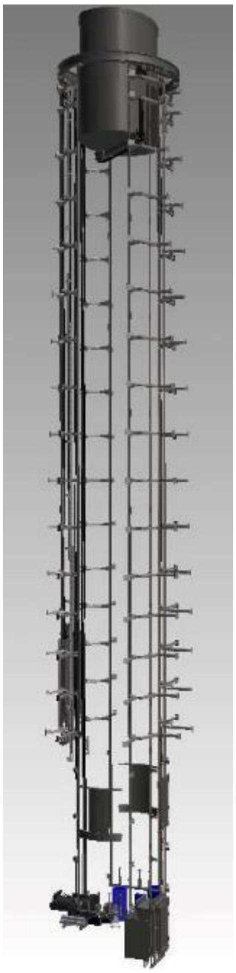

Figure 1 Lift schematic

2 REQUIREMENTS AND KEY CHALLENGES

After many years of service, Battersea Power Station (Grade II* listed), including its four iconic chimneys, was rebuilt between 2015 and 2017. Due to their state of disrepair, they were painstakingly reconstructed using the exact same methods utilised in the original build more than 60 years ago.

The northwest new chimney was designed to absorb up to 1 million newtons of force if the lift ever needed to come to an emergency stop. Part of the redesign included the ring beam, which was supported on corbels embedded into the chimney structure. The ring beam was to serve as the support for the pulleys, ropes, hitches and counterweight of the Panorama lift as well as those of the MIP lift with counterweight.

For chimney exterior maintenance, a walkway was also included in the ring beam taking the total weight of the ring beam to 11 tonnes (see Figure 2).

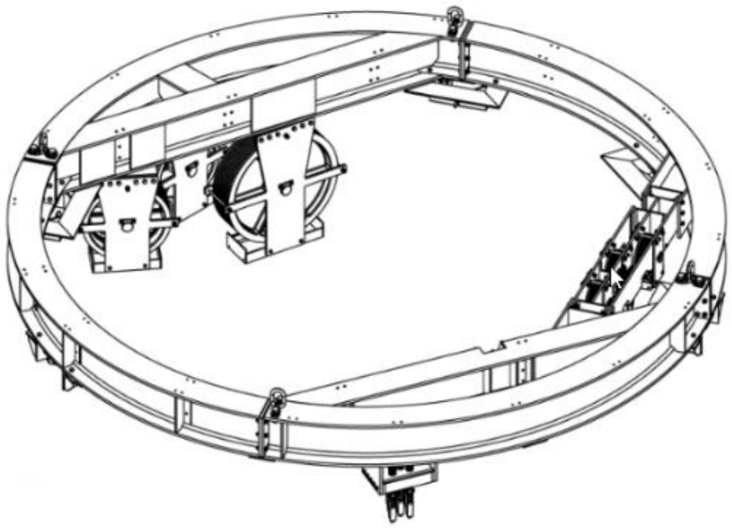

Figure 2 Schematic of ring beam

3 LIFT 109 - THE ENGINEERING SOLUTION

The Lift 109 project evolved constantly over its eight years of development and was a global effort to create a truly unique and innovative lift experience.

The lower cabin was built by Otis in Northern Germany, whereas the upper cabin was made in Southern Germany. Although both cabins were fully assembled in their factories, they weren't joined together until they arrived in the UK and installed inside the chimney itself.

Otis Berlin was responsible for the bespoke software and controls. The structural calculations and simulations for the ring beam were developed in Shanghai and USA.

3.1 Key figures – Panorama Lift

- Car weight: 16 tonnes
- Counterweight: 26 tonnes
- Combined weight: 42 tonnes
- Floor area: 12.7 m^2
- 6.6m car height: 3m for the panoramic cabin and 3.6m for the lower
- Rated load: 3000 kg
- No of persons: 40
- No of floors served: 1
- Number of entrances: 2 x Curved.
- Speed: 1.0 m/s
- Rise: 39 m
- Roping: 8 x 20 mm steel core (see Figure 3)
- Roping Arrangement: Car – 2:1
- Roping Arrangement: CWT – 3:1
- Guide Rails: 4 x 28 mm, with 2.5 m pitch between brackets

- Machine: Bottom drive – Wittur
- Pony Machine: Siemens
- Controller: GCS222MMR
- Drive: 280 amp
- Car Safety Gears: 4x Cobianchi
- CWT Safety Gears: 2x Cobianchi
- Parking Clamp Device: 4x Cobianchi
- Car Buffers: 8x Henning
- CWT Buffers: 9x ACLA
- Pulleys Specification: See Table 1

Table 1 Panorama Lift pulley specification

	Pulley 1	Pulley 2	Pulley 3	Pulley 4	Pulley 5	Pulley 6
Fixed to	car	car	ring beam	ring beam	cwt	ring beam
Diameter	Ø800mm	Ø800mm	Ø1150mm	Ø800mm	Ø800mm	Ø800mm
Weight	500kg	500kg	1300kg	500kg	500kg	500kg

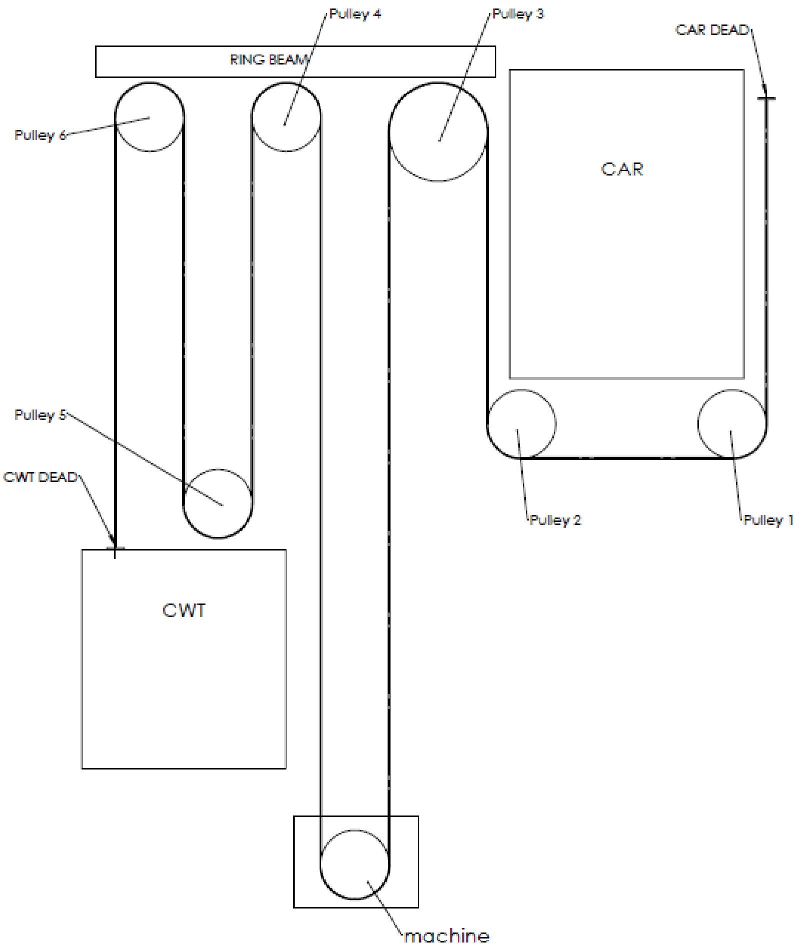

Figure 3 Panorama Lift roping arrangement

3.2 Key figures - MIP Lift

- Rated load: 600 kg
- No of persons: 8
- No of floors served: 2
- Dual entry: 2 x
- Speed: 0.5 m/s
- Rise: 6.5 m + variable to underside of Panorama lift
- Roping: 6x8 mm steel core (See Figure 4)
- Car: 2:1
- CWT: 2:1
- Guides: 2 x 16 mm guide rails, 2.5 m pitch between brackets
- Machine: Bottom drive - Wittur
- Pony Machine: Siemens
- Controller: GCS222MMR
- Drive: 60 amp
- Car Safety Gears: 2x Dynatech
- CWT Safety Gears: 2x Cobianchi
- Car Buffers: 2x ACLA
- CWT Buffers: 2x ACLA
- Pulley Specification: See Table 2

Table 2 MIP Lift pulley specification

	Pulley 7	Pulley 8	Pulley 9	Pulley 10	Pulley 11	Pulley 12
Fixed to	car	car	ring beam	ring beam	ring beam	cwt
Diameter	Ø330mm	Ø330mm	Ø410mm	Ø410mm	Ø410mm	Ø410mm
Weight	38kg	38kg	45kg	45kg	45kg	45kg

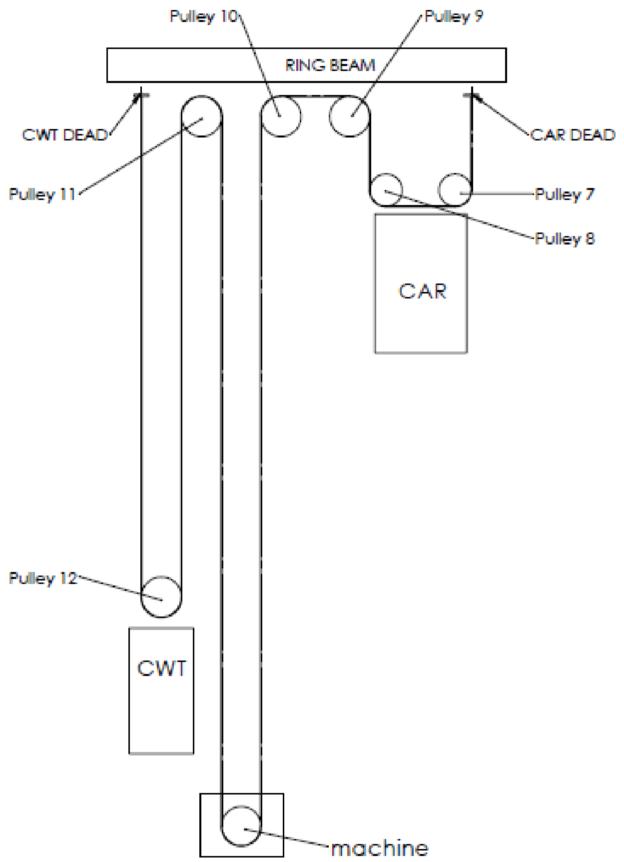

Figure 4 MIP Lift roping arrangement

3.3 Key figures – Platform Lift

- Rated load: 300 kg
- No of Persons: 2 persons or 1 person + wheelchair
- No of floors served: 2
- Entry: Single
- Speed: 0.03 m/s
- Rise: 2.9 m
- Drive: Screw jack with electric motor (see Figure 5).

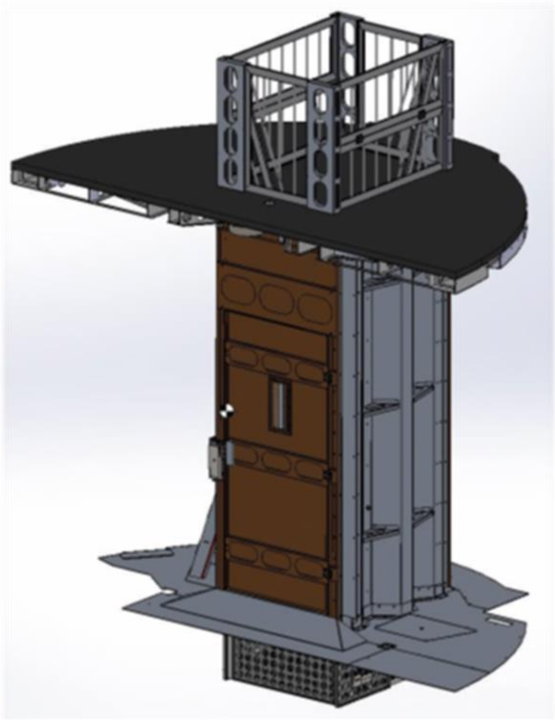

Figure 5 Platform Lift schematic

4 CONFORMITY ASSESSMENT

The risk assessment focused on two pieces of equipment both running in the same chimney. The first being the panorama lift and the second being a smaller passenger lift (MIP lift).

The MIP lift is also used to rescue any trapped persons in the panorama lift should it become stalled at any point in the lift chimney. It was crucial that the assessment of the Essential Health and Safety Requirements (EHSRs) determined the areas in need of specific analysis and then carried out those in order to ensure the design was safe.

In considering the specific legislation of the Battersea Chimney project, there was a need to examine the panorama lift and MIP lift cars separately and how they follow the Regulations.

Where any one of the lifts, including the platform lift, was not able to function as it was designed, it would instantly make the other lifts inoperable or fail to give the required support with any rescue of passengers. For this reason, the system was treated as one machine for the conformity assessment under the SoMSR, verified under a Type Examination and listed on a single Declaration of Conformity.

4.1 Panorama Lift

In preliminary discussions, there were two interpretations possible regarding the panorama lift and the applicable legislation under which it could fall:

- The Supply of Machinery (Safety) Regulations (SoMSR) [2] since its primary use is to transport persons to an upper stop but not for them to leave the lift car, so not meeting the definition in the Lifts Regulations 1997 [3]*: "lift" means a lifting appliance — (a) serving specific levels*.

- The Lifts Regulations since the lift can also be used to allow the maintenance persons to reach the upper maintenance platform, this then could be considered as a permanent level of the building which the lift serves.

The burden of conformity lies on the installer of the lift under the Lifts Regulations and on the manufacturer under the Supply of Machinery (Safety) Regulations. To resolve the situation the HSE was consulted to determine which specific piece of legislation should apply.

In their response, they confirmed that the panorama lift could not fall under the Lifts Regulations. Instead, this lift was to be considered as a machine, under the Supply of Machinery (Safety) Regulations (SoMSR).

SoMSR has conformity assessment procedures for certain types of machines such as "devices for the lifting of persons or of persons and goods involving a hazard of falling from a vertical height of more than three metres". Since such a unique project would not follow a designated standard, the procedure from Article 12 of SoMSR required either a Type Examination (by an Approved Body) or a full quality assurance system to be used, with Otis opting for the Type Examination route.

4.2 MIP Lift

The MIP lift serves two defined landings in the building to transport persons from the main arrival level to the panorama lift loading level, and under rescue conditions also serves a further 3rd level of variable position of the panorama lift. However, since the headroom is restricted and will not be in accordance with refuge spaces listed in BS EN 81-20 [1], derogation from BEIS would be required against the Lifts Regulations. While the MIP lift might have been treated as a separate lift for conformity assessment, its operation was integral to the operation of the main lift.

The design of both lifts was based on EN 81-20 [1] and EN 81-50 [5], since these standards are already risk-assessed and in conformity with the Essential Health and Safety Requirements (EHSRs) of the Lift Regulations and those of the Machinery Directive.

4.3 Platform Lift

In the event of a rescue, mobility-impaired passengers travel from the upper cabin to the lower cabin of the panorama lift by a bespoke platform lift, considered under the SoSMR, using BS 6440 [4] as supporting documentation.

A combination of the appropriate parts within the BS 8486 test documents was used as a basis to commission the panorama and MIP lifts, and where sections within the BS 8486 [6] or BS 6440 [4] test documents highlighted deviations, the approved body listed these against the machine following a detailed risk assessment for each section deemed as being non-compliant.

5 OPERATIONAL MODES

5.1 Normal Mode

Normal operation of all the lifts in the chimney is controlled by attendants throughout the journey but follows a strict electrical and mechanical sequence. Whilst the main sequence is software-based, mechanical switches are located throughout the chimney to ensure that the software is backed up.

The sequence allows for the MIP lift to transport passengers from the main arrival level of the chimney to the loading level of the panorama lift only when the panorama lift is located at the upper level of the chimney (whilst allowing passengers to view the skyline of London). The time passengers are held at the upper level is signalled via a timer; when 2 minutes remain, a signal is given to the MIP lift to return to the lower floor level (entrance of the chimney level). If the MIP has already begun a journey to the panorama loading level, it continues that journey and then returns down after not accepting any further calls, holding the panorama lift at the top of the chimney until the MIP has safely returned. Once the panorama lift has started the return journey, the MIP is held at the bottom level and doesn't accept any calls.

Reliable and safe day-to-day running is crucial for the success of the experience. A daily check of the vital systems allows for the reassurance that if anything were to malfunction or if a system may have a knock-on effect on one of the other lifts, passengers could be released.

Additionally, there was not only the normal running of the lift to consider but also modes including cleaning, chimney access, maintenance and rescue modes.

5.2 Cleaning Mode

Cleaning of the glass on a day-to-day basis allows operatives to access an additional deck located above the loading level of the panorama lift. Using the controls on that level, the lift can be driven to various heights where specialized cleaners then ensure that the top and sides of the upper deck are spotless for the passengers of the experience (see Figure 6).

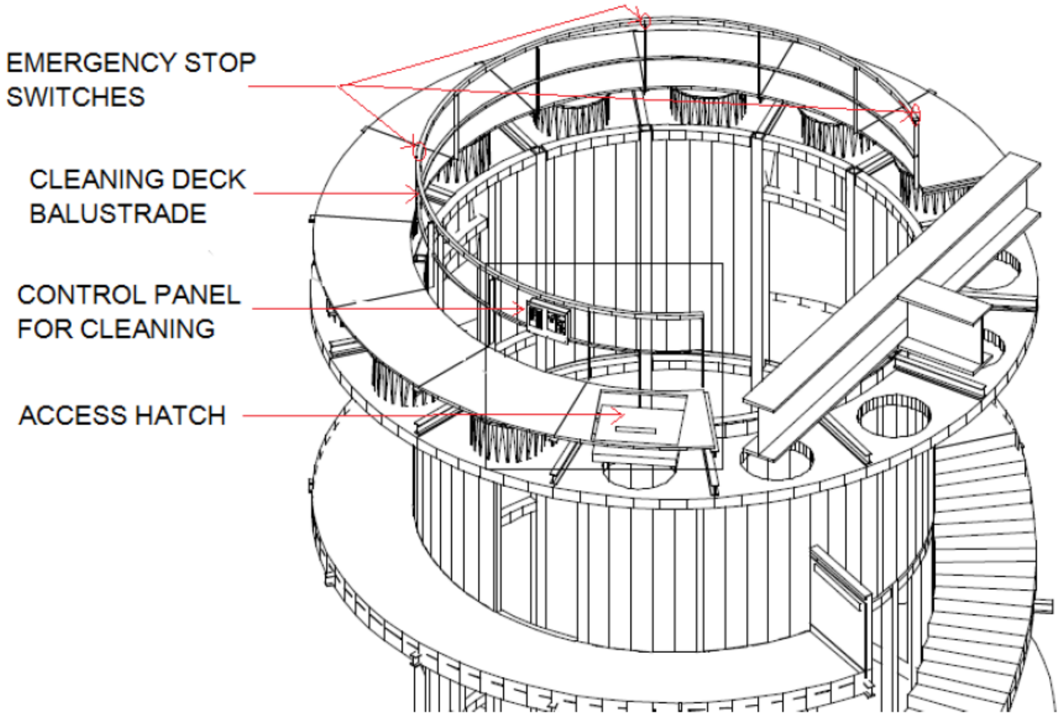

Figure 6 Cleaning schematic

5.3 Chimney Access Modes

Due to the structure of the chimney being made from cast concrete, the outer edge of the chimney needs to be inspected. Specialist engineers use the panorama lift to gain access by a mode which uses a secure Castell-type key exchange. The lift is driven to the upper level of the chimney where a second set of key exchanges allows for a set of car doors to be opened. The specialist engineers clip onto a rope access point and use the walkway to inspect the chimney and abseil down and around it.

5.4 Maintenance and Inspection Mode

Inspection of the components at the top of the chimney, including many pulleys and rope terminations, is vital as part of maintenance and for thorough examinations under the scope of the

Lifting Operations and Lifting Equipment Regulations (LOLER). The original intention was for maintenance and inspection to be carried out from inside the lower deck of the panorama lift. With the complexity of that work detail and the need for maintainers and engineer surveyors to physically access components, the solution was to revert to a more standard approach and work from the panorama lift car roof and use a temporary handrail system that provides suitable access (see Figure 7).

As this is a temporary handrail that is only in place during maintenance works, a number of safety switches for both normal and inspection modes had to be introduced. The design also had to provide sufficient strength of a suitable handrail without having any fixture points on a glass cabin. To achieve this as part of the complete temporary handrail system, four legs extend down to the lower cabin for support, with a cross-section and material that is light enough to be manually handled.

Some design considerations had to be met whilst developing the maintenance routine. Since there was no requirement for any of the lifts to be exposed out of the chimney, a maintenance limit was fitted, which meant that the engineers would be protected from the weather elements but also all components could be examined sufficiently. More importantly, if the lift malfunctions whilst it is located at the top of the chimney, the engineers can access the ladder which runs the length of the chimney.

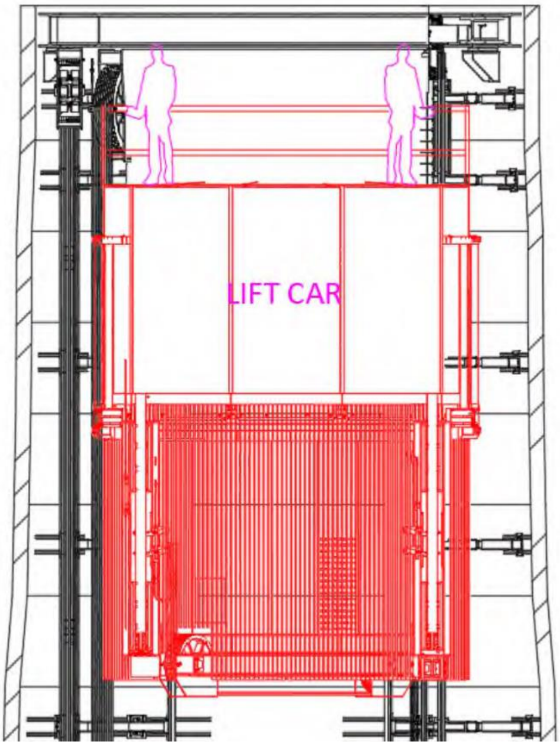

Figure 7 Maintenance and Inspection from the Panorama Lift

5.5 Rescue Mode

The evacuation of passengers in the event that the main lift is blocked or malfunctions was one of the most important challenges faced in the design. The original design intention was to install two separate cars with a car-to-car rescue from the upper deck of the main lift, but due to the client's requirements of a larger car dimension, the design was not progressed as this needed a single evacuation design (see Figure 8). This change required an assessment of how all those who visited the experience would be safely evacuated, especially where it concerned those with difficulties.

The solution was just as complex as the design of the lifts. Firstly, both the Panorama lift and MIP lift were supplied with primary and secondary power supplies. Secondly, an uninterrupted power supply (UPS) system was introduced, but it was acknowledged that air conditioning would be required at all times (normal or rescue modes) and the configuration of the electrical system meant that the incoming power supply would need to run in line with the UPS. Thirdly, the machines for both lifts were fitted with a pony motor, all giving optional methods to engage and drive the lifts in case of any power loss. This then left the challenge of the panorama lift being stuck; in this instance the MIP lift doubled up as a rescue lift.

Upon activation of the rescue mode, clamp devices on the panorama lift engage to all four guide rails to ensure it cannot move whilst the MIP lift travels beyond the normal levels it serves, docking with the lower cabin of the panorama lift (which can be at any point of the chimney) (see Figure 9). Constant pressure controls on the MIP lift are used to position the car, to couple with the lower deck entrance of the panorama lift, which allows passengers to be safely transferred to the MIP lift and returned to the bottom of the chimney. During the rescue, passengers can move from the upper deck to the lower deck, either by the internal staircase or by the platform lift.

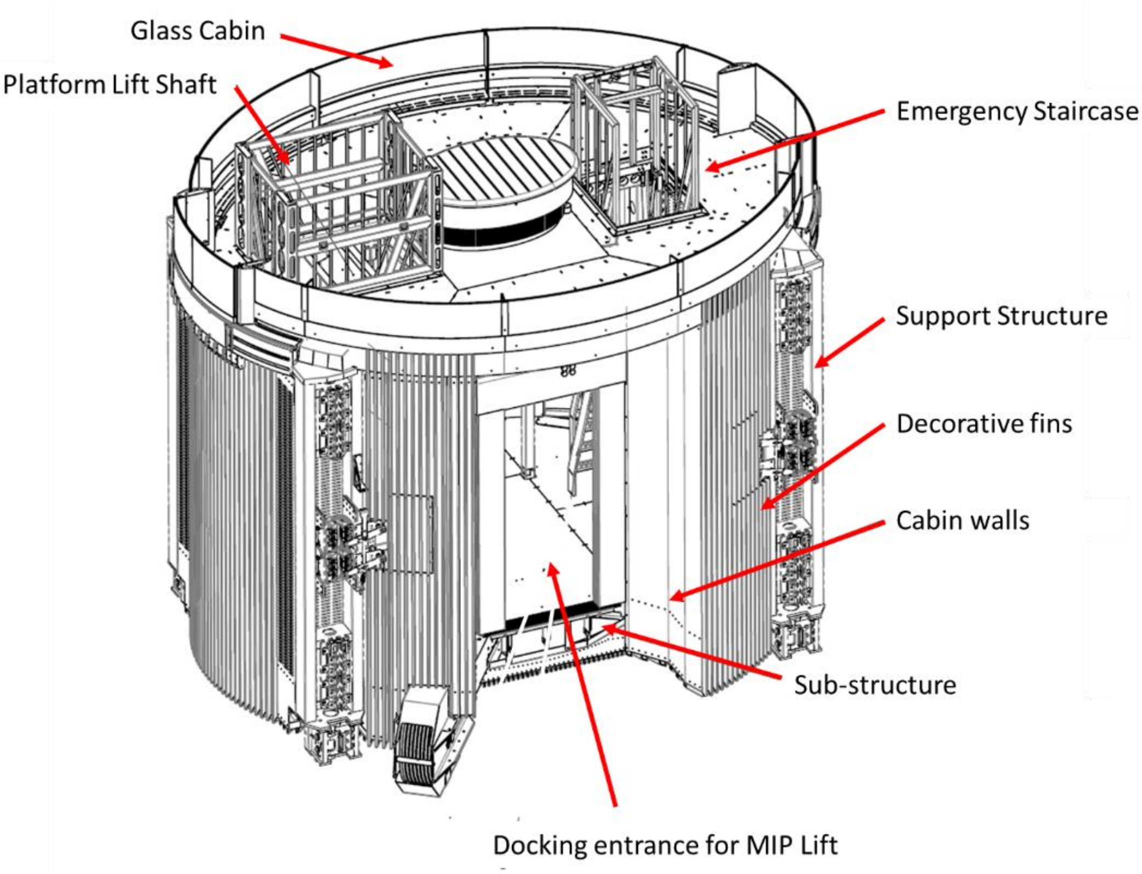

Figure 8 Panorama Lift and MIP Lift

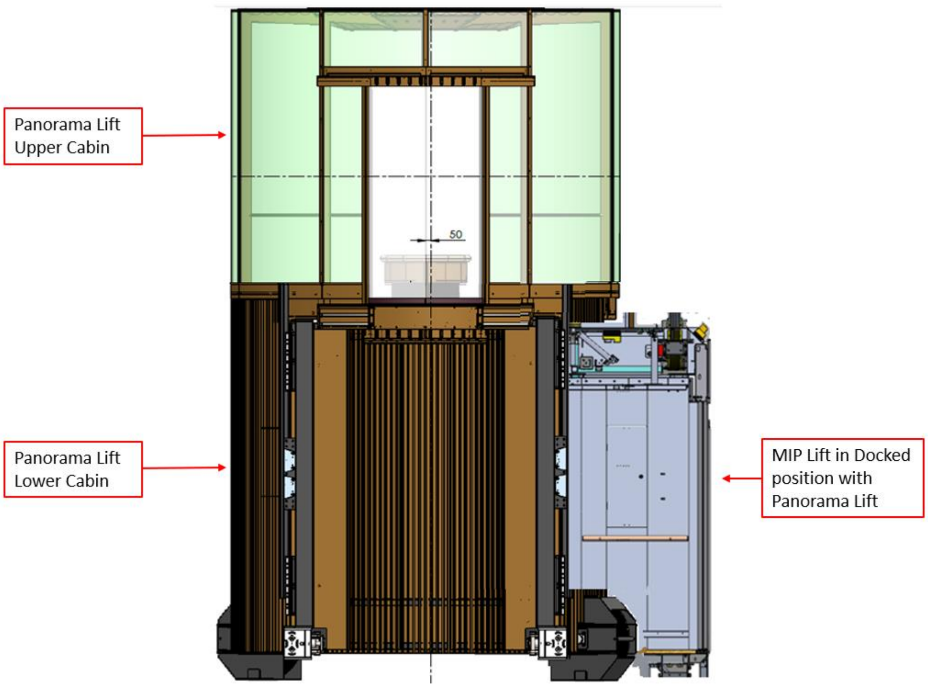

Figure 9 MIP Lift docked with Panorama Lift

The evacuation solution includes those who are able to walk un-aided using a set of stairs which link the upper deck of the panorama lift to the lower deck, and passengers who require step-free access using the platform lift to travel between the two decks.

In the upper panorama cabin, the platform and ladder hatches form part of the accessible floor. It is locked manually, with the locking electrically monitored and integrated into the safety circuit of the panorama lift (see Figure 10).

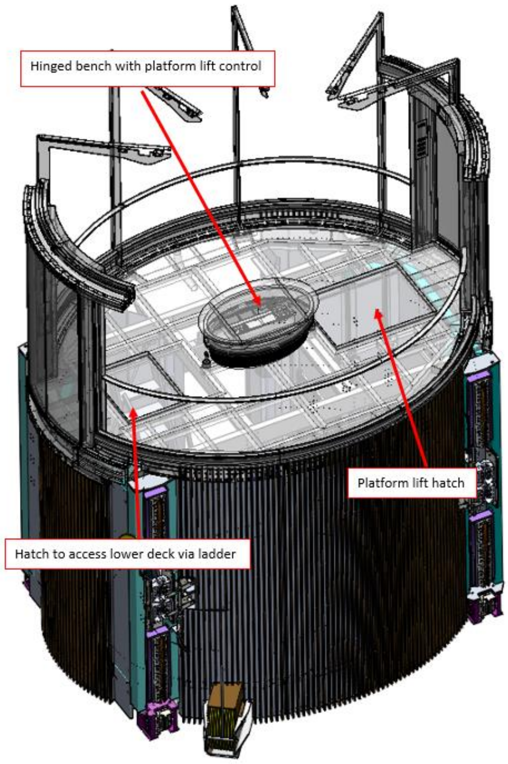

Figure 10 Panorama Lift hatches

In case of an emergency, the ladder hatch can be opened either with a triangular release lock in the upper cabin or from the lower cabin by an engineer. As part of the evacuation plan training, an experienced attendant must be kept up to date as they are critical when a malfunction takes place, not only to keep the passengers calm but also to keep in communication and assist with getting components in place for rescue purposes.

At the beginning of any evacuation, two engineers are required, one drives in the rescue operation of the MIP lift and the other assists with getting passengers from the upper to lower cabin.

To ensure the hatch and staircase are protected against people falling, a temporary handrail is extracted from the lower cabin manually.

Those passengers that can use the staircase travel down in small groups, enter into the MIP lift and are transported down to the lowest level.

Those that require an alternative method are guided to the platform lift.

Further handrails are placed around the passenger (see Figure 11). Only once all sections have been connected and in place, the electrical monitoring system unlocks the platform, and the use of a pendant control can transport the passenger down to the lower cabin ready for transporting in the MIP lift to the exit level.

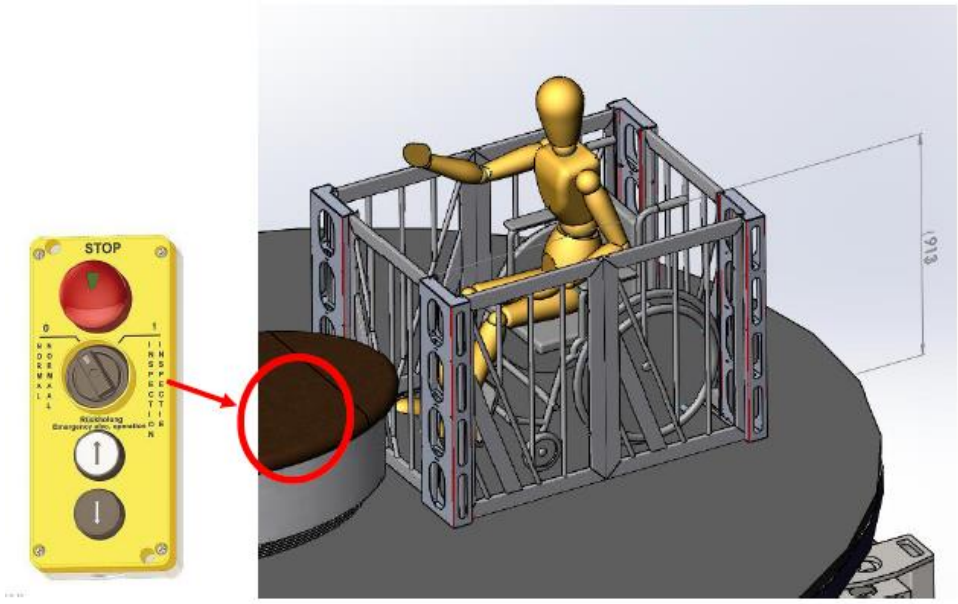

Figure 1**1** Platform **Lift** Handrails and Controls

After the Wheelchair user has descended to the lower deck, the manually operated swing door can be opened and transported down to the lowest level via the MIP lift (see Figure 12).

The sequence can be repeated where more than one wheelchair user is in the upper cabin.

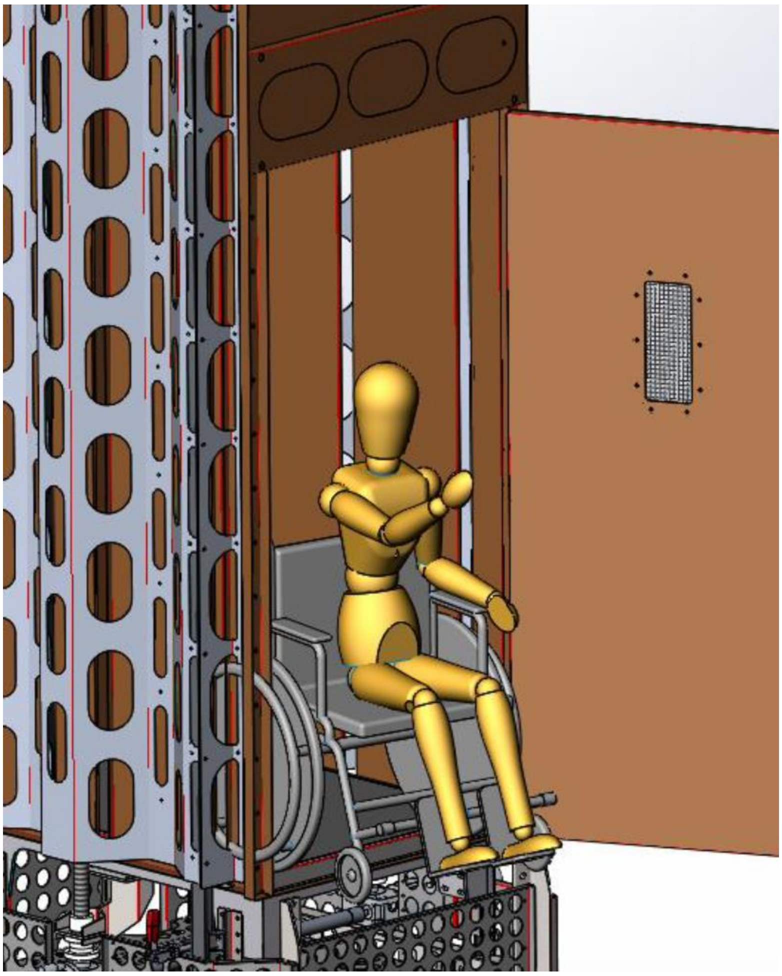

Figure 12 Platform Lift to Lower Deck Rescue Level

6 ENVIRONMENTAL FACTORS TO BE MONITORED AND CONSIDERED

6.1 Wind

The maximum safe operating average windspeed for the chimney was tested with an anemometer positioned at the top of an adjacent chimney which constantly monitors the average wind speed and automatically prevents the operation of the lift should the windspeed be more than the safe operating maximum. If the monitored average wind speed is 16 m/s or above, the indicator in the panorama lift cabin alerts the attendant of the potential high winds. If the wind speed is 21 m/s or above, the system follows the sequencing to return the lifts to the base of the chimney.

6.2 Humidity and temperature

With the effect of the glass of the panorama lift car, the temperature inside can get hot quickly. The panorama lift is provided with air conditioning to ensure passengers remain in a comfortable condition following the embarkation of the passengers at the entrance level. With the added temperature range from the base of the chimney and the top, the air conditioning also assists with keeping the car from fogging up where temperatures do not meet. Atmospheric pollutants, including salts due to proximity to the Thames, were all considered when the materials and equipment for the lift were selected.

6.3 Lightning

Having such large metallic components situated high in the air exposed, battling the effects of a lightning strike, meant that the earthing of the structure was suitably completed. This was taken from the Ringbeam down the chimney and onto the structural earth point.

6.4 Precipitation and ice formation

The precipitation events that occur influence the entire equipment. Due to the design of the chimney, the rainfall is pushed to the side walls and collects on a deck above where passengers enter the panorama lift. The drainage system then slopes around the chimney and diverts down and out of the chimney. Any ice formed on top of the car is carefully cleared during the daily cleaning schedules.

6.5 Bird fouling

It was always likely that bird fouling would occur. Having a protected area made it a perfect place to roost. Thankfully, the situation is managed by a Kestrel which is brought into the chimney and surrounding areas to move any birds away and minimise the risk of nesting and roosting within the chimney.

7 CONCLUSION

Battersea Power Station's silhouette has long been a prominent fixture on the London skyline. Built in the 1930s and operational as a power station until the early 1980s, at its peak, it generated one-fifth of London's power. Since then, the building has provided us with a whole lot more than electricity, becoming a cultural icon. With the building's rich heritage, architectural significance and enduring presence in popular culture, 'Lift 109' is now a magnet to the Battersea re-development and has rapidly become the 'must-see' landmark attraction for visitors to London. This project has been a journey with many trials, obstacles and lessons learnt. Now complete and reliably in daily use, we're proud to have taken this icon of the past into an icon of the future.

8 REFERENCES

[1] BS EN 81-20:2020, *Safety rules for the construction and installation of lifts – Lifts for the transport of persons and goods – Part 20: Passenger and goods passenger lifts*

[2] The Supply of Machinery (Safety) Regulations 2008

[3] The Lifts Regulations 1997

[4] BS 6440:2011: *Powered vertical lifting platforms having non-enclosed or partially enclosed liftways intended for use by persons with impaired mobility – Specification*

[5] BS EN 81-50:2020: *Safety rules for the construction and installation of lifts — Examinations and tests – Part 50: Design rules, calculations, examinations and tests of lift components*

[6] BS 8486-3:2017: *Examination and test of new lifts before putting into service – Specification for means of determining compliance with BS EN 81-20*

9 ACKNOWLEDGEMENTS

The authors would like to acknowledge Mr. Dave Ralphs who began the original design concept before his retirement and the late Mr. Ian Jones who ensured the legislative concept was met in liaising with the HSE.

Images in presentation courtesy of P&N Lift Installations and Battersea Power Station Development Corporation.

10 BIOGRAPHICAL DETAILS

Kevin Vinson, a Mechanical Engineer by discipline, previously worked globally in marine, oil & gas, and the special effects sectors before settling into Vertical Transportation in 2005. He is currently the Business Development Director for Otis UK.

Michael Grover-White has NVQs in Testing and Commissioning and Electrical Installations. He was the Technical Manager overseeing the technical requirements at Otis until moving to the Lift and Escalator Industry Association as Technical Manager. He is a Technician Member of the Institution of Engineering and Technology (IET).

Exploiting the Capacity of Industrial Hydraulic Buffers

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Keywords: Industrial hydraulic buffer, Characteristics, Limit force, Buffer exploitation.

Abstract. Industrial hydraulic buffers are standard equipment for industrial machinery. They are used for the reduction of impact loads on structures during processes of kinetic energy reduction. This is realized by a more or less constant buffer force acting along the stroke of the buffer. The product of buffer force and stroke results in the energy being dissipated during a buffering process. The typical constant, restricted buffer force makes sense in order to protect the surrounding structure. On the other hand, a non-constant, optimized buffer force may be useful to exploit the energy potentially dissipated by a buffer. The article considers the basics of hydraulic buffer technology, the question of a non-constant buffer force and the potentials arising with this option.

1 BUFFER DESIGN AND FUNCTION

Industrial hydraulic buffers as shown in Fig. 1 work according to a simple principle. The moving piston of the buffer presses hydraulic fluid through a throttle. The pressure drop at the throttle $\Delta p_{Throttle}$ produces a fluid pressure and an according piston force F_p.

Figure 1 Crane track limit buffer

The piston force Fp is used to decelerate a mass with its initial kinetic energy, a crane mass at the crane track limit e.g. For a first approach the piston force may be assumed to be constant against the piston rod position. As the product of constant piston force $F_{b,const}$ and stroke s_{stroke} in this case equals the energy dissipated W_{diss}, there are different design options for the buffer. A higher buffer force in combination with a smaller stroke gives the same energy dissipated as a lower buffer force in combination with a larger stroke. The choice of combination has a significant impact on the buffer force, the buffer stroke and the buffer geometric properties as the total buffer length in a relaxed condition (Fig. 2).

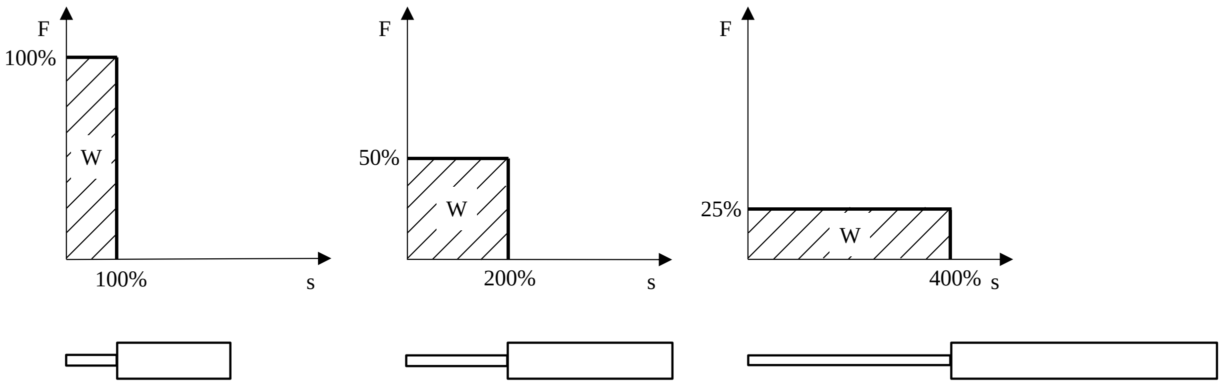


Figure 2 Buffer forces and buffer lengths at constant energy dissipated

In practice the buffer curve is not rectangular (Fig. 3). The slopes of the buffer curve at the beginning and the end of the buffer curve are not infinite e.g. This results in a maximum buffer force $F_{b,max}$ well above the constant buffer force $F_{b,const}$. The relation of the maximum buffer force $F_{b,max}$ to the constant buffer force $F_{b,const}$ is indicated by parameter k.

$$W = \int_0^{s_{stroke}} F\, ds = F_{b,const} \cdot s_{stroke} \tag{1}$$

$$F_{b,max} = k \frac{W}{s_{stroke}} = k \cdot F_{b,const} \tag{2}$$

with

$$k > 1 \tag{3}$$

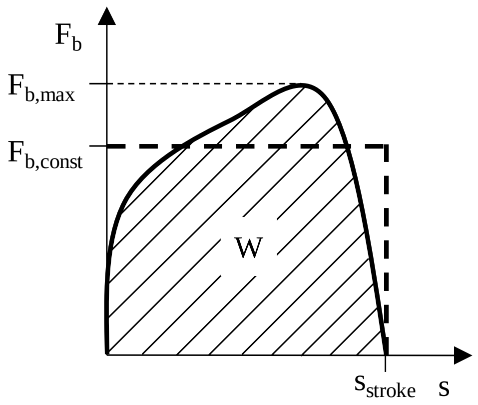


Figure 3 Theoretical vs. practical buffer characteristics

For several simple buffer types, a non-constant buffer force is typical. Metallic springs or cellulose buffers show a parameter k well above one. This leads to a high maximum buffer force $F_{b,max}$. Hydraulic buffers are designed to reach a parameter k of about one. For a certain stroke and a certain maximum buffer force $F_{b,max}$ they absorb the maximum energy. Hydraulic buffers absorb certain energy at a minimum buffer force $F_{b,min}$. This leads to a positive impact on static system requirements.

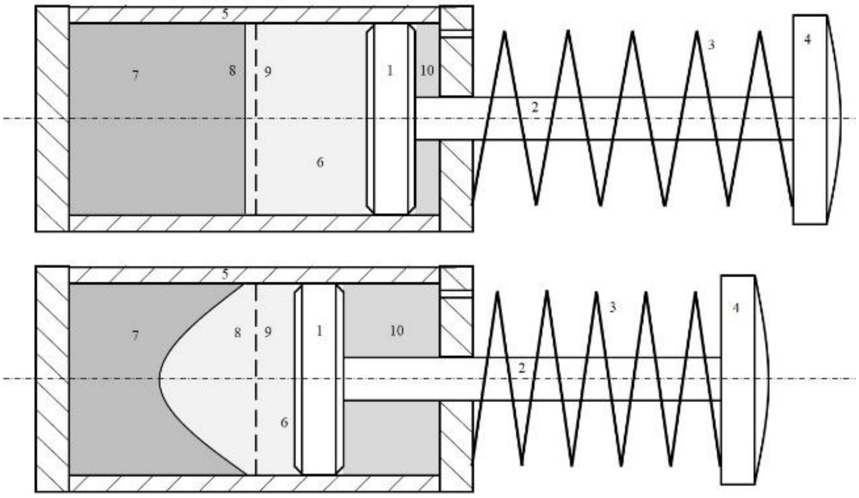


Figure 4 Hydraulic buffer in relaxed (above) and articulated (below) position

Fig. 4 shows a design principle of a hydraulic buffer. Shown above is the hydraulic buffer in its relaxed position. A hydraulic buffer consists of a piston (1) running in a cylinder (5). As the piston is loaded by forces onto the head (4) via a piston rod (2), it moves to the left-hand side. The closed space left of the piston is separated by a membrane (8). The space next to the piston is filled with oil (6), and the space behind the membrane is filled with gas (7).

With the piston moving to the left, the oil volume is pressed to the left against the deformed membrane and the increasing gas pressure behind the membrane (Fig. 4, below). The characteristics of the buffer during this movement are realized by the characteristics of the throttle (9) the oil is pressed through. On the right-hand side of the piston, all time exists outside air pressure (10). As the head is not loaded, the piston is reset to the original position, caused by the resetting spring (3) and the gas pressure.

There are further parameters besides the stroke influencing the buffer force. The oil pressed through the throttle (9) has to find new space. This space is delivered by the adjustable membrane (8), working against the gas pressure. This gas pressure has some initial value, to move the relieved piston rod against friction back to its initial position, even after small displacements. This task may be supported by a pre-stressed spring (3). The gas pressure varies according to the piston rod position and reaches its maximum at the maximum stroke. Additionally, the piston force does not only have to decelerate the mass. It also has to equalize an external driving force acting on the piston rod. External driving forces occur at movements in a gravitational field typically.

The shown principle of a hydraulic buffer may be modified by alternative designs of the gas containment, the moving border of the gas containment, the throttle, and the mechanism for withdrawal of the released piston e.g. The membrane may be substituted by a second piston system. The throttle may comprise an adjustment of characteristics depending on the piston position. This adjustability may be realized by throttle holes positioned along the stroke (Fig. 5). The moving piston covers a certain part of the holes and this causes a variable throttle cross-section and characteristics. A hydraulic buffer may allow refillability of gas volume in order to replace diffused gas share.

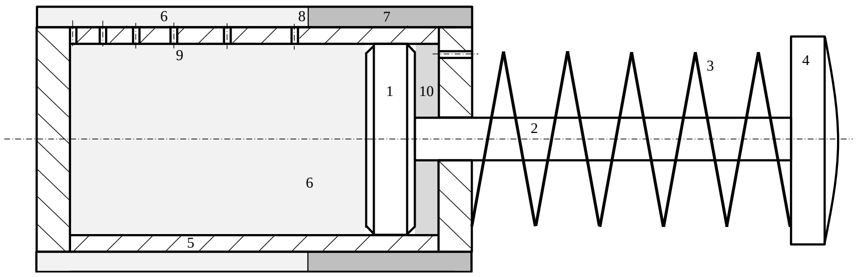


Figure 5 Hydraulic buffer with adjustable characteristics

The buffer comprises different limit states, restricting the performance:

- Cylinder strength
- Cylinder base fastening strength
- Throttle strength
- Piston rod buckling force strength
- Sealing mechanical strength
- Sealing heat strength
- Sealing wear lifetime
- Oil heat strength
- Oil lifetime e.g.

Exceeding a limit state probably means the limit energy to be absorbed was exceeded:

- Energy excess in the sense of excess mass
- Energy excess in the sense of excess speed
- Energy excess in the sense of excess driving force
- Energy excess in the sense of excess frequency.

2 REFERENCE BUFFER

A reference buffer situation with the following parameters is considered:

Throttle hole diameter	$d = 1 \cdot 10^{-3}$ m
Final throttle diameter	$d_{final} = 1 \cdot 10^{-3}$ m
Piston diameter	$d_p = 0.1$m
Driving force	$F_{Drive} = 0$ N
Load mass	$m = 1{,}280{,}000$ kg
Initial gas pressure	$p_0 = 500{,}000$ Pa
Maximum stroke	$s_{max} = 0.4$m
Rest stroke	$s_{rest} = 0.05$
Initial gas volume	$V_0 = 6 \cdot 10^{-3}$ m^3
Impact speed	$v_i = 0.5$ m/s
Initial speed of piston rod	$v_0 = 0.5$ m/s
Oil density	$\rho = 890$ kg/m^3
Isentropic exponent	$\kappa = 1.35$
Efficiency	$\eta = 1.0$

As the force braking the load F_{Brake} is assumed to be constant, the deceleration of the mass a_0 is constant as well. This results in a linear decrease of the mass speed over time and a quadratic increase of the mass displacement over time (Fig. 6). With these assumptions the speed gets very slow at the end of the stroke. As the position over time shows an asymptotic behaviour the piston seems not to move at the end of the stroke anymore (Fig. 6).

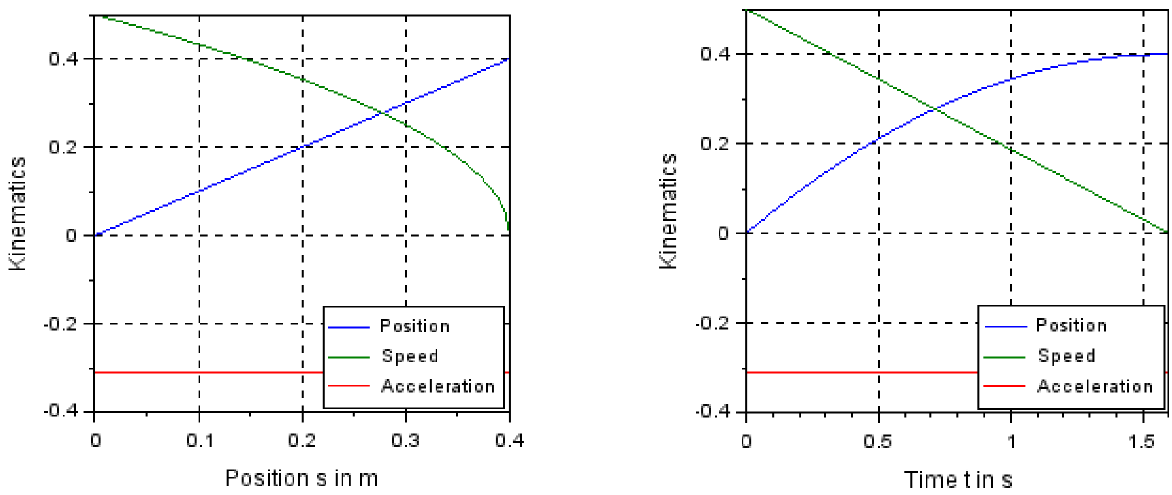


Figure 6 Kinematic values over position and over time

The initial speed of the piston rod v_0 is considered equal to the impact speed of the mass v_i. The impact process is neglected due to the relation of load mass m to piston rod mass. The constant braking force F_{Brake} required results out of the constant deceleration:

$$F_{Brake} = m|a_0| \tag{4}$$

The braking force F_{Brake} available constitutes out of the spring force F_{Spring}, the gas force F_{Gas}, the throttle force $F_{Throttle}$ and the driving force F_{Drive}:

$$F_{Brake} = F_{Spring} + F_{Gas} + F_{Throttle} - F_{Drive} \tag{5}$$

Frictional losses are neglected in this consideration (Efficiency η=1). A spring force is assumed not to be present here:

$$F_{Spring} = 0 \tag{6}$$

$$F_{Brake} = F_{Gas} + F_{Throttle} - F_{Drive} \tag{7}$$

The compression of the gas is assumed to take place as an isentropic compression with isentropic exponent κ. The pressure drop at the throttle is assumed to be proportional to the square of fluid speed with loss coefficient ξ.

The gas force F_{Gas} typically is quite small and of low influence. At a constant braking force F_{Brake} and a constant driving force F_{Drive} the throttle cross-sectional area A_T is about proportional to the piston speed v. Assuming all other sizes are constant or neglectable, the throttle cross-sectional area shows about the same characteristics as speed over position.

The throttle cross-sectional area A_{T0} constitutes out of the throttle cross-sectional area distributed over the stroke A_{dist} and of the throttle cross-sectional area located at the end of the stroke A_{final}. The throttle cross-sectional area located at the end of the stroke A_{final} is implemented to give the piston the opportunity to reach the dead point with finite speed.

Considering the final throttle cross-sectional area A_{final} this regime leads to the following characteristics for the throttle cross-sectional area A_T:

$$A_T = \sqrt{1 - \frac{s}{(s_{max} - s_{rest})}} (A_{T0} - A_{final}) \quad (8)$$

In practice, the throttle cross-sectional area may not distributed continuously. The throttle may be realized by discrete holes implemented at certain distances from each other. The real throttle cross-sectional area A_{Treal} depends on the hole diameter d and the number of holes N.

So far oil was assumed not to be compressible. Thus, oil pressure immediately depends on gas pressure and throttle pressure. In fact, oil is compressible. A certain stroke is required to build up oil pressure. At the very beginning of the buffering process, the stroke is realized at a lower buffer force level. It may be an option to implement this aspect to a more detailed model.

The discretized throttle cross-sectional area curve implements the decrease as singular oil outlet geometries. They have no extension with regard to length in the direction of the stroke. In fact, already simple holes have an extension with the hole diameter as length and certain characteristics. It may be an option to implement this in more detailed models. It may also be an option to consider more intrinsic geometries than round holes.

The reference buffer comprises a throttle suitable to create a constant buffer force against stroke. Four variations of this throttle are considered (Fig. 7):

- Continuous throttle, without final throttle.
- Continuous throttle, with final throttle.
- Discontinuous throttle, hole as step, with final throttle.
- Discontinuous throttle, hole as a ramp, with final throttle.

The continuous throttle without final throttle shows a throttle cross-sectional area converging against zero at the end of the stroke. All other variations show the final cross-sectional area up to the end of the stroke. The discrete throttle characteristics show a stepped change of throttle cross-sectional area. At the real throttle, the steps are represented by holes in the throttle bushing along the stroke. According to the models, the steps take place in certain hole centre positions (step) or along a certain distance corresponding with the hole diameter (ramp) (Fig. 7).

The initial cross-sectional area of the throttles differs for the discontinuous characteristics from the continuous characteristics. The continuous characteristics meet the theoretical value A_{T0}. As the discontinuous characteristics depend on a sum of holes, their initial cross-sectional area only can be close to the theoretical value A_{T0}.

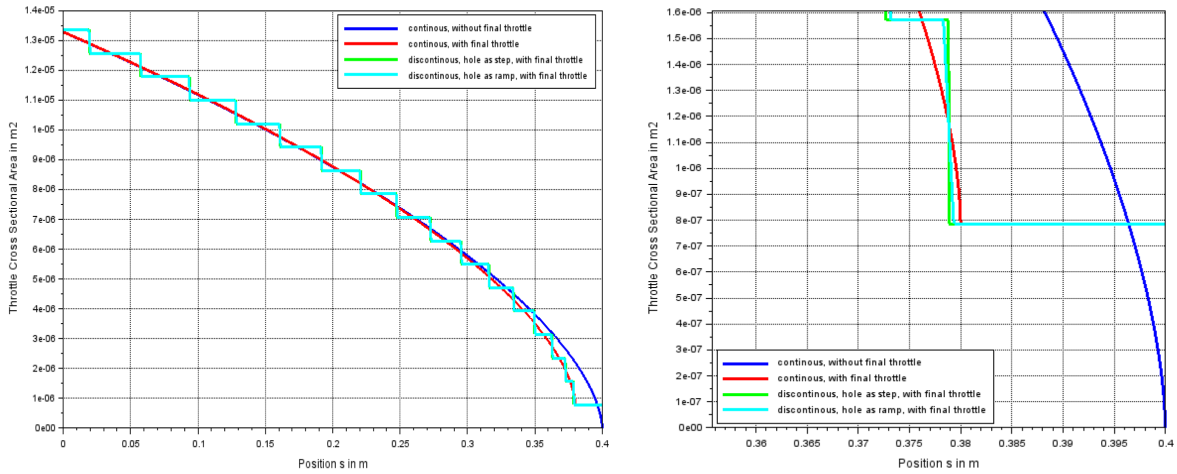


Figure 7 Throttle characteristics along the stroke

3 BUFFER CHARACTERISTICS

The throttle cross-sectional area with continuous distribution starts at $A_{T0} = 1.428 \cdot 10^{-5}$ m^2 and finishes with $A_{final} = 0$ m^2. The buffering process shows a deceleration close to being constant during the first part of the stroke. In the second part of the stroke, the acceleration decreases significantly. Speed over time at first is decreasing quite fast. Towards the end of the stroke, the speed is small. It takes quite a time to drive across the final distance. As a speed limit is taken as one termination condition for simulation, the simulation is terminated before the piston reaches maximum stroke. The total oil pressure consists of a high pressure drop in the throttle and a low gas pressure. This allows a high force at the working stroke of the buffer and a low force at the buffer back stroke afterwards. This allows high energy to be dissipated by the buffer. Finally, the total kinetic energy of E = 160,000 J is dissipated.

The throttle cross-sectional area with discontinuous distribution starts at $A_{T0} = 1.428 \cdot 10^{-5}$ m^2 and finishes with $A_{final} = 7.85 \cdot 10^{-7}$ m^2 (Fig. 8). At the end of the stroke, the throttle cross-sectional area is constant for some distance. The buffer with final throttle shows a behaviour quite similar to the buffer without final throttle. The piston reaches the region of the final throttle, but also not maximum stroke (Fig. 8). The main difference in comparison to a buffer without final throttle is that when the buffer reaches the throttle, there occurs a peak in throttle pressure and all associated conditions (Fig. 8, Fig. 9, Fig. 10). This is due to the non-continuous deviation of the throttle cross-section characteristics. The height of the peak in correlation with throttle characteristics in detail and in practice may be of interest.

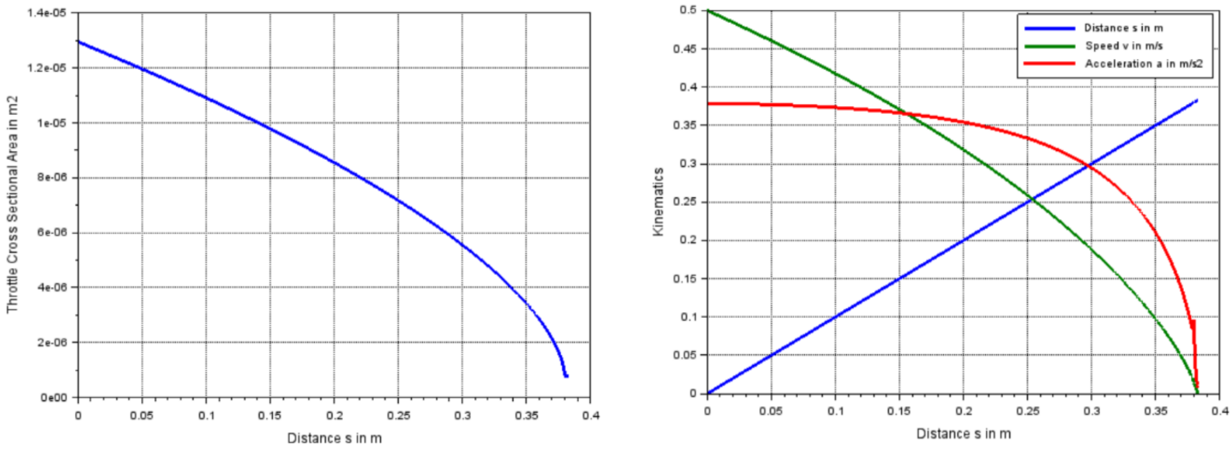
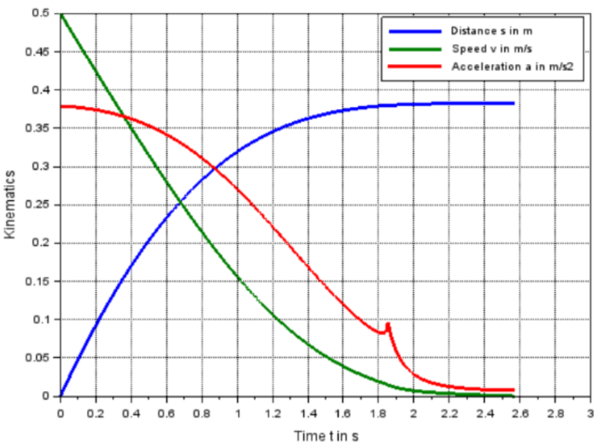


Figure 8 Throttle cross-sectional area, Kinematic values over position (Reference buffer)



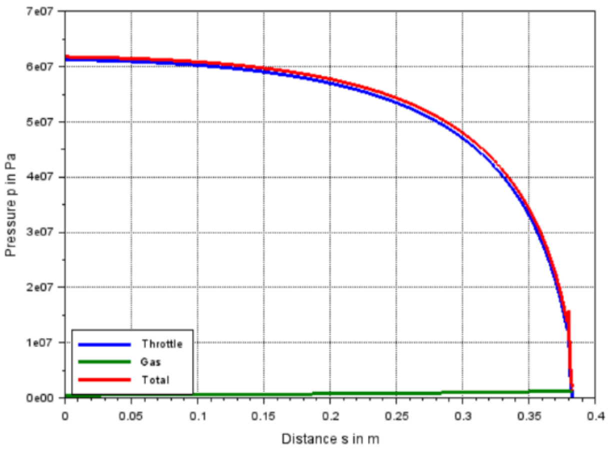


Figure 9 Kinematic values over time, Gas pressure, throttle pressure and total pressure (Reference buffer)

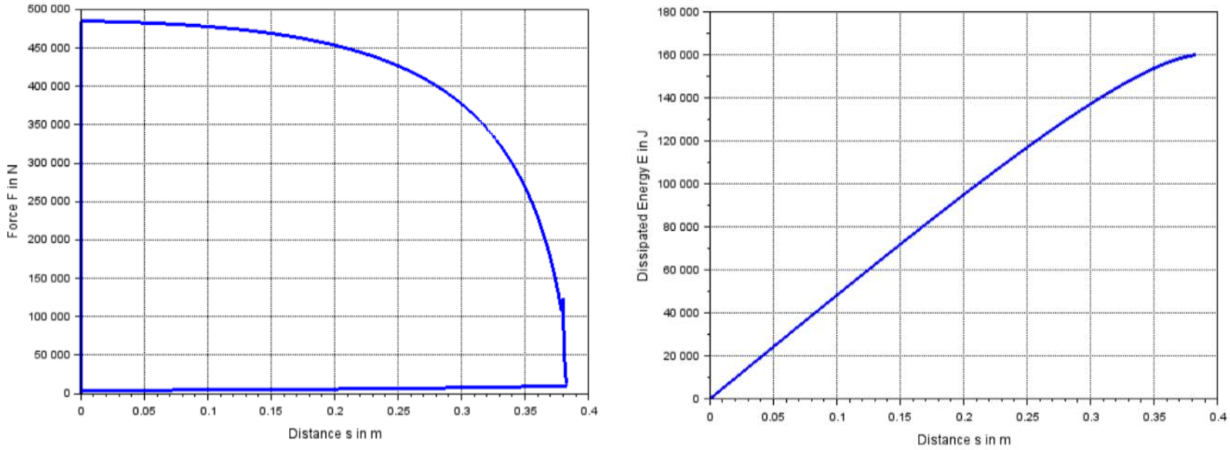


Figure 10 Buffer force, Energy dissipated (Reference buffer)

4 OPTIMIZATION OF BUFFER CHARACTERISTICS

Now two limit states of the hydraulic buffer are considered: the permissible oil pressure due to the sealings installed and the permissible piston rod force due to buckling of the piston rod. A certain maximum oil pressure leads to a constant limit force to the buffer. A maximum piston rod force leads to an inverse quadratic limit force to the buffer. The characteristics of different maximum oil pressures and certain piston rod diameters are shown in Fig. 11 (left).

As it absorbs the same energy as the reference buffer, the total absorbed energy of E = 160,000 J, a buffer with a maximum oil pressure of 400 bar and a piston rod diameter of 30mm is in focus now (Fig. 11, right). Up to piston positions of about x = 260mm, the maximum oil pressure defines the deciding limit state. Above piston positions of about x = 260mm, the maximum piston rod force with regard to buckling defines the deciding limit state. Based on these limit states for the certain buffer design, the maximum energy exploitance can be evaluated. This maximum energy exploitance might be of interest if a small buffer design is required rather than a constant buffer force. This represents a different optimization approach.

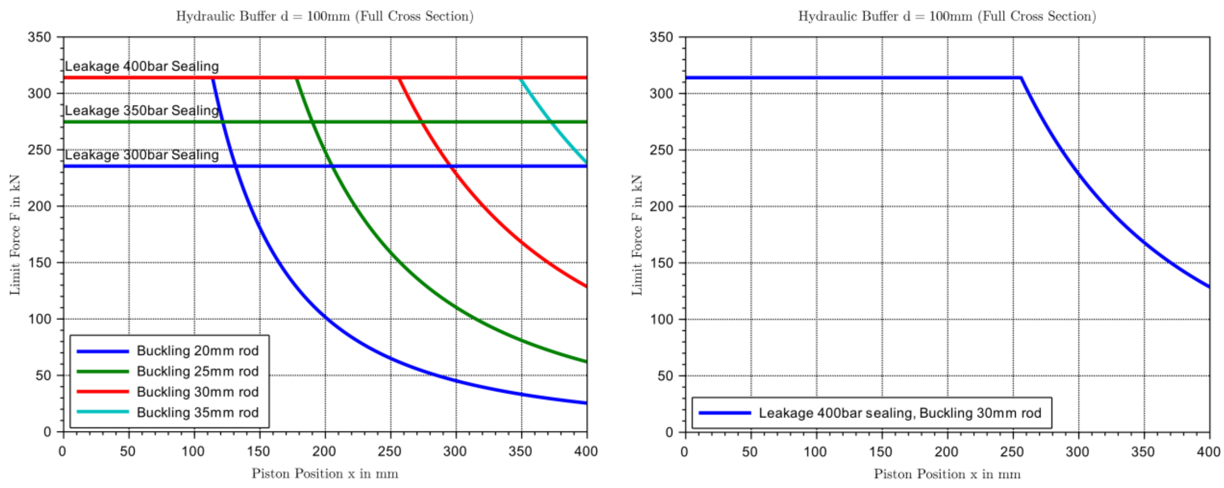


Figure 11 Buffer force limits, Buffer force characteristics intended

The continuous throttle cross section is now modified in order to meet the buffer force characteristics intended. The modified throttle cross-sectional area curve shows a starting value well above the value for the reference buffer. This is caused by the low buffer force limit at the beginning of the buffering process, caused by the buffer buckling force limit. At the passage from buffer force growth to constant buffer force, the throttle cross-sectional area shows a kink (Fig. 12, left).

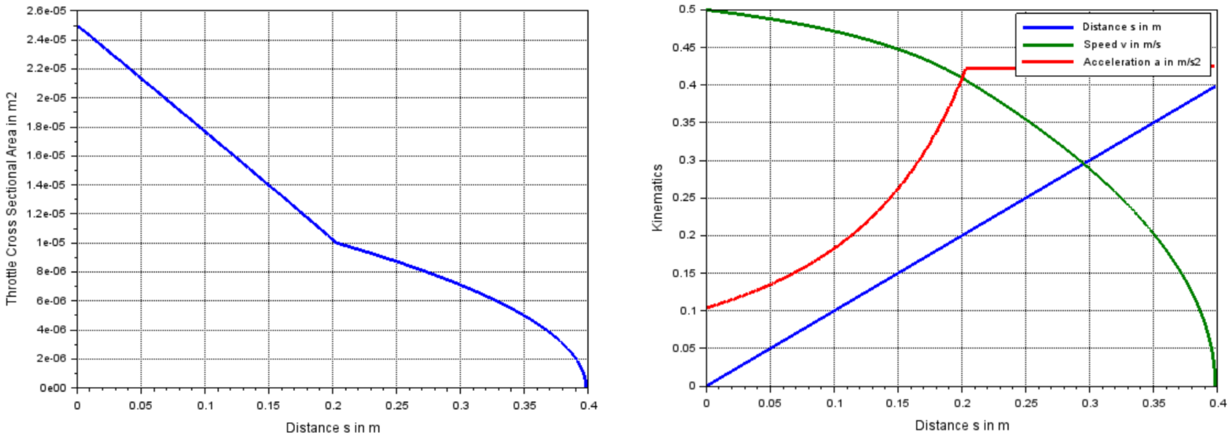


Figure 12 Throttle cross-sectional area, Kinematic values over position (Optimized buffer)

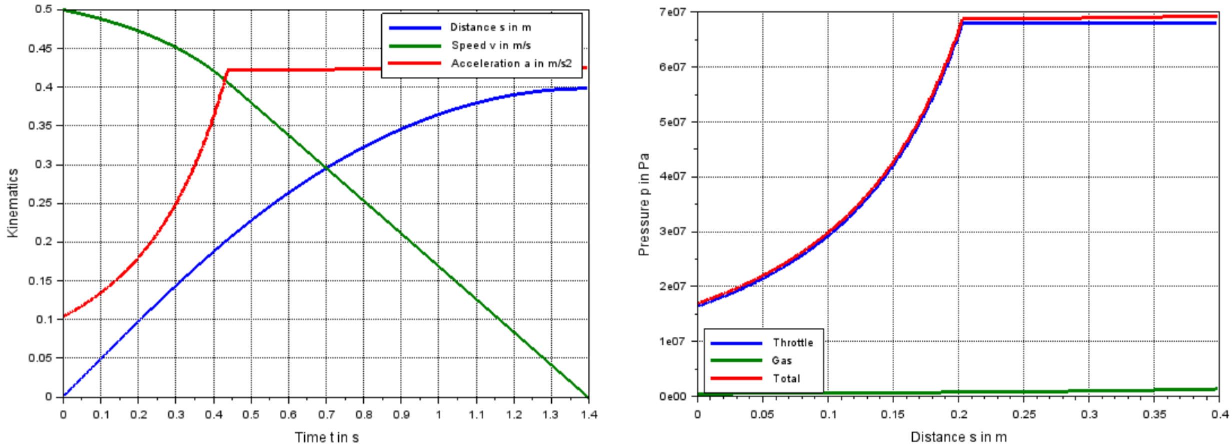


Figure 13 Kinematic values over time, Gas pressure, throttle pressure and total pressure (Optimized buffer)

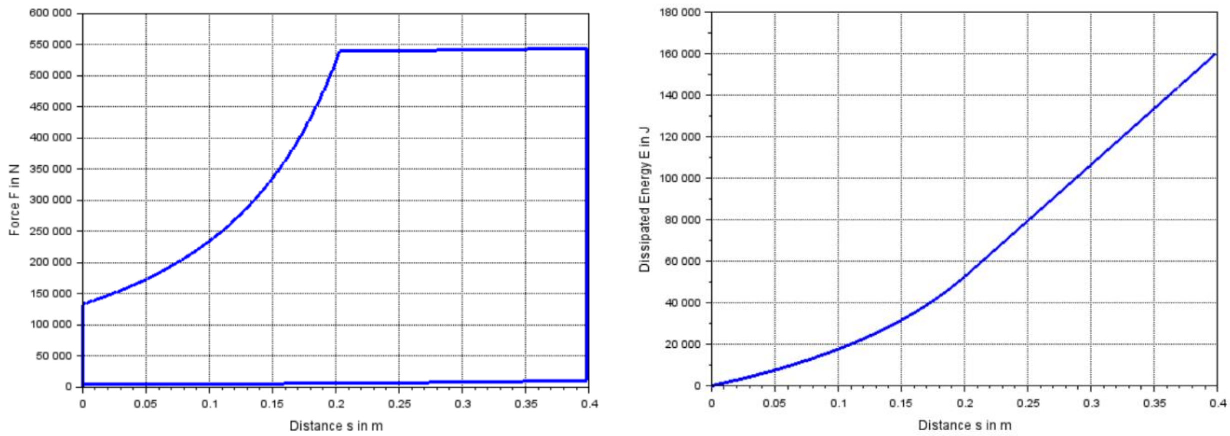


Figure 14 Buffer force, Energy dissipated (Optimized buffer)

The optimized buffer comprises a design suitable to absorb the same energy as the reference buffer (Fig. 14). As the initial throttle cross-sectional area for the optimized buffer is larger than for the reference buffer, the optimized buffer dissipates less energy at the beginning of the stroke and more energy at the end of the stroke (Fig. 15, right).

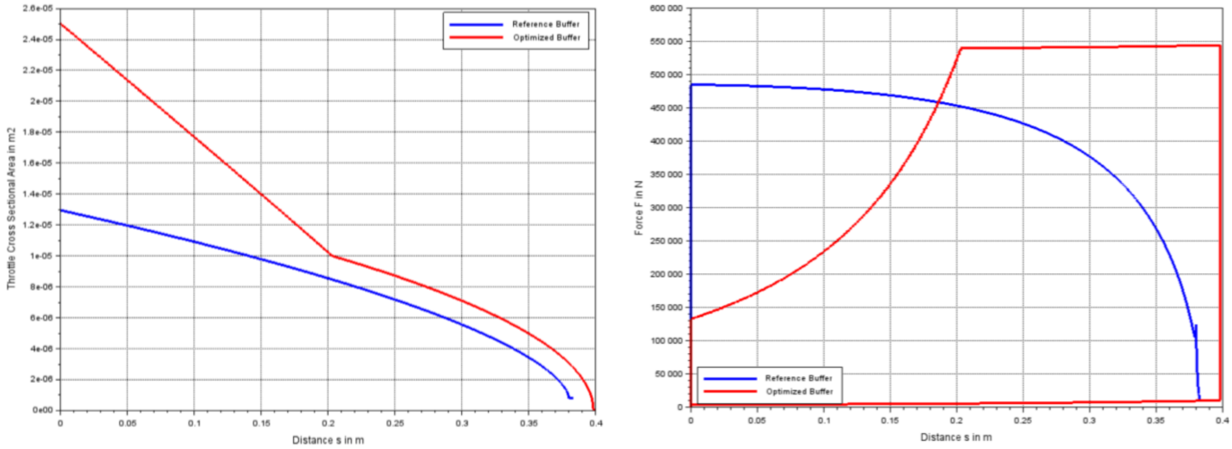


Figure 15 Throttle cross-sectional area, Buffer force (Reference buffer vs. optimized buffer)

As piston forces are quite low, the optimized characteristics give the potential to prevent buckling of the piston rod at the beginning of the stroke. The loss of energy absorbed may be compensated at the end of the stroke. There the buffer force may be larger than at the reference buffer. The buffer force is restricted by the sealings pressure limit e.g., maybe the maximum buffer force can even be lifted at the end of the buffer stroke. This gives the potential for a higher amount of energy to be absorbed by the reference buffer, just equipped with an optimized throttle (Fig. 15).

5 CONCLUSION

Means of calculation give tools to adapt buffer characteristics exactly to given conditions. This provides the possibility to adapt a drive force F_{Drive} changing over stroke; another possibility is the adaption of the different limit states of a buffer. In the first analysis, the optimization of the buffer force against the stroke was shown. These options are suitable to reach an improved exploitation of the buffer capacity. The adaption to further limit states may be found accordingly. An upcoming project will analyze an optimized buffer exploitation under consideration of various buffer limit states as listed in the article.

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- Mannesmann Demag Fördertechnik AG, Wetter, Head of Engineering Design Bridge Cranes
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