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Assessing lift maintenance performance of high-rise residential buildings

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Abstract

Lifts are essential vertical transportation facilities in tall buildings but they inevitably degrade with time. Aging lifts, in particular, require effective maintenance to ensure safe and reliable operation. Nevertheless, scant research has been undertaken to empirically examine the performance of lift maintenance services. To provide much-needed insight into this issue, this paper presents an in-depth case study to investigate the maintenance performance of 24 lifts in the eight high-rise buildings of a 24-year-old residential estate in the densely populated Hong Kong metropolis. Adopting both quantitative and qualitative research methods, a tripartite of primary corrective maintenance data, information collected from interviews with the estate's facility management personnel and on-site observations were analysed. Emergent factors that engendered high maintenance demand, including peak traffic periods during non-weekdays and false fault calls, were revealed. The effect of three archetypes of floor-serving configurations (lifts serving every floor, odd numbered floors and even numbered floors) on the lift maintenance performance, as identified, constitutes useful feedback information for lift zoning design and maintenance planning. Benchmarks of time-based lift maintenance performance indicators, including response time, repair time and downtime, were established. Suggestions for automatic data collection and tracking in the Industry 4.0 era, which would enhance the performance evaluation process, were also recommended. The approach of this study is original and it proves useful for empirical assessment of lift maintenance performance. Future research can take this approach and the study's findings as reference to investigate the maintenance performance of the lifts in other buildings.

Keywords

Elevator; evaluation; lift; maintenance; performance; residential

1. Introduction

Internationally, numerous tall buildings have been developed to maximize skyward property development to compensate for high land cost in densely populated cities (Liu et al., 2022). Besides iconic skyscrapers such as Burj Khalifa in Dubai of United Arab Emirates and Merdeka 118 in Kuala Lumpur of Malaysia, countless high-rise residential buildings (also known as apartments or condominiums) have been constructed (Statista Research Department, 2022). As habitats for billions of people worldwide, such buildings form an integral part of a safe and green built environment (U.S. Green Building Council, 2021). Among the world's most renown high-density cities, metropolises such as New York and Hong Kong have 5,818 and 6,588 high-rise buildings respectively (Patowary, 2013). With over 6,400 people packed into every square kilometer in Hong Kong, most of the city's seven million residents live in tall residential buildings (Rating and Valuation Department, 2022). All these tall buildings, which have lifts (or elevators) installed as an indispensable vertical transportation means, have to function properly round-the-clock.

In aggregate, about 80,000 lifts operate in Hong Kong (Au, 2020). While lifts have a product lifetime of 15 to 30 years, more than 30% of the lifts in operation were aged over 30 years (HKSAR Government, 2018). A lift is a complicated electrical and mechanical installation that is composed of multiple sub-systems including motor(s), control panel(s), suspension rope(s), counterweight(s) and so on. Ensuring safe and reliable lift operation hinges on correct and timely (to original manufacturer standards) maintenance of all its sub-systems. After a prolonged operation, deterioration or even failure of the sub-systems is often inevitable. Although the Government launched a HK$10.5 billion package to assist building owners to replace 8,000 lifts in buildings of 50 years old or above (South China Morning Post, 2019), two-thirds of the lifts have not yet fulfilled the latest safety requirements (South China Morning Post, 2021). Statistics published by the Electrical and Mechanical Services Department (EMSD) reveal that from January 2012 to September 2021 there were 109 serious lift incidents, with most of them involving passenger injuries and one extreme case resulted in fatality (Electrical and Mechanical Services Department, 2022a). Consequently, public concern over lift safety has increased sharply over the years and people are demanding better lift performance.

Attaining the safe and reliable operation of lifts entails periodic and quality maintenance works. Legislation in Hong Kong mandates that monthly maintenance and yearly tests and examinations for lifts shall be conducted by a registered lift contractor, who is also responsible for keeping a lift logbook up-to-date and providing maintenance services on contract terms (Lai and Yik, 2004; Lai, 2013). Older lifts usually require more corrective maintenance services (in addition to preventive maintenance) for resolving faulty operations such as lift call button failures and faulty doors. The increasing demand to fix such problems, especially for aging lifts, could lead to frequent breakdowns and lift service suspensions. More downtime and lower service availability, in turn, disrupt and undermine residents' quality of life. Effective lift maintenance therefore, is a crucial element of facility management for high-rise buildings.

2. Literature Review

2.1 Building maintenance and facility management

Building maintenance necessitates a combination of technical and associated regulatory procedures through which all buildings' components are guaranteed to operate and function to an acceptable level. Because these components deteriorate with time and usage, preserving good working condition requires regular maintenance (Seeley, 1987; Wood, 2009). Besides a building's structure and builder's works (such as grounds and roofs), building services installations are indispensable components for which maintenance effort is required to upkeep their functionality, thereby ensuring a safe and reliable indoor environment (Chanter and Swallow, 2007). Furthermore, building maintenance provides the basis for maintaining a building's prominent position and asset value (Lam et al., 2010). When provided with quality maintenance work, a building and its facilities can operate properly, with the building's value preserved and the lifespan of the facilities extended.

Integrating people, places, processes and technologies, facility management encompasses multiple disciplines to ensure the functionality of a built environment, improving people's quality of life (International Facility Management Association, 2022). Among the broad range of facility management services, maintenance is invariably a resource demanding and highly important function (Lai, 2011; Lai and Yik, 2011). It requires proper management methods that clearly define the arrangements to prevent and resolve failures or breakdowns of facilities.

Maintenance strategies can be broadly classified into two categories: (i) preventive maintenance, which includes time-based maintenance and condition-based maintenance; and (ii) corrective maintenance, which includes breakdown maintenance, opportunity maintenance and emergency maintenance (Chartered Institution of Building Services Engineers, 2014). Preventive maintenance refers to a constant and scheduled maintenance of the equipment; corrective maintenance means fixing an unscheduled failure that appears on the equipment (Costa and Balduino, 2018). Preventive maintenance work, conducted regularly, is often taken as the basic and routine necessity to safeguard equipment from functional failures (Moubray, 1997). In case an unscheduled failure happens, corrective maintenance work will be needed, which requires time to identify the problems, locate failure parts of the equipment, implement repair work and so on. For costly maintenance work, further time is required to seek funding approval and delivery of off-site materials for fixing the fault (Lee and Akin, 2009).

Unlike preventive maintenance with activities planned beforehand (and thus, not undermining work efficiency (cf. Cruzan, 2009)), corrective maintenance work is executed on demand and the suddenness of maintenance requests often hinders its efficiency (Edwards et al., 1998; Elazouni and Shaikh, 2008; Stenström et al., 2015). Despite the palpable advantage of preventive maintenance, facility management organizations often prefer the corrective maintenance approach (Le et al., 2018) because regular and frequent preventive maintenance activities would increase financial burdens on quintessentially limited maintenance budgets (Lai, 2010). Compared with the wider financial resources available to building owners, the expenditures on building maintenance accounts for a small portion even if corrective maintenance is adopted (Lee and Scott, 2009). Unless repeated failures occur, minor maintenance issues rarely attract the attention of facility management companies (Mydin, 2016). With limited influential power, a building maintenance team could hardly implement an effective maintenance plan (Au-Yong et al., 2017). But delays in clearing maintenance problems and accumulation of maintenance backlogs would shorten equipment lifespans and lead to user dissatisfaction.

2.2 Lift operation and maintenance (O&M) research

Lifts form an integral part of building services installations (Chartered Institution of Building Services Engineers, 2020). Skyscrapers in metropolises such as New York, Tokyo and Hong Kong rely on lifts to ensure the mobility and productivity of countless end users. The importance of proper and effective maintenance for lifts, therefore, has been increasingly recognized in parallel to the rapid increase in the development of high-rise buildings. Among research studies on lifts, many have focused on engineering aspects, e.g., optimization of lift energy consumption (Adak et al., 2013; Desdouits et al., 2015; Marsong and Plangklang, 2017; Tukia et al., 2017); and advancement of lift motor drives or control systems (Jung et al., 2012; Fernández et al., 2014; Mohaney et al., 2015; Kim et al., 2017; Arafa et al., 2018). Other studies emphasized the development of novel safety measures or fault diagnosis methods (Zhao et al., 2012; Sato et al., 2015; Huang and Yu, 2015; Skog et al., 2017). In recent decades, studies intended to identify ways for improving lift operation and maintenance (O&M) have expanded in number and topic areas. Examples include those on: new inspection techniques for lift maintenance (Park and Yang, 2010); analysis of lift maintenance service quality (Lee and Lai, 2011); investigations into the factors leading to the breakdowns of lifts (Au-Yong et al., 2018); novel performance-measurement models for lifts (Zubair and Zhang, 2020); development of appropriate maintenance strategies to extend the useful life of elevators (Zhang and Zubair, 2022); optimization of lift maintenance operations or periods (Gholami et al., 2021; Niu et al., 2021; Blakeley et al., 2003); and the use of IoT technology for lift maintenance (Lai et al., 2019; Ma et al., 2021).

Although the effectiveness of maintenance is pivotal to lift performance (especially in terms of service availability), scant studies have probed into the empirical maintenance performance of lifts in buildings, as real maintenance data are often sensitive and thus hard to obtain (Lai, 2015). Despite the limited empirical research findings on lift maintenance performance, prior studies on building O&M have developed some useful performance indicators that are applicable to lift maintenance performance evaluation.

2.3 Maintenance performance indicators

Various research studies in the facility management field have been conducted on maintenance performance indicators for built facilities. For example, Shohet (2003) developed key performance indicators (KPIs) for health-care facilities maintenance. Lavy et al. (2020) reviewed literature on KPIs for facility performance measurement. Lai and Man (2018a; 2018b) identified and shortlisted KPIs for facilities O&M in commercial buildings. Recently, Lai and Yuen (2021) established KPIs for managing facilities in hospital buildings. In the built environment context, time-based performance indicators have been used in evaluating building performance. For instance, a building project's performance can be assessed by comparing its allocated construction time with the actual completion time (Bubshait and Almohawis, 1994). Time variance, which is the ratio of actual construction time to targeted construction time, can be used to evaluate a refurbishment project's performance (Rahmat and Ali, 2010). Among the performance indicators that can be applied to assess lift maintenance performance, those based on measuring time durations are useful. Availability (i.e., the ability of an item to perform its required function at a stated instant of time or over a stated period of time (British Standard Institution, 2014)), is a well-known example.

Other time-based performance indicators have been extended for use in evaluating the maintenance performance of facilities. Failing to complete a maintenance task for a building component on time, for example, would affect the building's operation-as-normal stage (Kytucuoglu et al., 2001). Thus, time acting as a major maintenance performance indicator can specify the building components' functionality, human resources utilization and other aspects of the buildings. In particular, downtime is the time required to detect, repair or replace and restart a failed component or system. As a useful indicator for evaluating building maintenance performance (Bevilacqua and Braglia, 2000; Pascual et al., 2008; Batun and Azizoğlu, 2009), downtime comprises response time and repair time. The former is the duration between a maintenance request being raised and the time at which the request is attended on-site; the latter refers to the time duration required for executing the repair work to resolve the problem identified (Chartered Institution of Building Services Engineers, 2014).

The above review confirms the need of effective lift maintenance performance assessment and the growth of research on facilities maintenance performance. Yet, in-depth research findings that unveil the empirical maintenance performance of lifts in high-rise residential buildings remain limited. This research gap triggers the following questions: (1) How to assess lift maintenance performance, particularly the performance trend connected with maintenance work for correcting lift faults? (2) Are there any impacts of lift zoning arrangement on lift maintenance performance? (3) Are there any impacts of user travel pattern on lift maintenance performance? (4) How to use the time-based performance indicators including response time, repair time, downtime and service availability to properly assess lift maintenance performance? To answer these research questions, a deductive empirical study (cf. Edwards et al., 2020; Ameyaw et al., 2023) was conducted to investigate the lift maintenance performance of a typical residential estate in Hong Kong.

3. Materials and methods

The case study estate consists of eight high-rise buildings, providing in total over 2,200 residential units. In each building, there are three lifts; hence, there are 24 lifts in total. In line with the respective statutory requirement (Lai and Yik, 2004), a registered lift contractor was engaged for the lift maintenance service. On top of providing the basic, law-prescribed routine maintenance works such as monthly inspection and yearly examination of the lifts, the contractor is responsible for providing corrective maintenance works, which are executed on an as-needed basis.

3.1 Data collection

Taking a mixed methods approach, quantitative and qualitative research techniques were utilized to collect and analyse the primary corrective maintenance performance data of all the 24 lifts. Moreover, interviews and site visits were conducted to collate technical data of the lifts, including their operation patterns and maintenance demands. Other relevant information such as the maintenance practice for the lifts was also obtained from the estate's facility management office. Interviewees, selected using purposive sampling, are familiar with the lifts' usage and maintenance work arrangements. Prior to undertaking interviews, all participants were informed of the research purpose, given assurances that their names would not be disclosed and that all information collected would be used solely for the purpose of this study and presented in aggregate form (cf. Lai, 2010; Fisher et al., 2018; Stewardson et al., 2023).

The first interview was held with the estate management office's technical manager to solicit information about the maintenance organization and practice, including: the set-up of the maintenance team; the maintenance workflow; and the processes involved in communicating and recording maintenance information. Upon the interviewer's request, the technical manager provided the technical specifications of the lifts including their carrying capacity, floors served by each lift, control system, door operation type and service life. Copies of maintenance information archives including lift maintenance records, monthly lift failure reports (comprising a fault call report and a fault call summary) and lift logbooks, which cover the preceding 3-year period (2018 – 2020), were also provided. Data retrieved from these archives, which provide a comprehensive picture of the lift maintenance demand, include: i) date of fault call; ii) fault location; iii) time of fault call issued; iv) arrival time of maintenance worker; v) leave time of maintenance worker; vi) reasons for the fault; and vii) follow-up maintenance actions taken. Additionally, a maintenance procedure handbook provided by the technical manager delineates the lift check procedures and the follow-up maintenance actions for any faults identified.

Since building caretakers look after the buildings' daily operations, they are familiar with the conditions of the lifts. Therefore, two more interviews were made – one with a daytime caretaker and the other with a nighttime caretaker. They were asked to share their experiences and perceptions about the usage and operating conditions of the lifts, the frequency of lift failures, and the typical up-peak and down-peak periods of the lifts. During the interview with the technical manager, approval was sought for paying site visits to one of the buildings of the estate. The first visit was on a typical weekday and the second on a public holiday (i.e., non-weekday). Both visits started at 6:00 am and ended at 9:00 pm, during which the researcher was stationed at the main lift lobby and counted the number of lift passengers entering and leaving the lifts. Such primary data enables analysis to be made on the lift usage patterns.

3.2 Data analysis methods

Time was taken as the main basis for analysing the performance of the corrective maintenance service provided for the lifts under investigation. Following the analysis approach of Lai (2015) and using Equations (1), (2) and (3), the issue time (t_i), arrival time (t_a) and leave time (t_l) of each fault call recorded in the lift failure reports were used to calculate the response time (T_{rs}) of the fault calls, the repair time (T_{rp}) of the faults, and the downtime (T_d) of the lifts. The mean values of these time-based indicators, their standard deviations (SD) and their coefficients of variation (C_v) were computed. Then, comparisons were made on these computed values between the buildings in the estate and between the lifts in individual buildings.

$$T_{rs} = t_a - t_i \quad (1)$$

$$T_{rp} = t_l - t_a \quad (2)$$

$$T_d = T_{rs} + T_{rp} = t_l - t_i \quad (3)$$

$$H_o: \mu_1 - \mu_2 = 0 \quad (4)$$

$$H_a: \mu_1 - \mu_2 \neq 0 \quad (5)$$

$$A = 1 - \frac{T_{TD}}{T_{TO}} \quad (6)$$

To determine whether any significant difference exists in the maintenance performance between the lifts, two-tailed z-tests were performed on the calculated response time, repair time and downtime, of which the population means are:

μ_1 = mean response time (or repair time, or downtime) of fault calls (or faults) of Lift X
μ_2 = mean response time (or repair time, or downtime) of fault calls (or faults) of Lift Y

where Lift X and Lift Y are the pair of lifts (viz. Lift 1 and Lift 2, Lift 1 and Lift 3, or Lift 2 and Lift 3) under analysis.

The null hypothesis (H_o) and alternative hypothesis (H_a) for the above statistical tests are expressed as Equations (4) and (5). These hypotheses were tested using the z-test by estimating the difference between the two means (i.e., $\alpha = 0.05$) with a confidence level of 95%, and the critical value ($Z_\alpha = 0.5$) is 1.96.

Service availability (A), which is a common lift performance indicator, was further calculated using Equation (6), where T_{TD} is a lift's total downtime other than that due to scheduled maintenance and T_{TO} is the lift's total operating time. Commonly adopted as a performance target for lift maintenance service, service availability indicates the level that a lift is available to provide effective service to its users: the higher the service availability, the better the lift maintenance performance. While different building types and hence, different types of lifts may be set with different target levels of service availability, the monthly system service availability as stated in the EMSD's sample specification for procurement of lifts shall be maintained at not lower than 99% (Electrical and Mechanical Services Department, 2013).

4. Results and discussion

From the data and information provided by the technical manager, the technical specifications of the three lifts in each of the eight residential buildings are summarized in Table 1. All the lifts, designed for passenger use, had been in use for 24 years. Coupled with proprietary motors for hoisting purposes, the operating system and door operation mode of all the lifts are identical: 2-panel centre opening automatic sliding door with safety shoes.

Table 1 Technical specifications of the lifts

	Lift 1	Lift 2	Lift 3
Passenger carrying capacity	12 persons	13 persons	12 persons
Load carrying capacity	900 kg	1000 kg	900 kg

Rated speed	2.5 m/s	1.75 m/s	2.5 m/s
Floors served	Odd numbered	All	Even numbered
Number of stops	17-20	33-39	17-20

With a slight difference in passenger carrying capacity (12 and 13 passengers) and load carrying capacity (900 and 1000 kg), the lifts were designed with different rated speeds to suit the difference in lift zoning: apart from stopping at the ground floor main lobby, Lift 1 stops only at odd numbered floors (i.e., first, third, fifth, etc.), Lift 2 stops at every floor, and Lift 3 stops only at even numbered floors (i.e., second, fourth, sixth, etc.). With a comparatively lower rated speed (1.75 m/s), the number of stops of Lift 2 is the largest, ranging from 33 to 39.

The interview with the technical manager revealed the extent of works of the preventive routine maintenance for the lifts as well as the procedures of the lifts' corrective maintenance works stated in the lift maintenance contract. A single contractor provides both the preventive and corrective maintenance services for all the 24 lifts in the estate. Preventive maintenance, which was conducted every month and on average took about 30 minutes for each lift, included inspection, cleaning and servicing of the lift cars, doors, safety edges, operating control systems, etc. up to the stated work quality standard. As for corrective maintenance, once a lift fault call is made from the building caretaker to the lift maintenance company's hotline, technical staff in the nearest call centre of the company will travel to the concerned building to attend the fault raised. Upon arrival on site, the technical staff reports to the building caretaker, identifies and diagnoses any fault, and fixes the problem as needed. The timing of all these activities and maintenance actions taken by the technical staff, in line with the respective statutory requirement, is recorded in the lift logbook. During the preventive or corrective maintenance period of one lift, residents were recommended to use the other available lifts.

4.1 Fault calls

The number of lift fault calls, reflecting the level of maintenance demand, was counted from the records in the lift failure report. There were a total of 606 fault calls from January 2018 to December 2020. During this period, no major work such as renovation or modernisation was implemented for the lifts and the lift service was not suspended, although COVID-19 intermittently affected the daily life of the residents. Plotting the monthly number of fault calls along the 3-year period (Figure 1) shows that despite the fluctuations, the trend of the faulty calls generally declines. This suggests that the lift maintenance performance was improving. Another possible reason for the decreasing fault call trend was reduced lift usage due to the intermittent "work from home" and "study from home" arrangements during the COVID-19 pandemic period in 2020.

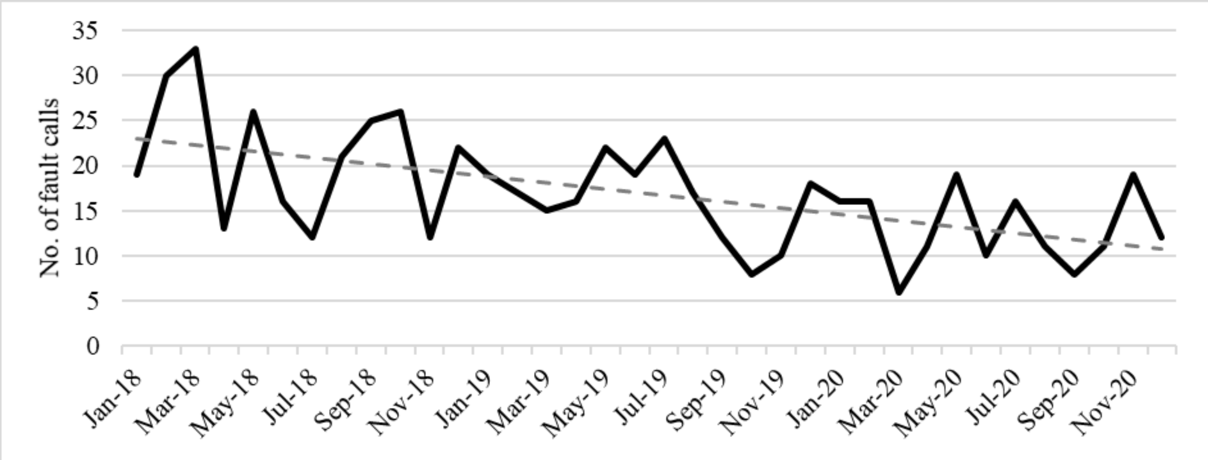


Figure 1 Monthly number of fault calls (2018 – 2020)

Figure 2 charts the aggregate number of lift fault calls in each month over the 3-year period and, for each year, the variations in number of monthly lift fault calls. Same for the three years, the monthly number of fault calls ranged between 5 and 25 per month. The numbers of fault calls (30 or more) recorded in February and March 2018 were comparatively large. Over these three years, more fault calls were raised during February and May. This finding suggests that the number of fault calls was correlated with the change in weather conditions – Hong Kong has its dry winter changing to humid spring in February and, in May, the humid climate changes to hot summer. Further studies are therefore recommended to investigate whether the changes in air temperature and/or relative humidity in the surrounding environments (e.g., lift shaft, lift machine room) lead to more faults, especially for the electronic components.

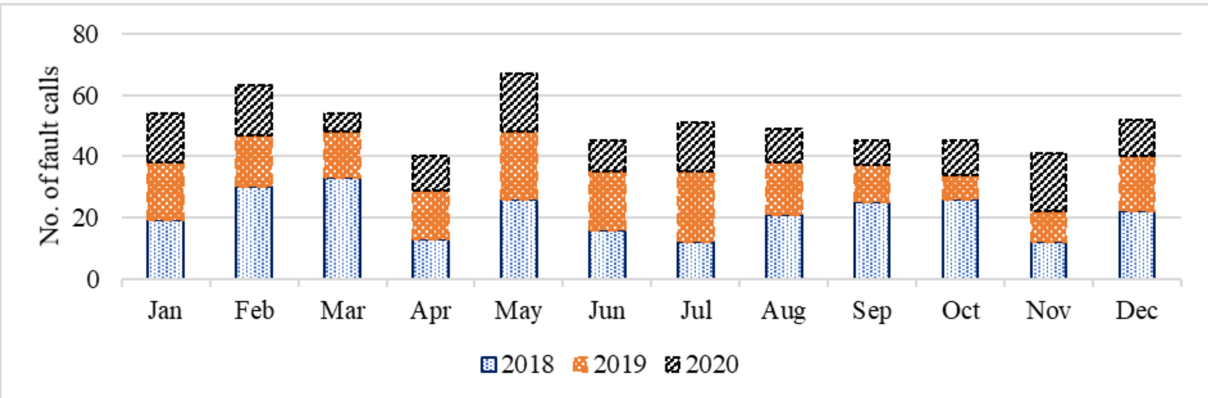


Figure 2 Aggregate and monthly numbers of fault calls (2018 – 2020)

4.1.1 Impact of zoning

Figure 3 shows the distribution of monthly number of fault calls for all the 24 lifts. In each building, Lift 2 attracted the highest number of fault calls (42%), while those from Lift 3 and Lift 1 were 33% and 25% respectively. These findings show that the larger the number of floors served by a lift (i.e., number of stops), the larger the maintenance demand for the lift. In fact, in each building Lift 2 serves every floor, while Lifts 1 and 3 stop only at the ground floor and the upper, alternate floors. Regardless of which floor a resident lives on, for convenience, the resident naturally calls for Lift 2 and another lift serving that floor, viz. Lift 1 (for an odd numbered floor) or Lift 3 (for an even numbered floor).

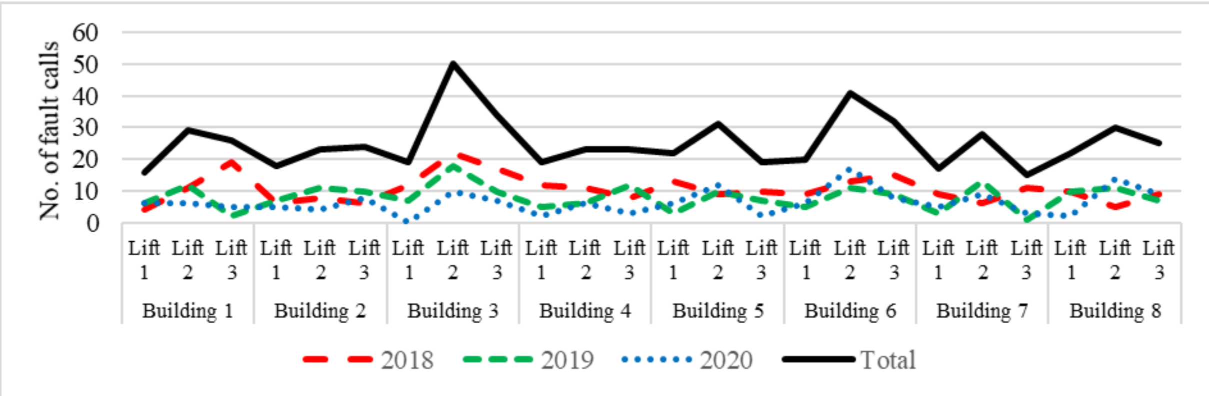
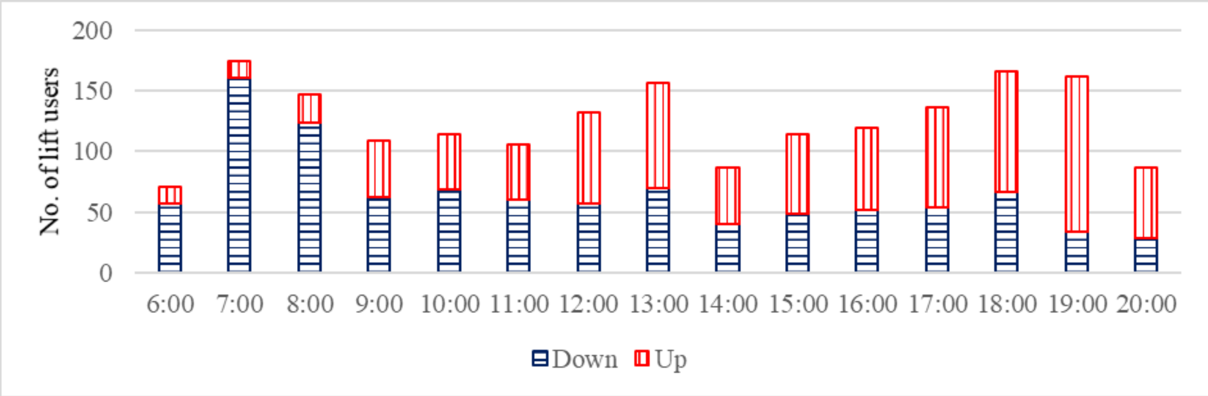


Figure 3 Distribution of monthly number of fault calls over the 3-year period

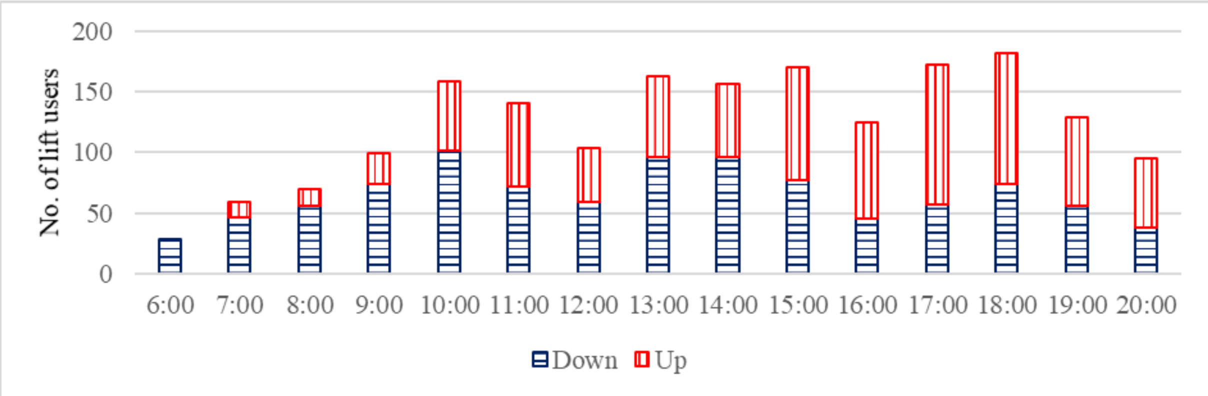
4.1.2 Impact of usage patterns

From 2018 to 2020, there were a total of 1,096 calendar days, of which 68% (or 741 days) were weekdays and 32% (or 355 days) were non-weekdays. In those weekdays, a total of 388 fault calls were recorded, accounting for 64% of all the fault calls, while the remaining 218 fault calls (i.e., 36%) were raised over the non-weekdays (including Saturdays, Sundays and public holidays) in that 3-year period.

Figure 4a illustrates the number of lift users counted at the main lift lobby of a typical building during the two site visits. It shows the hourly number of persons taking the lifts up or down on a weekday. In the morning, between 7:00 a.m. and 8:00 a.m., a large group of residents including those who went to work or school travelled down by taking the lifts. In the evening, from 6:00 p.m. to 7:00 p.m., a large number of residents returned to the building and took the lifts up to their homes. Apart from the peak demands of the lifts during these two periods, a high demand comprising both up-peak and down-peak lift traffics occurred during lunchtime, around 1:00 p.m.



(a)



(b)

Figure 4 Lift traffic on (a) weekday and (b) non-weekday

Figure 4b shows the number of lift users going up or down on a typical non-weekday. Compared with the weekday lift traffic, the morning peak lift traffic on the non-weekday occurred later, at 10:00 a.m. This could be ascribed to the norm that most people who are not at work or school on the non-weekday tended to wake up later than on weekdays. Overall, the other lift traffic peaks were found after lunchtime, including the periods from 1:00 p.m. to 3:00 p.m. and from 5:00 p.m. to 6:00 p.m.

The maintenance performance of the lifts was evaluated by referring to the number of fault calls per day. With 606 fault calls raised over 1,096 calendar days (from 2018 to 2020), the number of fault call per day was 0.55. Similar, the number of fault call per day was calculated respectively for the weekdays and the non-weekdays over the 3-year period. Table 2 summarizes the calculated results.

Table 2 Fault calls on weekdays and non-weekdays

Year	Weekdays	Non-weekdays

	No. of weekdays	Total fault calls	Fault calls per day	No. of non-weekdays	Total fault calls	Fault calls per day
2018	246	168	0.68	119	87	0.73
2019	246	127	0.52	119	69	0.58
2020	249	93	0.37	117	62	0.53
Overall	741	388	0.52	355	218	0.61

On weekdays in 2018, the number of fault calls per day was 0.68, which was higher than that in 2019 (0.52) and 2020 (0.37). On average, over the three years, the number of fault calls per day on weekdays was 0.52. While on non-weekdays, the number of fault calls per day in 2018 was 0.73, which was higher than that in 2019 (0.58) and 2020 (0.53). The average number of fault calls per day, over the non-weekdays of the three years, was 0.61. These findings show that the normalized maintenance demand was higher on the non-weekdays than on the weekdays.

4.2 Response time, repair time, and downtime

Processing the data collected by Equations 1 to 3, the response time, repair time and downtime of the lifts were calculated for the 3-year period as a whole and also for each of the three years. Based on these calculated values, descriptive statistics including mean, standard deviation (SD) and coefficient of variation (C_v) were determined, as summarized in Table 3.

Table 3 Downtime, response time and repair time of the lifts (in minutes)

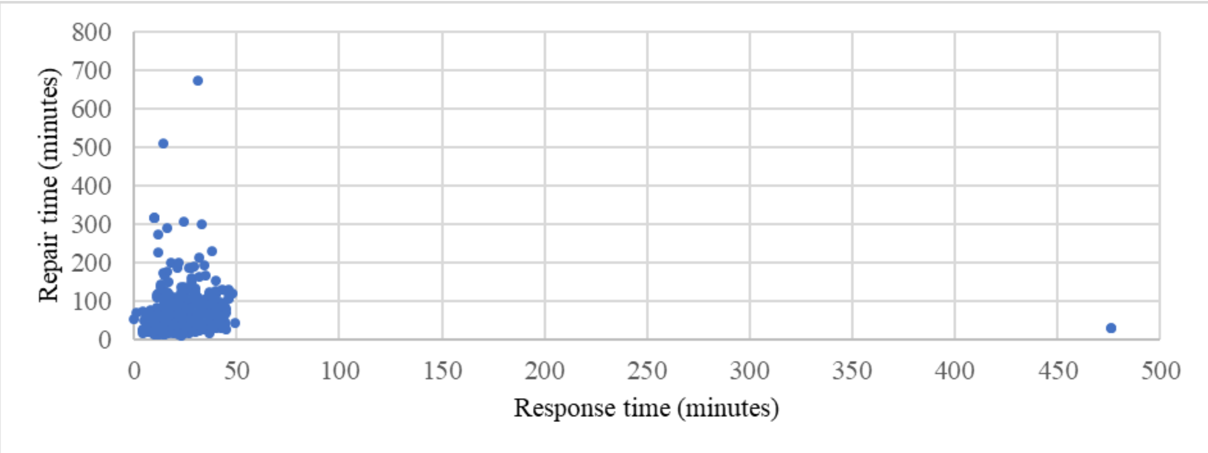
Year	Downtime			Response time			Repair time		
	Mean	SD	C_v	Mean	SD	C_v	Mean	SD	C_v
2018	89.5	76.0	0.85	24.7	41.3	1.67	64.8	64.3	0.99
2019	80.0	45.7	0.57	22.8	10.4	0.46	57.2	42.6	0.75
2020	77.7	52.2	0.67	20.6	10.0	0.49	57.1	49.8	0.87
Overall	83.4	61.8	0.74	23.0	27.9	1.21	60.4	54.5	0.90

Over the 3-year period, the mean downtime of the lifts was about 83 minutes. Among the C_v values of the three years, the highest was found with 2018, which means that the downtimes of the lifts were spread more widely in this year than in the other two years. Notwithstanding this observation, the overall C_v value was below 1, indicating that on the whole the variations in the lift downtimes were low.

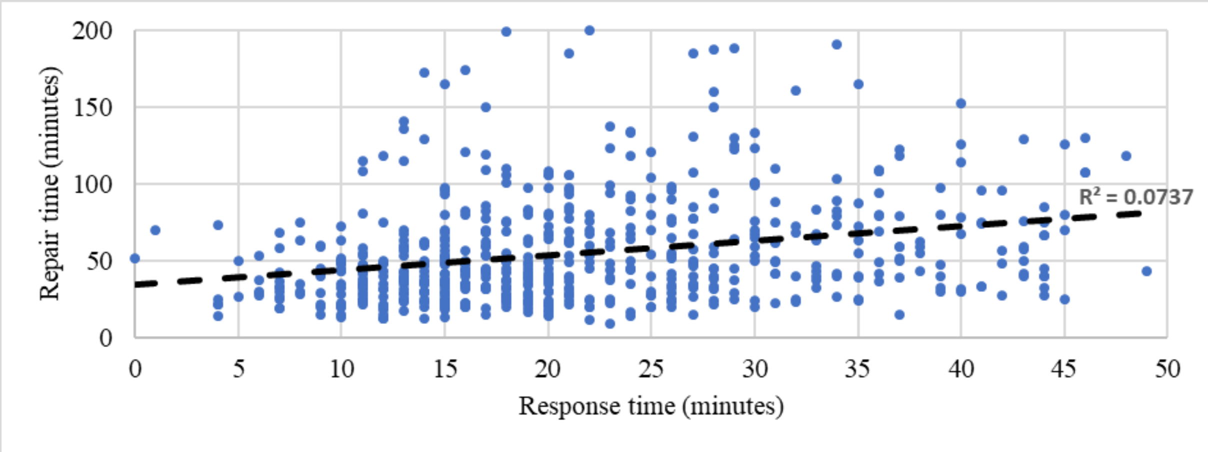
Over the three years, the mean response time of the lifts was 23 minutes. Comparing the C_v values of the response times across the three years found that the one pertaining to 2018 was as high as 1.67, meaning that the response times of this year varied significantly. Conversely, the variations in the response times of 2019 and 2020, at 0.46 and 0.49 respectively, were lower. According to the interviewees, the lift maintenance personnel usually arrived at the site within half an hour upon receipt of a fault call. This fulfilled the requirement of the lift maintenance contract: upon receipt of a fault call, the contractor shall attend to the incident within one hour. The fact that *"attending service calls within 30 minutes"* is a recommended practice (Building Services Operation and Maintenance Executive Society, 2019) should also have driven the lift maintenance contractor to promptly attend the fault requests.

As regards the lifts' repair times, the average value over the 3-year period was about 60 minutes. While its C_v values of the three years were all below 1, the comparatively higher C_v values pertaining to 2019 and 2020 indicate that the repair times in these two years varied more than the response times in the same period. This is also evidenced by the findings that the SD values of the repair times were greater than the counterparts of the response times.

The study of Lai (2015) found that for work orders issued for maintaining building services installations (such as air-conditioning systems), a longer response time is associated with a shorter repair time and vice versa. To visualize if such a relationship exists, a scatterplot of the repair times against the response times was made (refer to Figure 5a). Most of the plotted data points clustered in the region where the response times were small (below 50 minutes) and the repair times were up to around 300 minutes.



(a)



(b)

Figure 5 Repair time against response time: (a) all data and (b) data without the outliers

Nevertheless, there are outliers in Figure 5a. The first one refers to a lift fault with a response time of 476 minutes. This exceptionally long response time, according to the lift failure report, was caused by a suspension of the power supply system. The second and third outliers, with the corresponding repair times being 674 minutes and 510 minutes, were due to the faults with a lift operating panel and a lift car door. The main reasons for these long repair times were the difficulty in diagnosing the equipment failure and the lack of spare parts for replacing the faulty components.

With the outliers excluded and focusing on most of the data (with repair time within 200 minutes), Figure 5b was plotted. Unlike the relationship found between response time and repair time in Lai (2015), no apparent pattern could be observed here. The small coefficient of determination (R^2 = 0.07) also indicates a low goodness of fit for the trend line. Plausible reasons for the longer time for repair than for response include the following. First, the maintenance call center was not far away from the residential estate. Upon receipt of a fault call, the maintenance personnel could respond and arrive on site within a short period. Second, in each building there are three lifts. Given that one of these lifts serves every floor and the other two serve alternate floors (i.e., odd and even numbered floors), in effect every floor is accessible by two lifts. In case one of the lifts fails, the other could still provide a lift service to the users.

To further examine the lifts' maintenance performance, cumulative distribution curves of downtime, response time, and repair time were plotted in Figure 6. It shows that, with the Pareto Principle taken as a reference, about 80% of the lift faults were cleared within 115 minutes. This corresponds to 35 minutes for the response time and 80 minutes for the repair time. These distribution curves, together with the calculated benchmarks summarized in Table 3, can be used to monitor the future maintenance performance of the lifts.

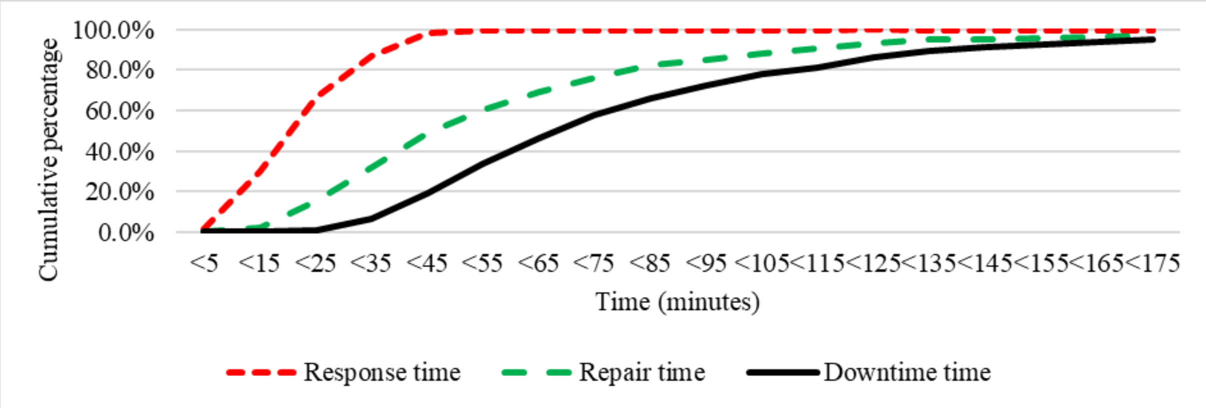


Figure 6 Response time, repair time, and downtime of the lift faults

4.2.1 Effect of floor-serving configurations

There are three configurations of the floors served by the lifts in each building: Lift 1 serves the odd numbered floors, Lift 2 serves every floor, and Lift 3 serves the even numbered floors. To determine whether there exists any statistical difference in the maintenance performance between the configurations, with reference to the analysis approach of Lai (2015), a series of two-tailed z-tests were applied to analyse the response time, repair time and downtime of the lifts. This was done firstly, between Lift 1 and Lift 2, secondly, between Lift 1 and Lift 3, and finally, between Lift 2 and Lift 3. Tables 4, 5 and 6 summarize the analysis results.

Table 4 Results of z-test between Lift 1 and Lift 2

	Response time		Repair time		Downtime	
	Lift 1	Lift 2	Lift 1	Lift 2	Lift 1	Lift 2
Mean	22.1	23.4	68.6	56.1	90.7	79.5
SD	9.9	30.2	81.6	41.0	83.5	51.8
Test statistic (z)	0.6251		1.7636		1.4963	
p-value	0.5319		0.0778		0.1346	

Table 5 Results of z-test between Lift 1 and Lift 3

	Response time		Repair time		Downtime	
	Lift 1	Lift 3	Lift 1	Lift 3	Lift 1	Lift 3
Mean	22.1	23.3	68.6	59.6	90.7	82.8
SD	9.9	33.8	81.6	41.5	83.5	53.3

Test statistic (z)	0.4408	1.2437	1.0172
p-value	0.6594	0.2136	0.3091

Table 6 Results of z-test between Lift 2 and Lift 3

	Response time		Repair time		Downtime	
	Lift 2	Lift 3	Lift 2	Lift 3	Lift 2	Lift 3
Mean	23.4	23.3	56.1	59.6	79.5	82.8
SD	30.2	33.8	41.0	41.5	51.8	53.3
Test statistic (z)	0.0547		0.8948		0.6684	
p-value	0.9564		0.3709		0.5039	

The mean response times of the fault calls of Lifts 1, 2 and 3 were between 22.1 and 23.4 minutes. Although the standard deviation of the response time pertaining to Lift 1 was much smaller than that of Lifts 2 or 3, the results of the z-tests revealed no significant difference in the response time between the three lifts. As regards the repair time of the faults, the average values of Lifts 1, 2 and 3 were between 56.1 and 68.6 minutes. The standard deviation of the repair time for Lift 1 was particularly higher, but there was no statistical evidence to show that there was any significant difference in the repair time between Lifts 1, 2 and 3. The mean downtimes of the faults of all the three configurations of lifts were between 79.5 and 90.7 minutes. Similar to that of the repair time, the standard deviation of the downtime of Lift 1 was particularly higher. Nevertheless, the results of the z-tests failed to show any significant difference in the downtime between the three archetypes of lifts. The p-values, which represent the probabilities of obtaining the test statistics at least as extreme as the observed ones, were not smaller than 0.05 ($<\alpha$). Thus, the null hypothesis that $\mu_1 - \mu_2 = 0$ could not be rejected, meaning that the maintenance performance of the three configurations of lifts had no statistically significant difference.

Unsurprisingly there was no significant difference in the maintenance performance between Lift 1 (serving the odd numbered floors) and Lift 3 (serving the even numbered floors), given that the numbers of floors they serve are comparable. But Lift 2, serving every floor in each building, has almost double the number of stops of that of Lift 1 or Lift 3. The reasons why the maintenance performance of Lift 2 was not significantly different from that of Lift 1 or Lift 3 include: i) once a fault call was raised, the lift was suspended from service until the fault was cleared. During the suspension period, no more fault calls were raised for the same lift; and ii) the frequency of fault calls was not extremely high and, with sufficient manpower of the lift maintenance contractor, the faults could be resolved within a reasonable period. As long as the lift maintenance personnel managed to clear the fault in hand before a fault of another lift is raised coincidentally, the response time, repair time and downtime of Lift 2 would not be lengthened. The same applies if the lift maintenance contractor deploys additional maintenance personnel in case of coincident fault calls for multiple lifts within the estate.

4.3 Service availability

The lift maintenance contract of the estate, which was formed with reference to the EMSD's recommendation (Electrical and Mechanical Services Department, 2013), requires that the monthly service availability of the lifts shall be maintained at not less than 99%. To ascertain whether this performance target is attained, the monthly service availability of the lifts over the 3-year period was calculated using Equation 6. The calculated results, plotted in Figure 7, show that the service availability exhibits an upward trend. This signifies a gradual improvement of the lift maintenance service over the years. As mentioned earlier, the improvement could also be contributed by the reduced lift traffic during the COVID-19 pandemic in 2020.

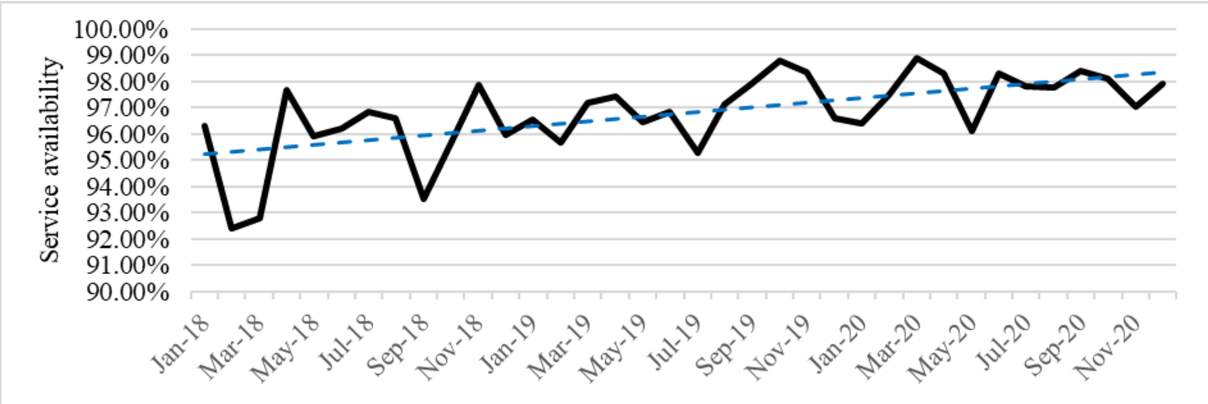


Figure 7 Monthly service availability of the lifts

Nevertheless, even the highest service availability, which was 98.9% in March 2020, fails to meet the performance target. To identify why the measured service availability was lower than the target level, further investigation was undertaken. Through scrutinizing the lift maintenance records, it was unveiled from the lift failure reports that some factors gave rise to the relatively low service availability. The first factor was vandalism. There were cases recorded in the reports where the lift faults were due to misuse(s) or misbehaviour(s), e.g., a lift user kicked on a lift car door. Such vandalisms, which often led to contractual disputes on maintenance responsibility (Lai et al., 2004), were beyond the control of the lift maintenance contractor. Another factor was false fault calls. Such calls included those raised by lift users (e.g., visitors) who were unfamiliar with the lift functions, or some fault calls for which the real cause could not be identified after diagnosis by the lift maintenance personnel. Consequently, it is recommended that in future studies of this kind, the effect of the above factors should be addressed and their influence on the measured service availability should be evaluated.

Furthermore, should the service availability of the aging lifts continue to lie below the desired performance level, the estate management office should consider implementing improvement works for the lifts. Lift modernisation, which can improve the performance of aging lifts, is to upgrade the individual components and/or the entire sub-systems one-by-one without completely changing the physical and mechanical structure of the lifts. Since 2019, the Hong Kong Government has implemented the "Lift Modernisation Subsidy Scheme" to promote lift modernization in the community through provision of financial incentive with appropriate professional support to eligible building private residential or composite building owners. Such modernization work can prolong the lifespan of the lifts, prevent a total replacement service, enhance lift safety, and minimise lift downtime (Hong Kong Building Rehabilitation Facilitation Services Limited, 2023).

5. Conclusions

This study investigates the corrective maintenance performance of 24 lifts situated in a typical high-rise residential estate in Hong Kong – a populous Asian city. Through interviews with the key facility management personnel and on-site observations, empirical data and documentary records were collected to reveal the technical characteristics, usage patterns and the maintenance demands of the lifts. Analyzing the 3-year maintenance data unveiled the trend of lift fault calls and also the impacts of lift zoning and usage patterns on the volume of the fault calls.

Time-based performance indicators, i.e., response time, repair time and downtime, were computed to assess the lifts' maintenance performance. The effect of the different floor-serving configurations of the three lift archetypes in the estate was also examined. Serving respectively the odd and even numbered floors in each building, Lift 1 and Lift 3 were less demanding in terms of fault calls, while Lift 2, serving every floor (with almost double the number of stops of Lift 1 or 3), recorded significantly more fault calls. This finding about lift zoning serves as useful feedback: facility managers would be better informed when formulating maintenance plans for the lifts in the estate, and building designers could take this information into consideration when calculating the lift traffic for similar high-rise buildings in future.

Despite the comparatively larger number of faults calls found with the lift serving every floor, an intriguing finding from this study is the insignificant difference in the response time, repair time and downtime of the three lift archetypes. Plausible factors attributable to this finding, as discussed, have also been identified. The benchmarks developed from this study, including monthly number of fault calls, daily number of faults calls (on weekdays and non-weekdays), mean values of the time-based performance indicators (viz. response time, repair time and downtime) are useful for evaluating the forthcoming maintenance performance of the lifts studied. Facility managers of similar residential estates can also use these benchmarks to ascertain the maintenance performance of the lifts they manage.

An implication drawn from this study is the revelation of higher maintenance demand during the non-weekdays. Not only is this finding significant for lift service contractors in scheduling maintenance manpower, but it is also useful for setting and differentiating targets of maintenance performance levels for different time periods, viz. weekdays and non-weekdays. A further implication, based on the findings about service availability, is the need to segregate real fault calls from false fault calls when assessing lift maintenance performance in future.

This study, akin to many others, is not without limitations. While the study team managed to solicit detailed lift maintenance data and collected extensive documentary maintenance records, the representativeness of the study findings is limited by the fact that only the estate's key facility management personnel were interviewed and that only the typical lift usage patterns were observed. In future research of this kind, endeavors should be made to cover interviews with more lift maintenance service stakeholders (e.g., user representatives). With the advent and increasing availability of smart technologies in this Industry 4.0 era (Riaz et al., 2017; Newman et al., 2020), automatic and electronic systems should also be deployed to enhance data completeness. Examples of such systems include people-counting cameras for recording a comprehensive lift usage pattern and digital logbooks for tracking lift maintenance activities (Electrical and Mechanical Services Department, 2022b).

CRediT authorship contribution statement

Roger Ng: Formal analysis, validation, writing original draft, visualization. **Joseph Lai:** Conceptualization, methodology, supervision, writing (original draft, review and editing) and project administration. **Oscar Leung:** Conceptualization, data curation, investigation, formal analysis, writing original draft, visualization. **David Edwards:** Validation, writing (review and editing).

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