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Extending the useful life of elevators through appropriate maintenance strategies

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ABSTRACT

The useful life of elevators is typically considered to be 20–25 years. However, there is no empirical evidence to support this recommendation. In practice, elevators may take a useful life that is a few years longer. This research statistically analyzed the 25,548 breakdowns attributed to 5400 elevators in Hong Kong. The results indicated that the useful life of elevators is 30 years under the notion of the bathtub curve. Furthermore, Pareto analysis revealed that faults in the controller, car door mechanism, landing door mechanism, and other equipment in the car cage are the four leading causes of breakdowns. The research also uncovered "faults in the controller" as the trigger which onsets the wear-out phase. Subsequently, enhanced risk-based maintenance of the controller would probably increase the useful life of elevators to 35 years.

1. Introduction

Hong Kong is widely known as the hub of Asian trade and commercial activities. With a population of around 7.4 million [1], approximately 6987 people live per square kilometre. Therefore, Hong Kong is considered among the densest modern cities [2,3]. The absence of available space has forced the city to grow upwards. Consequently, Hong Kong has many high-rise buildings, and elevators are an indispensable part of its life. On average, a person spends one day per year or two months of their life in an elevator [4].

Approximately 30% of the Hong Kong population resides in "Public Rental Housing (PRH)" buildings. PRH encompasses 179 public rental housing estates and comprises more than 760,000 flats which are overseen by the "Hong Kong Housing Authority (HA)" [5]. In these PRH estates, many elevators were installed 25 years ago [6], and the HA is currently executing an "Elevator Modernization Program" to upgrade them. According to previous research, the performance of elevators should be measured by considering the condition of equipment, level of service, and risks that may lead to failure of its service [7]. Amongst them, monitoring and control of risks were concluded as the most critical aspect affecting the performance of elevators. The five different factors signifying the risks included inadequacy of critical safety devices, deviation from statutory requirements and guidelines, equipment beyond its service life, high frequency of breakdowns, and unavailability of spare parts. Subsequently, the age of elevators is one of the critical factors affecting the performance of elevators, and those which have surpassed their useful life are much more vulnerable. The elevator modernization program also focuses mainly on the age of elevators and envisions upgrading those beyond 25 years of age [8]. It is worth noting that existing literature suggests that the useful life of elevators is between 20 and 25 years [9,10]. Subsequently, it can be inferred that the modernization program and literature are coherent in terms of their postulation regarding the useful life of elevators. However, this typically assumed benchmark, based primarily on expert opinion and past experiences, requires an empirical analysis for

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verification.

The concept of a well-known bathtub curve also uncovers the shortcomings of this assumption, according to which the life cycle of equipment is divided into three successive parts: (1) the infant mortality phase; (2) useful life; (3) the wear-out phase. Relatively higher initial breakdowns characterize the infant mortality phase; however, the failure rate decreases with time. Afterwards, the second phase begins when the breakdown rate is relatively low and remains constant for a specific period. Equipment spends most of the part of its useful life in this phase. Following the end of the second phase, the wear-out phase begins when the failure rate increases sharply [11]. It has been well-established that regular preventive maintenance (PM) can decrease the breakdown rate [12,13]. Since PM takes place monthly in PRH estates, this may be hypothesized that elevators above 25 years may have a breakdown rate similar to those below this age. Resultantly this may have increased the period of constant breakdown rate. In other words, the onset of the wear-out phase may have been delayed and increased elevators' useful life. Consequently, the assumption that the useful life of elevators is 25 years may not hold. Testing the authenticity of this hypothesis would result in an empirical determination of the useful life of elevators. Although elevators' performance mainly depends on the five factors mentioned above, our research primarily focused on two of them, i.e., breakdown rate and elevators age. This is primarily because analysis of these variables results in the determination of useful life.

Furthermore, modernization aims to improve elevators' reliability and safety [14]. Subsequently, the Electrical and Mechanical Services Department (EMSD) in Hong Kong has proposed a seven-point partial modernization guideline to support this cause. However, this guideline mainly focuses on improving the safety performance and recommends installing devices like ascending car over speed protection, unintended car motion protection, CCTV and intercoms, rope obstruction switches, double brakes, door interlock and safety edges and automatic rescue devices [15]. However, guidelines to achieve the second goal of the elevator modernization program are scarce. This situation is alarming since repeated failures of an elevator can cause severe economic losses, put passengers' health and safety in danger, and significantly reduce end-user satisfaction [7,16]. Moreover, the period of 8–10 months of elevator modernization, encompassing suspension of services, would be highly uncomfortable for the tenants, especially the older people and those using wheelchairs [8].

Subsequently, the above discussion culminates in identifying two significant shortcomings: (1) the useful life of elevators has been assumed to be 25 years; however, it lacks any empirical evidence. Besides, many elevators above this age are providing satisfactory services in PRH estates of Hong Kong. Thus, an empirically determined useful life can help ascertain the realistic age for elevator modernization; (2) the elevator modernization guidelines mainly focus on enhancing safety performance. Therefore, in this research, the gaps mentioned above have been addressed. Firstly, the useful life of elevators was empirically determined by analyzing the historical breakdown data of elevators in PRH estates. Afterwards, appropriate maintenance strategies were suggested to improve further the reliability of elevators which have surpassed their useful life. This approach may, in turn, lead to a further increase in the useful life of elevators.

2. Proposed approach

As mentioned above, elevators' useful life is assumed 25 years, lacking empirical evidence. Resultantly, a perception exists that elevators above this age have entered the wear-out phase and therefore possess low reliability. Therefore, this research aimed to empirically test this assumption's authenticity by analyzing the historical breakdown data of elevators. Subsequently, the period corresponding to the constant breakdown rate, indicating the useful life, was ascertained.

Appropriate maintenance strategies must be formulated for the elevators that have surpassed the useful life as modernization is not viable in many circumstances. Since elevators constitute a complex system of numerous interrelated components, this research posits that not all of these components in the elevators beyond their useful life need to have low reliability. Instead, there may be many components with reliability similar to those elevators that have not surpassed their useful life under regular preventive maintenance. Also, many components may have been replaced and repaired over the years in elevators above 25 years of age and performing at par with the new installations. Thus, we need to look into the overall reliability of elevators based on their age and identify those troublesome components which are currently deteriorating the reliability of elevators and triggering the onset of the wear-out phase in elevators. It is interesting to note that limited literature indicates the components frequently associated with elevator breakdowns, possibly due to the lack of historical data. For example, Park and Yang [16] identified the causes of elevator breakdowns in Korea by examining the data of 10,506 breakdowns that occurred in 1174 elevators over three years. They identified faults in components such as button and position indicators, landing door, car door, controller, and car as the significant causes of elevator breakdowns. However, these causes were identified without considering elevators' age; therefore, the trigger behind the onset of the wear-out phase was not identified. Therefore, after statistically examining the historical data of elevator breakdowns, this research determined the component responsible for the onset of the wear-out phase. Once these components were identified, alternative maintenance strategies were required to deal with their low reliability.

Generally, maintenance strategies are classified into three main types: corrective, preventive, and predictive maintenance. Corrective maintenance is the least recommended strategy as it takes place only on the onset of a failure to reinstate an element into a suitable state for performing its desired function [7,17–19], making it a non-viable strategy for avoiding sudden breakdowns. On the other hand, preventive maintenance, which is currently prevalent in PRH estates, encompasses the inspection, cleaning, oiling, and adjusting of the equipment at fixed intervals. The main drawback associated with PM is the unnecessary downtime accompanying such maintenance. Moreover, only visual inspection is undertaken to determine the equipment's condition, overlooking the underlying conditions [7].

In contrast, predictive maintenance is an advanced technique that employs sophisticated methods (e.g., infrared thermography, ultra-sonic detection, and vibration analysis), machine learning, and data analytics to predict a failure's probability [17]. However, high costs involved in acquiring advanced equipment, the necessary thorough maintenance staff training, and lack of availability of historical data limits predictive maintenance's practical application [7]. As the elevators in Hong Kong are subjected to preventive maintenance [20], and transition from preventive to predictive maintenance is a cumbersome and costly endeavour, it is required that the current maintenance strategies may be modified to improve the reliability of elevators that have surpassed their useful life and delay the onset of the wear-out phase. For achieving this objective, this research utilized the concept of risk-based maintenance (RBM). RBM involves prioritization of the equipment maintenance schedules based on the level of risk, i.e., the high-risk components are maintained and inspected more frequently and thoroughly than those with a lower level of risk [21], thus improving the reliability cost-effectively [22]. Therefore, this research posits that the trigger behind the onset of the wear-out phase, which intuitively is a high-risk component, may be subjected to RBM. At the same time, the PM of the remaining components could be kept at the current intensity. Thus, with a minimum alteration in the existing maintenance strategies, elevators' reliability experiencing the wear-out phase could be improved. Subsequently, an extension of the useful life of elevators may be achieved, and their modernization could be delayed in favourable circumstances. This concept is also illustrated in Fig. 1.

3. Overall methodology

Based on the proposed approach mentioned above, the methodology of this research is comprised of two main phases. The first phase involved empirical determination of useful life. The second encompasses identifying triggers causing an onset of wear-out phase. The detailed methodology employed in these phases is explained in the following subsections.

3.1. First phase

Based on the "bathtub curve" concept, determination of useful life is comprised of a two-stage process: (1) historical breakdown data processing (2) comparison of monthly breakdown rate (See Fig. 2 for details). The maintenance data and breakdown records of around 5400 elevators in service between August 2014 and May 2017 (34 months) in the PRH estates were collected from HA. It is worth mentioning that the historical data available to our research team could be deemed adequate because it is extensive and tracks the breakdowns of a vast number of elevators for around three years. Subsequently, this renders the results statistically significant and reliable. Furthermore, it was observed that the age of elevators in the dataset was diverse, ranging from new installations and those in service for more than 35 years. Thus, the data was suitable for the said analysis as it encompassed the breakdown data of elevators within the assumed useful life of 20–25 years and beyond them. Henceforth, it serves the purpose of empirical determination of useful life.

The historical data consisted of two different databases. Database A comprised of breakdown records in PRH estates in each of the 34 months. A unique identification number of the failed elevator and the technical fault causing the failure were indicated for each breakdown. Database A indicated that 5400 elevators in PRH estates experienced 33,415 breakdowns in 34 months, of which 7867 breakdowns were attributed to vandalism. Since vandalism does not represent any technical fault in the elevators, they were eliminated from further analysis. Database B indicated the elevators in service in the PRH estates in each of the 34-months and their installation dates. Based on their installation dates, the age of elevators was determined.

For determining the useful life, the elevators were divided into eight age groups, including: (1) 1–5 years, (2) 6–10 years, (3) 11–15 years, (4) 16–20 years, (5) 21–25 years, (6) 26–30 years, (7) 31–35 years, and (8) 36–40 years. An interval of 5 years in each group was kept because this arrangement resulted in a cohort of elevators between the assumed useful life of elevators (i.e., 20–25 years of age). This provides an opportunity to compare the breakdown rates of elevators belonging to this group and the others. Subsequently, the trend of breakdowns above and below the assumed useful life could be determined. Afterwards, the elevators in different age groups and those that remained in service each month were correlated. As a result, the "number of elevators in service each month in each group" was determined.

Furthermore, the identification number of failed elevators in Database A was correlated with the different age groups specified in Database B. Data mining using "Pivot tables" of Database A and Database B revealed the "Number of monthly breakdowns for each age group" and "Number of elevators in service in each month in each group", respectively.

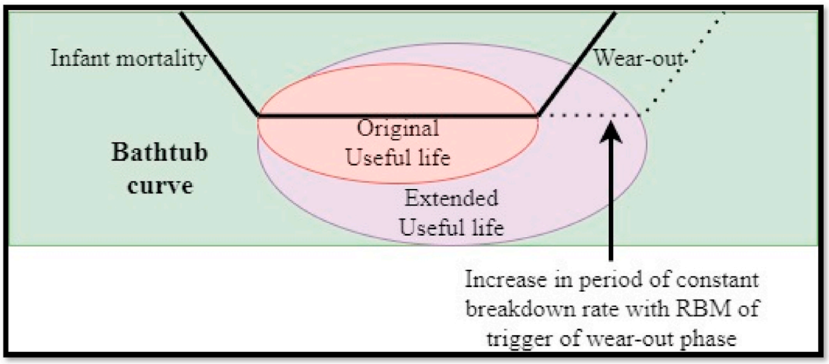

Fig. 1. Approach to improve the useful life of elevators.

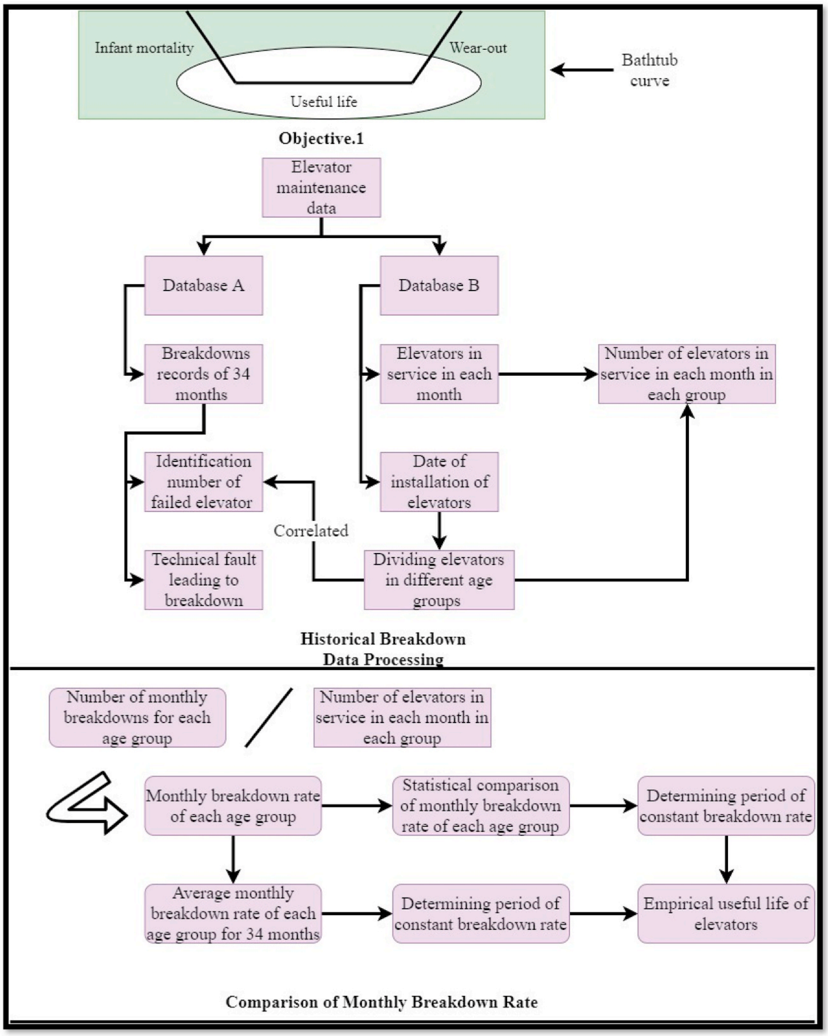

Fig. 2. Methodology to determine the useful life.

Afterwards, the monthly breakdown rate comparison was conducted using two methods: (1) simple line graph; (2) sophisticated statistical analysis. For plotting a simple line graph, the average monthly breakdown rate for each age group was calculated for the 34-months. Furthermore, sophisticated analysis was also employed to complement the results of the line graph by determining the statistical significance of the difference of breakdowns in different age groups. In this context, a set of null (H_o) and alternate (H_a) hypotheses were formulated:

Ho. There is no significant difference in the breakdown rates across different age groups.

Ha. There is a significant difference in the breakdown rate across different age groups.

The methodology for the selection of an appropriate method to test the hypothesis is shown in Fig. 3. If the data follows a normal distribution and fulfils the requirements of homogeneity of variance, one-way ANOVA may compare the different age groups [23,24]. However, if the data do not follow the normal distribution, it may be transformed using different methods available in the literature [25,26], following which the normality test may be conducted again. If the data fail to follow a normal distribution even after transformation, non-parametric tests, e.g., the Kruskal Wallis (KW) test, may be used to compare different age groups [23]. In an alternative scenario, the data may be normally distributed but have unequal variance. In this case, Welch's test may be performed [27]. Similarly, given that the data is non-normal but has the homogeneity of variance, the KW test may be employed to compare the different age groups [28]. However, if the data is non-normal and lacks homogeneity of variance simultaneously, the KW test may be used, but it may lead to inaccurate results [28]. In such a scenario, alternative methods may be required to analyze the data, which are out of the scope of this research. If the p-value is above 0.05, the null hypothesis can be accepted. This result would imply no difference in reliability between different age groups; otherwise, posthoc multiple pairwise comparisons may be examined. If the null hypothesis is rejected in one-way ANOVA, Tukey HSD results may be examined; in the case of Welch ANOVA, the Games Howell test result may be

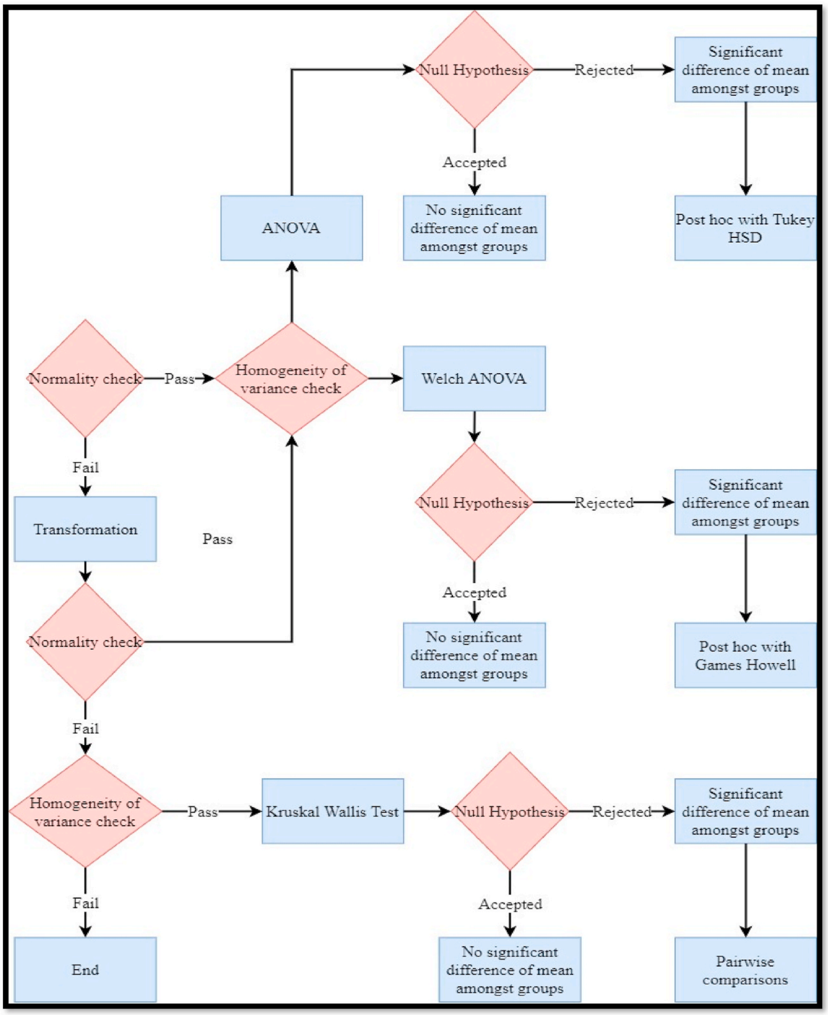

Fig. 3. Selection of statistical test.

examined [29]. For the KW test, the results of pairwise comparisons may be analyzed.

3.2. Second phase

Following the determination of useful life, the triggers resulting in the onset of the wear-out phase were identified. Subsequently, the triggers may be subjected to risk-based maintenance (RBM) to improve the elevator's reliability and thus extend its useful life. RBM necessitates prioritizing equipment maintenance according to the level of risk. Theoretically, the risk is calculated by multiplying the probability of the failure of a component and the impact of this failure [30]. Failure of some components (for example, governor) can cause safety concerns and thus have a higher impact. However, since this research primarily targets the reliability of elevators, the issue of safety is not considered. It is assumed that all types of components have the same impact if they fail: the breakdown of elevator service. Hence, the level of risk of a component is assumed to be directly proportional to its breakdown probability.

In the PRH estates, the technical faults of elevator breakdowns are assigned 18 different defect codes, each indicating a fault in a particular component that causes a breakdown. Faults in components that could result in elevator breakdown are represented with a defect code that begins with the letter E. Elevator components are classified into four areas based on their locations: machine room, car cage, elevator shaft and pit, and landing entrance. The components in the four locations, the associated elements of each component, and the defect codes of these components are given in Table 1. It is worthwhile to mention that the list of associated elements for each component is not exhaustive, and the inspector may assign a given breakdown a defect code that best defines the component causing the failure. The critical components leading to elevator breakdowns were determined by Pareto analysis. According to Pareto analysis, roughly 80% of the effects come from 20% of the many events' causes [31]. Subsequently, in the present study, the top 20% of technical faults are deemed the critical components/risks that affect the elevator's reliability. The breakdown rates of critical components within and beyond the useful life were compared using statistical methods. The critical components having a statistically different breakdown rate before and after useful life were considered triggers behind the onset of the wear-out phase.

Table 1
Defect codes.

Location	Defective equipment	Associated components	Defect code
Machine room	Controller	Direct current circuit breaker; Contacts; Relays; PLC; Overall functioning,	E01
	Hoisting Unit	Hoisting rope; Driving sheave; Traction machine; Brake.	E02
	Governor	Governor; Electrical safety. switch; Governor rope/Tension sheave.	E03
	Other Equipment in Machine Room	Landing sensor; Emergency stop button; Rope safety switch.	E04
Car Cage	Car Door Mechanism	Door motor, Controller, Gearbox, Door operator, Interlock.	E05
	Safety Edge	Safety edge.	E06
	Car Door Sill	Car door sill.	E07
	Car Door Fixtures	Car push-button panel; Position indicator.	E08
	Other Equipment in Car Cage	Roller/Guide shoe; Rope sheave; Car levelling switch; Emergency exit switch; Magnetic box; Overload weighing switch.	E09
Elevator shaft and pit	Travelling Cable	Travelling cable.	E10
	Switches inside Elevator Shaft or Pit	Buffer switch; Governor rope; Car limit switch; Oil buffer switch; Emergency stop switch; Compensation rope limit switch; Landing levelling sensor.	E11
	Other Equipment in Elevator Shaft and Pit	Governor rope/Rope sheave; Compensation Rope/Rope; sheave; Counterweight; Oil buffer; Guard rails.	E12
Landing entrances	Landing Door Mechanism	Interlock; Hanging roller; Door opening linkage mechanism.	E13
	Landing Door Sill	Landing door sill.	E14
	Landing Door Fixtures	Landing push button; Position indicator.	E15
	Other Equipment at Landing Entrances	Landing door; Architrave; Door shoes.	E16
	Power failure	Main supply.	P01

Unknown Reason U17.

4. Results

4.1. Empirical determination of useful life

The line graph of average breakdown rates indicated an increase from 0.118 to 0.190, as the corresponding age group number progressed from 1 to 8 (see Fig. 4), indicating that breakdown rates of the newest and the oldest elevators are not significantly different. This validates the premise of our research that under regular preventive maintenance, the breakdown rates are reduced even for elevators beyond 25 years of age and hence the useful life is much longer than assumed.

An analysis of Fig. 4 from the perspective of the bathtub curve revealed that the elevators did not experience the infant mortality phase; however, this is not uncommon and occurs for many other types of equipment. It is worth noting that apart from the absent infant mortality phase, the rest of the curve representing the average monthly breakdown rate of elevators resembles the second and third phases of the bathtub curve. Besides, it was observed that the average monthly breakdown rate of elevators remained nearly constant as the age of the elevator increased from 6 to 30 years. Under the bathtub curve, this constant breakdown rate period could be considered the useful life of elevators. Therefore, this analysis concluded that although the difference in the average breakdown rates

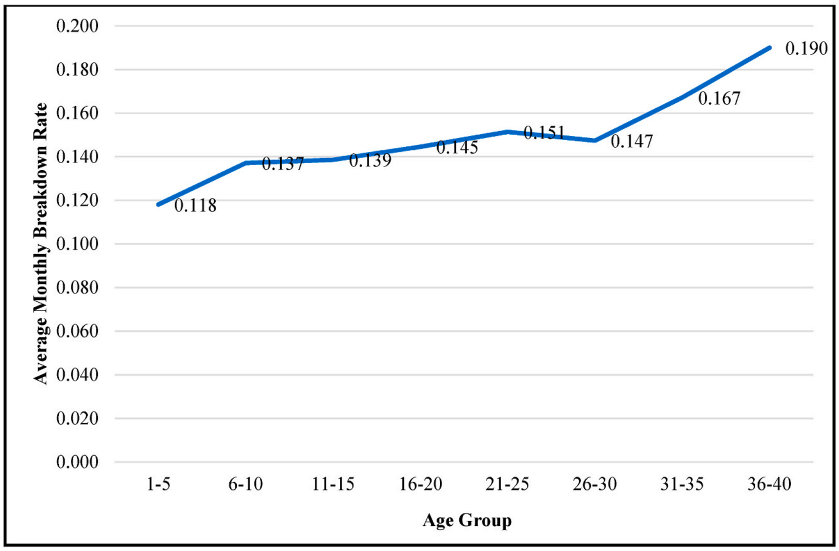

Fig. 4. Line graph of average elevator breakdown rate.

of elevators belonging to different age groups is minimal, from the perspective of the bathtub curve, useful life under current PM strategies is 30 years.

Afterwards, statistical tests were conducted using “Statistical Package for Social Sciences (SPSS)” to determine whether there is a statistically significant difference in the breakdown rate across different age groups. Before carrying out the analysis, the breakdown data associated with the elevators in the 8th age group were eliminated because of their much smaller sample size than other age groups. In line with the methodology of Fig. 3 the monthly breakdown data of the remaining seven age groups was first subjected to the Shapiro Wilk (SW), and normality of residuals were determined. Here, the null hypothesis is “the sample came from a normally distributed population”. The SW test indicated that the p-value was less than 0.05, meaning that the monthly breakdown rate of elevators does not follow a normal distribution. Hence, they were transformed using the two-step approach proposed by Templeton [26], and the normality test was conducted again. The p-value in SW test was then above 0.05 (i.e., 0.078). Next, the homogeneity of variance was analyzed by Levene’s test, a robust and popular tool to determine the equality of variance [32]. Here, the null hypothesis is “the variance is the same across all groups”. The p-value of Levene’s test was 0.688, confirming that the data satisfies the condition of homogeneity of variance. As the data satisfies the assumptions, the ANOVA test was consequently conducted. The ANOVA results in Table 2 indicate that the breakdown rate is statistically different across the seven age groups. Thus, the results indicate that although the breakdown rates of elevators appear to be similar across different age groups, they are statistically different.

Further, multiple comparisons were evaluated. Since the homogeneity of variance is satisfied, but the null hypothesis is rejected in one-way ANOVA, post hoc Tukey HSD analysis was conducted. The results (see Table 3 for details) revealed that the reliability of the first group (1–5 years) was similar to the second group (6–10 years) only. It is worth noting that the reliability of elevators belonging to the second (6–10 years), third (11–15 years), fourth (16–20 years), fifth (21–25 years) and sixth group (26–30 years) is similar. This may be construed as the period of constant breakdown rate. In other words, the monthly breakdown rate remains constant for elevators of 6–30 years of age and represents the second phase of the bathtub curve. Hence, the line graph analysis from the perspective of the bathtub curve and statistical analysis revealed similar results. Therefore, as the average breakdown rates of elevators belonging to different age groups have a minimal difference, and the statistical analysis also revealed a constant breakdown rate between 6 and 30 years of age, it may be reasonably concluded that the useful life of elevators is at least 30 years, following which the wear-out phase may begin. Therefore, the current practice of treating the useful life of elevators as 25 years is not valid. Subsequently, the benchmark set by the HA for elevator modernization may be increased from 25 to 30 years, provided the safety devices mentioned in the seven-point partial modernization guidelines are installed in these elevators and that these elevators are subjected to current maintenance practice.

4.2. Critical components causing breakdowns

According to the 80/20 Pareto rule, since there are 18 causes of elevator failures in our dataset, roughly the top four causes should be responsible for 80% of the breakdowns. These four causes included faults in the controller, car door mechanism, landing door mechanism, and other equipment in the car cage (see Fig. 5 for details). However, the cumulative percentage of breakdowns due to the faults in these four components was 70.64%. This is not surprising, and other combinations such as 70/20 (i.e., 70% of the faults originate from 20% of the components) and 90/10 may also be observed. The philosophy behind the Pareto rule is that distribution is generally unequal for most things, e.g., 90% of work in a company may be done by 10% of the employees, as everybody does not contribute in the exact similar way [31]. In addition, each of the remaining two components behind the 80% benchmark line in the Pareto Chart only causes around 3.5% of the breakdowns. Thus, only the top four components (corresponding to 20% of the causes) were considered critical components that lead to frequent elevator breakdowns. Overall, assigning a higher priority to these four components during maintenance would drastically improve elevator reliability.

4.3. Identification of the trigger

It was observed that these four components mentioned above caused most of the breakdowns of elevators irrespective of their age. It has been established above that elevators beyond 30 years of age enter the wear-out phase under the bathtub curve. Thus, there is a need to identify the trigger, which causes a minimal but statistically different increased breakdown rate in elevators above 31 years of age, leading them to the wear-out phase. Subsequently, enhanced trigger maintenance will further reduce the breakdown rate and increase the useful life. In this regard, the monthly breakdown rates of the four components were determined for each age group, and that of the 31–35 year group were compared to the remaining six groups. The component of which the monthly breakdown rate in the 31–35 year group (the group that is considered as beyond the useful life) is different from that of other age groups would be considered as the trigger behind the onset of the wear-out phase.

Understandably, faults in the controller cause the most frequent elevator breakdowns because the controller is the elevator’s brain that regulates all activities. The controller was comprised of a relay logic control system until the mid-1980s. Most elevators nowadays use the programmable logic controller (PLC). To test that whether a significant difference in the reliability of controllers exists between

Table 2
ANOVA results.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.045	6	0.008	10.557	0.000
Within Groups	0.166	231	0.001		
Total	0.211	237			

Table 3
Multiple comparisons for breakdown rate.

Category		Sig.
1	2	0.05
	3	0.02
	4	0.00
	5	0.00
	6	0.00
	7	0.00
2	1	0.05
	3	1.00
	4	0.95
	5	0.41
	6	0.71
	7	0.00

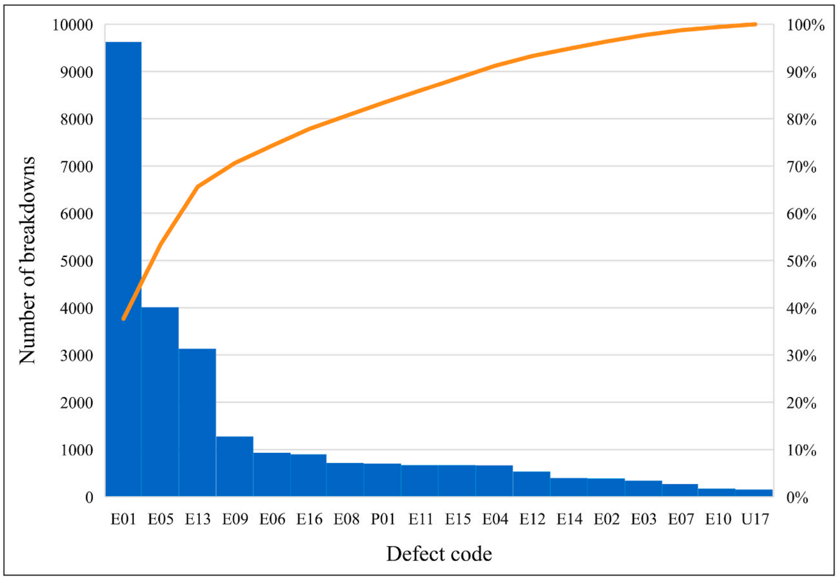

Fig. 5. Pareto analysis.

different age groups, the following set of null and alternate hypotheses was formulated:

Ho. The monthly breakdown rate of the controller is the same across all age groups;

Ha. The monthly breakdown rate of the controller varies with the age group.

The residuals of the monthly breakdown rate of the controller were analyzed to test the assumption of normality. First, it was observed that the data followed a non-normal distribution since the p-value in the SW test was less than 0.05. The data was then transformed using the two-step approach [26], following which it began to follow a normal distribution, and the p-value was 0.289 in the SW test. Further, Levene's test revealed that the data fulfils the requirement of homogeneity of variance (the p-value was 0.535). After that, ANOVA was conducted, revealing that the breakdown rate varies with the age group since the p-value was less than 0.05. Next, a post hoc Tukey HSD test was conducted, confirming that the controller's breakdown rate is statistically different between the 31–35 year group and all other age groups (see Table 4 for details).

Table 4
Post hoc results for the controller.

Category		Sig.
7	1	0.00
	2	0.00
	3	0.00
	4	0.01
	5	0.00
	6	0.00

According to the Pareto analysis, the second critical component was the car door mechanism, which consists of elements primarily associated with the opening and closing of the door. The same hypothesis and test process as employed for the controller was taken to the car door mechanism to analyze whether the monthly breakdown rate of the car door mechanism varies with age. Initially, the p-value of less than 0.05 in the SW test indicated a non-normal distribution of the breakdown data. Consequently, the data was processed using the two-step approach proposed by Templeton [26]. After this transformation, the p-value of the SW test was observed to be greater than 0.05, indicating the normality of the transformed data, and the p-value of 0.075 of Levene's test confirmed the homogeneity of variance of the transformed data. Finally, the transformed data were subjected to ANOVA and post hoc Tukey HSD. The ANOVA p-value of less than 0.05 revealed that the monthly breakdown rate of the car door mechanism varies with age. The results of Tukey HSD revealed that the monthly breakdown rate of the car door mechanism corresponding to the 31–35 year group is statistically similar to the 1–5, 6–10, 16–20, 21–25, and 26–30 year group (see Table 5 for details). Therefore, it can be concluded that the reliability of the car door mechanism is not a trigger of the wear-out phase.

The third critical component is the landing door mechanism, which consists of elements associated primarily with the opening and closing of the landing door. Similar to the case of the car door mechanism, the monthly breakdown rate of the landing door mechanism does not follow a normal distribution. Next, the "two-step approach" was taken, after which the breakdown rate follows a normal distribution. It also followed the assumption of homogeneity of variance. Subsequently, the ANOVA test was taken, and the corresponding p-value was calculated as 0.021. An inspection of the post hoc test revealed that the monthly breakdown rate of the landing door mechanism corresponding to the 31–35 year group is similar to the remaining groups (See Table 6 for details). Therefore, it can be concluded that the breakdowns due to the landing door mechanism do not lead to the initiation of the wear-out phase.

Regarding "other elements in the car cage", the monthly breakdown data does not follow a normal distribution. So then, the "two-step approach" was taken to transform the data, after which the data follows a normal distribution. Next, the Welch ANOVA test was taken as the data does not show homogeneity of variance. The p-value of the Welch ANOVA is 0.167 (See Table 7 for details), which indicates that the monthly breakdown rate due to the faults of other elements in the car cage is the same irrespective of age groups.

The analytical results discussed above indicate that the reliability of controllers in the 31–35 year group is different from all other age groups. In contrast, the other three critical components (i.e., car door mechanism, landing door mechanism, and other elements in the car cage) do not show statistical differences across different age groups. Therefore, the controller may be considered a trigger that causes the onset of the wear-out phase of the elevators reaching 31 years of age. The enhanced maintenance of the controller, based on the principle of RBM, would significantly improve the elevator's reliability, which may extend the elevator' useful life.

It is worth mentioning that this research is based on the premise that effective maintenance can increase the useful life of elevators. There is a limitation that the age of individual components has not been considered due to the unavailability of data. Some parts of some old elevators may have been repaired and replaced over the years. Our main focus was to identify those troublesome components which are currently increasing the breakdown rate of elevators and initiating the wear-out phase. Subsequently, the suggestion has been made to conduct RBM of controllers, which may involve more frequent inspections and replacement of defective parts. For example, Park and Yang [16] formulated guidelines for the maintenance of elevators and suggested that for controllers, relays should be visually inspected for wearing and trembling of the contactor.

Similarly, the main and brake contactor should be checked for wearing, melting, and capacity shortage and the safety circuit should also be visually inspected. The counter-strategy to eradicate these defects includes replacing and complementing the circuit. For circuit safety, it is suggested an inspection cycle of 12 months be followed. In general, maintenance activities should be performed more frequently as part of RBM for elevators beyond their useful life. Future research may focus on identifying the detailed maintenance tasks in this domain and developing a maintenance schedule for elevators beyond their useful life.

5. Conclusions

Typically building owners consider the useful life of elevators as 20–25 years. This empirical study analyzed the breakdown data of the 5400 elevators in the PRH buildings of Hong Kong, intending to provide some insights on useful life. The Pareto analysis revealed that faults in the controller, car door mechanism, landing door mechanism, and other elements in the car cage are the critical causes that affect the reliability of elevators.

Statistical analysis showed that (1) there is no statistical difference in the breakdown rate of elevators between 6 and 30 years of age; (2) when elevators reach 30 years of age, the breakdown rate begins to increase, concluding the useful life and initiating the wear-out phase; (3) the breakdown rate of elevators of 31–35 years of age due to the non-performance of the controller is statistically different from that of elevators under 31 years of age; and (4) there is no significant difference in the breakdown rate of elevators of 31–35 years of age due to other three critical causes.

These results indicated that the controller is the trigger that ends the elevator's useful life. In other words, the onset of the wear-out phase is attributed to the faults in the controller. Therefore, it is recommended that for the elevators having 30 years of age, or even in the years immediately before this age, enhanced risk-based maintenance actions should be taken to increase the controller's reliability, thus increasing the useful life of the elevator. As a result, the enhanced maintenance of the controller would likely extend the useful life of the elevator to 35 years.

CRediT authorship contribution statement

Xueqing Zhang: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Muhammad Umer Zubair:** Data curation, Writing – original draft.

Table 5
Post hoc results for the car door mechanism.

Category		Sig.
7	1	0.77
	2	0.45
	3	0.01
	4	0.06
	5	0.85
	6	1.00

Table 6
Post hoc results for the landing door mechanism.

Category		Sig.
7	1	1.00
	2	0.23
	3	0.86
	4	1.00
	5	0.99
	6	0.30

Table 7
Welch ANOVA results for the breakdown rate of other equipment in car cage.

	Statistic	df1	df2	Sig.
Welch	1.558	6	102.359	0.167

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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