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Maintenance performance: An examination of the computer-aided maintenance data of a large commercial building

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Introduction

Accommodating a variety of business activities such as office work, entertainment, shopping and dining, commercial buildings, which are ubiquitous in metropolises, are equipped with a wide range of facilities, including builder's work (e.g. grounds, wall finishes, false ceilings) and building services installations (e.g. air-conditioning, electrical and plumbing installations). The complexity and constructed quality of these facilities have continued to rise, and the end users' expectation on their reliability and operational performance is increasingly demanding, which could not be met without effective maintenance works.

Maintenance service level, to a certain extent, is correlated with occupant satisfaction level (Kwon et al. 2011). To enhance the effectiveness of maintenance operations, the need of computerizing maintenance management work has long been recognized, for example, in the manufacturing industry (Gilbert and Finch 1985) as well as in the building industry (Jones and Collis 1996). Since reliability of facilities is a critical concern in the heavy industries such as mining and aerospace, computerized maintenance management systems (CMMS) have been widely used to automate the recording of the status of operation and maintenance activities for their facilities (Duffuaa et al. 1999; Levitt 2007). Comparatively, builder's work and building services installations in commercial buildings are less critical. For some essential facilities, e.g. transformers for electricity supply, their desired reliability level is typically attained by provision of standby equipment (CIBSE 2008), e.g. emergency power generators. Therefore, it is often hard to justify the adoption of CMMS in commercial buildings solely on reliability grounds.

Nevertheless, an earlier study (Lai 2010) revealed that the substantial manpower cost for maintaining commercial buildings necessitates proper monitoring and evaluation of the associated human resources. Concurring with this finding, Elazouni and Shaikh (2008) developed a simulation model to determine the optimal number of crews for maintaining a large higher education facility. Besides, automated data collections have been developed for monitoring construction works (Navon and Goldschmidt 2002). Researchers such as Kwak et al. (2004), by examining air-conditioning system failure data of office buildings and processing computer simulations, developed some preventive maintenance models. Some others advocated using robotic systems for building maintenance (So and Chan 2002).

But the uncommon adoption of CMMS for maintaining commercial buildings (Lai et al. 2004) and the concerns of disclosing sensitive information such as maintenance cost, equipment failure rate, etc. (Lai et al. 2008) have seriously constrained the development of empirical research on building maintenance. While it is necessary to have more empirical research in the operations management context (Flynn et al. 1990), maintenance data continue to be underutilized (Lee and Akin 2009) and it has been rare to make empirical findings available for informing improvements, both on performance of facilities and on their cost-effectiveness. It is encouraging that Pati et al. (2010) had attempted to illustrate how the two types of key performance indicators – hard and soft – can be used to assess facility maintenance performance. To date, detailed examination of the maintenance performance of facilities in large commercial complexes remains limited.

Hong Kong, a metropolis with a limited land area of 1,104 km^2, is an international financial centre densely built with commercial buildings. According to the government's statistics (RVD 2011), the building stock of private office was 10,689,000m^2 and that of private commercial premises was 10,744,200m^2. The monthly average rental values of Grade-A office and retail premises, as high as \$796/m^2 and \$1,308/m^2 respectively, were in the top tier of the world.

Attempted to appraise the maintenance performance of facilities in commercial buildings, a pilot study was carried out to probe into the CMMS data of a hotel (Lai and Yik 2012). In order to analyze further the maintenance data of other types of commercial premises, an exploratory study was conducted on a large commercial building. Instead of a fully automatic CMMS, a computer-aided maintenance system (CAMS) was used in the commercial building to keep track of its maintenance works in a semi-automatic manner. The data retrieved from the CAMS were analyzed and the preliminary findings were presented earlier (Lai and Yik 2011a). Further work, as reported in the following, was carried out to examine the CAMS in more detail.

In the next section, the data collection procedure, the types of data collected including characteristics of the commercial building and its maintenance works, and the measures used for sorting out quality data for analysis are reported. After describing the data analysis process, the study results are discussed, which include: maintenance demand; response time, repair time and downtime of the maintenance works; and influence of maintenance demand and manpower input on the performance of the works. The conclusions drawn from the study and the further research work needed are given in the final section.

Material and Method

Data collection

With the support of the Chief Technical Manager of the building, a meeting was held with his maintenance team, during which the study team explained the purpose and methodology of the study and the kinds of data needed. Meanwhile, the maintenance team introduced their operations, including how their maintenance works were organized, how the work orders were issued and executed, and how the status of the orders were reported and recorded. Then the study team walked through the main areas of the building to obtain an overview of its characteristics.

After the walk-through visit, the study team made a series of communications with the maintenance staff to collect the required data records, including: electronic files stored in the CAMS recording the information of every work order for a period of 12 months; monthly schedules showing the duty periods of each maintenance worker; organization chart of the maintenance team; floor plans of the building; and factsheets showing the operation periods of different areas of the building.

The building and its maintenance set-up

Located at the city center, the building, consisting of a 60-storey high office tower (71,535 m^2) coupled with a shopping mall of 15 floors (55,742 m^2), has been in use for four years at the time of the study. The office premises have been fully occupied and the mall has been kept busy by tourists and shoppers. In the communal areas such as lobbies, corridors, staircases, and toilets (i.e. landlord areas), the builder's work and various trades of building services installations were provided and maintained by the landlord. As for the two main trades of building services (i.e. electrical and air-conditioning) in the tenant areas, luminaires with fluorescent tubes and variable air volume (VAV) boxes in the office areas were provided, with the former maintained by the tenants while the landlord was responsible for maintaining the latter. Within the retail shops, the lighting was provided and maintained by individual shop tenants. Instead of VAV boxes, fan coil units (FCUs) were installed by the landlord for providing air-conditioning to the shops. Such FCUs were maintained by the tenants of the corresponding shops; the landlord provided the maintenance for the FCUs serving the arcades outside the shop areas.

The maintenance team, with an establishment of 24 technicians, looked after all the corrective and preventive maintenance works for the building, except that the statutory maintenance works (e.g. regular lift inspections), which must be performed by registered contractors (Lai et al. 2011), were outsourced. The technicians were grouped based on their main trade of skill and worked in three shifts a day: 08:00 – 17:00; 14:45 – 23:45; and 23:30 – 08:30. Normally they were on duty for six days a week and the rest day for each technician was arranged in a way to make the on-duty manpower for each trade as even as possible.

Involving the use of an electronic database, a CAMS was utilized to semi-automatically record the maintenance work orders of the building. Typically, a request for maintenance work commenced from a call to the maintenance hotline, which was manned by an operator. After acknowledging the request, the operator issued a work order to the most available technician of the relevant trade. Meanwhile, the operator recorded into the database the issue time of the order and the description of the maintenance work. Then the assigned technician went to the scene and, upon his arrival there, called back to the operator, who in turn recorded the arrival time. If the problem was ordinary, the technician fixed it right away within the first visit and reported to the operator when the work was completed, i.e. Case A in Fig. 1.

Otherwise, the technician informed the operator the time he left the scene and allowed the problem to be fixed in a second visit (i.e. Case B).

Data quality check

Before analyzing the collected data in full swing, checking was made to ensure their validity and reliability. The queries found from the checking, in general, were readily resolved upon seeking clarifications from the maintenance team. Afterward, every entry in the work order records was inspected to identify if there were any invalid or missing data, similar to what had been experienced before in analyzing the maintenance data of a hotel (Lai and Yik 2011b). Such a detailed inspection was done by scrutinizing the time when an order was issued, the time when the assigned technician arrived at the scene, the time when he left the scene while the order was yet to be completed, and the time when the order was finally completed. Although this process was time-consuming, it enabled detection of the entries whose recorded times did not conform to the normal timeline of work orders (see Fig. 1).

Of the 17,364 orders issued, 632 were recorded with a false time sequence, e.g. the issue time (t_i) was after the arrival time (t_a), the latter was after the leave time (t_l), and so on. Another group of orders (388) were recorded without arrival date, leave date, complete time (t_c), etc. (Table 1). With these defective data sets discarded, 16,344 orders were included in the subsequent analysis. At the end of the data analysis process, a meeting was held with the maintenance team to discuss on the analyzed findings in order to find out the reasons for or the factors leading to the observations.

Results and Discussion

Volumes and types of maintenance demand

The analyzable work orders were grouped according to where the works were done and the trades and natures of works involved. Referring to the number of orders, the majority were issued for the retail area (58.0%) and the office tower (41.7%). The remaining negligible amounts of orders were for some ad-hoc works demanded by the adjacent hotel. Linked with the building via a footbridge, this hotel belonged to the same owner of the building but its maintenance works were basically handled by a team independent from that covered in the present study.

Grouping the orders by their work nature revealed that the vast majority of the orders were for corrective maintenance, including 88.1% of a general nature (e.g. replacement for a burnt lamp), 1.8% emergency works (e.g. repair work for a burst pipe), and 0.5% of a special nature (e.g. works that need to be outsourced). 9.6% of the orders were for preventive maintenance works (e.g. cleaning of air filters) performed on a scheduled basis. Fig. 2 shows the monthly variations in the proportion of various natures of work orders.

When categorized by work trade, the proportion of fire services (FS) orders carried out by the technicians was small (2.2%), given that all statutory FS maintenance works could only be performed by registered FS contractors. As the building management system (BMS) was maintained by a specialist contractor, the amount of orders issued for this kind of maintenance work and the associated extra low-voltage (ELV) work was even less (0.4%). The dominant group of orders was electrical (EE; 33.0%), followed by air-conditioning (AC; 26.6%), builder’s work (BW; 21.7%), and plumbing & drainage (PD; 16.1%).

The volumes of the four main trades of works were further classified by the places where they were carried out. As shown in Table 2, the demands for EE, BW and PD maintenance works in the retail area were all greater than those of the same trades in the office area. Because the areas of the office and retail portions were different and in order to make fair comparisons between the maintenance demands of these two areas, the numbers of work orders were normalized with respect to the areas for which they were issued (in No./10^3 m^2). Comparisons on this basis resulted in the same observation – the maintenance demands of the three trades of works in the retail area were higher. For the air-conditioning work, on the other hand, the number of orders issued for the office area exceeded those for the retail area. This was attributed to the fact that the landlord was responsible for maintaining the VAV boxes in the office premises but not the FCUs in the retail shops.

The annual profiles of the four main trades of work orders, as charted in Fig. 3, show that in common a low maintenance demand was found with February, during which the occupancy as well as the usage of facilities in the Chinese Lunar New Year holidays were low. While there was no other apparent observation from the undulating profile of electrical work, the maintenance demands of the other three trades, i.e. BW, AC and PD, exhibited a gentle growth trend over time.

The shopping mall operated between 11:00 and 23:00 and the normal business hours of the office premises were from 09:00 to 17:30. The hourly profiles of the total number of orders pertaining to the retail portion and the office tower, as depicted in Fig. 4, exhibited similar variations but their peaks and troughs did not appear to tie in with the normal operation hours of the offices and shops. Obviously, both the amounts of “office” and “retail” orders started to rise from 07:00 at which some logistic and support operations (e.g. goods delivery, food preparation in restaurants) began to take place. The volumes of orders dropped significantly at 13:00 (i.e. lunch time). Then the orders increased until the late afternoon (around 17:00) after which most office workers were off duty. The orders issued for the retail portion, in particular, recorded a maximum at midnight because the period thereafter allowed maintenance works to be carried out without affecting the normal businesses of the retail premises.

Response time, repair time and downtime

The performance of maintenance works can be reflected by the downtime (T_d) of facilities or, in more detail, by the response time (T_{rs}) and repair time (T_{rp}) of the works (BSRIA 1998). Such time components of each work order were computed using Eq. (1), (2) and (3) respectively, and their means and standard deviations (*S.D.*) as well as those pertaining to the orders issued for the retail and office areas were determined.

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

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

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

The calculated mean values of response time, ranging between 3.4 hours and 4.0 hours, were longer than expected. The counterparts of repair time and downtime, which lied between 26.2 hours and 74.2 hours, were even longer. According to the maintenance team, this was because for some orders, the technicians responded within the day on which the orders were issued but the needed repair work could not be finished in their first visit to the scene. The causes for this included: i) the materials or tools required for accomplishing the work were not readily available at the time of the first visit; ii) the technician found himself incapable of doing the work required; iii) the technician considered the work non-critical while he concurrently had another more critical problem to fix; iv) the work was beyond his scope of duties, e.g. a work that should be borne by the tenant instead of the landlord; v) the existing situation did not allow the work to be carried out upon the technician's arrival; and vi) the technician could only finish part of the required work because the time of the first visit was close to the end of his duty period on the same day.

The majority (10,944 nos., 67.0%) of the work orders were completed in the first visit. Based on the downtimes of this group of orders, a summary of statistics was prepared (Table 3), showing the fractions and values of mean, standard deviation (*S.D.*) and coefficient of variation (C_v). Disregarding 23 orders (0.2%) which were issued for the other areas, the numbers of orders for the shops (5,603) and offices (5,318) were comparable. The fraction of the aggregate downtime of the office area exceeded that of the shop area by 9.6%. The large *S.D.* and C_v values of the office area indicate that the downtimes of its work orders were widely spread and highly variable. Overall, the mean downtime associated with a work order was over 5 hours and that pertaining to the office area was close to 6 hours. A detailed scrutiny on the natures of the work orders found that such long downtimes were due to the long periods spent on the preventive maintenance works, which accounted for 9.6% of the number of all orders.

A scatter plot of the response time against the repair time of the corrective maintenance work orders enables a visual identification of their relationship. Two such plots, as displayed in Fig.

5, show that the range of response time of the work orders for the retail area was wider than that of the office area. The same observation was noted for the range of repair time. For both the office and retail areas, the majority of the work orders were responded and repaired in a short period.

For those work orders with long response time, their repair works were completed in a prompt manner. A major reason for this was that when the maintenance request could only be attended a long time after it was raised, the relevant end user, more often than not, would have lodged a complaint for the long response time. The technician, upon arrival at the scene, was usually under pressure to perform the repair work quickly. On the other side, some orders were given quick response but their repair times were comparatively long. This happened in cases where a technician received a new order while he had already another order in hand. When dealing with multiple work orders, the technician would respond to the new order but choose to tackle the most critical one.

To determine if there were differences in the performance between the maintenance works provided for the office and retail areas, the differences between the response time, repair time and downtime of the two areas were assessed, of which the population means were defined as:

μ_1 = the mean response time (or repair time, downtime) for all orders issued for the office area

μ_2 = the mean response time (or repair time, downtime) for all orders issued for the retail area

Suppose no difference exists in the performance of maintenance works for the two areas, the null hypothesis (H_0) and alternative hypothesis (H_a) can be written as:

$$H_0 : \mu_1 - \mu_2 = 0$$

$$H_a : \mu_1 - \mu_2 \neq 0$$

The z-test can be used to compare sample or population means for the purpose of determining if there exists a significant difference. Using a 2-tailed *z*-test to test the above hypotheses and for a 95% confidence interval estimate of the difference between two population means (i.e. α = 0.05), the critical value ($z_{\alpha/2}$) is 1.96. Analyzing all the orders collectively for the two areas found that the overall sample means and variances of response time, repair time and downtime of the office area were all smaller than the values of the retail area (Table 4). The *p*-values, representing the probabilities of obtaining test statistics at least as extreme as the observed ones, were all zero ($< \alpha$) and thus H_0 is rejected. Therefore, it can be concluded that μ_1 and μ_2 are not equal and so the maintenance works provided for the office and retail estates were different in performance.

Closer examinations were made by performing the *z*-test on each trade of maintenance works. As can be seen from the test results, the *p*-values of the parameters pertaining to the AC maintenance work were all smaller than the level of significance, indicating that the null hypothesis should be rejected. Thus, it can be concluded that the population means were equal and that the performances of AC maintenance work provided for the office and retail areas were different. In contrast, the *p*-values of the parameters of the EE trade, ranging between 0.2354 and 0.7768, indicate that the null hypothesis could not be rejected. This means that the performance of electrical maintenance work provided for the office area was not different from that of the retail area.

As long as the downtime of the BW maintenance work is concerned, the small p-value implies a rejection for the null hypothesis. In other words, the performances of such work provided for the office and retail areas, when evaluated in terms of downtime, were different. But when examined with respect to response time and repair time separately (*p*-value = 0.0943; 0.0546), their performances for the two areas were not different.

Similarly, the negligible *p*-values found with the response time and repair time of PD maintenance work indicate that the respective null hypotheses should be rejected. The null hypothesis, however, could not be rejected when judging based on the downtime's *p*-value, which was larger than α = 0.05. These results show that the performances of PD maintenance work provided for the office area and the retail area were different in terms of the durations for response and repair, but were not different if considering only the aggregate duration (i.e. downtime).

The foregoing analysis, which showed whether the performances of the maintenance works for the office and retail areas were different, was not able to reveal the extent by which they differed. To examine more clearly the levels of performance of the maintenance works, two cumulative downtime distribution curves, one for the orders issued for the office area and the other for the retail area, were constructed (Fig. 6). Based on a *Pareto* analysis, 80% of the “office” orders were completed in 220 minutes. But for the retail area, the same proportion of orders required 110 minutes more to complete. From this perspective, the maintenance works for the office area outperformed those for the retail area.

As the downtime of a facility comprises the response time and repair time for the corresponding maintenance work, the cumulative proportion curves of these two time components were prepared in a bid to identify their contributions to the difference in downtimes between the “office” and “shop” orders. As shown in Fig. 7, over half of the orders were responded promptly in less than 20 minutes. 80% of the repair works were completed within 35 minutes. Intriguingly, around 42% of the orders had a repair time shorter than their response time.

Likewise, the distributions of response time and repair time of the orders issued for the retail area were analyzed by referring to the distribution curves. Half of the orders were responded within 40 minutes, which doubled the counterpart of the office area. As compared with the finding of the office area, a longer period, i.e. 50 minutes, was needed for completing 80% of the repair works. A higher proportion (about 52%) of the orders for the retail area had a repair time shorter than their response time.

The monthly response time, repair time and downtime of the maintenance works, categorized by their work trades and the areas for which they were issued, were computed. Using Eq. (4) to (7), these time components were further normalized by the areas of the relevant places to serve as benchmarks (in minutes per 10^3 m^2), which can be used for comparing the performance of the same kinds of works in future as well as those in similar buildings (Table 5).

$$A_A = A_R + A_O \tag{4}$$

$$\tilde{T}_{d(X,Y)} = \tilde{T}_{rs(X,Y)} + \tilde{T}_{rp(X,Y)} \tag{5}$$

$$\tilde{T}_{rp(X,Y)} = \frac{\frac{1}{12}\sum_{n=1}^{N_{X,Y}}(t_{c,n} - t_{a,n})}{A_Y} \tag{6}$$

$$\tilde{T}_{rs(X,Y)} = \frac{\frac{1}{12}\sum_{n=1}^{N_{X,Y}}(t_{a,n} - t_{i,n})}{A_Y} \tag{7}$$

Where

A_Y is area (m^2) of the relevant place Y (A: all; R: retail; O: office)

$N_{X,Y}$ is number of orders of work trade X (EE; AC; BW; PD) executed for place Y

$\widetilde{T}_{rs(X,Y)}$ is normalized monthly response time (min/m^2) for work trade X and place Y

$\widetilde{T}_{rp(X,Y)}$ is normalized monthly repair time (min/m^2) for work trade X and place Y

$\widetilde{T}_{d(X,Y)}$ is normalized monthly downtime (min/m^2) for work trade X and place Y

Comparing the benchmarks between the office area and the retail area found that across the board, the response time, repair time and downtime of the builder's, electrical, and plumbing & drainage works for the retail area were longer. Air-conditioning work was the only exception where longer response time, repair time and downtime were needed for the office area. The major factors which gave rise to these observations included: i) the air-conditioning installations (i.e. FCUs) in the retail shops were maintained by the tenants while the landlord was responsible for maintaining those in the shopping arcade; and ii) maintenance works for the retail areas were allowed to be executed if they did not interrupt the operation of the shops, otherwise they were deferred to take place after normal business hours.

Influence of maintenance demand and manpower input

The performance of the maintenance works, which can be reflected by the time components that have been analyzed above, may depend on various factors. Besides maintenance demand, such factors may include the input resources for producing the maintenance works (Lai and Yik 2012). In particular, it is logical to expect that when more manpower is deployed for the maintenance works, the works can be responded earlier, repaired in a shorter period, and thus with their downtimes reduced; and vice versa.

To identify the monthly levels of manpower input, the amount of man-hours of each trade of work was calculated. This was done by counting the number of on-duty hours of every technician on each day as recorded in their monthly duty schedules. The results, as graphed in Fig. 8, show that the trade with the lowest yet the steadiest manpower level was PD. The manpower levels of EE and AC were highly variable, and the peak of the former was as high as 1,119.5 hours. A major reason for such variations, as revealed by an inspection on the duty schedules, was that the turnover rates of the EE and AC technicians were rather significant.

To determine whether the performance of the maintenance works was correlated with the maintenance demand and input manpower, a series of correlation analyses was carried out for the two groups of work orders – office and retail. The Pearson product moment correlation coefficients (*r*), calculated based on the monthly amounts of work orders, man-hours and downtimes of each of the four main trades, are summarized in Table 6.

Across the four trades of works for the office area, large *r* values (ranging from 0.834 to 0.923) were found with the correlations between number of orders and downtime, indicating the existence of strongly positive correlations (significant at the 0.01 level). This also implies that a larger amount of maintenance demand would lead to a longer downtime, or a lower maintenance performance. But the correlations between man-hours and downtime, with their *r* values lying between 0.057 and 0.497, were relatively low. This indicates that the variation in manpower input did not impose a strong influence on the maintenance performance.

While this may be due to ineffective manpower deployment, the limited range of manpower levels studied may also be a factor contributing to this observation.

As for the maintenance works for the retail area, significant correlation at the 0.05 level was only found to exist between number of orders and downtime of the AC work (r = 0.694) and between man-hours and downtime of the EE work (r = 0.694). These correlation levels, when compared with the counterparts of the office area, were weaker. Furthermore, there were no significant correlations between the parameters of the remaining trades of works.

In view of the above findings, a more focused analysis was made to examine the relationship between maintenance demand and maintenance performance. Firstly, linear regression plots between their representative parameters, namely number of orders and downtime, were constructed. As shown in Fig. 9, a small coefficient of determination (R^2 = 0.3230) was associated with the regression line for the retail area and that for the whole building was only moderate. A much higher coefficient (R^2 = 0.6976), i.e. a better goodness of fit, was found with the case of the work orders issued for the office area.

The preceding analysis has shown that the maintenance downtime of the facilities in the office area was largely dependent on the volume of maintenance demand. In order to examine more clearly if such a relationship existed for individual trades of maintenance works executed for the office area, further regression analyses were conducted. Plotting the monthly amounts of downtime against the monthly quantities of orders for each work trade, as shown in Fig. 10, revealed that strongly positive correlations existed, with the highest pertaining to the EE trade (R^2 =0.8433), followed by PD, AC and then BW (R^2 = 0.6755). Additionally, it was noted that the AC trade was distinct from the other trades in that there were much less variations in its downtime (2.29 - 5.77) while the range of its quantity of orders was much wider (2.97 - 7.67).

Conclusions

Although the use of CMMS to fully automate maintenance works for commercial buildings has not been common, the above study has demonstrated how to retrieve the maintenance data recorded in the CAMS of a large commercial building for evaluation of its maintenance performance. Owing to the manual data entry, some (5.9%) of the maintenance work orders were recorded with irregularities. The detection measures taken in the study, which proved useful for checking the data quality, can be used to ensure the reliability of data collected for this kind of studies in future.

For the building studied, the office area accounted for a bigger share but the proportion of the maintenance demand for the retail area was higher. In terms of volume of work orders, the most demanding trade was electrical, followed by air-conditioning, builder's work, and then plumbing and drainage. Most of the maintenance works were of a general corrective nature and the existing occupancy and business operation of the commercial premises were two major factors that affect the issue time of such work orders.

The majority of the maintenance works were completed by the technicians in their first visit and, through the on-site visit and the discussions with the maintenance team, the causes for those which required a second visit were identified. While these are important findings that can inform the room for improving the maintenance works, resolve and effort are needed to properly record the time components of the latter group of visits in order to enable analysis of their maintenance performance.

For both the office and retail areas, most of the maintenance works were responded and repaired in a short period. Given the constrained manpower resources, the works with long response time tended to be repaired speedily while those that were given quick responses, if found to be non-critical, were repaired less promptly. In addition, benchmarks of response time, repair time and downtime were established, which not only unveiled the differences in the performance of maintenance works between the office and retail areas, but also serve as references for future performance evaluation or benchmarking with the maintenance works of peer buildings.

The downtimes of the building's facilities, especially those in the office area, were significantly correlated with the maintenance demands - the larger the demand, the longer the downtime. A higher level of manpower input, in theory, should be able to cater for a larger maintenance demand, but there were no strong correlations between the input manpower and the downtime. Further works are needed to investigate in more detail the sensitivity of maintenance downtime and the effectiveness of manpower deployment.

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Fig 1

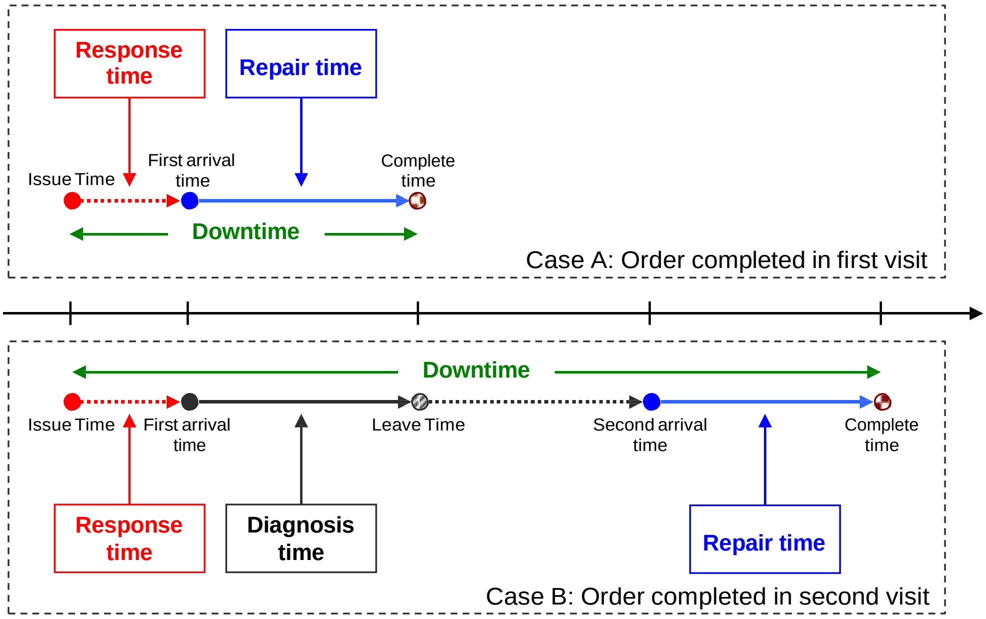
Response time
Repair time
Issue Time
First arrival time
Complete time
Downtime
Case A: Order completed in first visit
Downtime
Issue Time
First arrival time
Leave Time
Second arrival time
Complete time
Response time
Diagnosis time
Repair time
Case B: Order completed in second visit

Fig 2

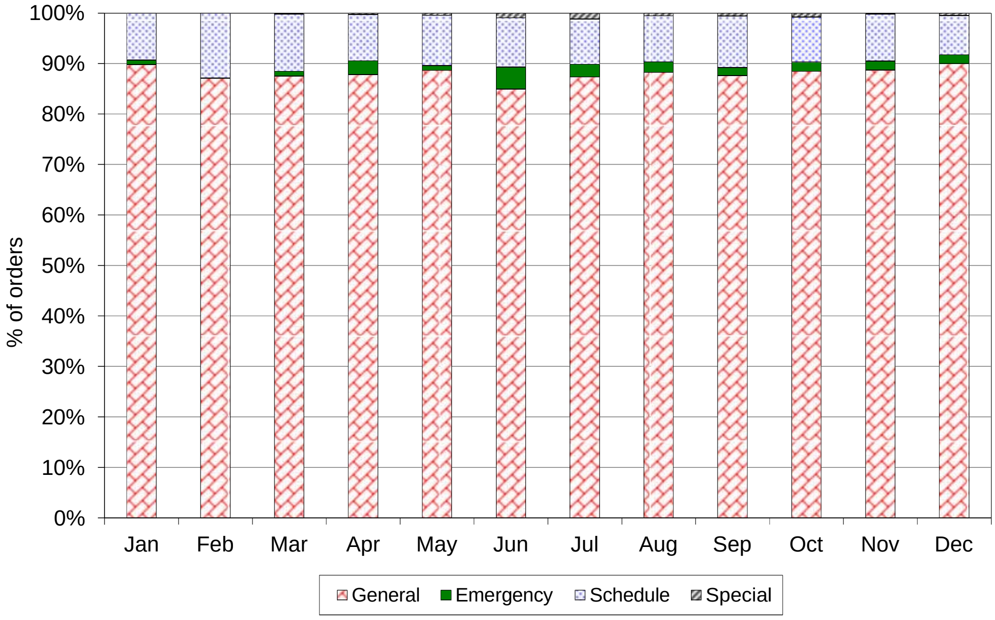
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of orders
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
General
Emergency
Schedule
Special

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Fig 3

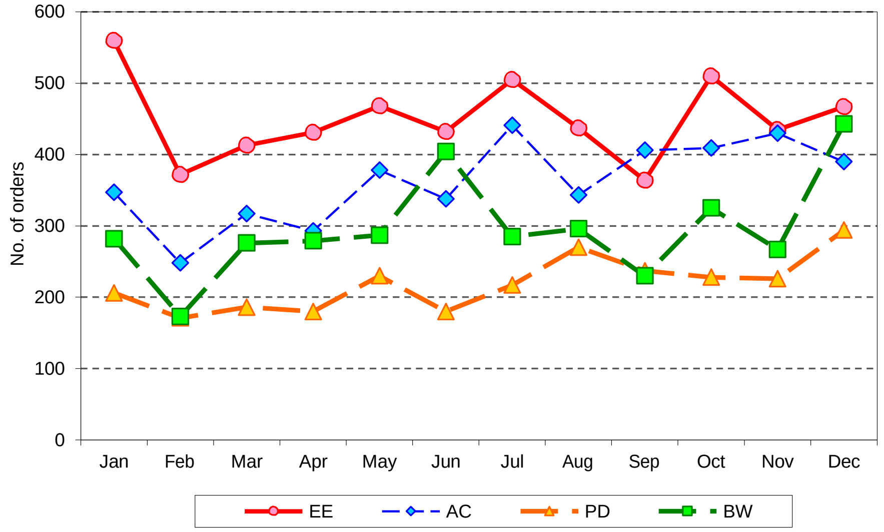
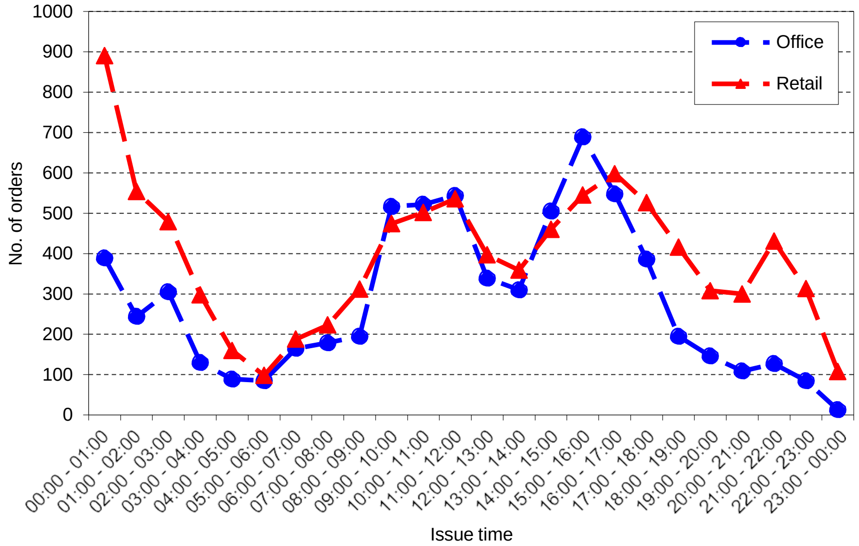
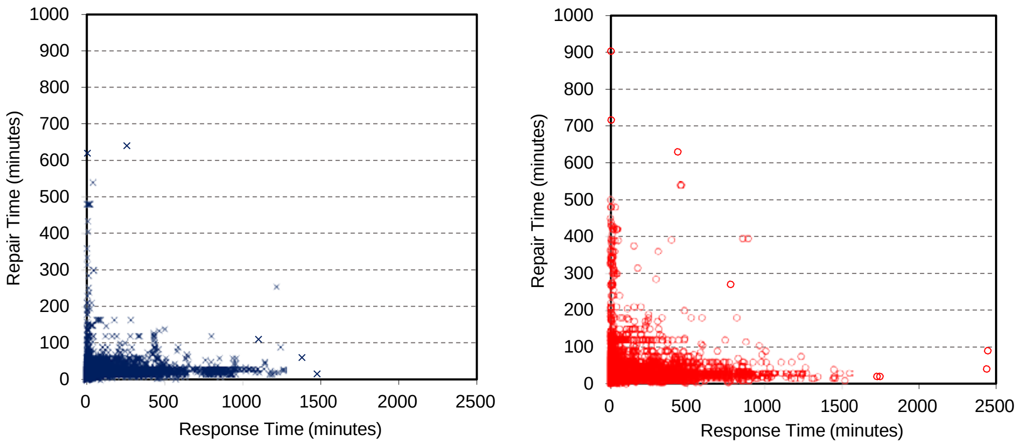


Fig 4



Office
Retail
No. of orders
0
100
200
300
400
500
600
700
800
900
1000
00:00 - 01:00
01:00 - 02:00
02:00 - 03:00
03:00 - 04:00
04:00 - 05:00
05:00 - 06:00
06:00 - 07:00
07:00 - 08:00
08:00 - 09:00
09:00 - 10:00
10:00 - 11:00
11:00 - 12:00
12:00 - 13:00
13:00 - 14:00
14:00 - 15:00
15:00 - 16:00
16:00 - 17:00
17:00 - 18:00
18:00 - 19:00
19:00 - 20:00
20:00 - 21:00
21:00 - 22:00
22:00 - 23:00
23:00 - 00:00
Issue time

Fig 5



(a) Office

(b) Retail

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Fig 6

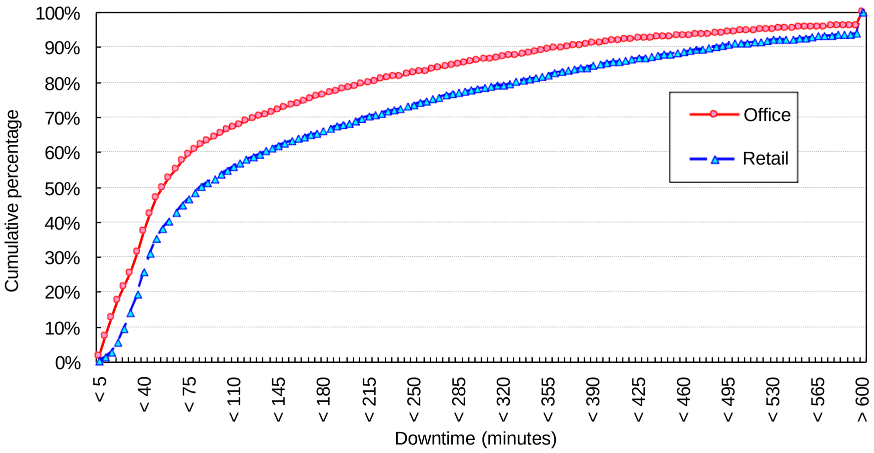
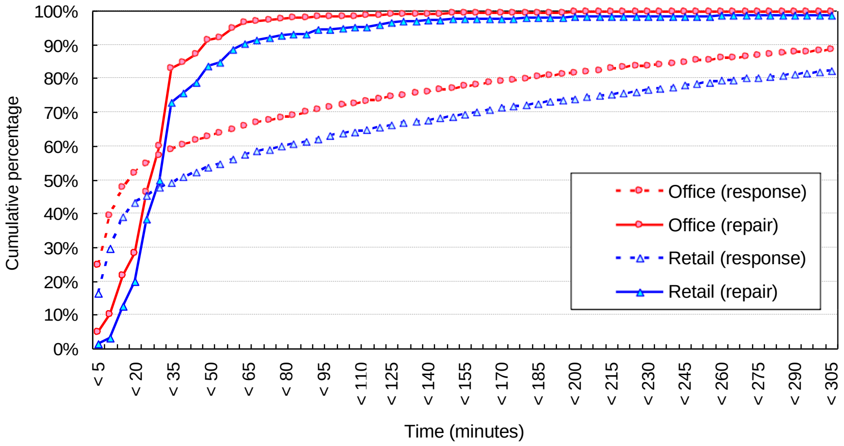
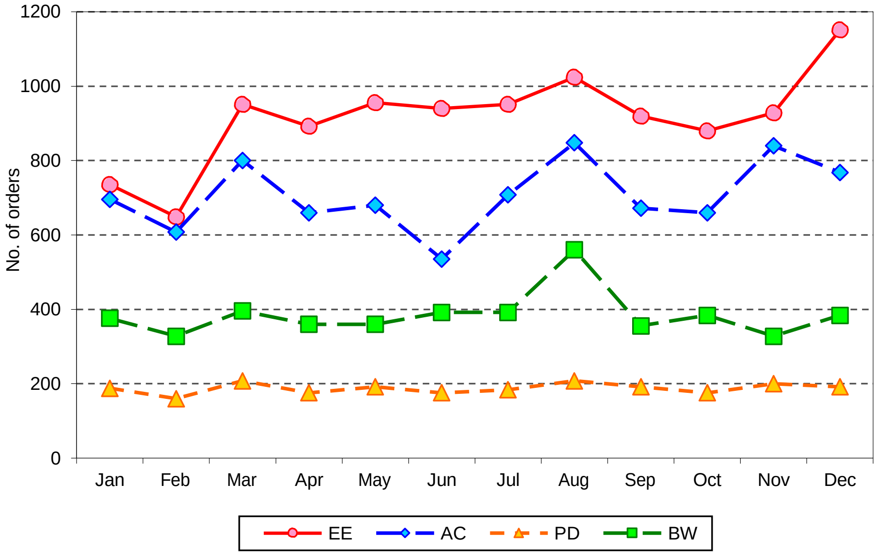


Fig 7


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulative percentage
Office (response)
Office (repair)
Retail (response)
Retail (repair)
< 5
< 20
< 35
< 50
< 65
< 80
< 95
< 110
< 125
< 140
< 155
< 170
< 185
< 200
< 215
< 230
< 245
< 260
< 275
< 290
< 305
Time (minutes)

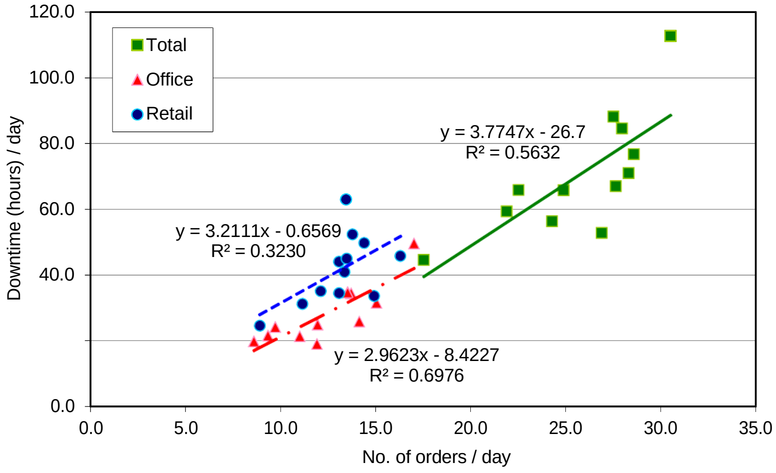
581 Fig 8



582

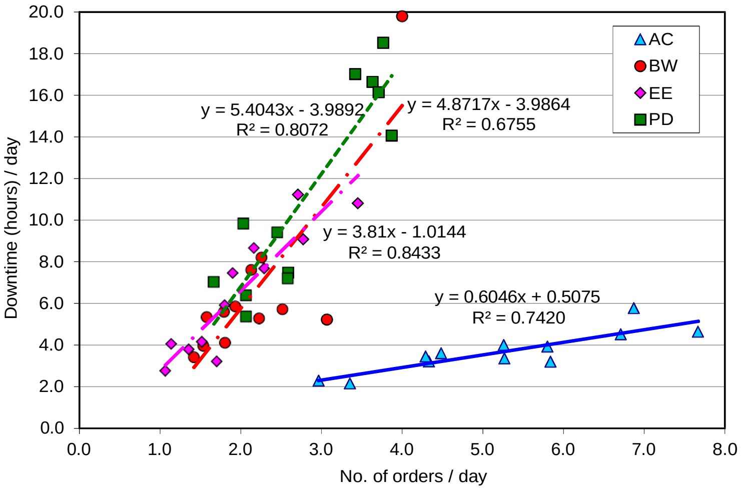
583

Fig 9



Total
Office
Retail
y = 3.7747x - 26.7
R² = 0.5632
y = 3.2111x - 0.6569
R² = 0.3230
y = 2.9623x - 8.4227
R² = 0.6976
Downtime (hours) / day
No. of orders / day
120.0
100.0
80.0
60.0
40.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0

Fig 10


Downtime (hours) / day
No. of orders / day
AC
BW
EE
PD
y = 5.4043x - 3.9892
R² = 0.8072
y = 4.8717x - 3.9864
R² = 0.6755
y = 3.81x - 1.0144
R² = 0.8433
y = 0.6046x + 0.5075
R² = 0.7420
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

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List of Tables

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Table 1. Orders recorded with irregularities

Orders with invalid times	No.	Orders with missing information	No.
$t_a > t_l$	67	No arrive & leave dates	340
$t_a > t_c$	180	No arrive, leave & complete dates	21
$t_a > t_l$ & $t_a > t_c$	65	No complete time	26
$t_i > t_a$	316	No complete time & $t_i > t_a$	1
$t_i > t_a$ & $t_a > t_l$	2		
$t_i > t_a$ & $t_a > t_c$	1		
$t_i > t_a$ & $t_a > t_l$ & $t_a > t_c$	1		
Sub-total	632	Sub-total	388

Table 2. Monthly average amounts of the four main trades of work orders

Trade	Area	No.	No./10^3 m^2
Electrical (EE)	Total	447.3	3.51
	Office	144.8	2.02
	Retail	302.4	5.43
Air-conditioning (AC)	Total	360.9	2.84
	Office	235.9	3.30
	Retail	125.0	2.24
Builder's work (BW)	Total	294.3	2.31
	Office	86.3	1.21
	Retail	208.0	3.73
Plumbing & drainage (PD)	Total	218.8	1.72
	Office	92.3	1.29
	Retail	126.4	2.27

Table 3. Downtime (minutes) of orders completed in the first visit

Area	Fraction	Mean	*S.D.*	C_v
All	100%	312.5	1649.7	5.3
Shop	45.1%	275.5	311.0	1.1
Office	54.7%	351.8	2344.4	6.7

Table 4. Results of *z*-test for the work orders in the office and retail areas

Trade	Response time		Repair time		Downtime	
	Office	Retail	Office	Retail	Office	Retail
Overall						
Mean	107.6	149.6	29.7	40.6	137.3	190.1
Variance	35836.8	53546.6	1003.4	2821.3	37356.5	55457.1
Test statistic (*z*)	-9.6384		-12.1081		-11.9073	
p-value	0.0000*		0.0000*		0.0000*	
EE						
Mean	168.0	173.1	30.1	28.2	198.1	201.4
Variance	51338.5	68794.3	1102.1	1185.9	52402.3	71885.9
Test statistic (*z*)	-0.4539		1.1866		-0.2835	
p-value	0.6499		0.2354		0.7768	
AC						
Mean	18.5	39.5	23.6	48.9	42.1	88.3
Variance	1901.4	10527.9	804.0	5768.7	3023.7	16824.1
Test statistic (*z*)	-4.8297		-7.9457		-8.4461	
p-value	1.4E-06*		2.0E-15*		0.0000*	
BW						
Mean	144.7	159.8	38.7	42.1	183.4	201.9
Variance	40321.4	51963.4	1197.7	2823.3	40506.7	53341.7
Test statistic (*z*)	-1.6730		-1.9223		-2.0399	
p-value	0.0943		0.0546		0.0414*	
PD						
Mean	205.1	173.8	34.2	49.3	239.3	223.1
Variance	58266.2	53277.8	1074.7	2892.1	58313.8	53352.0
Test statistic (*z*)	3.0481		-7.8746		1.5729	
p-value	0.0023*		3.3E-15*		0.1157	

Note: *p*-value = P(Z<=z) two-tail; *< α = 0.05

Table 5. Benchmarks of monthly response time, repair time and downtime

Trade	Area	Response time	Repair time	Downtime
EE	Total	218.3	36.9	255.3
	Office	143.1	25.6	168.7
	Retail	315.0^	51.4^	366.3^
AC	Total	38.6	48.6	87.2
	Office	41.5^	52.7^	94.1^
	Retail	35.0	43.3	78.3
BW	Total	251.4	66.5	317.9
	Office	135.2	36.2	171.4
	Retail	400.4^	105.6^	506.0^
PD	Total	263.2	58.5	321.7
	Office	246.8	41.2	287.9
	Retail	284.3^	80.7^	365.0^

^ Longer time when compared between the retail area and the office area.

Table 6. Summary of Pearson product moment correlation coefficients

Trade	Monthly	Office			Retail		
		Man-hour	Order no.	Downtime	Man-hour	Order no.	Downtime
EE	Man-hour	1	0.565 (0.055)	0.497 (0.100)	1	0.353 (0.261)	0.698* (0.012)
	Order no.	-	1	0.923** (0.000)	-	1	0.548 (0.065)
	Downtime	-	-	1	-	-	1
AC	Man-hour	1	0.281 (0.377)	0.342 (0.276)	1	0.218 (0.497)	0.320 (0.310)
	Order no.	-	1	0 .865** (0.000)	-	1	0.694* (0.012)
	Downtime	-	-	1	-	-	1
BW	Man-hour	1	0.254 (0.426)	0.057 (0.859)	1	0.184 (0.567)	0.231 (0.469)
	Order no.	-	1	0.834** (0.001)	-	1	0.548 (0.065)
	Downtime	-	-	1	-	-	1
PD	Man-hour	1	0.474 (0.119)	0.335 (0.287)	1	0.356 (0.256)	0.339 (0.280)
	Order no.	-	1	0.898** (0.000)	-	1	0.500 (0.098)
	Downtime	-	-	1	-	-	1

*Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level; 2-tailed significance values are in the parentheses.