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Maintenance cost of chiller plants in Hong Kong

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Abstract

Research findings about maintenance costs of chiller plant - a ubiquitous installation in large buildings, are rare. The study reported in this paper was conducted through inspection of 40 maintenance contracts, their associated monthly service reports and payment records; and interviews with the contract administrators. Routine maintenance cost was found to dominate among the maintenance resources. Repair maintenance work accounts for a less, but significant portion. The cost incurred for emergency maintenance work is minimal and condition analysis is seldom applied. Large chiller plants, by virtue of their scale, can economise on their maintenance cost. Total maintenance cost varies with plant age following a 'bell-shape' pattern, with relatively less expenditure for new and old plants whereas that incurred for middle-aged plants spreads over a wide range. Factors which potentially affect the cost relation between preventive maintenance and corrective maintenance have been identified. Apart from investigating clearer their effects, future work is needed to explore how to improve the practice of recording plant faults, which are crucial performance data to reflect whether the costs spent on maintenance are value-for-money.

Practical application

The study has revealed the significance of various maintenance cost elements and the empirical cost relation between preventive maintenance and corrective maintenance. The effects of plant capacity, age of plant, operation period, and heat rejection method on maintenance cost have also been analysed. Understanding the influence of these factors can help practitioners prepare maintenance budgets and perform benchmarking exercises. Besides, the lack of proper record of plant faults, as identified, is a barrier which needs to be overcome before evaluating the value of maintenance service.

Keywords: Chiller; Maintenance cost, Plant fault; Preventive; Corrective; Building

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Introduction

Air-conditioning has been an indispensable provision for buildings in cities with a hot and humid subtropical climate. Whereas distributed systems using unitary air-conditioning units to serve small buildings or buildings with subdivisions of small premises are common, package chillers have been widely used in large buildings to refrigerate chilled water for circulation in centralised systems. Large commercial and institutional buildings aside, the increasing development of serviced residential high-rises has added on to the popular installation of chiller plants.

The performance of chillers rests not only on their proper operation, but also on maintenance work which comprises a wide range of tasks. Examples include inspection of their physical conditions; oiling of moving parts; cleaning of deposits; charging of replenishments (e.g. refrigerant); testing of critical components; calibration of measuring devices; repair of damaged parts; replacement of defective components; and collection of field samples (e.g. lubrication oil) and their analysis in laboratory. Even building management systems have been commonly used to automatically monitor and control chiller plants, their coverage is typically confined to some critical sensors and devices. Manpower, anyway, is needed to take care of routine operations such as switching on and off of circuits, recording of physical defects (e.g. damaged condenser fan blade), manual logging of operating parameters, attendance of alarms and emergency calls, etc. Because undertaking these works necessitates specialist knowledge and skills to deal with proprietary parts which are available only from the original manufacturer, chiller maintenance service has long been a monopoly. With little competition, there is no incentive for the maintenance service providers to disclose their contract price for comparisons. As for building owners, given the common barriers to benchmarking operation and maintenance service,[1] it is unknown whether the service they obtained is value-for-money.

Because of high energy cost of air-conditioning systems where chillers are the major user, a considerable volume of studies has been devoted to study their energy performance (e.g. Yik *et al.*,[2] Yu & Chan[3]). While the costs for maintaining chiller plants are also significant and their effectiveness would impinge on the plant performance, their investigations were seldom successful owing to difficulties such as:[4-6] no proper tracking of maintenance expenditure by the organisations; no clear delineation of different maintenance cost categories (e.g. in-house and outsourced resources, labour and material costs, etc.); and no cost breakdowns for different types of air-conditioning equipment.

Rather than some cost data of chiller plants, Smith[7] surveyed on the maintenance costs for buildings. CIBSE[8] lays down some guidelines for collecting maintenance cost data but the costs for maintaining chiller plants are not given. IFMA[9] provides some survey statistics about facility maintenance cost and proportions between preventive maintenance and repair maintenance, yet they are ballpark data in terms of cost per unit rentable area of building. Similarly, ASHRAE[10] lists out some ballpark maintenance cost data which are associated with air-conditioning system as a whole instead of chiller plant in particular. It also suggests that among others, factors such as quantity and type, run time, complexity and age of equipment would affect maintenance costs. But their significance of influence is yet to be known.

So far research findings about chiller plant maintenance costs remain unavailable. Without understanding what factors and how they would influence the costs needed to maintain chiller plants, one would be unable to prepare proper maintenance budgets, not to mention benchmarking maintenance costs. In view of this niche area of knowledge, a study was undertaken to investigate the significance of various maintenance cost elements of chiller plant and how they are affected by factors including plant capacity, age of plant, operation period and heat rejection method.

Method and Data

Maintenance cost data are sensitive and thus hard to obtain. Their collection by postal survey is common but the reliability of data collected is often uncertain. To ensure the quality and accuracy of data, the current study inspected the maintenance contracts, their monthly service reports and payment records provided by a leading chiller maintenance contractor in Hong Kong. The contract administrators were also interviewed to: obtain information including building type and age of chiller plant which were not indicated in the documents; clarify any queries found from the documents and; solicit their experience about the factors which determine the significance of various maintenance cost elements.

The typical contract period is 1 year but the contract commencement dates vary among the buildings. To minimise the effect of inflation/deflation on contract price, contracts commenced in the same year (i.e. 2005) were collected. The information retrieved from the maintenance contracts cover quantity, type, capacity, operation period and heat rejection method of chillers; scope of work; and contract sum together with its breakdowns. Corresponding to each maintenance contract, there were 12 monthly service reports and payment records. Data recorded in the service reports include: faults occurred and their rectification works, incidents of emergency call and, duration and number of workers who attended the calls. The payment records show the amount of monthly payments for different types of maintenance works (as will be elaborated later).

Initially information pertaining to 86 buildings was collected, but 46 of them were discarded because:

1. Owners with distinct maintenance policies of maintaining their chillers have greatly different requirements on the contract scope. Only the majority group of contracts with similar scopes was taken for study.

2. In some contracts, the maintenance cost for chillers is lumped together with that for other air-conditioning equipment. Without relevant cost breakdowns, the former could not be singled out. This kind of contracts, therefore, was eliminated.

3. Service reports which contain incomplete or unclear record of information, for instance, a temperature sensor failure was recorded without mentioning which part of the chiller it belongs to, were discarded.

Data of the remaining 40 buildings, which involve 40 maintenance contracts, 480 monthly service reports and payment records, were analysed. Of these contracts, 10 embrace maintenance for air-side equipment (e.g. air handling units, fan coil units, etc.) in their scope of work and the other 12 further cover annual fire damper inspection, which is a statutory requirement for ventilating systems.[11] Cost breakdowns for these items, which are additional to the chiller plant maintenance work, were calved out from the analysis. Common to all these contracts, maintenance of chilled water pumps is part of the scope but there was no breakdown for its cost. Detailed examination of the contract documents found that it mainly requires visual check and recording of the pump condition. Greasing of bearings, as and when required, is the only item involving materials. According to the interviewees, the manpower and material costs for these works are negligible when compared to those incurred for maintaining the chillers.

Table 1 summarises the key information of the samples, which consist of 25 commercial buildings, 7 residential buildings, 4 hotels, 2 schools, 1 hospital and 1 church. The aggregate plant capacity of these buildings is 46,736 tons of refrigeration (TR; 1 TR = 3.517 kW) and the aggregate maintenance cost is HK$5.4 millions, which embraces the costs for preventive maintenance (i.e. routine maintenance and condition analysis), corrective maintenance (i.e. repair maintenance and emergency maintenance) and those for hiring operators from the service contractor to station on-site.

Routine maintenance work was carried out on a lump sum and fixed price basis (see Lai *et al.*[11]). Schedule of rates was not incorporated in the contracts; repair work was executed by way of quotations subject to negotiation and agreement between the owner and the contractor. Attendance of emergency calls within normal business hours was covered by the contracts, whereas condition analysis and resident operator service were optional. The ambits of these maintenance categories are highlighted in Table 2.

All the samples required routine maintenance service on a monthly basis. Condition analysis, if applied, was only once a year. It was done in 6 of the samples, among which 4 used both oil analysis and vibration analysis to detect the extent of wear and tear of compressors' moving parts as well as to examine the vibration level of compressors; the remaining 2 used only one these two techniques. Their uncommon application, according to the interviewees, was mainly because: (i) the charge for these services is rather high, especially to those clients who had limited maintenance budget; (ii) the deliverable of these analyses, in the form of a report indicating the condition of the monitored components, was sometimes regarded by clients as a service on paper or even untrustworthy; (iii) clients often prefer to spend money on tangible maintenance work which is readily measurable and; (iv) clients typically would save the cost of condition analysis for use in future repair or replacement work.

Twelve samples did not require any repair maintenance work during the sampling year and a greater amount (15 of them) had not called for any emergency maintenance work. The reasons for these observations include: (i) some minor defects were rectified during routine preventive check; (ii) some non-critical defects were grouped to form small projects covered by separate contracts; (iii) some of the plants were not required to operate after normal business hours and; (iv) two of the plants were provided with resident operators who can promptly tackle minor problems on-site without calling for emergency service from the maintenance contractor.

Analysis and discussion

Plant faults and emergency calls

The monthly service reports were to record the faults of the chiller plants, but they appear to be mainly a document for fulfilling the contract requirement - a prerequisite to receiving monthly contract payments, rather than a report that identifies clearly different types of faults and their frequency of occurrence. The descriptions used to record the faults were not standardized, with some even using jargons.

Attempts were made to figure out the statistics of faults by retrieving records in the on-site log books. They were in vain because, unlike in some countries where proper keeping of log books have become mandatory,[13] the on-site records were found to be even more loose and incomplete than the service reports. Further effort was made to look at records generated by the building management systems. But because only those critical parameters are monitored (e.g. temperature, pressure), the information so obtained is partial. As a result, the faults recorded in the service reports were categorised manually by referring to the chiller maintenance manuals. Queries found during this process were clarified through interviews with the contract administrators.

It was found that compressor of chillers, which contains moving parts to pressurize refrigerant, is a troublesome component exhibiting a number of fault categories. Leakage of refrigerant was the most common fault among the samples (Figure 1). Other types of faults which commonly occurred in over 10% of the samples include failure of oil temperature sensor, high-cut switch, motor, and suction pressure transducer of compressor. Note should be taken that these statistics do not represent the frequency of fault occurrence. For instance, an incident of refrigerant leakage happened in a plant last month and a similar fault recurred in the next month. This plant was counted as a sample encountering the fault irrespective of its frequency of occurrence.

Other moving parts, namely condenser fan and its motor, are also components where faults commonly occurred (Figure 2). The latter was found in over one-fourth of the samples, and two other faults which are rather common to condenser are coil leakage and failure of water flow switch. Although the number of fault categories associated with control panel, evaporator and expansion valve appears to be less, they were identified in not less than 20% of the samples.

Emergency call attendance service during normal business hours is included in the maintenance contracts. Unless the calls whose rectification works were beyond the contract scope, no additional costs were charged. Figure 3 displays the frequency and duration of emergency maintenance service, which are not substantial for the reasons as explained earlier. The total number of emergency calls correlates perfectly with the total amount of man-hours demanded for their attendance and the maximum amount of man-hours per call. The most frequent emergency calls were with the control panels and compressors. Rectifying the faults with the former was more onerous because:

1. Typically each chiller is equipped with one control panel. Failure of the control panel often leads to stoppage of the corresponding chiller. But for chillers with multiple compressor circuits in each unit, frequently the faulty circuit would be isolated for troubleshooting without affecting the operation of the other healthy circuits. Provided the load demand is not at its peak level, the isolated part would be repaired or replaced later, with the involved man-hours counted out from emergency call attendance.

2. It is more difficult to rectify faults with control panels than those on compressors, as defective electronic parts of the former is often undetectable by visual inspection whereas mechanical defects of the latter is often visible.

3. Electronic spare parts of control panels are costly and delicate, thus are typically stored in the contractor's inventory centre. It takes time for returning to the centre to collect the parts before replacing the faulty components.

Instead of some explicit formulas, contract clauses were used to describe how emergency maintenance service fees would be charged. While the contracts follow more of the same format designed by the service provider, the charging of emergency maintenance cost (C_{EM}) varies among the chiller plants. It can be generalised by the cost model in Equation (1), where i (= 1, 2 or 3) corresponds to different categories of contract (Table 3), k_i is minimum charge for emergency call attendance, t is duration of call attendance, and m_i is a multiplier applicable for call attendance exceeding 2 hours.

$$C_{EM,i} = \begin{cases} k_i & \text{, where } t \leq 2 \\ k_i + m_i(t-2) & \text{, where } t > 2 \end{cases} \quad (1)$$

The title of the various contract categories was not indicated in the contracts. But from the interviews, a 'standard' contract is one for chiller plant not operating round-the-clock, without particularly adverse maintenance history. Plants which require non-stop operation were classified in the '24-hour' category, where cost is charged at a higher minimum fee for the first 2 hours of call attendance and also a higher rate thereafter. Regardless of their operation period, emergency maintenance service for plants whose past failures were frequent and troublesome were all charged according to the scale of 'high-risk' contract. Nevertheless, the interviewees pointed out that the demarcation between different categories of contract, which often varies with the working relation with the client, is not crystal clear. Escalating the charge from a lower scale to a higher one on grounds of longer operation period or deteriorating plant conditions is often uneasy, while requests from clients for charge reduction in parallel with declining economy are common.

Total maintenance cost and its elements

Faults identified during routine maintenance service, condition analysis or emergency call attendance, whose rectification are not urgent, would fall into the category of repair maintenance. The cost incurred for such work would be charged in addition to the basic monthly payment for the routine maintenance work, and any charge for emergency maintenance or condition analysis. The sum of these cost elements is the total maintenance cost, which is shown in monthly payment records of the contracts.

Summing up the 12 monthly payments of each contract gives the annual total maintenance cost, which increases with chiller plant capacity (Figure 4). The two outliers, corresponding to the two largest chiller plants, required the provision of resident operators by the service contractor. Since cost breakdowns for hiring these operators were unavailable for elimination, these two samples were discarded in the ensuing analyses to ensure the costs are compared on an equal basis. And the maintenance cost elements are all annual costs normalised by their plant capacity (i.e. in HK$/TR) to facilitate cross comparisons among the samples.

In Figure 5, total maintenance cost generally decreases with plant capacity, upholding the principle of economies of scale. The costs for the majority group – commercial buildings vary largely between HK$29/TR and HK$282/TR. Their mean value, HK$129/TR, is negligibly different from that (HK$130/TR) of the second majority group – residential buildings. The costs for the remaining groups lie within the range of the commercial group, yet no definite observation can be made given their small number of samples.

Closer examination was made by breaking down the total maintenance cost into its components. Figure 6 depicts their mean proportions among the samples, with routine maintenance expenditure being dominant, followed by repair maintenance cost. Since the demand for emergency maintenance work was infrequent and the application of condition analysis was even sparse, their shares are minimal. Note, however, that because condition analysis was applied in only 6 samples (Table 2), its cost in individual case is actually more than that incurred for emergency maintenance work, as can be seen from its larger maximum and mean values in Table 1.

Figure 7 displays the variation of preventive maintenance cost over chiller plant capacity. Clearly, only a few samples had made use of condition analysis and the cost so incurred, when compared to that for routine maintenance work, is negligible. The latter, with a mean value of HK$87/TR, declines with increasing chiller plant capacity – a trend similar to that of the total maintenance cost.

In Figure 8 where the costs for corrective maintenance work are plotted, the expenditure on repairing faulty components which are not of an emergency nature is much larger than that on emergency maintenance work. With 12 cases involving no repair maintenance cost, the mean value among the samples is HK$35/TR, i.e. 40% of the routine maintenance cost. The repair maintenance cost variation also demonstrates a decline similar to that of the routine maintenance, but the trend is comparatively less apparent.

Effect of plant age

It has been a perennial belief that the older the plant, the bigger the maintenance effort is needed. Based on this premise, analysis was performed to investigate the relation between age of chiller plants and their maintenance costs. Figure 9 shows the variation of total maintenance cost against chiller plant age, which resembles a 'bell-shape' pattern. The majority of the samples, aged between 5 to 15 years, vary widely from a minimum of HK$48/TR to a maximum of HK$282/TR. The reasons for this pattern include:

1. The new chiller plants, because of their relatively healthy condition, required less work to maintain their performance and thus lower maintenance cost.

2. The middle-aged plants, after several years of operation, would have their components significantly deteriorated. More concerned and financially capable owners, according to their stringent maintenance policy or the need to satisfying demanding users, would spend more to maintain them. Chillers serving average to lower-quality buildings would be given less resources for their maintenance.

3. The old plants aged over 15 years are near to the end of their economic life. Owners of these plants would plan for their replacement while refraining from investing on their maintenance. Minimal maintenance resources were deployed to keep these plants functional.

The effect of plant age on total maintenance cost is further scrutinized by grouping the samples according to their age. As can be seen from Figure 10, the fitted curved for the first subgroup of plants aged between 1 to 7 years lies below the other two subgroups – middle-aged (8-14 years) and old (above 14 years). The difference between the curves of the latter two is not distinctive. Further analysis of their costs, as in Table 4, reveals that preventive maintenance cost generally increases with plant age whereas corrective maintenance costs of the new and old plants are comparable. While spending less on corrective maintenance work, relatively more preventive resources were needed to maintain the functioning of the old plants. There is no significant difference in the mean total maintenance cost between the middle-aged and old plants.

Effects of operation period and heat rejection method

It is suspected that when the chillers are operated more intensively, more resources are needed to maintain them. This is examined by grouping the samples into 3 categories, namely 'highly intensive' for chillers operating on a non-stop basis (i.e. 24 hours), 'moderately intensive' for those required to operate between 11 and 16 hours daily, and 'non-intensive' for those whose daily operation period is less than 11 hours. Ignoring the final group which contains only one sample serving the church for 5 hours daily, the fitted curves pertaining to the first two groups almost overlap with each other (Figure 11). This insignificant difference in maintenance cost can be ascribed to:

1. Although the 'highly intensive' plants were virtually in non-stop operation, many of them are among the 25 commercial buildings which embrace some office buildings or where a significant portion of them is office premises. Their chiller plants or part of these plants were idle during Sundays and public holidays.

2. Each plant contains multiple chillers which are typically arranged to operate following some programmed sequences. During part-load condition, some of the chillers were not in operation.

3. Chiller plants are often oversized.[14] The level of spare capacity available would affect the intensity of usage of the chillers, and hence the demand for their maintenance.

The effect of heat rejection method on total maintenance cost for chillers was investigated by referring to Figure 12 where data of the water-cooled plants and the air-cooled plants are plotted. Since using fresh water for heat rejection was not allowed until recent years,[15] only the smallest chiller plant and a few large plants made use of seawater or fresh water (with special approval) as their heat rejection medium. The vast majority of the samples are air-cooled plants, with their total maintenance costs ranging between HK$53/TR and HK$269/TR. In contrast to the smallest water-cooled plant, the large-capacity plants required relatively low maintenance costs. This may be because their maintenance work can be economised by virtue of their scale while maintenance for equipment on the condenser water side (e.g. seawater water pump, heat exchanger) was covered by separate contracts. Given the small sample of water-cooled plants, no conclusion can be drawn as to which of the two heat rejection methods costs more to maintain.

Relation between preventive maintenance and corrective maintenance

In principle, prevention is better than cure. Paying higher preventive maintenance cost (C_{PM}) to carry out more routine maintenance work and condition analysis should be able to reduce the resources entailed for corrective maintenance (C_{CM}), which includes repair and emergency maintenance works. This can be illustrated by the theoretical indifference curve in Figure 13(a). However, the scatter plot of the collected data (Figure 13(b)) does not seem to firmly uphold the principle.

As discussed in the foregoing section, idling periods and oversized (hence spare) plant capacity render the operation period an insignificant factor to chiller plant maintenance cost. And the effect of heat rejection method could not be identified with confidence. But the variations of preventive maintenance cost and corrective maintenance cost over plant capacity can be seen in Figure 14. With the former exhibiting a wider spread, both of them generally drop as the plant capacity increases. In Figure 15, a larger variation is also found with preventive maintenance cost as compared to corrective maintenance cost. Similar to Figure 9 where a 'bell-shape' pattern is observed, these two costs are low for new and old plants, and they vary significantly among the middle-aged plants.

As noted from the interviews, apart from the above factors there are others that may give rise to the discrepancy between Figure 13(a) and Figure 13(b). First, some major maintenance work, for instance, replacement of compressor, may have been done some years before. The cost for such work could not be traced and the corresponding effect on reduced maintenance burden was not taken into account in the current study. Second, deferred corrective maintenance work is potentially another factor. Although it is not rare that some repair works are deferred for reason of inadequate maintenance budget, it is not uncommon that a number of repair works are packaged to form some improvement projects for execution under separate contracts. Furthermore, type of chillers (e.g. reciprocating, centrifugal, screw, etc.) may also be an influential factor. But investigating its effect is infeasible because some plants made use of more than one type of chillers, while the corresponding maintenance cost breakdowns were not available for analysis.

Conclusions and remarks

The study has unveiled that although proper record of chiller plant faults is generally in lack, refrigerant leakage is rather common. Demand of emergency maintenance call is insubstantial, while emergency rectification of faults with control panel is comparatively more burdensome. A cost model has been worked out to represent the charging of emergency maintenance fee, which varies with the anticipated risk of emergency call demand.

Routine maintenance work, typically undertaken once a month, dominates among the maintenance resources for chiller plants. The cost for repair maintenance work, paid on top of the basic coverage of the contracts, accounts for a less but significant portion. The share due to emergency maintenance work is minimal, as spare capacity is available from over-sized plants and there are off-peak and idling periods of the plants. Condition analysis is costly, but its share is even small because of its uncommon application.

Large chiller plants entail more maintenance resources which, nonetheless, can be economised by virtue of their scale. Maintenance cost varies with plant capacity following a ‘bell-shape’ pattern, with relatively less expenditure for new and old plants whereas that incurred for middle-aged plants spreads over a wide range. With limited samples of water-cooled plants, no concrete conclusion can be drawn as to which heat rejection method would entail more maintenance resources. To investigate clearer the effect of operation period on maintenance cost, further study may collect data about actual run time of individual chillers, spare capacity of chiller plant, and periods of their part-load and full-load conditions.

Capacity and age of chiller plants are factors which make the empirical relation between preventive maintenance cost and corrective maintenance cost deviated from the relation in theory. The distortion may also arise from improvement works done before or repair works deferred beyond the study period. Future study may take a longitudinal research approach to collect data of these works to examine their effects on the preventive-corrective maintenance cost relation.

The focus of the study was on the costs for chiller plant maintenance service. While the findings are information useful to maintenance budgeting and its benchmarking, investigating whether the service is value-for-money also requires assessing the performance of chiller plants. But the logging of plant faults, as identified, is less than satisfactory. This is a problem which warrants further exploration.

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List of table captions

List of figure captions

Table 1 Key information of the samples

	Min.	Max.	Mean
Quantity of chillers (No.)	1	12	3.5
Plant capacity (TR)	100	9,200	1,168
Plant age (year)	1	22	11
Daily operation period (hour)	5	24	17.7
Routine maintenance cost (HK$/year)	14,400	841,848	83,726
Condition analysis cost (HK$/year)	0	85,000	4,863
Repair maintenance cost (HK$/year)	0	114,360	43,863
Emergency maintenance cost (HK$/year)	0	7,200	1,343
Total maintenance cost (HK$/year)	15,300	1,107,597	133,794

Table 2 Ambit and existence of maintenance categories/sub-categories in the samples

Maintenance category	Maintenance sub-category	Typical ambit	No. of plants*
Preventive	Routine	Regular (typically monthly) inspection of plant condition, recording of performance data, oiling of moving parts, cleaning of deposits, and replenishment of consumables.	40
	Condition analysis	With the use of condition monitoring techniques, the operating condition of equipment was analysed so as to determine the time for their maintenance or repair. This is an optional service.	6
Corrective	Repair	Rectify faults which are not of an emergency nature. The labour and material resources needed for such repair work would be negotiated and agreed between the contracting parties before execution.	28
	Emergency	Rectify faults which are of an emergency nature. Such rectification work typically involves urgent attendance by contractor staff at the scene and simple manual on/off/reset operation of the plant, using no or minimal material resources. It primarily is to resume the plant operation temporarily.	25
Resident operator		Other than performing daily checking and inspection of plant condition, the resident operator would need to standby on-site to attend to faults of the plant.	2

*Note: Figures denote the number of chiller plants where cost was incurred for the corresponding maintenance category/sub-category.

Table 3 **Parameters of the emergency maintenance cost model**

	Maintenance contract category		
	Standard	**24-hour**	**High-risk**
i (no unit)	1	2	3
k_i (HK$)	800	1000	1600
m_i (HK$)	400	600	800

Table 4 Mean maintenance costs of different age groups of plant

	Chiller plant age		
	1-7 years	**8-14 years**	**Above 14 years**
No. of samples	10	17	11
Preventive maintenance (HK$/TR)	64	95 (+31%)	102 (+59%)
Corrective maintenance (HK$/TR)	35	41 (+17%)	34 (-3%)
Total maintenance (HK$/TR)	99	136 (+37%)	136 (+37%)

Note: Values in parentheses represent the differences from those of the age group of 1-7 years.

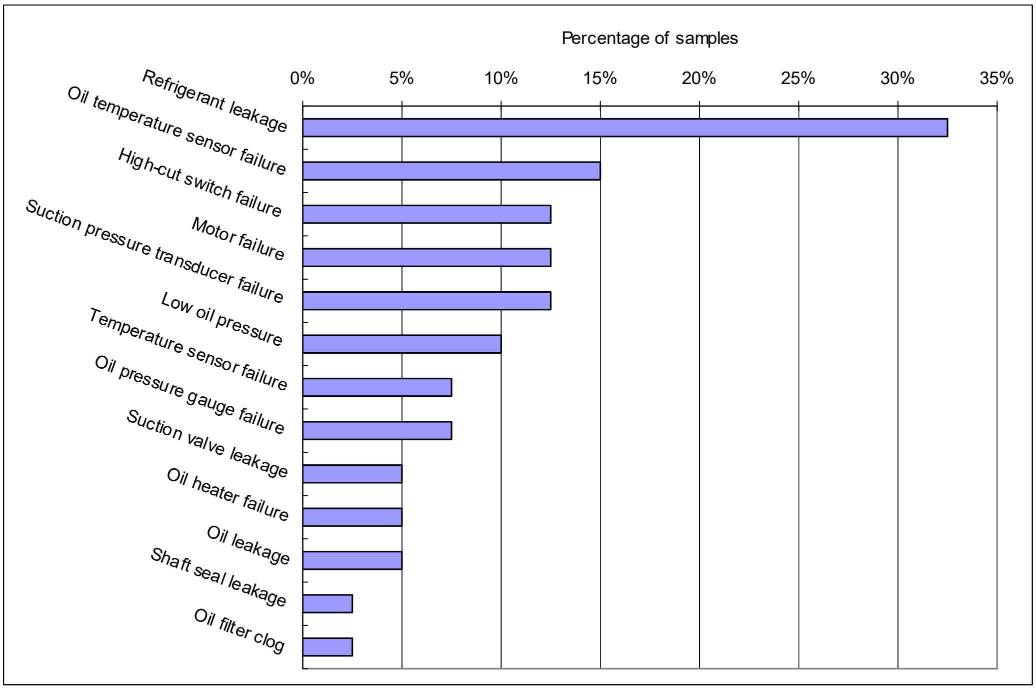


Figure 1 **Faults with compressor**

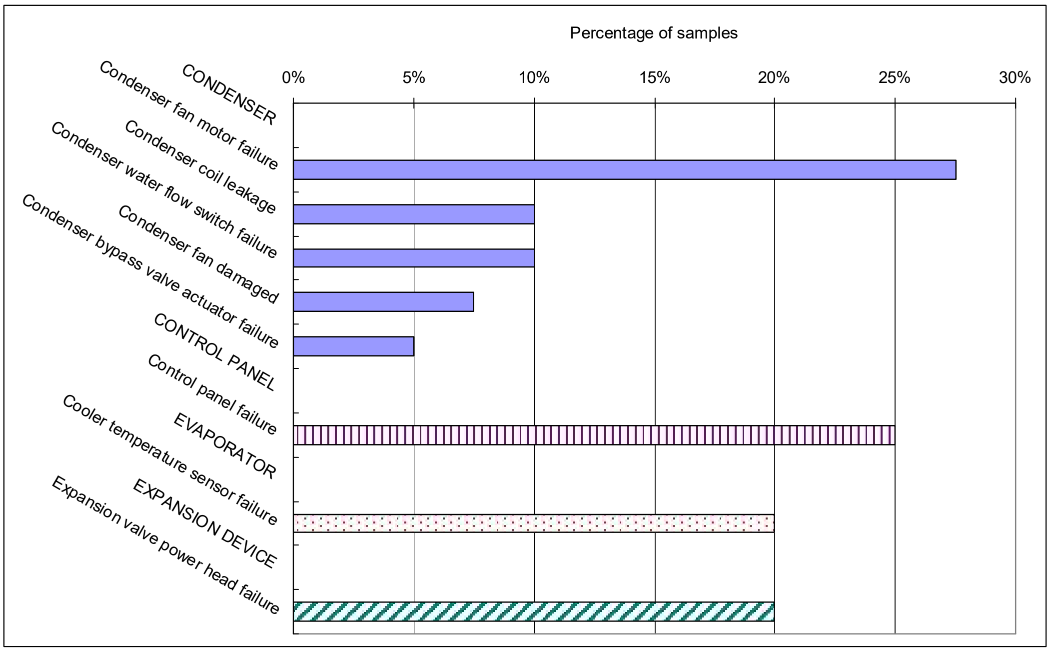


Figure 2 **Faults with condenser, control panel, evaporator and expansion device**

Figure 3 **Annual man-hours and number of emergency calls**

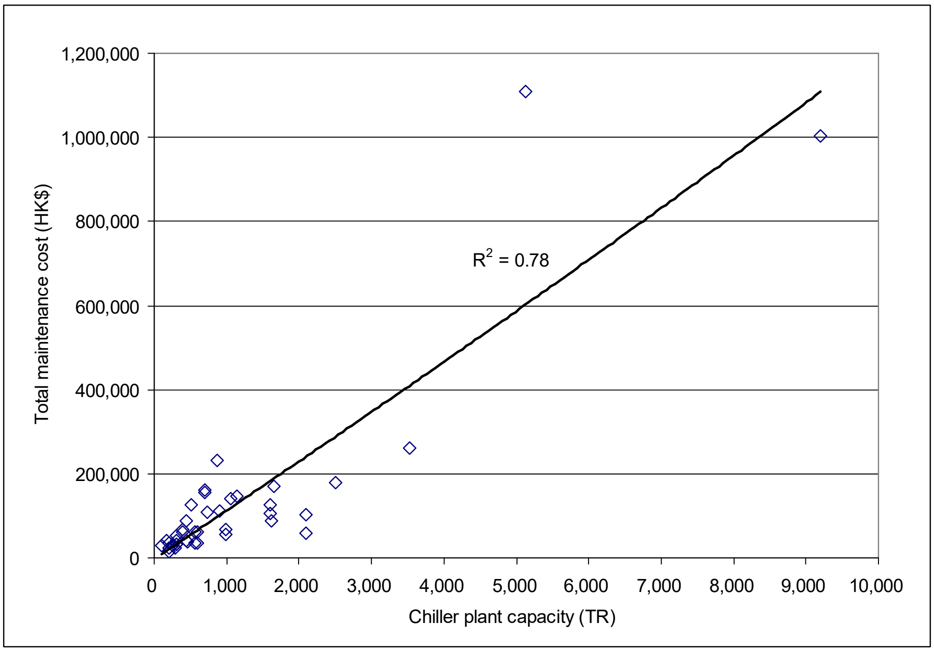


Figure 4 **Raw total maintenance cost against plant capacity**

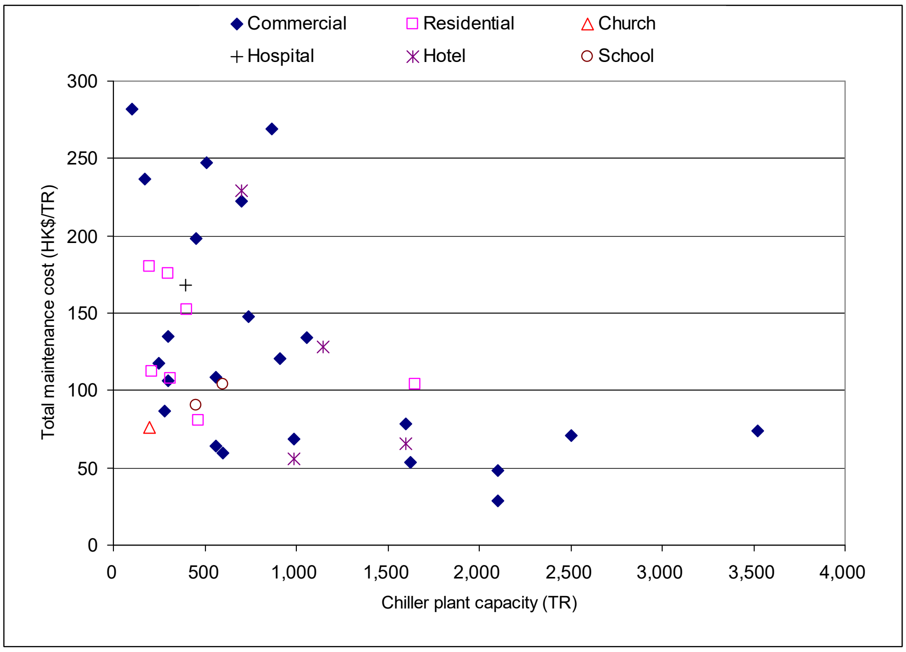


Figure 5 **Total maintenance cost against plant capacity**

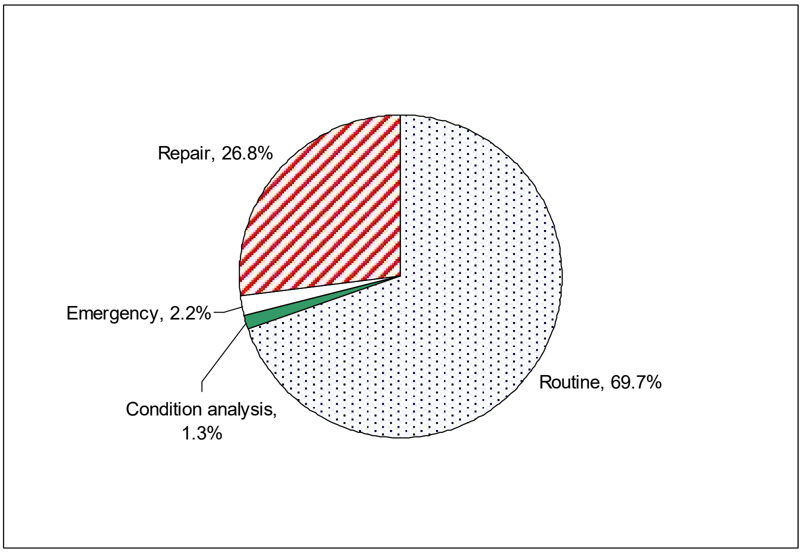


Figure 6 **Proportion of maintenance cost elements**

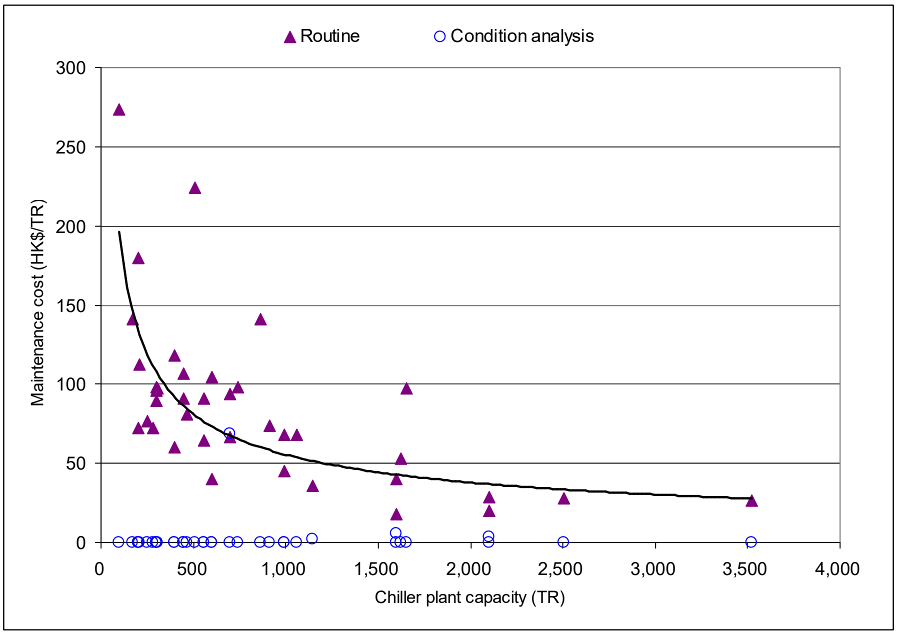


Figure 7 Routine maintenance and condition analysis costs against plant capacity

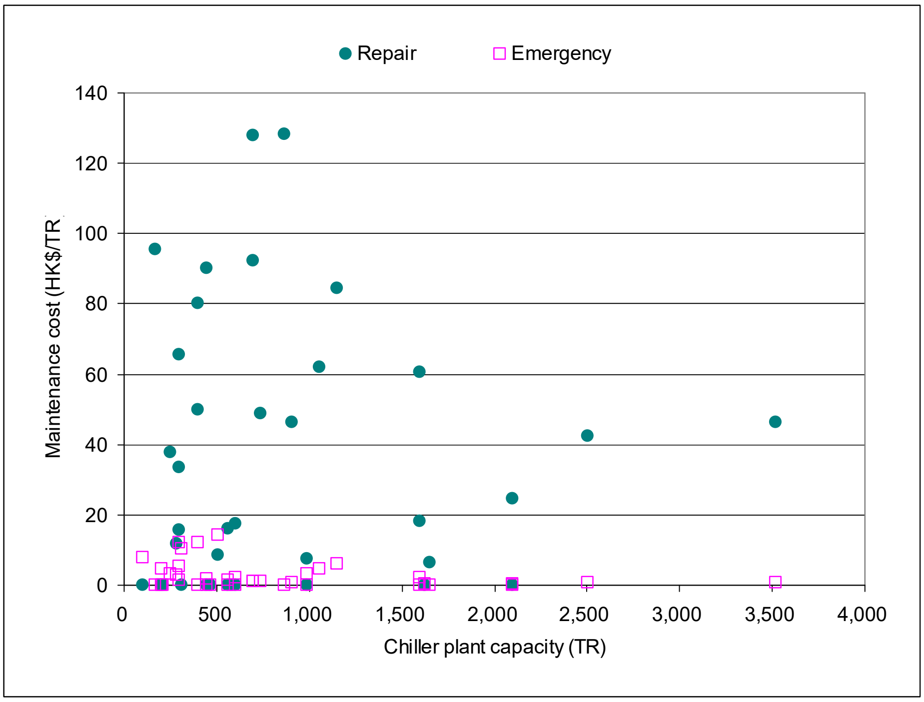


Figure 8 **Repair maintenance and emergency maintenance costs against plant capacity**

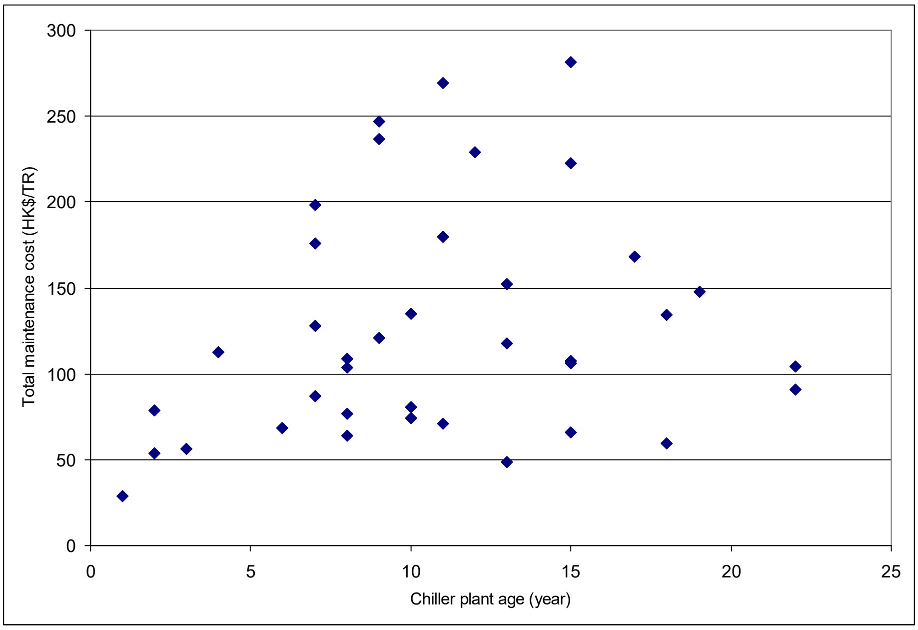


Figure 9 **Total maintenance cost against plant age**

Lai, J.H.K., Yik, F.W.H. and Chan, A.K.P. (2009), Maintenance cost of chiller plants in Hong Kong, Building Services Engineering Research and Technology, Vol. 30, No. 1, pp. 65-78

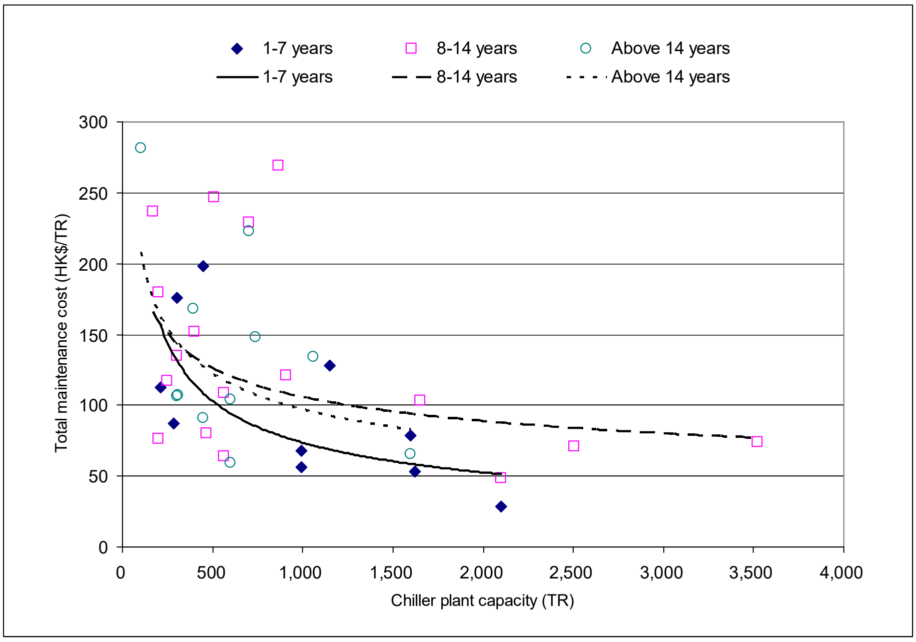


Figure 10 **Total maintenance cost of chiller plants in different age groups**

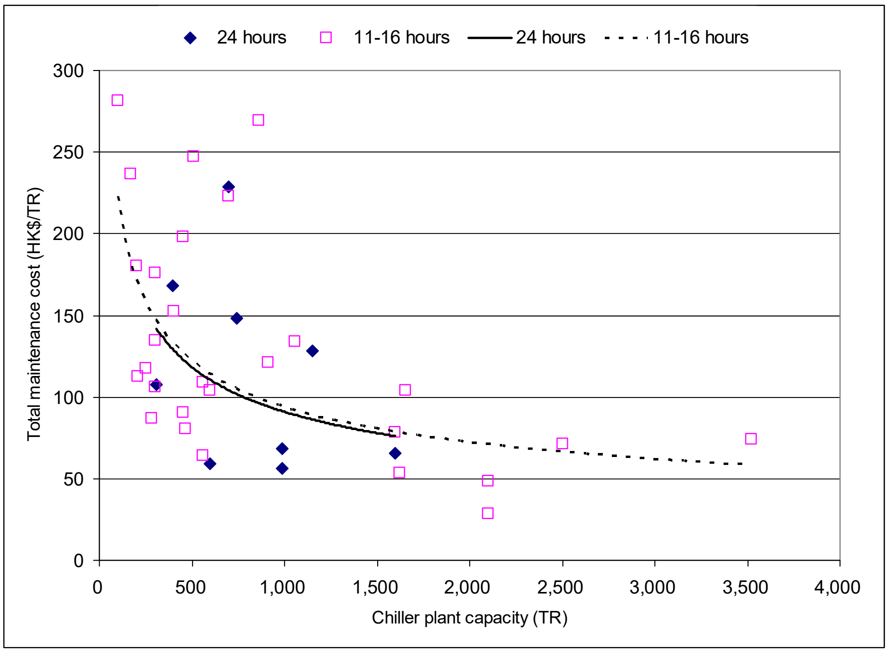


Figure 11 **Total maintenance cost of chiller plants with different operation periods**

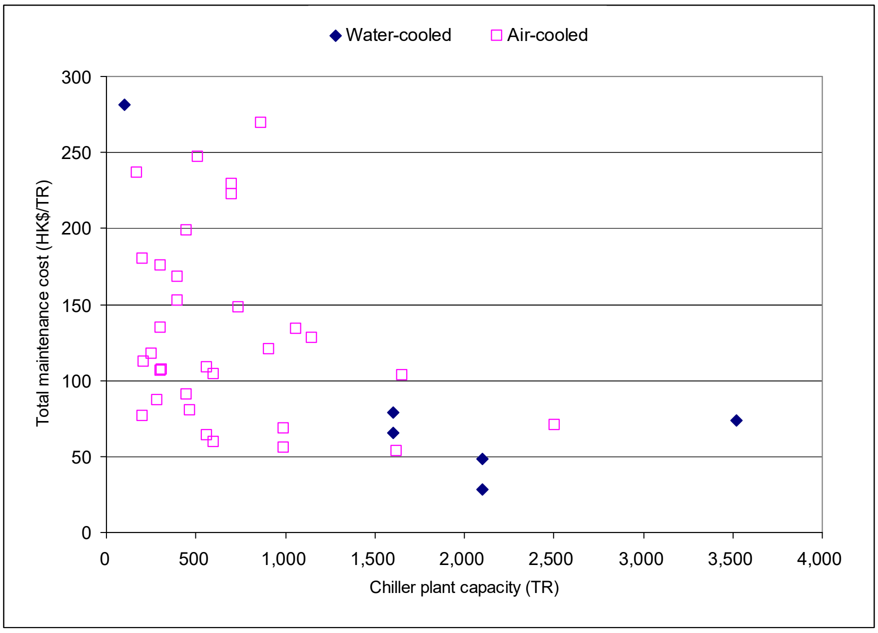
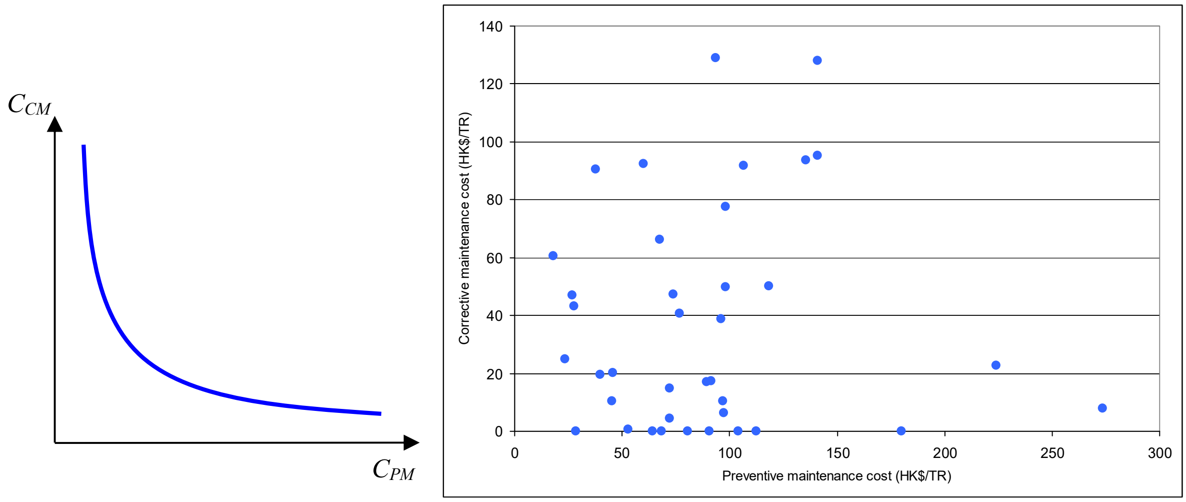


Figure 12 **Total maintenance cost of water-cooled and air-cooled chiller plants**



(a) (b)

Figure 13 **Cost relation between preventive maintenance and corrective maintenance: (a) in theory; (b) in practice**

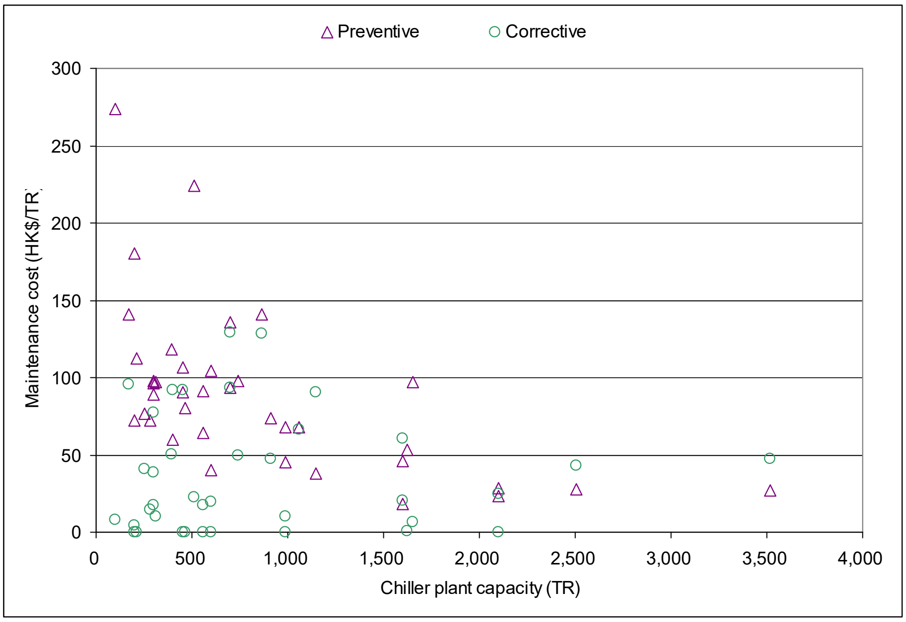


Figure 14 **Preventive maintenance and corrective maintenance costs against plant capacity**

Lai, J.H.K., Yik, F.W.H. and Chan, A.K.P. (2009), Maintenance cost of chiller plants in Hong Kong, Building Services Engineering Research and Technology, Vol. 30, No. 1, pp. 65-78

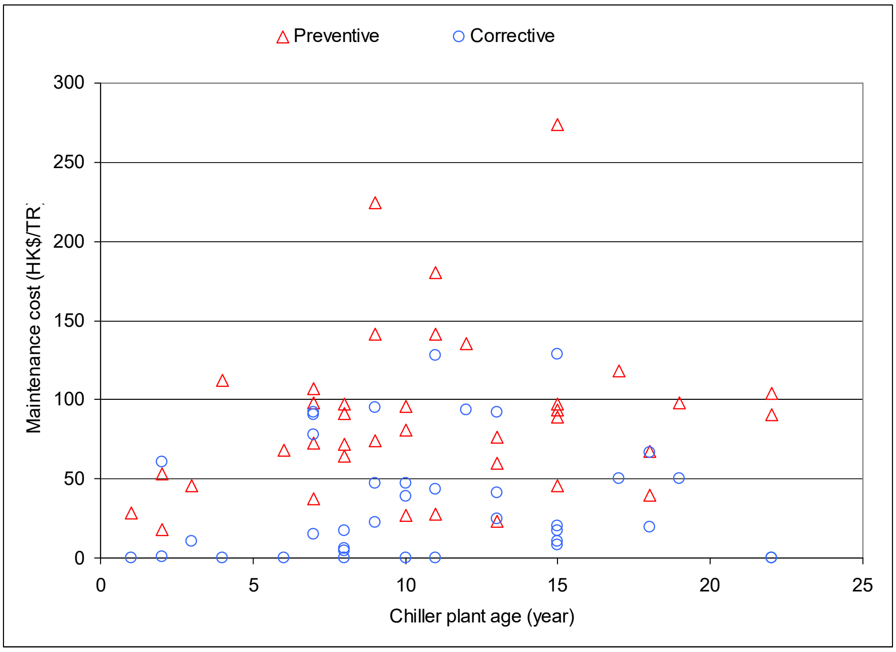


Figure 15 **Preventive maintenance and corrective maintenance costs against plant age**