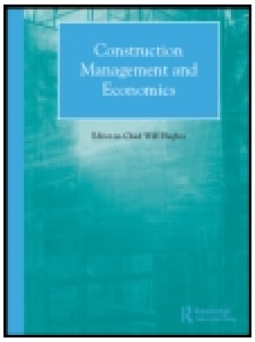

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Priority setting in maintenance management: a modified multi-attribute approach using analytic hierarchy process

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In the current economic climate, budgets for the maintenance of public buildings are unlikely to meet the ever-increasing maintenance needs. Although it is unlikely that this problem can be overcome completely without an injection of further resources, it is possible for government maintenance authorities to improve the situation by ensuring that the best solution in terms of 'value for money' is achieved in the planned maintenance programme. A maintenance plan which is based on a rational assessment of priorities and up-to-date knowledge of the condition of the property stock will help to ensure the best use of available resources. Based on the multi-attribute maintenance prioritization model developed by Alan Spedding, Roy Holmes and Qiping Shen at the University of West of England, which is simple in practice and flexible from a management point of view, this paper presents the results of some further research into this area by modifying the original model using an analytical hierarchy process in deciding the weightings of the criteria set out in the prioritization model. This modified model is more quantitative and objective than the original model. The validation of the framework is also discussed.

Keywords: Planned maintenance, multi-attribute prioritization, priority setting, public buildings, analytic hierarchy process (AHP)

The need to prioritize planned maintenance works

In the current economic climate, budgets for public building maintenance are unlikely to meet the ever-increasing maintenance need. This can be illustrated by examples in Hong Kong and the UK.

In Hong Kong, public building maintenance funds have been curtailed since the mid 70's when Hong Kong was suffering from an economic slowdown. The money given was sufficient for only breakdown maintenance of public buildings. The planned maintenance programme had to be trimmed down significantly while preventive maintenance was implemented only to a limited extent. General maintenance or major repairs were limited to essential items related to safety, health and security. As a result, buildings aged rapidly, especially those used heavily by the public and junior staff quarters where the density was high.

The negative effects of the deferred maintenance due to the lack of funds became more and more evident ten years later. The deterioration began to pose dangers to structures and cause health hazards to users as well. It also led to serious operational problems and lowered the living standards, which were inconsistent with the booming economy. Complaints from the public and the users of the buildings were commonplace. Restoration became too expensive for the limited maintenance budget.

During the period 1968–1988, Hong Kong's population has increased from 3 million to about 5 million and the government infrastructure services and public buildings had to be expanded accordingly. This rapid building progress has resulted in two current problems: (i) untested design and construction methods, and (ii) many components are approaching their 20–30 years design life and now need replacement. For example, carbonation of concrete has reduced protection of reinforcement steel and the low quality cast iron pipes carrying salt water have begun to take their toll. The above situation demands a rapid increase of resources for maintenance and replacement work in a certain period of time.

Although the Hong Kong government acted since 1985 to expand public facilities and services to serve the Hong Kong community, such as adopting a policy to take the recurrent maintenance expenditure into consideration when evaluating the capital investment of a new project and providing a separate fund for refurbishing the dilapidated buildings, the total maintenance budget is still less than 2% of the replacement value of the total assets, while a minimum of 3.5% of the replacement cost is required for maintenance work and management overheads (Chan, 1993). This means that about 40% of the maintenance requirements have not been met.

This situation of deferred maintenance is by no means unique to Hong Kong. Maintenance is almost always at the bottom of the agenda in the national budgets of many countries. The economy always looks good with maximum return from investment. Spending on building maintenance will only de-dramatize the apparent commercial achievement. Any problem arising from the lack of maintenance is somebody else's business in the future.

In the UK, according to the Department of Education and Science (DES, 1985), the backlogs of main structural works in primary and secondary schools in local authorities, as required by the Education Regulations 1981 to bring schools to a defined minimum standard, approximate to £490 million and £370 million, respectively. This has been confirmed by the Audit Commission for Local Authorities in England and Wales (ACLAEW, 1988), who state that the overall condition of the authorities' buildings had declined over some years and the state of repair in many local authority schools may be well below the level required to preserve the assets in the longer term. As shown in Fig. 1, the Commission predicted also that there will be a corresponding time bomb for the maintenance of schools. The maintenance need will rise steeply from the mid 1990s and will not reach its peak until year 2008. This demand is in addition to the existing backlog in the public building maintenance of the government.

As shown in Fig. 2, the annual survey conducted by the Society of Chief Architects in Local Authorities (SCALA, 1993) in Britain revealed that the approved maintenance budgets for educational buildings in local authorities for the 1992–93 financial year were considerably lower than the estimated maintenance needs for the same year. The average actual expenditure on repairs and maintenance of educational buildings was £8.04/m^2 which was far lower than the £20.25/m^2 required to maintain the buildings in a safe, dry, warm and comfortable condition. The average maintenance shortfalls for primary and secondary schools were £13.09/m^2 and £7.91/m^2, respectively. Because fewer authorities were able to provide reliable information, this may be a considerable underestimate.

In the light of the recent report produced by the Audit Commission (1993), there is a pressing need to develop a framework within which maintenance can be prioritized more rationally and limited resources can be allocated more wisely to achieve best value for money. The mounting maintenance backlogs in schools call for innovative actions from local authorities to ensure that limited resources are used wisely.

Although this problem is unlikely to be solved completely without an input of further resources, it is possible to improve the situation by ensuring that the best solution in terms of 'value for money' is achieved

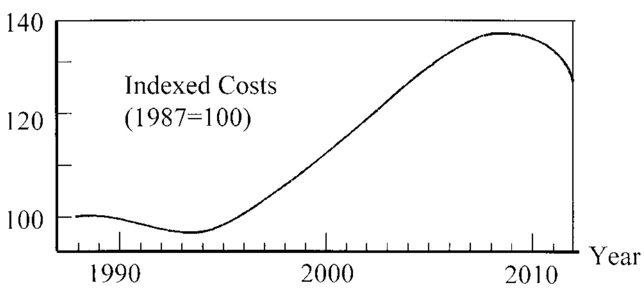

Figure 1 Maintenance time bomb for schools (Audit Commission, 1988)

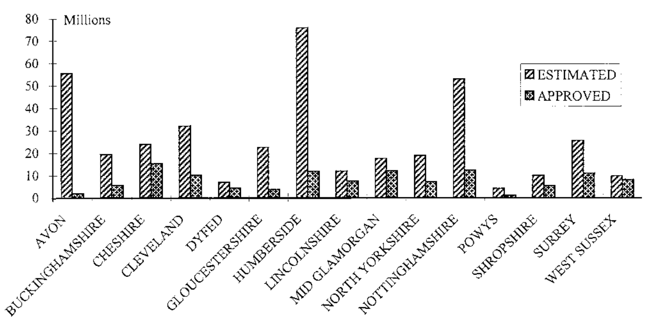

Figure 2 Estimated and approved maintenance expenditure of educational buildings in local authorities for the period 1992–93

in the maintenance programme. A maintenance plan that is based on a rational assessment of priorities and up-to-date knowledge of the condition of the property stock will help to ensure that difficult long term decisions are not outweighed by short term considerations.

It is clear that increasing pressure is being brought to bear on the resources available for maintenance management, and the setting of priorities has always been a problem for property managers, who need to take a number of factors into consideration during the prioritization process. The techniques in assessing value for money for planned maintenance are not robust, and the resources for addressing the problem have become increasingly scarce (Spedding *et al.*, 1994). Decisions concerning the use of resources on planned maintenance normally are based on qualitative assessment, containing large amounts of subjective elements which can lead to inadequate spending on repairs and maintenance, particularly for strategic work. Although senior staff are aware of the benefits of setting up priorities, little effort has been put into the development of a systematic approach to prioritizing work by drawing upon maintenance databases and factors which often influence the decision-making process in planned maintenance.

The objective of the research undertaken at the Hong Kong Polytechnic University is to improve planned maintenance management of public buildings in terms of value for money by setting up a viable prioritization model that takes into account factors and issues which managers have to consider before decisions are made. A mathematical model has been developed for the priority setting process in an effort to connect the factors identified with quantitative data from condition surveys. This model provides a method of ranking maintenance and repair proposals on the basis of agreed criteria, in the knowledge that the application of common standards would reduce the subjective element that has featured so largely in maintenance decisions.

The current practice of maintenance priority setting

Maintenance prioritization practice in Hong Kong

In Hong Kong there are two government authorities with large amounts of building stocks, the Architecture Services Department (ArchSD) and the Housing Department. For the purpose of maximizing the use of resources and good management, each of the above two authorities has its own approach to maintenance prioritization.

The ArchSD is responsible for the construction and management of all sorts of government properties in Hong Kong, including government offices, hospitals, clinics, police stations, fire services stations, post offices, prisons, laboratories and workshops. In the 1990–91 financial year, the ArchSD's Property Services Branch (APB, 1992) was responsible for maintaining 6000 buildings across more than 65 government departments. The overall expenditure was in the order of HK$1000 million and the total number of work orders was around 200 000 per year (Chan, 1993). APB has a condition and priority related maintenance programme. The essence of this programme is to plan for or accept the possibility of restricted maintenance as a result of fiscal stress. The technical needs of the buildings are established through cyclic condition surveys. A priority system reflects stated policy in standards of maintenance for different types and parts of buildings, health, safety and legal requirements. It is employed to assess their condition-related maintenance proposals. Projects are selected according to priorities until the funds allocated are fully committed.

This method produces a 'needs budget' which relates real physical needs to available maintenance funds. The condition of buildings offers a central source of information. Condition is reflected in the on-site condition survey results which are recorded in computers. Regular update of condition details will gradually elevate deteriorating items or elements to a high priority which will secure funds. The result of this approach is that: (1) APB can justify a needs budget, i.e. APB knows what work must be done and can explain to the administration the effect of not proceeding, and (2) APB can tailor the works programme to the funds allocated. In the event that the actual allocation does not reach the same value as the justified needs budget, APB will ensure essential works (high priority projects) are undertaken.

The Housing Department in Hong Kong is one of the largest home-makers in the world, providing housing for around 3.2 million people, half of the population in Hong Kong. Its annual budget represents 2% of Hong Kong's GDP. At present, the department has a housing stock of 870 000 public flats together with some 3 million m^2 of commercial and other facilities.

The Housing Department has a planned maintenance programme called CARE which is the acronym of condition, appraisal, repair and examination. The concept is to deal systematically with the maintenance and improvement of each public housing block by first carrying out a condition survey and then appraising the findings and arranging for works to be carried out in an intensive repair period of about 2 years. Tenants would be able to enjoy a low breakdown 'quiet' period of 4 years and an improvement in maintenance standards. The quiet period is also called the examination period during which building condition data would be collected for the next CARE cycle.

Guidelines are developed for determining the priorities of the estates in the CARE programme. The priorities are as follows in descending order: (1) work necessary to maintain the safety of persons; (2) work necessary to keep property habitable, e.g. by reasons of hygiene, security, electrical and water supply; (3) work necessary to keep buildings operational; and (4) work necessary for the appearance of the property, the provision or upkeep of non-essential services or facilities.

Maintenance prioritization practice in the UK

It is a common practice that property professionals in the local authorities in Britain assess the priority of each maintenance item for inclusion in their planned maintenance programmes. According to the report produced by the Architects and Building Group of the former Department of Education and Science (DES, 1985), although priority ratings may differ in detail between local authorities, the following are regarded as typical.

1st Priority – work needed immediately or in the near future to meet legislative or contractual requirements and to ensure the health and safety of building occupants and users; work required to prevent the imminent closure of accommodation or serious dislocation of activities.

2nd Priority – work necessary within one year to prevent serious deterioration of the fabric or services, such as those which are likely to lead to higher future costs of repair or renewal.

3rd Priority – work as above which may be deferred beyond one year; work desirable to maintain the environmental quality of buildings and grounds, such as internal decorations, fencing, etc.

The above ratings are generally in line with the results of a questionnaire survey conducted by Holmes and Shen (1994) between August and October 1994 among 46 local authorities in England and Wales, and the results from interviews with principal building surveyors and other senior maintenance officers in several local authorities which participated in this priority setting research project. For example, the methods of prioritizing planned maintenance in one of the selected local authorities is as follows.

County B has a policy of keeping its built assets operational. Maintenance problems are tackled as they arise. Works which may cause health and safety problems and required by relevant legislation usually are given the first priority. The second priority goes to works that are essential for keeping buildings operational and safeguarding the fabric. The third category is cyclic maintenance such as external painting and flat roof repairs. The fourth and the fifth priorities are given to works which are desirable to prevent further deterioration and works which are required to bring buildings up to current standards.

The examples above represent the current practice in most local authorities in the UK. There are at least two fundamental problems associated with the practice. First, since the decision-making process is not clear, it is difficult to tell why and how a surveyor assigns a certain priority to a particular maintenance item; subjective elements can be introduced very easily into the process. Second, since maintenance budgets in most local authorities are significantly less than the real maintenance needs, the cut-off line usually falls somewhere in the middle of a priority category. This means that maintenance managers often are faced with the difficult task of deciding which items should be included in the next planned maintenance programme and which items should be moved to the backlog list.

It was also found by Holmes and Shen (1994) that where formal computerized prioritization methods are not yet in use, maintenance managers have the difficult annual task of confirming or amending the priorities of many thousands of work items, initially given by individual surveyors. Almost all maintenance managers interviewed by the research team experienced some degree of frustration in allocating limited resources to the ever-increasing maintenance demands.

The multi-attribute approach for prioritizing maintenance

This method was developed by Spedding, Holmes and Shen (1994) at the University of West of England, based on a comprehensive study of the current practice of planned maintenance prioritization in British local authorities and various existing prioritization methods. The method was simple from the practical point of view and flexible from the management point of view. It could also increase client–user satisfaction through their participation of the more transparent prioritization process. The following is a brief description of the method.

As proved by Spedding *et al.* (1994), in the process of setting priorities for planned maintenance, a number of major factors will normally be considered by maintenance managers (see Fig. 3). Within their framework, criteria used for priority setting will be ranked according to their relative importance, and subsequently a weighting will be assigned to each criterion. Every maintenance work identified during a condition survey or inspection will be measured and a score will be given in respect of each criterion selected earlier. Suppose n criteria $C_1, C_2, \ldots, C_i, \ldots, C_n$ are used in the prioritization process, their relative weights are $W_1, W_2, \ldots, W_i, \ldots, W_n$, and work j was scored $S_{j1}, S_{j2}, \ldots, S_{ji}, \ldots, S_{jn}$ in respect of criteria $C_1, C_2, \ldots, C_i, \ldots, C_n$. The priority index S_j for job j can then be calculated by using the following formula:

$$S_j = S_{j1}{\star}W_1 + S_{j2}{\star}W_2 + \ldots S_{ji}{\star}W_i + \ldots + S_{jn}{\star}W_n \qquad (1)$$

The criteria used in the prioritization process and their weightings may be different among different local authorities. This reflects the differences in their maintenance objectives, policies and practices. Based on the survey conducted by Holmes and Shen (1994) among property services departments in local authorities in England and Wales, six major criteria have been identified as the most commonly used criteria in setting up maintenance priorities. They are as follows.

1. *Building status* (BS). The relative importance of the building (where the defective element is examined) compared with others, in terms of function, current and intended future usage, e.g. an infant school might have a higher status than a leisure building.
2. *Physical condition* (PC). The physical condition of the defective element being examined, and its possibility of breakdown or failure, e.g. elements in very bad condition would be given higher priorities than those in fair condition.
3. *Importance of usage* (IU). The importance of the functional unit (in relation to other units within the same building) where the defects are situated, e.g., the reception area would be more important than storage rooms.
4. *Effects on users* (EU). The effects of breakdown or failure of the defective element(s) on the occupants and users of the building (including staff and members of the public), e.g., a problem relating to health and safety would be more important than an aesthetic problem.
5. *Effects on fabrics* (EF). The cost implication of breakdown or failure of the defected element(s) on maintaining the overall condition of the building fabric and building services, e.g., a defective roof would be given a high priority because if it is not repaired promptly the eventual cost will be higher due to possible damage to other building elements.
6. *Effects on service provision* (ESP). The cost implication of breakdown or failure of the defected element(s) for the provision of the services for which the building is used.

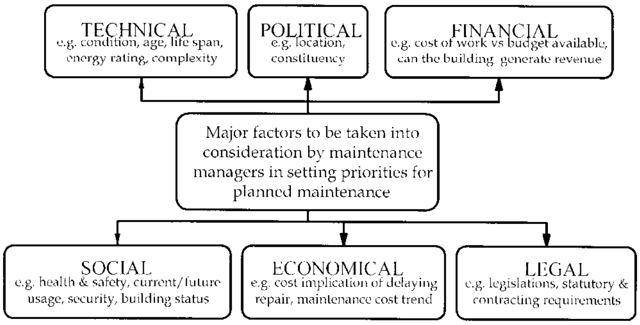

Figure 3 Major factors for planned maintenance prioritization (Spedding *et al.*, 1995)

In addition to the standard criteria listed above, some special criteria, such as legal requirements, special maintenance policies, and pressures created from day-to-day maintenance, also need to be considered when assessing maintenance priorities. These special criteria sometimes override the standard criteria. For instance, a low priority could be assigned to a maintenance job according to the standard criteria; however, because the work is required to comply with a conservation order, a very high priority will be assigned to keep it in the next maintenance programme.

In order to ensure consistency, detailed guidelines for assigning scores to maintenance works, also were designed for surveyors to use. For example, against the criterion 'physical condition', a score of 5 will be given to the item under examination if it is in a very bad condition and requires immediate attention; a score of 4 will be given if its overall condition is bad but does not need immediate attention.

The above framework was presented to the participating organizations, and their comments were taken into consideration in the modification of the framework. For example, to ascertain which factors contribute to the weighting of a criterion in priority setting, two organizations were contacted and discussions were held with chief surveyors and other senior members of staff regarding their views on the weightings. From this information a questionnaire was designed for collecting weightings used in other participating organizations.

The model for prioritization of maintenance work has been tested also with real data provided by a participating local authority in the UK. During the test, a total of around 60 maintenance items were picked up from the backlog and the existing maintenance programme. They were mixed up with each other and their origins were removed. The chief surveyor from the participating authority was then asked to rank those items using the above approach. Five criteria were chosen by the survey, and weightings were assigned based on their relative importance. They are: BS = 8, PC = 9, IU = 5, EU = 10, EF = 6, which reflects the authority's maintenance policy. In respect of each selected criterion a score was given for a maintenance item by the chief surveyor. A priority index (PI) was calculated for each item by using formula (1). Based on the priority index, all the maintenance items were rearranged in a descending order of priority. Table 1 shows a subset of the 60 selected items with high priority indices. The PI for the first listed item, for example, is based on: $3 \times 8 + 5 \times 9 + 4 \times 5 + 5 \times 10 + 5 \times 6 = 169$. The accumulated cost is used for placing a cutoff line among maintenance items to separate items in the current maintenance programme from those in the backlog.

The test indicated that by using the framework it was possible to speed up the priority setting process with increased transparency and reduced subjectivity. The results showed that, although most of the maintenance items in the current programme appear at the top 1 of the list, a few items in the current maintenance programme appeared near the bottom of the rearranged list. The main reason for these 'low-score' items being included in the current maintenance programme was the fact that they satisfied some special criteria. For instance, according to this authority's policy, the 2nd phase of a project will be given a very high priority to put it in the next year's planned maintenance programme regardless of its current condition and effects on users etc.

The modified multi-attribute approach using AHP

The modified multi-attribute approach for maintenance prioritization developed at the Hong Kong Polytechnic University is based on the above multi-attribute prioritization model developed by Spedding,

Table 1 Example of multi-attribute evaluation

Pr No.	Work description	BS	PC	IU	EU	EF	Es Cost	Ac cost	PI
5425	Hyflex treatment to kitchen roof.	3	5	4	5	5	£450	£450	169
5399	Replace 8 no obsolete fittings.	3	5	4	5	5	£450	£900	169
5340	Eradication of furniture beetle in roof space of school house.	3	5	4	5	4	£350	£1250	163
5422	Replacement of night storage heaters.	3	5	3	5	4	£9000	£10250	158
5356	Reslate roof and renew valley. Phase 2.	3	5	5	3	5	£15900	£26150	154
5350	Rewire and refurbish mains installation and rewire whole school.	3	5	3	5	3	£5000	£31150	152
5366	Provision of a GH system to replace obsolete night storage heaters.	3	5	3	5	3	£20000	£51150	152
5345	Revise mains switchgear, install 1 no composite f/board.	3	5	3	5	3	£1000	£52150	152
5361	Replace mains insulation switches and distribution boards.	3	5	3	5	3	£800	£52950	152
5400	Re boiler infants.	3	4	5	4	4	£5135	£58085	149
5342	Damp proof walls to classroom No 1 (Reception) and redecorate.	3	4	5	4	3	£2800	£60885	143
5428	Install boiler control panel and update controls.	3	5	4	4	2	£3000	£63885	141
5367	Install lightning protection system.	3	5	2	4	3	£8500	£72385	137
5425	External painting of kitchen block LEA contribution.	3	5	4	3	3	£1100	£73485	137
5332	Replacement of 6 no night storage heaters.	3	5	3	4	2	£4500	£77985	136
5342	Rm 2 hack off plaster and damp-proof and redecorate.	3	4	5	3	3	£2500	£80485	133
5342	Hack off plaster, damp-proof and redecorate to the hall.	3	4	5	3	3	£2500	£82985	133
5340	Ext redecoration of school house, rainwater gullies window repairs.	3	5	2	3	4	£3200	£86185	133
5351	Remove leaning chimney stack.	3	4	4	4	2	£800	£86985	132
5342	Classroom 3- Hack off ceiling & walls, damp-proof and redecorate.	3	5	3	3	3	£1500	£88485	132

Holmes and Shen at the University of West of England in the UK. The main addition to the original method is to decide the weighting of each criterion in the multi-attribute prioritization model with a more accurate and quantitative method: the analytic hierarchy process (AHP).

Introduction to the analytic hierarchy process

The analytic hierarchy process was developed by Thomas L. Saaty (1990) in the early 70's to help individuals and groups deal with multi-criterion decision making problems. By incorporating both subjective and objective data into a logical hierarchy framework, AHP provides decision makers with an intuitive or common sense approach to evaluate the importance of every element of a decision through a pair-wise comparison process. This method allows the decision makers to structure complex problems in the form of a hierarchy or a set of integrated levels. In general, the hierarchy has at least three levels: the goal, the criteria and the alternatives.

The process begins by determining the relative importance of the criteria in meeting the goal. Then pair-wise comparisons are made between the alternatives with respect to each criterion to decide the relative importance of one alternative versus another. Finally, the results of the two analyses are synthesized to compute the relative importance of the alternatives in meeting the goal.

The pair-wise comparison information is represented in a pair-wise comparison matrix. If there are n items that need to be compared for a given matrix, a total of $n(n-1)/2$ judgements are needed. The eigenvector of each pair-wise comparison matrix provides a regional priority ordering, and the eigenvalue gives a measure of the consistency of judgement. After synthesizing the results, a global priority order of each alternative with respect to the goal is given by the synthesized eigenvector. A global consistency ratio of less than 0.10 is acceptable, otherwise some judgements need to be revised.

The AHP is suited best to a multi-criterion problem in which accurate quantification of the impact of the alternatives on the decision-making problem is not possible. For this reason, the AHP is ideally suited to the maintenance priority setting problem.

Setting up weightings for the maintenance criteria

The AHP approach can be applied to the maintenance priority setting problem to decide the weighting of each criterion. It consists of the following steps, as illustrated in Fig. 4.

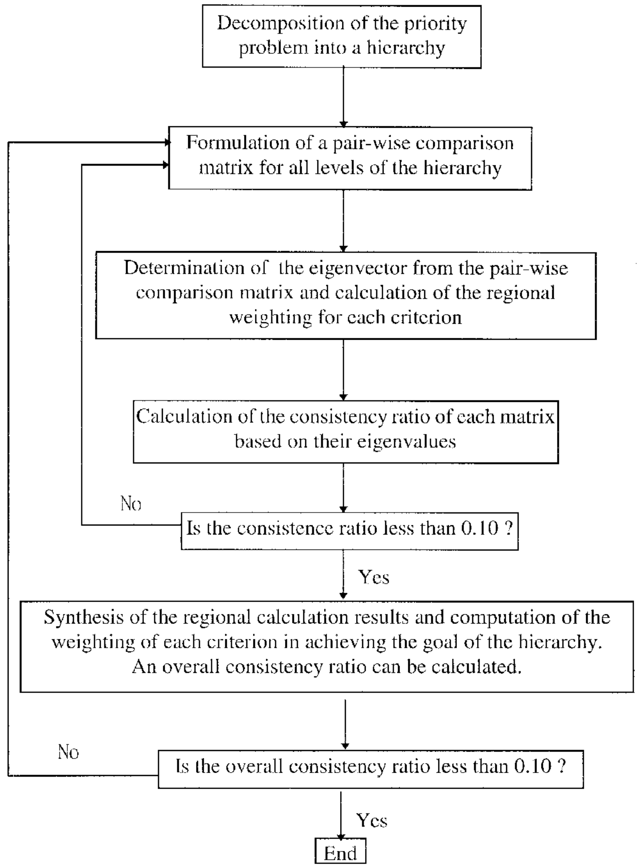

Figure 4 Prioritization process with AHP

Formation of a decision-making hierarchy

The prioritization problem can be broken down into a hierarchy of interrelated decision elements as shown in Fig. 5. Level 1 describes the objective of the decision-making problem. Level 2 contains factors that are perceived as important attributes to achieve the objective described in level 1. In theory, this process can be extended to include many levels. Factors listed at each level are perceived as important attributes that affect attributes at the upper level. It is for simplicity reasons that the number of levels in Fig. 5 has been restrained to two. All information within the hierarchy will be provided by managers with decision-making responsibilities. The criteria selected in the illustration can be changed based on the real life situations and problems encountered.

Formulation of pair-wise comparison matrix

The decision makers are now asked to make pair-wise judgements for the criteria selected. Each pair-wise comparison involves assessing the relative importance of one factor with respect to the other factor using a ratio scale. Table 2 shows the commonly used scale suggested by Saaty (1990).

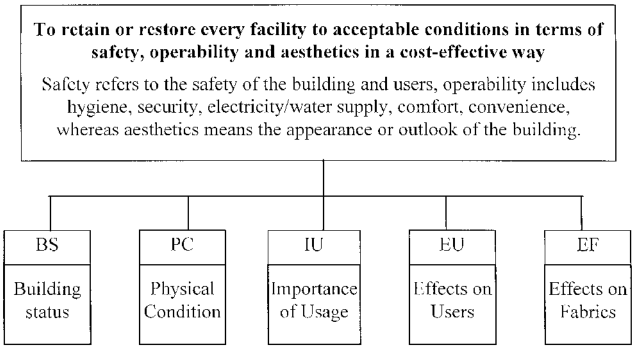

Figure 5 Hierarchy for prioritization of planned maintenance of public buildings

As shown in Table 3, by answering question 'with respect to the given criterion, what is the importance of factor *i* over factor *j*?', the pair-wise comparison matrices are formed. For instance, if a decision maker believes that 'safety' is absolutely more important than 'aesthetics' with respect to the goal, a value of 9 to 'safety' expresses this judgement. If 'effects on users' are moderately more important than 'effects on fabrics', a value of 3 can be assigned to 'effects on users'. The weightings in the last column of the table are calculated based on the method introduced in the next section.

Computation of priorities and consistency ratio

From the pair-wise comparison matrix, the eigenvector and the maximum eigenvalue could be calculated using the right eigenvector method. The eigenvector provides the weightings of the criteria while the maximum eigenvalue is used to obtain a measure of the consistency of the judgement.

The use of the right eigenvector method was proposed first by Saaty (1990) and it is the most widely used method, employing the more general eigenvector equation

$$AW = \lambda_{max}W$$

where, A is the pair-wise comparison matrix, and $W = (W_1\ W_2\ W_3\ W_4\ W_5)^T$ is the vector of actual relative weightings of the criteria.

Table 2 Fundamental ratio scale in pair-wise comparison (Saaty, 1990)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favour one over another
5	Essential or strong importance	Experience and judgement strongly favour one over another
7	Very strong or demonstrated importance	An activity favoured very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between adjacent scale value	When a compromise in judgement is needed
Reciprocals of above nonzero	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	A reasonable assumption
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Table 3 Pair-wise comparison matrices

With respect to goal	BS	PC	IU	EU	EF	Weighting
BS	1	1/3	3	1/4	2	0.123
PC	3	1	5	1/2	4	0.280
IU	1/3	1/5	1	1/9	1/3	0.043
EU	4	2	9	1	6	0.471
EF	1/2	1/4	1/4	1/6	1	0.083

Table 4 Value of random consistency (Saaty, 1990)

Size of matrix	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Saaty (1990) has proposed the use of a consistency ratio (CR) to measure the inconsistency in the pair-wise comparison: CR = CI/RI, where CI is called the consistency index, defined as $CI = (\lambda_{max} - n)/(n - 1)$, and RI is the random consistency obtained by averaging the consistency index of a randomly generated reciprocal matrix from a scale of 1 to 9. The value of RI could be obtained from Table 4.

Based on this method, the results for the matrix shown in the previous section are as follows: $W = (W_1\ W_2\ W_3\ W_4\ W_5)^T = (0.123\ 0.280\ 0.043\ 0.471\ 0.083)^T$, $\lambda_{max} = 5.10$, CI = (5.10–5)/(5–1) = 0.025, CR = 0.025/1.12 = 0.02.

The validation of the modified multi-attribute method

The modified model for prioritization of planned maintenance also has been tested with the same data as presented in the test of the original model described earlier. The new weightings are BS = 0.123, PC = 0.280, IU = 0.043, EU = 0.471 and EF = 0.083, yielding scores for the recalculated priority index shown in Table 5.

As shown in Table 5, the priority order resulting from the recalculation using the modified multi-attribute model is similar to that from the original multi-attribute model. This is mainly due to the similarity of the weighting sequences of the above two models. In the former calculation with the original model, the weighting sequence is: EU (10) > PC (9) > BS (8) > EF (6) > IU (5) while with the modified model the weighting sequence is: EU (0.471) > PC (0.280) > BS (0.123) > EF (0.083) > IU (0.043). As long as the variation of the weighting values has not been large enough to change the weighting sequence, it has only a minor influence on the final priority order, which indicates the flexibility of both multi-criterion prioritization models.

It is necessary to point out that the above validation has not been totally strict. The pair-wise comparisons

Table 5 Example of modified multi-attribute prioritization

Pr No	Work description	BS	PC	IU	EU	EF	ES Cost	Old PI	New PI
5425	Hyflex treatment to kitchen roof.	3	5	4	5	5	£450	169	4.711
5399	Replace 8 no obsolete fittings.	3	5	4	5	5	£450	169	4.711
5340	Eradication of furniture beetle in roof space of school house.	3	5	4	5	4	£350	163	4.628
5422	Replacement of night storage heaters.	3	5	3	5	4	£9000	158	4.585
5400	Re boiler infants.	3	4	5	4	4	£5135	154	3.812
5350	Rewire and refurbish mains installation and rewire whole school.	3	5	3	5	3	£5000	152	4.502
5366	Provision of a GH system to replace obsolete night storage heaters.	3	5	3	5	3	£20000	152	4.502
5345	Revise mains switchgear, install 1 no composite f/board.	3	5	3	5	3	£1000	I52	4.502
5361	Replace mains insulation switches and distribution boards.	3	5	3	5	3	£800	152	4.502
5356	Reslate roof and renew valley. Phase 2.	3	5	5	3	5	£15900	149	3.920
5342	Damp proof walls to classroom No 1 (Reception) and redecorate.	3	4	5	4	3	£2800	143	3.837
5428	Install boiler control panel and update controls.	3	5	4	4	2	£3000	141	3.991
5367	Install lightning protection system.	3	5	2	4	3	£8500	137	3.988
5332	Replacement of 6 no night storage heaters.	3	5	3	4	2	£4500	137	3.603
5425	External painting of kitchen block LEA contribution.	3	5	4	3	3	£1100	136	3.948
5351	Remove leaning chimney stack.	3	4	4	4	2	£800	133	3.366
5342	Classroom 3 – Hack off ceiling & walls, damp-proof and redecorate.	3	5	3	3	3	£1500	133	3.366
5342	Rm 2 hack off plaster and damp-proof and redecorate.	3	4	5	3	3	£2500	133	3.600
5342	Hack off plaster, damp-proof and redecorate to the hall.	3	4	5	3	3	£2500	132	3.711
5340	Ext redecoration of school house, rainwater gullies window repairs.	3	5	2	3	4	£3200	132	3.56

were conducted by the research team at the Hong Kong Polytechnic University, rather than by the same chief surveyor of the local authority in the UK. Additional tests will be conducted at the next stage of the research project. Agreements have been made with two public organizations with large building stocks, the Property Service Branch of the Architectural Services Department and the Maintenance Branch of the Housing Department in Hong Kong, to test further the model.

Conclusions

A modified prioritization model for planned maintenance is developed based on the multi-attribute prioritization model in which the weighting of each criterion has a vital influence on the final prioritization results. Modifications are made in the modified model to use AHP in deciding the weightings for each criterion, which makes the original model more scientific and objective. This approach also improves client and end user satisfaction through improved transparency in the prioritization process and their increasing awareness of and participation in the process.

In the light of discussions with more participating maintenance authorities the model is being refined for further implementation. It is necessary to test the model further in two aspects: (i) to see how well building surveyors in Hong Kong respond to the modified method of data collection during their condition surveys or inspections; and (ii) to test further the validity and weightings of the criteria identified.

Although the above method was designed mainly for the planned maintenance of public buildings, the concepts and principles could be extended easily to the private sector. In order to facilitate the testing of the model, a method for collecting data was introduced. Guidelines for assigning scores to maintenance works have been prepared for surveyors to ensure consistency in the scoring process, which is critical to the success of the new method. The documentation for data collection and the procedures for using the model are now ready for the full testing process in both the public and private sectors.

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