Property Management

Building maintenance strategies: planning under uncertainty

Hans Lind Henry Muyingo

Received February 2011
Revised June 2011
Accepted June 2011

Building maintenance strategies: planning under uncertainty

Hans Lind and Henry Muyingo
Department of Real Estate and Construction Management, Division of Building and Real Estate Economics, Royal Institute of Technology, Stockholm, Sweden

Abstract

Purpose – The purpose of this article is to critically evaluate maintenance strategies and determine to what extent models from other sectors can be applied to building maintenance.

Design/methodology/approach – The paper is a theoretical paper based on a number of Swedish studies, both case studies and questionnaires. From these a number of stylized facts have been identified and the purpose is to explain and draw conclusions from these.

Findings – The main finding is that there are a number of specific uncertainties that affect building maintenance planning making more detailed long-term plans less meaningful. A new structure for maintenance is proposed focusing on long-term strategies goals for various buildings/components and then short run adjustments when new information comes up.

Research limitations/implications – The case for the new model needs to be strengthened by further studies, including studies from other countries.

Practical implications – Maintenance activities will be more important as the large building stock from the 1950s and 1960s needs to be renovated or demolished. A rational structure and realistic expectations concerning maintenance planning is then important.

Originality/value – The most important contribution of the article is to underline the importance of different types of uncertainty for the structure of maintenance planning for building.

Keywords Property management, Maintenance planning, Maintenance programmes, Uncertainty management

Paper type Research paper

1. Introduction

The interest in building maintenance has increased in recent years, as more and more of the housing stock built in the decades after the Second World War is in need of major renovation. For example, approximately 1 million dwellings were constructed in Sweden in the period 1960-1970. The public sector also made large investments in, e.g. schools and hospitals during the same period. Currently, there is growing concern in Sweden and internationally about the expected huge cost of maintaining this aging housing stock (see, e.g. Boverket, 2002; Femenias and van Hal, 2009; Dieleman and Jobse, 1991).

Managers in the manufacturing industries have seen a paradigm shift in maintenance from something seen as a necessary evil to something that is an integral part of the business process with a focus on reliability and cost effectiveness (see, e.g. Moubray, 1997; Bejrum, 1999; Shen, 1997; Horner *et al.*, 1997; Ahuja and Khamba, 2008). The successes of various maintenance methods and strategies in the industrial sector have been well documented (see, e.g. Pintelon *et al.*, 2006; Pun *et al.*, 2002; Swanson, 2001; Bertling, 2002; Bevilacqua and Braglia, 2000; Chuenusa *et al.*, 2004;

Property Management
Vol. 30 No. 1, 2012
pp. 14-28

0263-7472
DOI 10.1108/02637471211198152

Lazim and Ramayah, 2010; Jonsson, 1997). However, the research on property maintenance is underdeveloped, as argued, e.g. in Wu *et al.* (2010).

This article focuses on maintenance planning. Property maintenance here primarily concerns the structural elements and fundamental systems in the building, not on more tenant related systems and service such as computer networks. Several Swedish studies, (e.g. Lind and Hellström, 2006; Muyingo, 2009b, c) show that many property owners make three- to five-year maintenance plans, but that they do not adhere to them for more than perhaps a few months. In a questionnaire reported in Muyingo (2009b) property managers were asked about how much of this year's maintenance that was included in last year's plan for this year, and the answer was around 50 percent. The share was of course even lower for earlier plans. This situation is a source of dissatisfaction for property managers who believe that maintenance plans should be followed to a larger extent and that postponement of planned measures was irrational from an economic perspective.

The main thesis in this article is that there are a number of uncertain factors that determine what is reasonable to do with a building. Therefore, it is not rational to make rather detailed long-term plans and then follow them. The proposition in this article is that there is a need to rethink maintenance strategy and maintenance planning from the perspective that we live in a world with a large number of uncertain factors.

The structure of the paper is as follows: In the next section the concepts of maintenance and strategy are discussed. Some results from studies of maintenance planning in other sectors are presented in section 3. Section 4 presents a number of stylized facts from studies of building maintenance which is followed by a description of the different types of uncertainty that affect maintenance planning and how they can explain the stylized facts. In section 5 we sketch a maintenance strategy that takes this uncertainty into account. Concluding comments can be found in section 6.

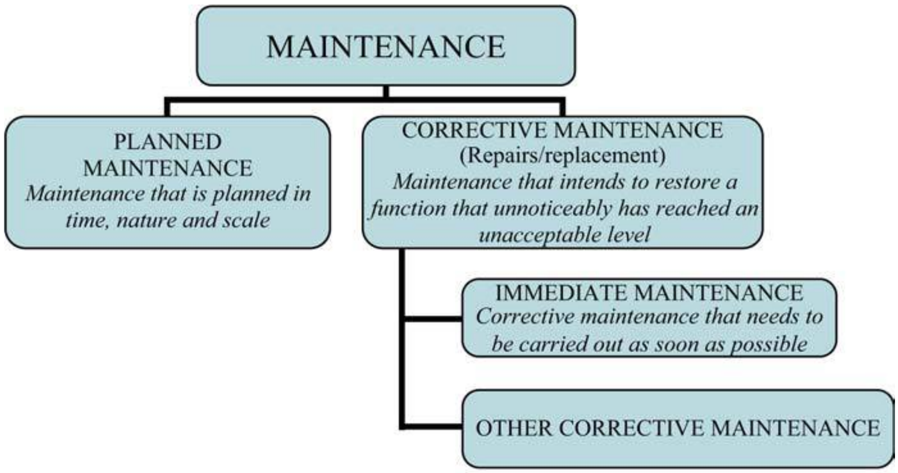
2. Defining "maintenance strategy"

2.1 Maintenance concepts

In this article maintenance will simply stand for measures taken in a given object. Often there is a distinction between maintenance, where the focus is on keeping up or restoring an existing function, and investment, where there is some kind of improvement of the object. This distinction has been questioned in Lind and Muyingo (2009a; cited in Muyingo(2009a)) but for the purpose of this article there is no need to draw an exact line and maintenance will here be given a broad meaning covering "all" measures taken concerning an existing building.

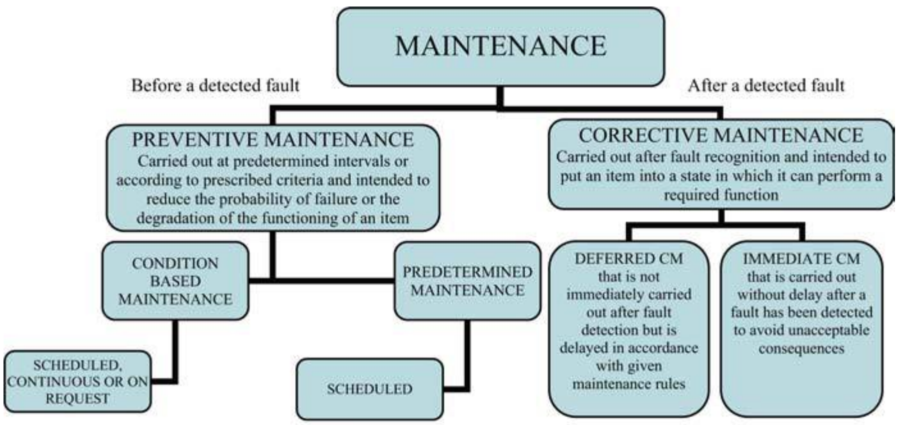
Maintenance can be divided into a number of specific types. Maintenance has been classified in a number of different ways. In AFF04, which is used in Sweden, and the European EN 13306 maintenance strategies are subdivided in the way described in Figure 1 and 2.

Corrective maintenance, also known as breakdown, failure based, run to failure or unplanned maintenance is the simplest type of classical maintenance policies where an item is used until it breaks/faults with the only activity centring on repair and servicing of the parts. Corrective maintenance can then be subdivided according to whether it is done immediately or deferred to a later date, and perhaps included in a longer run maintenance plan.



Source: Svenska Byggtjänst (2004)

Figure 1.
Overview of maintenance in AFF 04



Source: European Standards (2009)

Figure 2.
Overview of maintenance in EN 13306

Preventive (or planned) maintenance refers to cases where repairs and/or replacement take place without the occurrence of any specific fault. As the name indicates, the plan is to prevent failures. In many preventive maintenance models, the system is assumed to be as good as new after each maintenance whereas a more realistic situation is one in which the failure pattern of a preventively maintained system changes to somewhere between as good as new and as bad as old (Ben-Daya and Duffuaa, 1995). The preventive maintenance effects can be subdivided into a perfect, a non-effect and an imperfect effect where the perfect effect restores the system to good-as-new, a non-effect to bad-as-old, and an imperfect effect to partly good.

Preventive maintenance is usually further subdivided into condition-based maintenance, which is preventive maintenance where the object is inspected on a regular basis and the object serviced or replaced when a certain condition is observed, or time-based maintenance, which is preventive maintenance, whereby tasks are performed at a frequency dictated by the passage of time, regardless of the actual condition of an item. This may at times create problems where none existed before (Saranga, 2002).

Figure 3 presents some further concepts that can be found in the literature.

A new concept here is Opportunistic maintenance: This concept covers the case where various things are done because there arises an "opportunity" to carry out a certain activity in a cost-effective way. Typically during the performance of a scheduled or unscheduled maintenance action, a situation might arise where it is cost effective to carry out corrective maintenance on another previously undetected failing item or to reschedule another maintenance activity so as to take advantage of scale economies in the ongoing activity. Genetic algorithms as in Saranga (2004) or robust optimization as in Kuhn and Madanat (2006) can be used to decide on whether a particular item needs opportunistic maintenance and how cost effective this would be in comparison to a later grounding.

Advances in technology have made it possible to develop time-based and condition-based maintenance schedules. A predictive maintenance policy is one in which data is analyzed for a trend that would make it possible to forecast the performance degradation. Maintenance activities are then scheduled based on the expected time of future failure and other relevant aspects. Fault prognostic techniques in predictive maintenance can be utilized in an intelligent maintenance system with the purpose of achieving near-zero-downtime performance of equipment. McKone and Weiss (2002) present an evaluation of the simultaneous use of continuously predictive tools and traditional periodic maintenance tools.

2.2 Maintenance strategy

Strategy is defined in various ways in the literature and is not sharply demarcated from its closely related terms policy or concept as shown below.

A "policy", according to the Webster dictionary (Merriam Webster, 2011) is "a definite course or method of action selected from among alternatives and in light of given conditions to guide and determine present and future decisions." Waeyenbergh and Pintelon (2004) define maintenance policy as "a rule that specifies, depending on state variables, what to do exactly in a particular situation. According to Bevilacqua

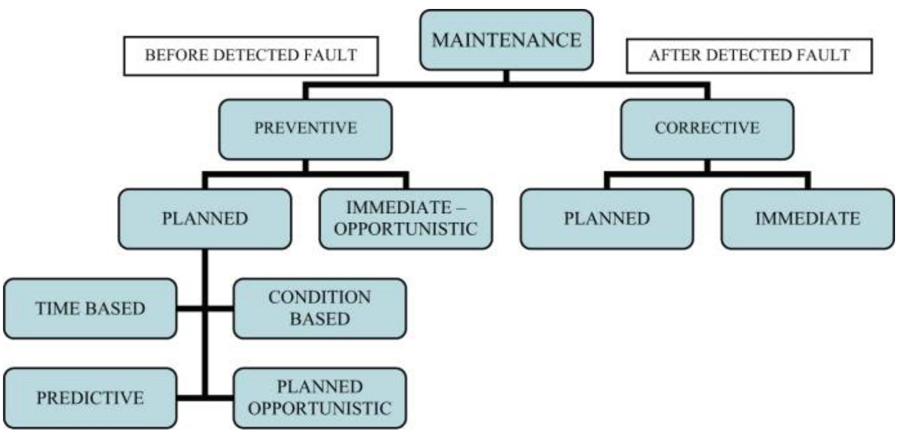


Figure 3.
An alternative model

and Braglia (2000), each maintenance policy is a strategy of its own and they use the term "concept" as a synonym. In contrast, Pintelon *et al.* (1999) define maintenance concept as "the set of various maintenance interventions (corrective, preventive, condition-based, etc) and the general structure in which these interventions are brought together". Horner *et al.* (1997) and Al-Najjar (1996) also refer to the above activities as concepts but they list them under maintenance strategies.

Dunn (2003) defines a maintenance strategy as "a long-term plan, covering all aspects of maintenance management which sets the direction for maintenance management, and contains firm action plans for achieving a desired future state for the maintenance function." In ISO 9000, which consists of standards and guidelines relating to quality management systems and related supporting standards, a strategy is defined as "an elaborate and systematic plan of action". However, the European standard on maintenance (EN 13306) simply defines a maintenance strategy as "a management method used to achieve the maintenance objectives" and no distinction between a maintenance strategy and a maintenance type is made.

Moubray (1997) traces maintenance through three generations depicted by a "fix it when it broke" mentality before World War 2, the development of preventive maintenance between 1950 to the late 1970s and a more condition-based maintenance approach from the early 1980s to the present. He ascertains that in order to choose or develop an appropriate maintenance strategy the firm needs to "determine the maintenance requirements of each asset in its operating context and then decide what resources are needed to fulfil those requirements."

3. Maintenance in other sectors

A study of the status of maintenance management in Swedish manufacturing firms found that only 48 percent of the companies had a documented strategy while 23 percent of the companies did not have any maintenance strategy at all (Jonsson, 1997). It was further noted that "the proportion of firms having fully developed written maintenance strategies is probably actually lower than the 48 percent reported, since some of the respondents considered ISO 9000 to be the written strategy". An elaborate analysis of success factors and problems in ISO 9000 Maintenance can be found in Wahid and Corner (2009).

Lind and Muyingo (2009b; cited in Muyingo (2009a)) find some especially interesting features in the maintenance models used in different sectors outside the real estate sector as given below:

- There is a focus on collection of information that makes it possible to predict failure rates. The assignment of responsibility to a smaller group of people is also a way to increase the available information about how a system works. It is clear that in order to have cost effective maintenance an accessible and dynamic information bank of all maintenance activities at all levels is essential as applied in the aircraft industry; the electric power distribution industry and in power generation (see, e.g. Almgren et al., 2008Bertling, 2002; Backlund and Akersten, 2003; Landqvist, 2004).
- There is also an explicit modelling of the "revenue" side of maintenance, based on failure rates and failure costs. In this model an optimizing framework can be formulated where the cost of a specific maintenance policy can be compared to the expected revenue from this maintenance policy as applied in the sectors

mentioned above as well as in the train and military tanks industry (see, e.g. Allström and Bengtsson, 2002; Bengtsson, 2007).

- There is a move away from time-based maintenance to condition-based maintenance. The problem with time-based maintenance is that it tends to lead to over-maintenance, especially if it is based on recommendations from a manufacturer where reducing the risk of failure of their product is more important than reducing costs. This move towards condition-based maintenance can also be seen as the result from a more systematic collection of information that increases knowledge about the relation between the condition of a specific structure and the effects on production and the probability of failure. Examples can be found in the shipping industry (see, e.g. Gunnarsson and Andersson, 2006; Mokashi *et al.*, 2002); the food industry (see, e.g. Tsarouhas, 2007) as well as the train industry presented in Allström and Bengtsson (2002).

The results from the case studies from different sectors listed above are also in line with general ideas about when different maintenance strategies should be used.

Corrective maintenance. Corrective maintenance is justifiable when the impact of failure is rather small. As corrective maintenance can lead to inconvenience caused by the unplanned failure and corresponding downtime in dependant systems, and the situation must be such that these costs are rather small. Alternatively there must be an organization (personnel, spare parts) for carrying out corrective maintenance quickly. The problem with corrective maintenance is that faults may occur in unexpected ways and at the "wrong time" leading to higher costs than expected.

Preventive maintenance. Preventive maintenance is rational if the consequences of a fault are high in relation to the cost of doing something that in advance reduces the risk for a fault. Preventive maintenance also provides the advantage of being able to perform activities when it is convenient to the user. The decision to carry out preventive maintenance can be based either on the age, the period between activities or on the monitored conditions of the item, depending on the specific situation. This approach provides a reduced probability of equipment failures and extends equipment life. However, under this approach a number of unnecessary tasks will be carried out on items that could have remained in a safe and acceptable operating condition for a much longer time. These costs will be high if it is difficult to predict when something has to be done in order to reduce the risk for faults, and when it is important to avoid faults. This can explain the increased focus on collecting information mentioned above.

As noted by Tsang (2002) the replacement schedule is often drawn up on the supplier's recommendation. The supplier, however, has limited or no local knowledge of actual use conditions or past experience in the specific case, and, as mentioned above, an incentive to overestimate the need for replacement. Nowlan and Heap (1978)[1] identified six patterns of failure and showed that close to 90 percent of all items experienced failures where reliability would not have been improved by a time-based schedule. Zhao (2003) suggests a preventive maintenance policy based on a critical reliability level and not time. The stochastic nature of deteriorations has been modelled in a number of operational research optimization models. Tsai *et al.* (2001) use genetic algorithms to obtain an optimal solution that maximizes unit-cost life based on the extended life after a preventive maintenance action. Badia *et al.* (2002) suggest an optimal period for the inspection as well as preventive maintenance of units with revealed and hidden failures.

One way to reduce the cost of preventive maintenance strategies is to use a condition-based maintenance strategy, as it is then more likely to make repairs only when necessary. This strategy is however also based on some assumptions, e.g. that the current condition is a good predictor of the probability of faults. It is also assumes that it is possible with continuous survey and that this provides useful information. Electrical faults are an example of hard faults that are difficult to localize but easy to rectify when found. Mechanical faults are an example of soft faults that are easily identified but require a lot of time to restore. Bahrami et al. (1998); Saranga and Knezevic (2000); Marseguerra *et al.* (2002); and Barbera *et al.* (1999) all discuss and provide models for the optimal condition-based maintenance of continuously deteriorating systems.

As some items might be inaccessible it is impossible to monitor every item in a system in a cost effective way which limits the extent to which condition-based maintenance can be efficient. In such cases an alternative policy is that of opportunistic maintenance as described above.

The choice between corrective and preventive maintenance is implicitly or explicitly analyzed as a balancing of what could be called errors of type 1 and errors of type 2, using some concepts from statistics. In this context the following interpretations could be given:

- *Error of type 1*: When preventive maintenance is used, an action can be taken though afterwards it is observed that it was not necessary. This is the basic risk of "preventive maintenance", whereby things are done that in the end would not have been necessary, e.g. because it is shown that the component has a longer life than expected, or because some external events necessitate more drastic measures.
- *Error of type 2:* When preventive maintenance is not used then it might happen that a series of corrective measures are needed when something happens. With hindsight - it would have been much cheaper if parts have been replaced before they broke down. This could be the case whereby the corrective measures turned out to last a much shorter time than expected due to the condition of the system being worse than expected.

A conclusion that we will return to later is that in a world of uncertainty, all maintenance policies can, with hindsight, turn out to be mistakes.

4. Building maintenance strategies and uncertainty

4.1 The stylized facts

The results from several studies about building maintenance in Sweden (e.g. Lind and Hellström, 2006; Muyingo, 2009b, c) can be summarized in the following stylized facts:

- A large share of maintenance activities are corrective maintenance carried out when faults suddenly are observed.
- Detailed maintenance planning covers a short period of time, maybe a year, and the specific maintenance actions are rescheduled all the time. In Muyingo (2009b) a question was asked as to the size of this year's maintenance that was included

in last year's plan and the answer was that approximately only 50 percent of the work carried out. When more long run plans are made, maybe three to five years, it only takes a few months before they are outdated.

- There is a considerable amount of opportunistic maintenance. When, e.g. a building is to be changed in a specific way because the tenants' needs have changed, or some corrective maintenance must be carried out, other maintenance measures are taken at the same time.
- Maintenance measures are affected by the budget situation. When a property owner, especially a public authority, has money left in its "investment budget", or when the economic situation is good, then more maintenance is carried out. When the economic situation becomes tougher, then maintenance expenditure is reduced.

The standard reaction to the stylized facts above is that planning of building maintenance is underdeveloped and the goal should be to build up a system that resembles the systems from various industrial sectors, e.g. the airline industry, where there are more detailed plans that are followed rather closely.

The main thesis in the follow sections is that this view is mistaken, and that the building maintenance patterns above can be explained as a rational adaption to the different types of uncertainty that have a bearing on building maintenance. An overview of different types of uncertainty and their general effect is given in the next section. The focus is on what we believe are the main types of uncertainty.

4.2 Uncertainties affecting building maintenance

Uncertainty about the structure of the object. One special problem when planning maintenance on buildings is lack of information about the actual structure of the building:

> Original specifications may not be available for older buildings, and even if they are available they may not be correct as adjustments and changes might have be done on the worksite, or that changes were made later but not recorded as noted by Lundqvist (2003) in his study involving the reconstruction of office buildings. Mattsson (2008) provides examples of cases where contractors found out just before maintenance work was about to start that the objects – in this case bridges – were not built in the way believed.

This has the effect that changes in the maintenance plans might have to be made when the "true" characteristics of the object are found out. As maintenance on this object may become more expensive than expected, the consequence can also be that other maintenance measures have to be postponed.

Uncertainty about expected life-times. When objects have a long life it is more difficult to build up knowledge about the expected life-time of the object, especially as technical changes over time lead to changes in techniques used and a situation where each object is unique and built on site. A building consists of several integrated systems, and even if it would be possible to build up knowledge about each specific part, knowing how they interact is another thing. Ilina (2010) describes how one of the major safety problems in nuclear power plants today is that most power plants have gone through major renovations and that there are uncertainties about how the old system and the new system interact.

This can be compared with the situation in some of the articles above that analyzed identical manufactured objects produced in large numbers (see, e.g. the study on trains and military tanks in Bengtsson, 2007). Mass production makes it is possible to build up knowledge rather quickly about probabilities of break-down in various parts and optimal times for planned replacements are then easier to calculate.

Quicker technical changes can however make the differences smaller, and even if there are changes in the mass production – such as that of a new car model almost every year – the underlying platform may not change so much and then it would still be possible to build up knowledge of the degradation process and optimal times for various measures.

The degradation process may also depend on specific unknown characteristics and on the interaction with the environment. Jakobsson (2008) describes a case where a number of similar buildings built at the same time degraded very differently. The study focused on sewer pipes and the differences in actual characteristics where believed to be caused by quality differences between batches of the plastic pipes or in differences in the quality of the on-site works, but in some cases also in differences in the micro-climate.

If the expected life-time is uncertain, the two risks described above becomes very serious. If one wants be on the safe side, measures have to be taken very early and this drives up costs. According to Muyingo (2009a), one of the explanations of the higher maintenance costs in Swedish municipal housing companies is that they are doing things "too early" compared to more profit maximizing private companies. Whatever the strategy followed incidents might still happen earlier than expected and then the unexpected urgent measures lead to postponement of other less urgent actions.

Uncertainty about costs of specific measures. Even if there are no surprises concerning the technical conditions and technical breakdowns, maintenance plans might still be changed because of uncertainty about the cost of a specific measure. Most organizations work within some kind of economic framework, such as yearly budgets, that should be kept in the public sector. In private companies there is typically also a wish to show stable results and therefore an interest in smoothing costs. This means that when there is a difference between expected cost and actual cost then it will in general lead to rescheduling of other measures.

The reason for the change in cost might of course be related to the technical aspects mentioned above but there might also be changes in prices. Many larger maintenance works are procured on the open market where prices are sensitive to the general business cycle and this can lead to both higher and lower prices than expected.

The value of the option to wait. In a situation of uncertainty it might be rational to wait whereby new information can affect the value of this option. A typically case is when a new technique is introduced, e.g. relining instead of replacement of sewer pipes. Initially, a technique is more uncertain and more costly as few firms have knowledge of the technique. In such a situation the value of the option to wait might increase as new information indicates that a new cheaper technique might be available in a few years.

The alternative to wait might also be more attractive when there are signals about policy changes, e.g. subsidy to energy efficiency measures. It might thus be rational to put a measure on hold in a situation where there might be subsidies in a near future.

The value of waiting might also change because of changes in the expected need of the building. When an economic crisis hits a country industrial firms may reduce building maintenance because the probability of having to close down the factory has increased. Many municipalities in Sweden are affected by new policies that allow parents to freely choose schools for their children away from the principle of automatic placement in the school closest to the child's home. The municipalities do not know how many of their schools will be needed in the future and then it is rational to postpone maintenance measures in a school that might not be needed in a few years time.

Summing up. The different factors described above must be seen as a set of interacting factors. The combination of more or less binding yearly budgets in combination with the technical uncertainties and cost uncertainties leads to constant rescheduling of maintenance activities. A precondition is of course that there is a set of maintenance activities that are economically rational to carry out, but where the exact timing of the measure might not be so important. It is possible to wait with a number of measures without any known serious consequences, or to put it more formally: a curve showing the profit for various alternative replacement times is rather flat within a rather large interval. Given the risk of leaks the roof should be replaced after around 50 years, but if it is replaced after 45 years or 55 years is not so clear.

5. Maintenance planning under high uncertainty

The analysis above does not mean that everything is well with building maintenance, but it suggests that the goal should not be to copy maintenance planning from other sectors. Building maintenance planning has to be adapted to the specific circumstances described above.

Here are some general ideas, based primarily on a study of maintenance planning for schools in Swedish municipalities described in Lind and Hellström (2006) and Lind and Lundström (2010).

(1) A precondition for good planning with unpredictable objects is a good information system with a conscious balancing of costs and benefits of different alternative ways of collecting the types of information needed. This information includes the needs and plans of the users of the building, e.g. plans for the development of the school sector and the condition and functioning of the building. There are number of ways of collecting such information, e.g.:

- automatic monitoring, e.g. found in modern ventilation and heating systems;
- inspections rounds with intervals; and
- feedback from users.

This can be seen as a type of decision support system such as discussed in Zavadskas *et al.* (2010) that focuses on real estate, or as a knowledge management system of the type discussed for infrastructure in general in Illina and Sundquist (2010). Useful questions to ask in the consideration of the decision support system are: for what building systems should automatic monitoring systems be installed; how should inspections be scheduled and is there a way to learn from experiences from other owners of similar buildings?

(2) Divide the buildings into core and non-core buildings with different maintenance strategies, with more planned and preventive maintenance on the core buildings and more corrective maintenance in the non-core buildings. This is even more crucial especially for special purpose buildings where the planning should be based on and carried out together with the user. It is easy to

find examples where maintenance has been carried out rather close in time to a close-down of an activity. That this happens now and then is inevitable, but sometimes it has occurred because of lack of communication between the manager of the building and those responsible for the activities in the building.

(3) Divide the components of the building into components that are more or less crucial for the long run value of the buildings and for the activities carried out in the building. Typically the shell of the building is given general priority and also other systems crucial to the building's activities, e.g. the heating system in an old-age home or the electricity system in a hospital.

Point 2 and 3 also affects the amount of resources that should be spent on collecting various types of information. For crucial features in core buildings it can be rational to invest more in collecting information, e.g. through automatic systems with sensors.

(4) Working with a set of projection/plans with different time spans and levels of details. It can be rational to have, e.g.

- One very rough 20-year plan primarily made to identify the risk that a lot of maintenance activities have to be carried out at the same time. An example: The public sector expanded quickly in Sweden during the 1960s and 1970 when also urbanization was strong. If, e.g. windows and roofs have to be replaced or maintained after 40-50 years then a peak in maintenance was to be expected 2000-2020. Knowing this in advance makes it possible to perhaps start a little early and also investigate different maintenance strategies that may reduce cost and spread the cost over a longer period of time.
- A somewhat more detailed 3-5 year plan where major renovations and maintenance activities are scheduled.
- A detailed plan for maintenance activities the coming year. Given the uncertainty described above and the importance of corrective and opportunistic maintenance the yearly plan has to be updated several times a year and the three- to five-year plan every year.

(5) In the public sector for example, it also important with continuous information to the users and perhaps also the general public about plans for specific buildings coupled with continuous updates. This makes a web-based system ideal where, e.g. users can log-in and find out the situation concerning the planned maintenance. The plans mentioned above can then be integrated with this information system.

6. Concluding comments

Maintenance activities will become more and more important given the high volume of building activities carried out in the post-war period, and the planning and implementation of these plans are crucial for economic efficiency. In this article we especially underlined the importance of adapting maintenance planning to the specific characteristics of the real estate sector. Unique and complex objects with a strong interaction with the environment makes in almost impossible to predict the degradation process and the lift-time of different components. Economic changes also affect what is rational to do with a specific building. This means that a flexible planning system has to be built up, where continuous adjustment of the plans is an integrated part of the system. A decision support or knowledge management system is then as crucial as the direct planning system.

With reference to future research one area that is also important to study is the procurement of maintenance activities. For new buildings in the public sector there is for example a lot of discussion about the use of Public Private Partnership where construction and maintenance is integrated in the initial procurement as discussed in Borg and Lind (2010) and other articles in the same issue. For existing buildings there is a choice between more long-term maintenance contracts based on functional characteristics as discussed in Lind and Mattsson (2009) or separate procurement of specific maintenance activities. What should be done in-house and what should be procured is then of course also an important question to consider.

Note

1. Cited in Dunn (2003).

References

Ahuja, I. and Khamba, J. (2008), "Total productive maintenance: literature review and directions", *International Journal of Quality & Reliability Management*, Vol. 25 No. 7, pp. 709-56.

Allström, R. and Bengtsson, M. (2002), Tillståndsbaserat underhåll – En överblick av underhållsteorin samt teknikensmöjligheter på spårfordon (Condition-based maintenance-An overview of the maintenance theory and its potentials on rail vehicles), masters thesis, IDT-Mälardalens Högskola, Mälardalens University, Västerås.

Almgren, T., Andréasson, N., Anevski, D., Patriksson, M., Strömberg, A.-B. and Svensson, J. (2008), "Optimization of opportunistic replacement activities: a case study in the aircraft industry", Math Department, Chalmers University, Gothenberg, available at: www.math.chalmers.se/Math/Research/Preprints/2008/45.pdf (accessed January 29, 2011).

Al-Najjar, B. (1996), "Total quality maintenance: an approach for continuous reduction in costs of quality products", *Journal of Quality in Maintenance Engineering*, Vol. 2 No. 3, pp. 4-20.

Backlund, F. and Akersten, P.A. (2003), "RCM introduction: process and requirements management aspects", *Journal of Quality in Maintenance Engineering*, Vol. 9 No. 3, pp. 250-64.

Badia, F., Berrade, M. and Campos, C.A. (2002), "Optimal inspection and preventive maintenance of units with revealed and unrevealed failures", *Reliability Engineering and System Safety*, Vol. 78 No. 2, pp. 157-63.

Bahrami-Ghasrchami, K., Price, J. and Mathew, J. (1998), "Optimum inspection frequency for manufacturing systems", *International Journal of Quality & Reliability Management*, Vol. 15 No. 3, pp. 250-8.

Barbera, F., Schneider, H. and Watson, E. (1999), "A condition-based maintenance model for a two-unit series system", *European Journal of Operational Research*, Vol. 116 No. 2, pp. 281-90.

Bejrum, H. (1999), "Se om sitt hus. Strategi för underhåll av offentliga fastigheter" (Maintain Your House – Strategies for Maintenance of Public Properties), report written for the Organisation of Local Governments in Sweden, Stockholm, Svenska Kommunförbundet, Stockholm.

Ben-Daya, M. and Duffuaa, S.O. (1995), "Maintenance and quality: the missing link", *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 1, pp. 20-6.

Bengtsson, M. (2007), "On condition-based maintenance and its implementation in industrial settings", doctoral thesis, IDT-Mälardalen University, Västerås.

Bertling, L. (2002), "Reliability centred maintenance for electric power distribution systems", doctoral dissertation, Department of Electrical Engineering, Royal Institute of Technology, Stockholm.

Bevilacqua, M. and Braglia, M. (2000), "The analytic hierarchy process applied to maintenance strategy selection", *Reliability Engineering and System Safety*, Vol. 70 No. 1, pp. 71-83.

Borg, L. and Lind, H. (2010), "Service-led construction: is it really the future?", *Construction Management and Economics*, Vol. 28 No. 11, pp. 1145-53.

Boverket (2002), *Bättre koll på underhåll* (*Better Tracking of Maintenance*), Boverket, Karlskrona.

Chuenusa, C., Ramnik, B. and Jiju, A. (2004), "The status of maintenance management in UK manufacturing organisations: results from a pilot study", *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 1, pp. 5-15.

Dieleman, F.M. and Jobse, R.B. (1991), "Multi-family housing in the social rental sector and the changing Dutch housing market", *Housing Studies*, Vol. 3 No. 3, pp. 193-205.

Dunn, S. (2003), "The fourth generation of maintenance", available at: www.plant-maintenance.com/articles/4th_Generation_Maintenance.pdf (accessed January 29, 2011).

European Standards (2009), EN – 13306 maintenance terminology, available at: www.en-standard.eu/csn-en-13306-maintenance-terminology/ (accessed January 29, 2011).

Femenias, P. and van Hal, A. (2009), "Pathways for sustainable housing transformations: an international comparison of retrofitting strategies for (social) housing", *Proceedings of the International Conference on Smart and Sustainable Built Environment*, available at: www.sasbe2009.com (accessed May 31, 2011).

Gunnarsson, C. and Andersson, T. (2006), "Tillgänglighetsbaserat underhåll för ubåtssytem" (Availability-based maintenance for a submarine system), master's thesis, Marina System, KTH, Stockholm.

Horner, R.M., El-Haram, M.A. and Munns, A.K. (1997), "Building maintenance strategy: a new management approach", *Journal of Quality Maintenance Engineering*, Vol. 3 No. 4, pp. 273-80.

Ilina, E. (2010), "Understanding the application of knowledge management to safety critical facilities", doctoral thesis, BYV-KTH, Stockholm.

Illina, E. and Sundquist, H. (2010), *Challenges to Transport Infrastructures and a Need for Knowledge Management*, BYV-KTH, Stockholm.

Jakobsson, J. (2008), "Fastighetsbolagens arbetsmetoder vid förnyelsen av Järva", master's thesis, Department of Real Estate and Construction Management, Royal Institute of Technology, Stockholm.

Jonsson, P. (1997), "The status of maintenance management in Swedish manufacturing firms", *Journal of Quality in Maintenance Engineering*, Vol. 3 No. 4, pp. 233-58.

Kuhn, K.D. and Madanat, S.M. (2006), "Robust maintenance policies for Markovian systems under model uncertainty", *Computer-aided Civil and Infrastructure Engineering*, Vol. 21 No. 3, pp. 171-8.

Landqvist, S. (2004), "Jämförelse av underhållsmodeller vid de nordiska kraftverken" ("A review of maintenance models within the Nordic nuclear power plants"), master's thesis, EE-KTH, Stockholm.

Lazim, H.M. and Ramayah, T. (2010), "Maintenance strategy in Malaysian manufacturing companies: a total productive maintenance (TPM) approach", *business strategy series*, Vol. 11 No. 6, pp. 387-96.

Lind, H. and Hellström, A. (2006), "Kommunala underhållsstrategier och underhållsplaner – med fokus på skolbyggnader" ("Local government maintenance strategies and maintenance plans – with a focus on school buildings"), report written for the Organisation of Local Governments in Sweden, Svenska Kommunförbundet, UFOS, Stockholm.

Lind, H. and Lundström, S. (2010), "Fastighetsföretagande i offentlig sektor: strategiska frågor och den samlade kunskapen" ("Real estate management in Swedish public sector: strategic issues and collected knowledge"), report written for the Organisation of Local Governments in Sweden, SKL Kommentus, Stockholm.

Lind, H. and Mattsson, H. (2009), "Experiences from procurement of integrated bridge maintenance in Sweden", *European Journal of Transport and Infrastructure Research*, Vol. 9 No. 2, pp. 143-63.

Lind, H. and Muyingo, H. (2009a), *Investment Theory and Why We Do Not Need the Concept of Maintenance*, BYFA, KTH, Stockholm.

Lind, H. and Muyingo, H. (2009b), *Is There Anything Special with Building Maintenance?*, BYFA, KTH, Stockholm.

Lundqvist, J. (2003), "Risker i ombyggnadsprojekt – utredning av juridiska, tekniska samt marknadsmässiga risker vid ombyggnad av kommersiella lokaler" (Risks in reconstruction projects – study on legal, technical and market related risks in reconstruction of commercial properties), Master's thesis, ABE-KTH, Stockholm.

McKone, K.E. and Weiss, E.N. (2002), "Guidelines for implementing predictive maintenance", *Production and Operations Management*, Vol. 11 No. 2, pp. 109-24.

Marseguerra, M., Zio, E. and Podofillini, L. (2002), "Condition-based maintenance optimization by means of genetic algorithms and Monte Carlo simulation", *Reliability Engineering and System Safety*, Vol. 77 No. 2, pp. 151-65.

Mattsson, H.-Å (2008), "Integrated bridge maintenance – evaluation of a pilot project and future perspectives", doctoral thesis, BYV-KTH, Stockholm.

Merriam Webster (2011), "Definition of policy", available at: www.merriam-webster.com/dictionary/policy?show=0&t=1297688292 (accessed February 14, 2011).

Mokashi, A.J., Wang, J. and Vermar, A.K. (2002), "A study of reliability-centred maintenance in maritime operations", *Marine Policy*, Vol. 26 No. 5, pp. 325-35.

Moubray, J. (1997), *Reliability-centred Maintenance*, Industrial Press, New York, NY.

Muyingo, H. (2009a), "Property maintenance – concepts and determinants", licentiate thesis, ABE-KTH, Stockholm.

Muyingo, H. (2009b), "The effect of the ownership category on the maintenance costs of housing companies", paper in licentiate thesis, ABE-KTH, Stockholm.

Muyingo, H. (2009c), "Managing special purpose propoerties: a case study of the current practises in the state, county and industrial companies in Sweden", paper in licentiate thesis, ABE-KTH, Stockholm.

Pintelon, L., Nagarur, N. and Van Puyvelde, F. (1999), "Case study: RCM – yes, no or maybe?", *Journal of Quality in Maintenance Engineering*, Vol. 5 No. 3, pp. 182-91.

Pintelon, L., Pinjala, S.K. and Vereecke, A. (2006), "Evaluating the effectiveness of maintenance strategies", *Journal of Quality in Maintenance Engineering*, Vol. 12 No. 1, pp. 7-20.

Pun, K.-F., Chin, K.-S., Chow, M.-F. and Lau, H.C. (2002), "An effectiveness-centred approach to maintenance management: a case study", *Journal of Quality in Maintenance Engineering*, Vol. 8 No. 4, pp. 346-68.

Saranga, H. (2002), "Relevant condition-parameter strategy for an effective condition-based maintenance", *Journal of Quality in Maintenance Engineering*, Vol. 8 No. 1, pp. 92-105.

Saranga, H. (2004), "Opportunistic maintenance using algorithms", *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 1, pp. 66-74.

Saranga, H. and Knezevic, J. (2000), "Reliability analysis using multiple relevant condition parameters", *Journal of Quality in Maintenance Engineering*, Vol. 6 No. 3, pp. 165-76.

Shen, G.Q. (1997), "A comparative study of priority setting methods for planned maintenance of public buildings", *Facilities*, Vol. 15 Nos 12/13, pp. 331-9.

Swanson, L. (2001), "Linking maintenance strategies to performance", *International Journal of Production Economics*, Vol. 70 No. 3, pp. 237-44.

Tsai, Y.-T., Wang, K.-S. and Teng, H.-Y. (2001), "Optimizing preventive maintenance for mechanical components using genetic algorithms", *Reliability Engineering and System Safety*, Vol. 74 No. 1, pp. 89-97.

Tsang, A.H. (2002), "Strategic dimensions of maintenance management", *Journal of Quality Maintenance Engineering*, Vol. 8 No. 1, pp. 7-39.

Tsarouhas, P. (2007), "Implementation of total productive maintenance in food industry: a case study", *Journal of Quality in Maintenance Engineering*, Vol. 13 No. 1, pp. 5-18.

Waeyenbergh, G. and Pintelon, L. (2004), "Maintenance concept development – a case study", *International Journal of Production Economics*, Vol. 89 No. 3, pp. 395-405.

Wahid, R.A. and Corner, J. (2009), "Critical success factors and problems in ISO 9000 maintenance", *International Journal of Quality & Reliability Management*, Vol. 26 No. 9, pp. 881-93.

Wu, S., Neale, K., Williamsson, M. and Hornby, M. (2010), "Research opportunities in maintenance of office building services systems", *Journal of Quality in Maintenance Engineering*, Vol. 16 No. 1, pp. 23-33.

Zavadskas, E.K., Kaklauskas, A. and Banaitis, A. (2010), "Real estate's knowledge and device-based decision support system", *International Journal of Strategic Property Management*, Vol. 14 No. 3, pp. 271-82.

Zhao, Y.X. (2003), "On preventive maintenance policy of a critical reliability level for system subject to degradation", *Reliability Engineering and System Safety*, Vol. 79 No. 3, pp. 301-8.

Further reading

Bengtsson, P. (2003), "Study of method for analysis of the preventive maintenance as a part of the system evaluation process for JAS 39 GRIPEN", thesis, Mälardalen University, Västerås.

International Organisation of Standardisation (ISO) (2011), ISO-9000, available at: www.iso.org/iso/iso_catalogue/management_and_leadership_standards/quality_management.htm (accessed January 29, 2011).

Corresponding author

Hans Lind can be contacted at: hans.lind@abe.kth.se

This article has been cited by:

1. Adnan Ali Enshassi, Farida El Shorafa. 2015. Key performance indicators for the maintenance of public hospitals buildings in the Gaza Strip. *Facilities* **33**:3/4, 206-228. [Abstract] [Full Text] [PDF]
2. Sunday Julius Odediran, Job Taiwo Gbadegesin, Mujidat Olubola Babalola. 2015. Facilities management practices in the Nigerian public universities. *Journal of Facilities Management* **13**:1, 5-26. [Abstract] [Full Text] [PDF]
3. Mangano Giulio, De Marco Alberto. 2014. The role of maintenance and facility management in logistics: a literature review. *Facilities* **32**:5/6, 241-255. [Abstract] [Full Text] [PDF]
4. Taewoo Ko, Moonseo Park, Hyun-Soo Lee, Hyunsoo Kim, Sooyoung Kim. 2014. Fuzzy-based Decision Support Model for Determining Preventive Maintenance Works Order. *Korean Journal of Construction Engineering and Management* **15**, 51-61. [CrossRef]
5. Elena Fregonara, Rocco Curto, Mario Grosso, Paolo Mellano, Diana Rolando, Jean-Marc Tulliani. 2013. Environmental Technology, Materials Science, Architectural Design, and Real Estate Market Evaluation: A Multidisciplinary Approach for Energy-Efficient Buildings. *Journal of Urban Technology* **20**, 57-80. [CrossRef]