

“Durability and Reliability, Alternative Approaches to Assessment of Component Performance Over Time”

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Abstract

This paper will describe some of the findings of the current UK Teaching Company Directorate funded collaborative research between consultants, Building Performance Group and the University of the West of England. The objective of the research is to provide a practical database on the durability of components and materials used in the construction industry. The current second stage of the research is focused on mechanical and electrical services systems and components in commercial buildings. The paper will compare the type of service life data available for commercial building services systems and components with building fabric components. The different types of data and failure pattern curves indicate that a different approach to maintenance management may introduce higher levels of reliability and sustainability in buildings.

The use of reliability engineering in the assessment of component service life is contrasted with the construction industry's current approach using durability. Techniques including reliability-centred maintenance and condition monitoring will be discussed in relation to the assessment of environmental, economic and life cycle performance. There will also be an analysis of one statistical method of modelling performance that can be used to optimise maintenance and renewal of building services systems and components.

Keywords : Building fabric, building services, durability, function, life-cycle, maintenance, sustainability, reliability, service life, statistical analysis, Weibull.

1 Introduction

In response to the increased need for data on the service life of building components, Building Performance Group (BPG) and the University of the West of England have been carrying out a four year research project sponsored by the UK Teaching Company initiative. The current research relates to mechanical and electrical (M&E) building services components in commercial and industrial buildings. The main objective of the research is to produce a unique database of building component service life data. The research has already contributed to the Housing Association Property Mutual (HAPM) “Component Life Manual” [1], and it is hoped that a similar component manual will be produced for M&E services components.

This paper examines the differences in the types of data, and failure distributions between fabric components and M&E services components in buildings. It is desirable to integrate the two types of data sets into a common format in order to facilitate the development of a single “cost in use” model for buildings. It seems that the construction industry has a definite need for the data in this format. The principle of reliability will be discussed in comparison to durability together with a review of the relevance of historical data. The findings indicate that a different approach to maintenance management based on reliability studies may promote more cost-effective and sustainable use of resources. Techniques including reliability-centred maintenance and condition monitoring will be discussed in relation to the life cycle, environmental, and economic performance over time. There will also be an analysis of the statistical models for service life prediction that can be used to optimise renewal of building services systems and components.

2 Different Approaches to Data Collection

The first phase of the research developed a broad methodology for the service life assessment of building components and has been adapted to building services :

- Identify potential existing sources of data on the durability of building services plant and equipment by reference to relevant organisations and published sources.
- Assemble a knowledge base of information on the durability and failure modes of selected building services plant and equipment.
- Extend the scope of the existing building component lifespan database to include data on a range of building services components and equipment for commercial buildings.

The assessment of building services life and failure compared with building fabric has highlighted some key differences. Due to the dynamic nature of M&E services components, failure may cause much greater disruption to the operation of business than fabric materials. For example, the failure of a boiler is far more of a problem than a cracked floor tile or peeling paint. On the other hand, concrete gets stronger over time, while bearings wear out. Failure and service life of M&E components are thus examined in terms of reliability rather than durability. Reliability engineering is a science in itself with

component life generally measured more accurately in hours rather than years.

M&E services components can fail due to a wide range of failure modes. The commissioning process and warranty period should resolve many of the early stages of potential failure with M&E components. This represents the “burn-in” or “infant mortality” stage of a failure distribution (see Figure 1). Failures occurring in the stages **after** this period are perhaps the most important from a service life point of view, especially when **failures** are often beyond warranty periods provided by manufacturers, and can lead to full-scale replacement rather than repair. The following describes what data and methodologies are available for failure management, and how this data can be used to ensure selection of reliable building services components. The technical failure history issue has attracted much discussion in the field of reliability engineering. Numerous paradoxes and shortcomings occur in relation to maintenance policy and historical life data :

- (1) It has been suggested that if we are collecting failure data then it is because the failures are not being prevented (“The Resnikoff Conundrum”) [2].
- (2) Planned preventative maintenance (PPM) prevents the failures occurring for which we need data to optimise PPM.
- (3) PPM often leads to failures occurring either due to human error or simply de-stabilizing and disruption of a sophisticated system.

“Burn-in” failures are in effect re-introduced each time “preventive” maintenance is carried out. Studies on the reliability of boiler plant [3] illustrated this fact in the concluding thoughts on the research : *“A disturbing outcome of the study has been the effects of servicing on plant reliability. The probability of plant failure increases considerably in the months following a service visit?”* In addition some of the worst industrial catastrophes in recent history have been caused by unnecessary maintenance intervention, eg. Piper Alpha and Bhopal [2]. Further discussion on the effects of maintenance policy on component lives is further discussed in section 6.

It is often thought that the ultimate aim in service life data collection is to gain real data from installations where the history is well known or has been modelled over a certain period of time. It is true that this may be the most useful situation but the discussed failure process issues must first be taken into consideration. Historical records do, however, have a major part to play and should be used to reduce routine maintenance to the minimum, and determine less disruptive maintenance programs.

The problem of deciding on the level of data collection required to manage maintenance and performance has been identified in other industries, and has led to a “paradigm flip” [4]. The old paradigm was to gather information in hope of improving performance, in terms of service life which may be equated to the study of durability. The new paradigm is to ask what information is needed to determine the possible performance, reduce the gap between current and possible performance, and maintain that new performance level. The research aims to provide an indication of what performance is possible with components through the study of their reliability. Where there are large numbers of identical components in a system and there is a cost consideration to failure, then the collection of real life data is practical. For components that follow an age related failure distribution and where costs of failure are high, then collection of real data is also feasible.

Various organisations are now introducing programmes of asset life cycle management which include an element of verification of performance and life data. In the petrochemical industry companies are combining smart sensor technology, neural networks, expert systems and computer technology to predict plant failure. These “systems” are based on those developed for aircraft maintenance and include computer software that provides data collection, intelligence to diagnose a problem, assess risk, and recommend action [5].

3 Reliability v. Durability : “In building and construction, reliability is often called durability” [6]

For the purpose of the research, we have adopted the following definitions given in BS5760 :

- Durability is “the ability of an item to perform its required function under stated conditions of preventative or corrective maintenance until a limiting state is achieved”.
- Reliability is defined as “the ability of an item to perform a required function under a stated period of time”.

Manufacturers see reliability as **having** “a vital effect upon the life-cycle efficiency, profits and market share” [6]. Economic asset management has long recognised the importance of quality and performance indicators to assess whole life performance. A particular item of building services plant or equipment, like a building, will certainly be produced to fit into a particular band of quality. The reliability of equipment is measured in relation to a product quality definition supplied by the manufacturer. It is thus possible to refer to ‘good’ and ‘bad’ reliability targets and maintainability figures. This form of asset performance profile modelling allows the establishment of a reliability confidence range or benchmark [5]. Reliability then relates to success or failure in service or use and is attained **if the** quality provided by the producer is adequate. Manufacturers of mechanical and electrical components investigate their product’s reliability, and even demonstrate expected failure rates. They recognise the need to supply data in order to allow the assessment of confidence for life cycle cost estimates. Manufacturer supplied data is available for M & E building components in relation to failure and reliability. The level of information provided in relation to reliability and maintenance data is increasing due to increased competition, complexity of installation, and guarantee packages provided. There is still, however some scepticism in the construction industry in providing service lives. A number of reliability data banks have been set up to provide indications of expected failure rates, which include M&E building components [7], but not building fabric components. In the UK the HAPM Component Life Manual is still unique in giving “insured lives” for building fabric components, and some M&E components.

The information on component **failures** may be expressed as Mean Time Between Failure (MTBF), Failure Modes, and Failure Mode and Effect Analysis (FMEA). The MTBF is defined as the average life of a particular component [6] which is statistically different from expected service or useful life of a component. The use of MTBF in particular situations is, however not to be relied upon as the sole basis for maintenance decision making, and

does not indicate the required frequency of maintenance tasks. It can be used in calculating desired availability, frequency of failure-finding testing, and whether planned maintenance is worth doing, but not how often. It is accepted however that in many cases reliability and maintenance data will not be available. This refers to actual real time to failure which can enable verification of estimated data in relation to the life cycle of M&E building components. This data can also be used to calculate optimum replacement strategies from components using statistical modelling techniques as discussed later.

Durability has long been studied in relation to the performance of fabric building components, but the above definition of durability highlights the absence of the “period of time” aspect. Reliability concentrates on this factor and is used in an engineering context when looking at the service life of M&E services components, and also is :

- Qualitative, as it examines freedom from operational failure in service or use on a comparative scale.
- Quantitative, as it is concerned with the probability that an item will operate in a prescribed fashion for a prescribed period of time under prescribed conditions without suffering any event predefined as a failure.

4 Failure Distribution Patterns

Traditionally the “bath-tub” distribution is used to model component failure. This has been called “the folklore of reliability engineering” [8], and other failure distributions have been identified in other industries, which are of relevance to building components. The following Figure 1 [2] illustrates most of the failure distributions that might be found in a building and its associated components :

- A:** “Bath-tub curve” with high incidence of failure (*infant mortality* or *burn-in*) followed by random or gradually increasing failure rate, then by a wear-out zone.
- B:** Random or slowly increasing failure probability, ending in a wear-out zone.
- C:** Slowly increasing probability of failure, but there is no identifiable wear-out stage.
- D:** Low failure probability when the item is new or just out of the shop, then a rapid increase to a constant level.
- E:** Random probability of failure at all ages
- F:** High infant mortality, which drops eventually to a random or very lowly increasing failure probability.

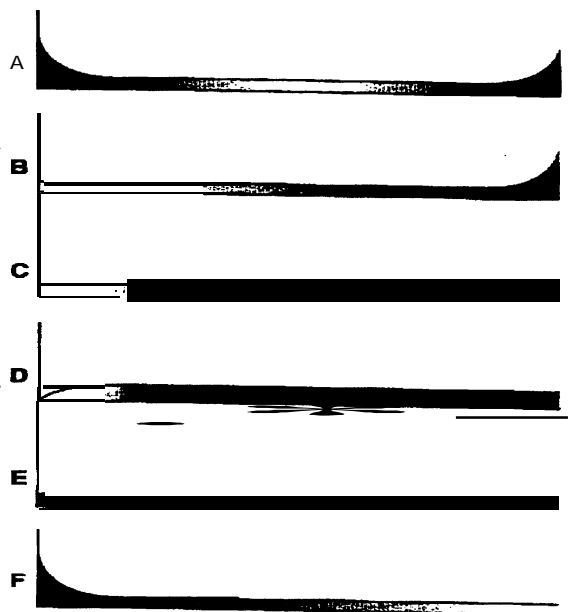


Figure 1 - Failure Patterns [2]

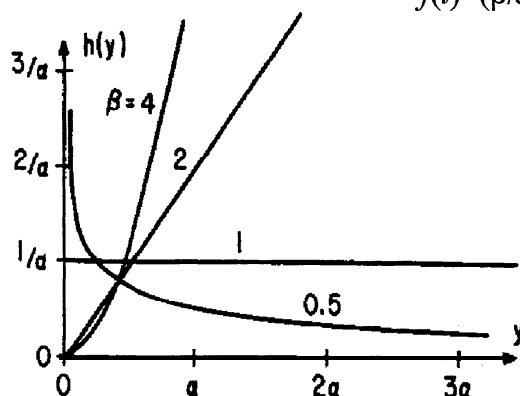
The basis of any maintenance policy or accurate life-cycle analysis is the understanding of the failure characteristics of individual components. Studies in the Civil Aviation Industry [2] have showed that 4% of items conform to pattern A, 2% to B, 5% to C, 7% to D, 14% to E, and 68% to pattern F. As M&E services components grow more complex, patterns E & F are likely to become more common. These findings suggest that there is not always a link between operating age and reliability and hint at the paradoxes with failure data discussed in Section 2.

5 Statistical distribution and the Weibull function

Several statistical functions can be used to model the failure rates and distributions discussed above including log normal, Gaussian, gamma, and Weibull [10]. The Weibull distribution is suitable for use in this context, and is widely used and preferred as it *“has a great variety of shapes which enable it to fit many kinds of data, especially relating to product life”* [2]. Predicting future trends or patterns associated with a common failure mode affecting a specific component is an essential part of maintenance planning for mechanical and electrical services. A predictive technique must estimate the time at which the failure rate is deemed unacceptable, not simply the time to first failure, which may itself be difficult to anticipate. As a starting point this may involve an assumption that all failures will simply continue at their current rate or perhaps incorporate some element of “educated guess” for a moderate increase.

Predictions of component failures can be made with greater confidence by using the Weibull Distribution Function which is seen as a powerful and versatile statistical tool for the analysis of reliability life data and hazard probabilities. It is uniquely able to model situations irrespective of whether the failures represent part of an increasing, decreasing, or constant exposure to failure mechanisms. Figure 2 below illustrates the ‘hazard function’ which highlights the variety of shapes which can be attributed to the full range of failure patterns shown previously in Figure 1. The data required in order to carry out a Weibull analysis is the time-to-failure of the components being studied. Statistically the Weibull frequency distribution (or probability density function) is :

$$f(t) = (\beta/a^\beta) t^{\beta-1} \exp[-(t/a)^\beta]$$



Weibull hazard functions.

Figure 2 - [Source :10]

The Weibull Beta value achieved from the above equation dictates the shape of the curve [10] and where :

Beta < 1 - burn-in failure is occurring, which equates to pattern F [Figure 1]

Beta = 1 - random failure is occurring, which equates to pattern E

Beta > 1 - wear out failure is occurring, which equates to pattern B

6 New Approaches to Maintenance Management

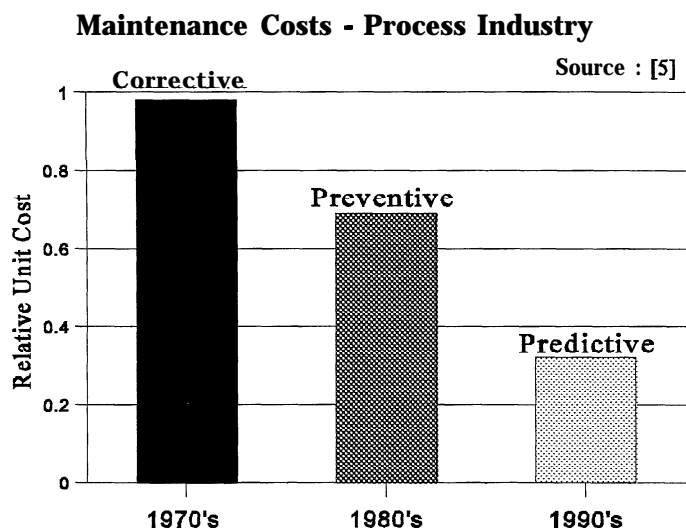
It is widely acknowledged that once a failure distribution is known or modelled, a suitable maintenance policy can be determined [10]. Recognition of the maintenance policies available have changed much since the early 1980's. Possible failure management policy options available today to improve life cycle performance include:

- | | |
|---------------------------------|--|
| (1) Predictive maintenance | (5) Change the design or configuration of the system |
| (2) Preventive maintenance | (6) Change the way the system is operated |
| (3) Condition-based maintenance | (7) Just-in-time maintenance |
| (4) Failure finding | (8) Run-to-failure |

Processes are available to help identify a suitable failure management policy for dealing with each failure mode in the light of its consequences and technical characteristics. One such process is "Reliability Centred Maintenance " (RCM) which finds its roots in the American Civil Aviation industry in the early 1960's, and is used world wide especially in the process, aviation, and defence industries. The RCM process importantly first defines what users want in terms of function (safety, environmental and sustainable integrity, reliability, durability), and then quality (precision, accuracy, consistency and stability), control, comfort, containment, economy, customer service etc. The next step is to identify ways in which the system can fail to live up to these expectations (failed states), followed by an FMEA (failure mode and effects analysis), in order to identify all the events which are reasonably likely to cause each failed state [2]. This allows the selection of the most suitable building maintenance strategy and has been successfully used in a number of major commercial buildings. Recent technological developments in condition monitoring equipment and that can be used to detect failure before it occurs have led to greater emphasis on policies such as predictive, condition-based and just-in-time maintenance. Building services components often have a detectable or measurable progression to failure and are therefore suitable for such techniques. For example the mechanical failure of bearings in a centrifugal pump would be characterised, over regular time intervals, by :

- | | |
|-------------------------------------|-----------------|
| (1) vibration, | Figure 3 |
| (2) noise, | |
| (3) heat, | |
| (4) smoke and possibly fire. | |

The process industry has done much work in assessing the effect of different maintenance policies in order to lower the life cycle costs of components [5], as illustrated in Figure 3 :



7 Conclusion

Policies for the life cycle analysis and maintenance management of mechanical and electrical building services components are being heavily influenced by new technologies from other sections of industry. The actuarial approach to data collection is often less useful than statistical analysis in predicting component failure used in deciding maintenance management policy options. Failure patterns can vary extensively and do not necessarily fit the “bath-tub” distribution. Data on failure rates is certainly available for M&E building components from manufacturers and data banks that can assist in making correct maintenance decisions, but this data is not readily available for building fabric components. It has been shown that incorrect planned maintenance strategies can actually increase life cycle costs, and reduce reliability and service life.

Differences in the data format and the data collection process for fabric and M&E components are evident, and the use of the Weibull function has been suggested as one example method for data analysis. Reliability theory may be used as a single methodology to assess building component performance of both mechanical and electrical services and fabric components. This would allow the development of a common cost-in-use model for life cycle analysis. In order to use such a model effectively, there is still a definite need for data giving actual time-to-failure or replacement in order to verify and explain existing service life predictions for building components in general, and allow more cost effective predictive maintenance.

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1. The UK Teaching Company Directorate (Department of Trade and Industry).
2. Building Performance Group Ltd.
3. Faculty of the Built Environment, University of the West of England, Bristol.

9 References

1. HAPM (1992) *Component Life Manual*, E.& F.N. Spon, London.
2. Moubray, J. (1996) *RCM II - Reliability-centred maintenance*, Butterworth-Heinemann, Oxford.
3. BSRIA (1980), *TN 1/80 - Reliability of Boiler Plant*, Butler, H & Petts, C.
4. Lamb, G.R. (1997) *HP In Competitiveness*, Hydrocarbon Processing, August 1997.
5. Honeywell (1997) *Equipment Health Management*, Honeywell Loveland, USA.
6. British Standards Institute (1994) *BS 5760 - Reliability of systems, equipment and components*, BSI, London.
7. Smith, D. J. (1992) *Reliability, Maintainability and Risk*, B&H, London.
8. Shooman, M.L. (1968) *Probabilistic Reliability : An Engineering Approach*. McGraw-Hill, New York.
9. Nelson, W. (1980) *Applied Life Data Analysis*, J. Wiley & Sons., USA.
10. Grover, R. J. & Grover, C. S. (1984) *Life Cycle Costing and Reliability Theory*, Proc. 3rd Symposium on Building Economics, CIB Working Commission W-55, Ottawa, July 1984, pp 29-37. Vol 1.