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Development of a range of methods for estimating the service life of buildings and engineered structures

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Abstract: The prediction of the service life of buildings and engineered structures is complex. Such predictions are usually carried out on a component-by-component basis but must incorporate variations in component design, material type, usage and environment. In practice, life estimates are required not just for a single structure but for a collection of buildings (public housing owned by city authorities) or a fleet of transport vehicles. Thus there is the need for extensive databases of life prediction that cover a huge number of component/environment/usage combinations that exist in a building or engineered structures. In fact, a simple calculation illustrates the size of the predictive task; there are more than 1000 different components in a dwelling which may exist in at least five different microclimates, within Australia in at least ten climatic sub-zones and a minimum of five pollutant zones. In addition there are up to five different material combinations per component built to three levels of quality, with three levels of workmanship in installation and three levels of maintenance. The total possible combinations exceed 15 million.

Furthermore, life prediction is carried out for a range of different purposes defined by different professional needs, for instance a designer may be primarily interested in total life estimates for a range of competing materials given only a general design while a building maintainer will be interested in the remaining life of a particular component in particular conditions.

In addition a methodology is required to take into account differences in conditions between the actual component under analysis and the reference component in the database. The actual level of detail and specificity required will depend on the use of the data. For example if the life prediction data are being used early in the design process to make comparisons between possible material types a full understanding and matching of the exact environment and usage conditions would not be required but if the life prediction estimate is being made to estimate maintenance scheduling of an actual building or structure then accurate matching of the service environment and usage patterns with those being modelled is required.

This paper will look at the diverse methods used to model the life of components in structures including data mining of maintenance and service records, expert opinion surveys (Delphi surveys), multiscale process modelling and sensing. The possible methods of deriving life prediction data are analysed in terms of the research questions highlighted above and their applicability to meet the differing uses of life prediction data. For two methods – Delphi Studies and Process-Based Models – detailed case studies are presented. In each case the strengths and weaknesses of the methods are analysed with respect to the final uses of life prediction.

Keywords: *Service life prediction, process modelling, Delphi study*

1. INTRODUCTION

The prediction of building life is most accurately undertaken on a component-by-component basis which necessitates development of large databases of component life under diverse conditions. Further there is a wide variety of uses for life prediction information, as illustrated below:

1. *Life prediction of known products in known environments*- this is important for the manufacturer who provides guarantees on his product, and the designer for material selection.
2. *Comparative materials selection based on life estimates of known materials in known environments* – this has always been important for the designer but is increasing in importance as on-line Life Cycle Assessment (LCA) tools allow selection of a variety of designs and material types.
3. *Comparative life prediction in new environments* – as for points 1 and 2 above.
4. *Effect of design changes on component life* – as for point 3.
5. *Estimation of maintenance schedules of already built facilities* – critical for the maintainer and the portfolio manager of buildings.
6. *Estimation of maintenance schedules from the design of facilities* – this is important for the designer, maintainer and owner of buildings.
7. *Effect of workmanship and human factors on maintenance and component life* – critical for the builder, owner and maintainer of dwellings.
8. *Prediction of remaining life of inspected facilities* – critical for owners or managers of a portfolio of buildings.

The different uses require levels of detail in the service life databases. Thus the generic problem of life prediction can be seen as how to use a wide variety of information sources (historic data, survey information, modeling and expert opinion etc.) to generate information on an enormous number of conditions. Buried within this overall question are a number of subsidiary questions:

- *What are the different classes of information available and what are the different methodologies to be followed in their use?*
- *How can project service life from a known case be transferred to an unknown case where not all the conditions are the same?*

2. CLASSES OF INFORMATION

The degree of knowledge available for any case can be classified into four levels, with increasing uncertainty:

1. Well known and documented situations.
2. Known but not documented.
3. Life and damage rate are not known but are predictable from damage causes (environmental and human) even if this prediction is complicated.
4. Damage causes and damage progression is not predictable but can be measured.

The most reliable prediction can be made if the situation is well known and documented. This is the case where code books or databases have been derived from years of observation and measurements. The next step down from this is where the situation is understood but has not been documented. This may be reflected in expert knowledge that may be extracted by surveying expert opinion or information buried in maintenance records that may be extracted by data mining. However, these forms of knowledge are not able to deal with new situations. Where the factors that cause damage are known, if these causes are predictable then modeling can be used to predict the progression of damage. This works well when there is a strong relationship between damage and the damage causes. This class would include data derived from service life models.

If the known causes of damage can not be well defined but are able to be measured then sensor-based approaches can be used to predict damage. This method is particularly relevant when the onset of damage is controlled by human factors, such as building usage or workmanship. It is very difficult to predict human errors but areas of risk can be monitored by sensing. In addition, life estimation can also be based on accelerated testing. In principle, this is a special case of condition 1 with the particular issue of how can a well-documented measure of component life developed in one situation (accelerated testing) be applied in another (real service conditions).

3. CASE STUDIES

In this section of the paper, two examples of methods to estimate component life will be given in depth in order to expand on the issues highlighted above.

3.1. Expert Opinion – Delphi Survey

As indicated previously surveying expert opinion is one method of acquiring a large amount of information in an efficient way. In particular, 'Delphi Surveys' offer an established protocol to refine the responses through feedback loops. A project applying the principles of a Delphi Survey to collect expert opinion on the durability of building components (Cole *et al*, 2004a) was undertaken. The project aimed to assess:

1. *Whether the opinion of experts would be sufficiently consistent to derive life estimates for components.*
2. *Would the opinion of experts be internally consistent across different component and environmental types?*
3. *Would the opinion of experts be consistent with both lifetimes predicted by other methods?*

The Delphi technique consists of a number of 'rounds' of opinion collection and feedback. A series of questionnaires are used for opinion collection, with the results from each round being used as the basis for the formulation of the questionnaire used in the next round (Duffield, 1993).

3.2. Application of Delphi Survey to Building Components

Thirty different building components were chosen as the basis of the survey ranging from nails and ducting through to roofing, window frames and door handles. The survey included both service life (with and without maintenance) and aesthetic life, and time to first maintenance. It included marine, industrial, and benign environments, and covered both commercial and residential buildings.

The questionnaires were web-based with respondents being asked to designate a length of life for each component in a variety of situations and environments. The predicted life was given as an interval, eg. 15-20 years. The aggregated responses to individual questions were classified into four classes based on a simple rule relating the consistency of the responses:

Class 1. One interval contained more than 50% of responses.
Class 2. Two adjacent intervals contained more than 50% of responses.
Class 3. Three adjacent intervals contained more than 50% of responses.
Class 4. None of the above.

The second round of the survey was used to gain additional information for categories that initially fell into class 3 or 4 due to lack of consistency in the responses. At the end of the second round the information was collected into a database, a table for users to look up predicted lifetimes for metallic components in a comparable environment. The predicted life is stored in the table in two forms: the mode and the mean as well as a standard deviation for the mean value.

Returning to the methodological questions discussed above:

1. The Delphi survey did lead to consistent responses from the three groups of experts with 78% of the sets of responses for each component falling in either class 1 or class 2 after stage 1 of the survey and 95% after stage 2.
2. The Delphi survey is internally consistent. For example it would be expected that responses on commercial roofing material and domestic roofing material should be very similar as in this case the use does not significantly change the life and in fact in all conditions for all materials the difference between roof sheet life and gutter life for the different types of buildings was never more than 4 years and generally less than 3.
3. The survey is consistent with basic physical and chemical principles and with results of data derived from other means. Again considering roofs, basic corrosion science indicates that roof life in a marine environment should be shorter than in an urban setting as is demonstrated by the survey. Roof life should also increase when the protection level of the component is increased, i.e. the life of Colorbond®>zincalume>galvanised. This is in fact observed. Further in Table 1, the life in the Delphi survey is compared with comparable values derived from experimental studies, process modelling and from maintenance records.

Table 1. Comparison of database and survey predictions for roof sheeting

Data	Environment	Mode	Mean	SD
Delphi	Marine	10–20	12	6
Experimental	Marine	5–10	14	12
Process Model	Marine	5–10	9	5
Maintenance	Marine		16	
Delphi	Benign	30–50	35	13
Experimental	Benign	>50	>50	
Process Model	Benign	>50	>50	
Maintenance	Benign		41	4

Thus the Delphi survey does appear to provide reasonable estimates of component life in known environments and could be used to select between known materials (usages 1 and 2). It cannot in itself account for variations in environment, workmanship or usage but it could be combined with the factor method to extend its flexibility in this regard. It is not capable of assisting in usage requirements 3–8.

The factor method was developed to estimate the condition of a component in 'real' conditions (the predicted service life or PSL) where factors such as workmanship, material quality etc can vary given that a 'reference service life (RSL)', where such factors are assumed to be constant, is known (Arseth and Hovde, 1999). The PSL (ISO, 2001) is:

$$PSL = RSL \cdot f_A \cdot f_B \cdot f_C \cdot f_D \cdot f_E \cdot f_F \cdot f_G$$

where the 'f' values are the factors (with values between 0 and 1) that account for variations in design, use, workmanship etc., such that:

A = quality of component
B = design
C = work execution
D = indoor environment
E = outdoor environment
F = in-use condition
G = maintenance

There are a number of issues or limitations that currently affect the method. On a theoretical basis there is no rigorous reason why the various factors should be treated independently. For instance, the quality of work execution could easily impact on both the indoor and outdoor environment. Secondly large databases need to be derived to define the factors and the derivation of these databases is complicated by fact that the factors are not truly independent. Nevertheless, the factor method is currently the only internationally accepted method of estimating predicted service life from reference service life. It does extend significantly the utility of databases on service life by allowing them to be applied outside the narrow domains from which the original reference service life data was collected. Thus the combination of RSL databases and the factor method can be used in theory for all the uses 1–7 listed in the introduction with perhaps the exception of 5. In contrast, databases of RSL could only be useful for uses 1 and 2.

3.3. Process Models

As discussed above, process models offer the possibility of direct prediction of component life and can, in principle, take into account the local and usage factors that control the life of individual components. The issues and capabilities of such process models will be outlined with reference to the holistic model of corrosion as outlined in a series of papers (Cole *et al*, 2003, Cole *et al*, 2004b, Cole and Paterson, 2004, Cole *et al*, 2004c, Cole *et al*, 2004d, Cole *et al*, 2004e, Cole and Paterson, 2006).

The basic holistic model combines processes (see Figure 1) that control atmospheric corrosion on a range of scales, from macro through meso to local, micro, micron and lastly electrochemical (Cole *et al*, 2003) to estimate the corrosion rate of exposed plates and relatively simple components (roof sheeting etc.).

In Australia, corrosion is promoted by the effect of marine aerosol so the model analyses the production, transport and then deposition of these aerosols. A major source of aerosols is the pickup of aerosol by the wind blowing over or across breaking waves (so-called white caps) in the open ocean and the extent of aerosol pick up is proportional to the white cap coverage (% or fraction of the ocean that is covered by breaking waves). The aerosol production and transport models are linked in a geographical information system (Cole *et al*, 2004b) that allows the airborne salinity to be calculated in the vicinity of a building. The efficiency of aerosol deposition onto objects and dwellings will depend on aerosol size, air speed and air turbulence. The fact that efficiency depends on air turbulence leads to marked variations in deposition across a building with heightened deposition onto building edges where air is more turbulent. The practical effect of this in the multiscale model is that pollutant deposition onto gutters and downpipes is heightened with respect to the general deposition onto walls and roofs leading to correspondingly faster degradation rates of gutters and downpipes. Given knowledge of pollutant level on surfaces and these local climatic parameters the state of the surface (dry, wet from rain or wet from the wetting of hygroscopic salts) is predicted. The damage that occurs over a three-hour period in each state is calculated from a damage model that has been derived from laboratory tests.

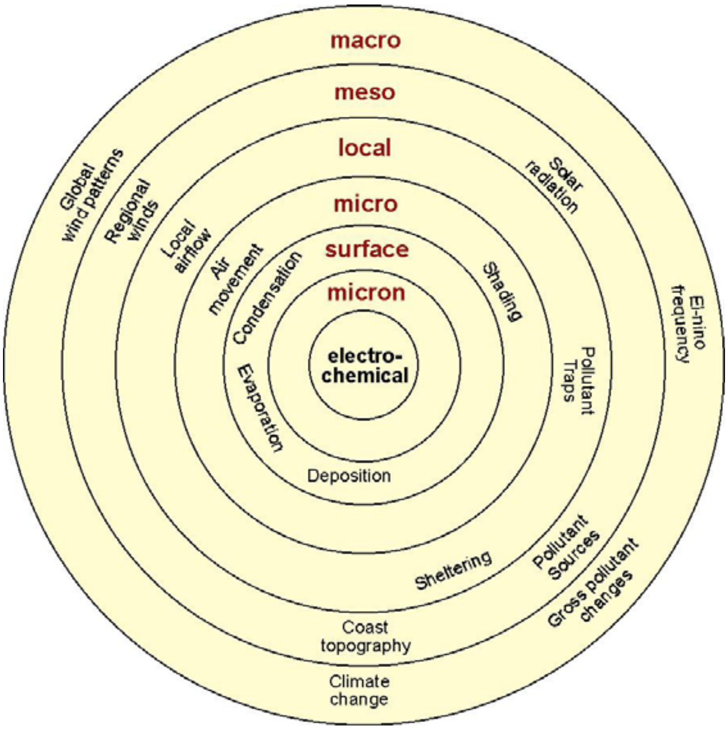

Figure 1. Schematic of multiscale model of corrosion.

Once the generic knowledge of microclimate and corrosion on a building is understood the model must be modified to take into account factors pertinent to individual components. Figure 2 outlines how the basic model is adapted for downpipes. The base structure of the holistic model is maintained so that meteorological data and pollutant and local microclimate models are combined to predict the state of the surface and thus the life. However use and exposure cases are allowed to modify this sequence so that whether the downpipes are maintained or not is considered, as are special features such as cut edges. The set of 'downpipes' are divided into a series of cases (six in all) that reflect different environments and usage of the different sections of a downpipe (Table 2). Firstly the downpipe is divided into the exterior surface or the interior surface. The exterior surface is further broken into two, the section just below the roof eaves which is sheltered from rain and the sections at the lower part of the wall which will be cleaned (though not from vertical rain). The interior of the downpipe is firstly broken into two usage cases, maintained (in this application that is equivalent to cleaned) and not maintained. If the downpipe is not maintained it may become blocked due to the accumulation of leaf litter and other debris which then leads to three more classes (above, at and below the blockage).

As indicated in Figure 2 the usage cases will change different parts of the model, for example if the surface is covered in debris (leaf litter etc.) it will trap the salts and significantly decrease the efficiency of rain cleaning. Further the debris will also absorb moisture, prevent evaporation and thus increase the time of wetness within the interior of a blocked downpipe. In Table 3, some predictions from the model are compared with the Delphi survey and a condition survey. The table quotes the worst case and best case for the modified model. In general there is a reasonable agreement between the worst case holistic model and the other two methods.

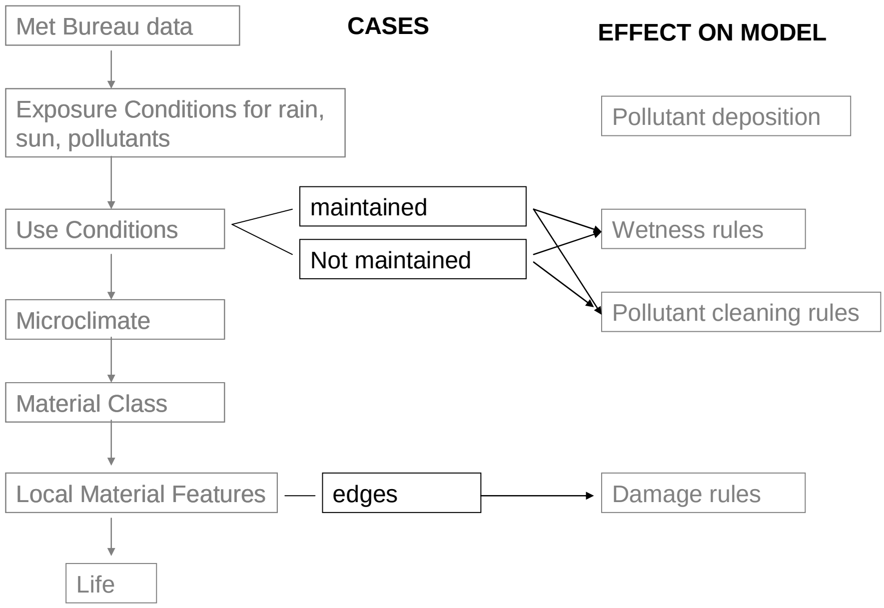

Figure 2. Model flow pattern for the analysis of downpipes.

Table 2. Sub-component and usage cases for downpipes

Case	Sub-component	Exposure	Usage	Position
1	Exterior	Sheltered from rain	All	
2	Exterior	Exposed to rain	All	
3	Interior	All	Maintained	
4	Interior	All	Not maintained	Above blockage
5	Interior	All	Not maintained	At blockage
6	Interior	All	Not maintained	Below blockage

Table 3. Comparison of modified holistic model, Delphi and condition survey for down pipes

	Model – worst case	Model – best case	Delphi	Condition survey
Benign –maintained	25	>50	33	>50
Marine – maintained	11	>50	11	
Benign – not maintained	15		21	18
Marine – not maintained	1		10	

The model can readily predict the life of specified products in known and new environments. It can be used to compare the life of components made from different materials and the effect of maintenance, as long as it can be defined in terms of changes to the materials response or local micro-climate (as in the example of the effect of maintenance on downpipes). The model can be used to determine the required maintenance from designed facilities. It can, in principle, be used to calculate the impact of design and workmanship and human factors, again as long as these changes can be translated to changes in microclimate and material response. However this last task is complex, but could be completed if the multiscale model approach was integrated with that of building pathology. The estimation of maintenance of already built facilities and the prediction of remaining life are best accomplished with other techniques.

4. SUMMARY

This paper has outlined the different types of information that can be constructed to define the service life of components. The appropriateness of each technique to the different usages of component life predictions has been discussed . As indicated in the introduction some of the usages such as prediction of the effect of design on service life will require rich information with service life being developed as a function of component geometry, service issues and microclimate and so will require a rich database such as developed with process models. Other usages such as knowledge of known products in known environments require relatively shallow data which can be derived by simple databases such as those formed by degradation curves or expert opinion.

There is a second dimension to this problem, some of the usages require information which has a low predictability, such as the effect of workmanship or human factors on life and thus their effect is better assessed by techniques that permit direct assessment of the built facilities such as Condition surveys or sensing.

The paper has highlighted (but not resolved) two contradictory requirements in life prediction. If all components in a building are analysed under all the variations in condition that may pertain then the number of cases is literally in the millions. On the other hand if component life is to be analysed accurately to give the depth of dependency required to address design and maintenance conditions each component may need to be broken into a number of sub-cases which can be analysed by refined and time intensive techniques such as process modeling. Clearly it would not be possible to analyse the millions of possible cases by a process modeling approach. A combination of techniques will have to be developed where the majority of life data are obtained by efficient techniques such as expert opinion while the components at high risk of failure are analysed by more precise techniques such as process modeling.

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