



Chapter 5

Closure

1 Overview

This research originated from a lack of means to integrate two established preventive maintenance strategies, statistical failure data analysis and vibration monitoring. Intuitively such an integration could have enormous benefits because of the well known successes that these two techniques have had on their own in the past. After studying typical vibration monitoring practices in the industry, it was decided that the most logical route to overcome the lack of integration between the two techniques, was by using regression models in renewal theory. The strategy followed was as follows:

- (i) A thorough literature survey on existing regression models in renewal theory.
- (ii) Identification of the most suitable model for the specific application.
- (iii) A comprehensive, in-depth study on the chosen model with the emphasis on its practical use.
- (iv) Practical evaluation of the theory for this application with a case study from the industry.

The literature study on regression models revealed that the Proportional Hazards Model (as in (1.1.)) was most suitable regression model to integrate failure time data and vibration information (in the form of covariates).

$$h(t, \bar{z}(t)) = h_0(t) \cdot \exp(\gamma \cdot \bar{z}(t)) \quad (1.1.)$$

The three most important reasons for this selection are: (1) The PHM has the widest theoretical foundation; (2) Parameter estimation for the PHM (and specifically the fully parametric PHM) is relatively tractable; and (3) The PHM has been used in similar reliability applications before.



An in-depth study into the PHM showed that the fully parametric Weibull PHM (see (1.2.)) was most suitable for this application and numerically the most attractive.

$$h(t, z(t)) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \cdot \exp(\bar{\gamma} \cdot \overline{z(t)}) \quad (1.2.)$$

Parameters were successfully estimated with four different optimization routines of which the modified Newton-Raphson method proved to be the most economical. Various goodness-of-fit tests for the PHM were found in the literature – all striving to test the PHM assumptions, in one way or another.

Only one decision making method for the PHM could be found, that of Makis and Jardine^[13,14]. This method predicts the optimal hazard rate that will result in the minimum long term life cycle cost.

Suitable data to test the theory was found as SASOL, Secunda. The collected data was not perfect according to requirements but was still useful enough to produce, as far as is known, the first publishable case study on vibration covariates in the PHM. The case study revealed that close practical involvement is crucial in the modelling process and that statistical tests alone could easily lead to a misleading model. Only two of a total of twelve covariates were identified to be good predictors of failure by the PHM.

The decision model was proved to be valid and useful by several theoretical evaluations but also to be practical, by additional data. The case study showed that huge cost savings could have been brought about if the recommendations of the PHM were known and were acted upon.

2 Recommendations

From facts discovered and experience gained through this research project, three recommendations for future research/practices can be made:

- (i) It is very surprising that so little research has been done on the PWP-model up to date. (Chapter 2, section 4.). This model has enormous potential because of its extreme versatility. It adds a third dimension to the PHM by taking previous replacements of the same item into account and it can handle both renewal and repairable systems situations. This model may have the ability to be a much better representation of practical situations than, for example, the PHM. It is recommended that the PWP-model's abilities are investigated further and it is



predicted that a major contribution to reliability modelling would be the result.

- (ii) The concept of minimum long term life cycle cost (Chapter 3, section 3.1.) is not accepted very well in the industry. People involved with reliability of items reject this concept as soon as an item lasts longer than the estimated time of minimum long term life cycle cost. Many reliability engineers have expressed their need for a decision making technique that predicts the 'exact' time to failure of an item rather than the minimum long term life cycle cost. Such a technique would certainly be possible if used with a model allowing for covariates, although no such technique was found in the literature during this research. A remaining service life estimation technique based on a regression model will be of wide practical interest if developed successfully.
- (iii) Vibration data recording practices in the South African industry were found to be very incomplete and ineffective. (Chapter 4, section 2.2.). This is mainly due to a lack of commitment to vibration monitoring by managers but also due to unfriendly and disorganized CMMS's. It is believed that the successful case study described in this dissertation will improve these practices if published widely enough.