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A new maintenance efficiency model and inference method for interval censored failure data

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1. A new maintenance model

GRTgaz owns and operates the longest high-pressure natural gas transmission network in France. Its industrial assets include more than 32,500 kms of pipeline and 26 compressor stations. The R&D center (RICE) of GRTgaz is developing tools to model these assets for optimizing their management, particularly in terms of maintenance policies. These tools are based on reliability distributions that consider equipment aging and maintenance models. Intrinsic ageing is modeled using probability distributions (Weibull with parameters α and β) for the operating time of an unmaintained system. Effect of maintenance is between minimal and perfect, this is known as imperfect maintenance.

The assessment of the system requires the application of probabilistic models and the statistical estimation of their parameters from the observation of field data. The considered imperfect maintenance models are the virtual age models of type ARA (Arithmetic Reduction of Age). Virtual age models consider that each maintenance rejuvenates the system, so that, at time t, the maintained system is equivalent to a new unmaintained system of age $V(t)$ smaller than t. $V(t)$ is the virtual age of the system at time t. Among the virtual age models, the ARA models assume that, between two maintenances, virtual age evolves like the calendar time.

An industrial asset from GRTgaz is put into service at time 0. It undergoes failures, PM and CM actions. PM are planned at deterministic times. $\forall i \geq 1, \tau_i$ is the time to the i^{th} maintenance. When a failure occurs (at a random time), the associated CM is delayed to the time of the next PM. Even if it is failed, the system continues to deteriorate until the next PM. Maintenances durations are assumed to be negligible. Therefore, there are two types of PM. The first type (simply denoted PM hereafter) is PM such that no failure has occurred since the last maintenance. The effect of these PMs is that which was planned by the initial maintenance plan. The second type (denoted PCM hereafter) is PM such that at least one failure has occurred since the last maintenance. The effect of these PMs cumulates the effect of the initial PM and the effect of the CM associated to the previous failures. Therefore, the failure and maintenance process consists of a sequence of recurrent events of 3 types, failures and two types of PM (PM and PCM).

We propose a stochastic model for this process, in which the maintenances are imperfect, of the ARA type. Since at failures times no maintenance is performed, this is equivalent to assume that a minimal as bad as old (ABAO) repair is performed. Let M1 be the imperfect maintenance model associated with PMs and M2 the imperfect maintenance model associated with PCMs. Then, the new model is written F ABAO-PM M1-PCM M2. We tested all the combinations corresponding to PM and PCM effects of type ARA_1 and ARA_∞ which are sub-models of ARA models. Depending on the combination, the virtual age will be different.

2. Statistical inference for censored data

In the GRTgaz case, failure times are not observed, they are detected at the time of next PM. Therefore, the data are interval censored. Two situations are considered: the Poisson case, for which the number of failures in each interval is known, and the Bernoulli case, for which we only know if at least one failure has occurred in each interval. In order to estimate the model parameters, we compute the likelihood associated to both censored observations situations.

2.1. *The Poisson case*

For k maintenances, the observations are the realizations $\Delta n_1, \dots, \Delta n_k$ of the random variables $\Delta N_1, \dots, \Delta N_k$ where for all $i \geq 1$, ΔN_i is the number of failures between the *(i-1)*-th and i-th maintenance. At the failure times, no maintenance is performed. Thus, a non homogeneous Poisson process (NHPP) is observed between two successive maintenances. The properties of NHPPs lead that the likelihood function is written :

$$\mathcal{L}(\theta; \Delta n_1, \dots, \Delta n_k)$$

$$= \left[\prod_{i=1}^{k} \frac{\alpha^{\Delta ni} \left[[V_{i-1} + \Delta\tau_i]^\beta - V_{i-1}^\beta \right]^{\Delta n_i}}{\Delta n_i!} \right]$$

$$\exp\left[-\alpha \sum_{i=1}^{k} \left[[V_{i-1} + \Delta\tau_i]^\beta - V_{i-1}^\beta \right] \right]$$

where V_i is the virtual age at the i^{th} maintenance.

2.2. *The Bernoulli case*

For k maintenances, the observations are the realizations $b_1, \dots, b_k$ of the random variables $B_1, \dots, B_k$. $\forall i \geq 1$. B_i equals to 1 if there has been at least one failure in $[\tau_i, \tau_{i+1}[$, and 0 otherwise. Therefore, the likelihood function is:

$$\mathcal{L}(\theta; b_1, \dots, b_k)$$

$$= \prod_{i=1}^{k} \left(1 - \exp\left[-\alpha\left[[V_{i-1} + \Delta\tau_i]^\beta - V_{i-1}^\beta \right] \right] \right)^{b_i} \exp\left[-\alpha\left[[V_{i-1} + \Delta\tau_i]^\beta - V_{i-1}^\beta \right] \right]^{1-b_i}$$

3. Résults and conclusion

The quality of the proposed estimators has been assessed through an extensive simulation study. Of course, the more data (systems and failures), the better the estimates. Unsurprisingly, the results are better in the Poisson case than in the Bernoulli case, due to the amount of information in each case.

Finally, the method is used to assess the ageing and maintenance efficiency of real system from GRTgaz.

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