Received: 27 April 2022 | Accepted: 4 May 2022

DOI: 10.1002/asmb.2690

COMMENTARY

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Discussion of signature-based models of preventive maintenance

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We congratulate Asadi, Hashemi, and Balakrishnan for a comprehensive review of age-based maintenance strategies and a thorough study of the statistic "signature" for age-based maintenance of multi-component coherent systems. Among many contributions, Asadi, Hashemi, and Balakrishnan's paper also provides a taxonomic framework with which to categorize and classify the plethora of age-based maintenance models. Section 2 is of great importance, providing new researchers with a reliable nomenclature. What is missing in this section, however, is a detailed explanation of the notation "coherent system," which will also help clarify the type systems to which the notation signature is applicable. Case study in this article covers a wide range of scenarios, and the two exemplar systems are also representative. However, the case study serves more as a tutorial rather than a proof of superiority. The tables and figures are for demonstrating the (uniqueness of) optimization results, but not for justifying the advantages of using the statistic signature. It would be of much practical value to compare the relative performance of maintenance models with and without using signature.

As claimed in the article, one "important advantage of using signature and other related concepts in writing the corresponding cost criteria and other related criteria is that one can take into account the failure of individual components and related costs", and we have a couple of comments about this.

It would be challenging to extend the application of signature to maintenance techniques other than age-based maintenance, such as condition-based maintenance and predictive maintenance. Condition-based maintenance generally utilizes multi-view data (sensor monitoring data, manual inspection data, and lifetime data), and hence is commonly accepted to be superior to age-based maintenance (that only utilizes lifetime data).[1,2] Likewise, predictive maintenance policies utilize streaming data to infer the remaining useful lifetime.[3] However, it is difficult to explicitly express an evaluation criterion (cost or availability) as a function of signature for condition-based or predictive maintenance policies, especially for multi-component systems with complex structures. We are curious about the applicability of signature and its related concepts in data-rich maintenance settings. We think there are mainly two technical hurdles to be surmounted before the notion signature receives universal acceptance: assumption and computation.

While it is natural to assume that, for a new multi-component system, components of the same type have the same lifetime distribution, this assumption is untenable for a system that has gone through multiple rounds of maintenance (either perfect or imperfect maintenance of individual components). For such an "old" system, each component will have a different (residual) lifetime distribution, and hence the signature vector $\boldsymbol{s}$ is no longer topological invariant (i.e., $s_i \neq |A_i|\,/n!$). Consequently, this assumption will greatly limit the application of signature (to new systems only). The case of maintaining "old" systems is ubiquitous in practice. For example, in condition-based maintenance and predictive maintenance, we need to repeatedly update (i.e., plan a new) maintenance policy for a highly reliable system, as we have acquired more information since its operation. Other assumptions that make the notion brittle and unlikely to be adopted in general practice are listed in the concluding remarks. Our viewpoint on signature is that it should not be positioned as a formulation strategy competing with existing maintenance objective formulations, but as an auxiliary tool for explaining component-level details to engineers and stakeholders. That is, there will be two maintenance objective formulations, what we might call the pragmatic formulation and the signature-based formulation. The pragmatic formulation is tailored for the practical configurations of a system, and the signature-based formulation provides a decomposition of the pragmatic formulation and hence further insights into our decision making. We can interpret this two-formulation paradigm in the context of multi-fidelity optimization, where the signature-based formulation is a low-fidelity surrogate.[4] In this paradigm, the restrictive assumptions for signature, made for mathematical convenience rather than practical needs, are now acceptable, and the notion signature could even be extended to condition-based or predictive maintenance strategies. For example, one could group all the components' remaining useful lifetime distributions into a few clusters using, for example, functional data clustering.[5] Structural information can also be utilized to perform semi-supervised clustering.[6] Each cluster corresponds to one type, and then we can calculate the survival signature. Note that we do not need to provide the signature-based formulation at each decision-making point, as it is mainly for interpretation, not for decision making. This will partially overcome the second hurdle—the computation.

Although briefly mentioned in the article, we would like to comment on the computational complexity of the signature-based formulation of maintenance objectives. The run-time complexity includes not only the optimization of an evaluation criterion but also the calculation of the signature vector. While it is apparent that a signature-based maintenance model is computationally expensive, it is not clear what exactly the time complexity is. We hope to read more future works that explicitly quantify the time complexity of the whole maintenance optimization procedure using the big O notation, which will also facilitate the comparison and selection among different maintenance models. We have mentioned above one way to reduce the computational burden: formulate the signature-based evaluation criterion only when interpretation is required. Another line of approach is to replace the exact calculation of the signature vector (through permutation) with Monte Carlo simulation. The sampling approach presented in Behrensdorf et al.[7] constitutes an early attempt to numerically approximate the signature vector. However, future works should focus on evaluating the efficiency of sampling algorithms through the convergence rate. On the other hand, efforts can be made to create a signature-vector e-handbook to provide ready reference for standard or well-regulated system structures. Finally, the optimization result from the pragmatic formulation can be used as a warm initialization for optimizing the signature-based formulation, and vice versa.

To conclude our discussion, we argue that the applicability of a maintenance model that is built on signature warrants further investigation. However, we do believe that the notion signature provides a powerful tool for interpreting and understanding maintenance polices and can be generalized to other maintenance techniques than age-based maintenance. Moreover, signature-based formulation can be used for exploratory analysis before optimizing a high-fidelity maintenance model, for example, providing a rough estimate on component relative importance and a rough estimate on the optimal maintenance policy. We suggested a new research paradigm and provided a few guidelines on tackling the combinatorial complexity problem. We look forward to reading future works on materializing or refuting our ideas.

ACKNOWLEDGEMENT

Open access funding provided by IReL.

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How to cite this article: Zhang M, Liu B. Discussion of signature-based models of preventive maintenance. *Appl Stochastic Models Bus Ind*. 2022;1-3. doi: 10.1002/asmb.2690