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Abstract

A new graphic tool is presented to test aging trends based on life data. The graphical test is developed by means of scale and space inference about the Total-Time-on-Test transform and its first and second derivatives. The graphical tool SiZer is defined considering nonparametric local polynomial kernel estimators and constructing the corresponding (simultaneous as well as punctual) confidence intervals around the curve. The finite sample properties of the method are evaluated by a simulation study and the comparison with other non-graphical tests shows that the graphical test helps localize discrepancies of empirical data concerning a given hypothesized aging property, thus allowing to solve the problem locally.

Keywords	Total-Time-on-Test transform; Kernel smoothing; Order statistics; SiZer map
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Suggested reviewers	Sudheesh Kattumannil, BO HENRY LINDQVIST, Maria Dolores Martinez Miranda

Submission Files Included in this PDF

File Name [File Type]

Responses.pdf [Response to Reviewers]

highlights.docx [Highlights]

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TTT-SiZer: A graphic tool for aging trends recognition

Revision for *Reliability Engineering and System Safety*

February 2020

Dear Editor,

Please find attached the revision of our paper, “TTT-SiZer: A graphic tool for aging trends recognition” by M.L. Gámiz, R. Nozal-Canãdas and R. Raya-Miranda.

Thank you for reviewing our paper and the valuable feedback from the Reviewers. We have worked on the paper following your suggestions and comments and produced an improved version of the paper as well as response letters below for the Reviewers.

We hope you will find suitable our revision.

Yours sincerely,

M.L. Gámiz

Reply letter to the Associate Editor

Please revise the paper carefully for a second round review. Try to make the paper more relevant to this journal, as we rejected a number of papers discussing mainly probability/statistics issues. Please modify the writing style as well as theorem/proof style tends to focus on pure analytical issues. Thanks.

Response: Thank you for reviewing our paper and the valuable feedback from the Reviewers. Following your suggestions, we have tried to make the paper more relevant to this journal. To enhance the interest of practitioners in reliability engineering we have included more real examples in this field to emphasize the practical usefulness of the methods. We have worked hard on the introduction to make it clear that both, the topic discussed in this paper (aging) as well as the statistical tool considered (TTT transform) have been recurrent topics in reliability analysis (theory and practice) during the last decades.

Aging classes and the TTT curve are still nowadays catching the interest of researchers and practitioners in the area, as can be deduced from the extensive recent bibliography. To highlight this point we have added a considerable number of updated references that are conveniently quoted in the text.

The main purpose of this paper is to bring modern techniques based on nonparametric statistics into the statistical toolbox of reliability analysis, which is not so frequent among reliability engineers compared to parametric methods. To do it we introduce a new and powerful tool to be used with data before looking for a stochastic (parametric) model. Following the suggestions of the Associate Editor and Reviewers, we have modified the structure of the manuscript and some mathematical developments have been sketched and moved to an Appendix section added at the end of the manuscript. We have reduced to the minimum the mathematical description of the methods. We hope this new writing style is considered appropriate for the journal.

Reply letter to Reviewer #1

Dear Reviewer,

Thank you very much for your comments regarding our paper. We have prepared a revised version of the paper following your comments and suggestions, which are included below using italic font for your easy.

Review report

Based on first and second derivatives of Total-Time-on-Test (TTT) transform the authors developed a new method to detecting aging pattern of a lifetime data. By means of Monte Carlo simulation they evaluated the finite sample properties of the graphical tool TTT-SiZer. Overall the paper worth publishing in Reliability Engineering and System Safety subject to major revision.

Thank you for your recommendation for publishing subject to major revision. We respond below in detail to your Major and Minor Comments.

Major Comments

(1) In Definition 1.1, The conditional survival function is obtained; conditional on what? one need to specify. Also, Let X a lifetime should be Let X be a lifetime random variable)

Response: Corrected.

(2) In Definition 1.1 why the definition of DMRL is given. It can be removed as no further discussion on it(except Proposition 2.1). Otherwise they can add the definitions of NBU and IFRA classes. What is the possibility of developing a test against DMRL based on the proposed methods.

Response: We have removed the definition of DMRL class since it is not further considered in the paper. It is our purpose to generalize the work in this paper to have into account other aging behaviors. However, this subject will be developed in a future research.

(3) Some notational inconsistency in the algorithm 1 (definition of X^ and $\hat{\mu}_j^*$). Please correct it.*

Response: Corrected.

(4) In Table 3 why the power decreases as the sample size increases. Authors should give a proper justification.

Response: A paragraph has been added to explain this issue (page 28, lines 558-603). Specifically it is written:

Note that for sample sizes $n = 500; 1000$ the maps have been built taking in total 401×11 pixels, whereas for $n = 100$, 51×11 pixels, and for $n = 50$, 60021×11 pixels are considered in the maps, which means that the results are not fully comparable. Table 3 shows the good performance of our test given that the results presented in the table imply a percentage of rejection is reasonable to high for almost all models and sample sizes.

Please note that in the simulations presented, only for sample sizes $n = 500$, and $n = 1000$ the map is constructed with exactly the same specifications, and in this case, the power of the test increases as the sample size increases, as expected.

(5) The authors discuss two test procedure, test against NBUE and test against IFR. It would be nice to give brief discussion on test against other aging classes in the conclusion test. For example Klefsjo developed a test against IFRA class based on scaled TTT transform. The new aging classes which mentioned in the conclusion can be defined in Definition 1.2.

Response: Following your suggestion, we have rewritten the conclusion section including a brief discussion on tests against other classes. Also Definition 1.2 has been rewritten.

Minor Comments

(1) In abstract based on life data should be based on lifetime data. Similar changes can be made in other places too.

Response: Corrected.

(2) The last four lines in Page 4 can be rewritten as it was not well written and lengthy.

Response: This paragraph has been removed in the new version of the paper.

(3) Page 4, line 93, Based on the sample order statistics we can construct the empirical distribution function. This can be changed to Based on the sample order statistics empirical distribution function is given by. (it is the representation available.)

Response: This part of the paper has been removed in the new version of the paper.

(4) Page 14 line 216 Montecarlo should be Monte Carlo.

Response: This paragraph has been moved to the Appendix in the new version of the paper, and this point has been corrected.

(5) Page 28, line 490, we simulate samples of size $n = 100$; 500; and 100, $n = 50$ is missing.

Response: Corrected.

(6) What are $P75$ and $P95$ in the Tables 2 and 3. Please clearly specify it.

Response: In the current version of the paper, we have replaced Table 2 by a new one, where we have added results of evaluating the finite sample performance of the test based on SiZer-0, which had not been considered in the previous version of the table. The experiment consists of simulating a total of $M = 1000$ samples from an Exponential distribution. For each sample we construct the corresponding SiZer maps: SiZer-0 map for alternative hypothesis “NBUE but not Exponential”, and SiZer-2 to test against the alternative “IFR but not Exponential. For each case, we compare with the corresponding true map, and count the total number of pixels where the color in the empirical map is not the same as in the true map (i.e. a completely gray map under the null hypothesis). This count is divided by the total number of pixels in the map and represents the proportion of type I error. We run the experiment a total of $M = 1000$ times. So, Table 2 gives a summary of these $M = 1000$ proportions. Specifically, we present the mean, the median and the quantile of order 0.75.

(7) References 18 and 19 are not mentioned in the text.

Response: Thank you for pointing out this issue. We have now properly quoted these two references.

(8) References should be written uniform fashion. For example some cases volume number is not given.

Response: We have revised this aspect and the references are now correctly written according to the journal style.

(9) There are several inconsistencies in the notations, please correct it in the revised version.

Response: Corrected.

Reply letter to Reviewer #2

Dear Reviewer,

Thank you very much for your comments regarding our paper. We have prepared a revised version of the paper following your comments and suggestions, which are included below using italic font for your easy.

Review report: *Dear Editor*

This is my review on manuscript number RESS-2019-1329 titled “TTT-SiZer: A graphic tool for aging trends recognition”. This paper has aimed to present a new procedure to explore life data for discovering aging trends in the underlying life distribution. In this regard, a new graphical test is presented by means of scale and space inference about the Total-Time-on-Test transform and its first and second derivatives. Here I left some comments on the manuscript. This is an interesting paper and I suggest its acceptance after revision. To help improve quality of this paper, I provide my comments as below:

Thank you for your suggestion of acceptance after revision.

We respond below to your comments.

1) Introduction section is very short. The research mentioned in this section is not well described. The literature is not well treated and there is no enough mentioned up-to-date papers as references. The authors made no effort to organize the information and to provide a structured literature review.

Response: Following your suggestion we have completely rewritten the introduction. In the new introduction, we have made a great effort to demonstrate that the topic of the article, as well as the mathematical tools considered, have attracted a deal of attention by practitioners in Reliability as can be deduced from the vast literature published in the area in recent years.

We have worked hard in the writing. The structure of the Introduction is as follows. We have first reviewed the contributions to mathematical modeling of different types of aging. Next, we have revised and quoted some papers on the important reliability concept of Total-Time-on-Test, and finally, we have reviewed a series of contributions on hypothesis testing aimed at assessing the exponentiality hypothesis, in other words, non-aging of an item or system, against different aging alternatives.

We have paid special attention to papers that deal with tests based on the TTT-plot tool.

Finally, we have quoted several works in which, among others, the objective is to demonstrate the practical use of these methods by solving specific problems in the field of reliability engineering.

Following your suggestions, we have modified the structure of the manuscript and some mathematical developments have been sketched in the Appendix section added at the end of the manuscript. We have reduced to the minimum the mathematical description of the methods.

We hope this new writing style is considered appropriate for the journal.

2) In Section 2 the Total-Time-on-Test transform is defined. TTT transform in the other references such as (Rausand and Høyland, 2003 or Zaretalab et al. 2018) is described completely. Therefore, it is not necessary to present these concepts in the present manuscript. It is enough to refer to the sources that provide it.

- Rausand, M., & Hoyland, A. (2003). System reliability theory: models, statistical methods, and applications (Vol. 396). John Wiley & Sons.

- Zaretalab, A., Haghighi, H. S., Mansour, S., & Sajadieh, M. S. (2018). A mathematical model for the joint optimization of machining conditions and tool replacement policy with stochastic tool life in the milling process. The International Journal of Advanced Manufacturing Technology, 96(5-8), 2319-2339.

Response: Thank you for pointing out this issue. We have now included these two references. In fact, the first one had been omitted in the previous version of the paper by mistake. With respect to the second one, we are grateful to the reviewer because we have studied this paper and have realized that it is well connected to our work, in the sense that the authors also consider a least-squares optimization problem to fit a model to a dataset by means of the TTT-plot. They consider a parametric model while our perspective is non-parametric.

3) Particularly authors should highlight what are the main advantages and what is the novelty of the proposed method. Why constructed local-polynomial estimators for the TTT-curve and its first and second derivatives have better performance than other methods?

Response: We explain this point in more detail in the new version of the paper. Specifically in the paragraphs from page 3, line 77, to page 4, line 98.

4) Please have your paper proof read by a native English Speaker or a person more familiar with the English language. The paper should be written in 3rd

person not 1st person. If you refer to yourself do not use “I” or “we” use “the authors” but use it only if you want to stress a point or state this is your important opinion.

Response: We have had our paper revised by a native English Speaker and we have completely changed the language style. Impersonal style is used in the current version.

5) Conclusion needs to be extended by comparison with similar studies and discussion about unique results of the study.

Response: Following your suggestion we have written a new Conclusion Section including more details of our study.

Reply letter to Reviewer #3

Dear Reviewer,

Thank you very much for your comments regarding our paper. We have prepared a revised version of the paper following your comments and suggestions, which are included below using italic font for your easy.

Review report: *The authors introduce a new graphical tool to test aging trends on life data. A graphical test is developed and several examples are presented in order to illustrate its applicability. I think the paper is interesting, well written and deserves publication. However, several comments should be taken into account.*

Thank you for your suggestion of publications.

We respond below to your comments.

*- A brief introduction to SiZer. How this tool can be used directly by the user?
Is it linked to a particular software?*

Response: We have added a brief introduction to the SiZer graphic tool at the beginning of Section 4 “A graphic tool for evaluating aging trends”.

On the other hand, we would like to mention that we have developed original programs to implement all methods described in the paper. All the routines for producing the graphs and the calculations of the estimators have been performed using the programming language R and are available from the authors. At the moment we are developing a package under the environment R that will be available to users in brief.

The original idea of SiZer Map is due to J.S. Marron and the first software was created using Matlab. It is available from his webpage: <http://marron.web.unc.edu/sample-page/marrons-matlab-software/>

- For reproducibility: explain how you get the data used in the examples.

Response: The data that we use in the examples have been obtained from previously and well known references. In each case we explicitly refer to the corresponding source.

- Nair and Sankaran (2013) and Franco-Pereira and Shaked (2014) are recent references related to the topic and that should be included.

Response: Following your suggestion we have included these references and have properly quoted in the text.

Reply letter to Reviewer #4

Dear Reviewer,

Thank you very much for your comments regarding our paper. We have prepared a revised version of the paper following your comments and suggestions, which are included below using italic font for your easy.

Review report:

The paper aims at presenting a new graphic tool to test aging trends based on life data. Although quite a bit of results are shown, I feel that the paper is not suitable for this journal. The focus and analysis are about the statistical properties, and the results are of much more interest for different journals than reliability engineering. The authors probably could rewrite it with more examples and presenting more engineering insights from the study. Analytical results could be put in an appendix if they are of great importance. The authors should also carry out a more extensive literature search and discuss more recent and related works. In particular, works in reliability engineering journals should be discussed to make the paper more relevant. I see that the references are also rather old, and there is only one references from last 3-4 years.

Response: The motivation of this work is to study a classical and crucial issue in reliability analysis such as aging. For this, we present a powerful and useful graphical tool that can be beneficial from a practical point of view. To demonstrate the strength of our method it is necessary to study its theoretical statistical properties. We understand that the theoretical support of a new methodological proposal is important for the quality standards of the journal. In addition, the extensive study of simulation and the applications with real cases that we present demonstrate that our proposal is interesting and has a huge potential for reliability engineering in practice.

Following your suggestion and the Editor's comments, we have changed the structure of the paper in order to make it more readable. Some mathematical explanations, which could be jumped in a first read, have been moved to the Appendix. The introduction section has been rewritten in the new version of the paper. An extensive literature review is provided including up-to-date works published (some of them in the last year) in several reliability engineering journals.

Finally we provide the necessary computer support for the implementation of the method. In this respect, at the moment we are developing a specialized R package that will be available in brief for the interested practitioners.

We believe that our proposal is interesting and worthwhile from a theoretical and practical point of view and we hope that in its current version it is found to fit well the profile and standards of Reliability Engineering and System Safety.

Ref: RESS_2019_1329_R1

Title: TTT-SiZer: A graphic tool for aging trends recognition

Journal: Reliability Engineering and System Safety

Highlights:

- Scale-space inference through SiZer map
- Smooth estimation of the Total-Time-on-Test transform
- Visual testing for lifetime model selection
- Aging properties evaluation based on data
- Implementation of methods in by means of self-programmed code in R

TTT-SiZer: A graphic tool for aging trends recognition



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Abstract

A new graphic tool is presented to test aging trends based on lifetime data. The graphical test is developed by means of scale and space inference about the Total-Time-on-Test transform and its first and second derivatives. The graphic tool TTT-SiZer is defined considering nonparametric local polynomial kernel estimators and constructing the corresponding (simultaneous as well as punctual) confidence intervals around three different curves. The finite sample properties of the method are evaluated by a simulation study and the comparison with other non-graphical tests shows that the graphical test helps localize discrepancies of empirical data concerning a given hypothesized aging property, thus allowing to solve the problem locally.

Keywords: Total-Time-on-Test Transform, Kernel smoothing, Order statistics, SiZer map

2010 MSC: 90B25, 62N05

1. Introduction

In a technical context, aging is usually understood as a gradual decrease in performance over time, so it can be expected that the aging of a component or system increases the probability that it will fail.

5 Let X be the random variable that represents the lifetime of a mechanism. A natural measure of aging is the probability that X exceeds a time $t + x$, assuming that the mechanism has an age of at least t . This idea leads to

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the concept of residual life. Also, the instantaneous propensity to the failure of a mechanism as a function of its age, that is, its failure rate, is a useful
10 measure of aging.

Aging trends evaluation of units and systems is a challenging subject in reliability and maintainability analysis and has attracted the attention of an increasing number of researchers. As a result, during the last years of the past century, different notions of aging have given rise to a well-known
15 nonparametric classification of life distributions, which can be found in [1], [2], [3], [4] and [5], among others. Since then, the literature in reliability about stochastic aging and its different characterizations have been prolific and new aging criteria have been mathematically formulated, see for example [6], [7], [8], [9]. The monograph [10] provides an excellent revision and
20 summary of the most widely studied aging concepts that are based on reliability characteristics such as the failure rate, the survival function or the mean residual life. Several examples of lifetime distributions together with their aging properties are given, with special attention to the aging behavior of finite mixtures of life distributions.

The mathematical description of aging is mainly done based on the failure rate, residual life functions, and the survival function so an inspection of the shape of these functions is helpful to evaluate the performance of a system in the future, which is very important for making decisions in many practical applications in reliability and maintainability. In [11] aging criteria based
30 on the failure rate and mean residual life are considered. It is particularly interesting whether a specific property of aging defined in terms of a reliability measure implies the same property, or some other criterion is presented with another reliability measure. Other approaches have contributed to extending the mathematical formulation of aging in different application areas where
35 the concept of failure rate, for example, is not so usual. Recently, in Chapter 4 of [12], the authors review some of the important results of the mathematical treatment of aging and translate the basic definitions to make them amenable for a quantile-based analysis. In [8], [9], a family of generalized aging intensity functions of univariate absolutely continuous lifetime random variables is
40 introduced and studied. They allow the analysis and measurement of the aging tendency from various points of view.

In this paper, the attention is focused on the Total-Time-on-Test (TTT) concept. The shape of the TTT curve is studied to figure out different types of aging of elements and systems. Our proposal is a useful and novel graphical
45 tool that allows recognizing some important types of aging from empirical

data. The TTT plot was introduced by [13] as a tool for analyzing failure data and some important classes of life distributions can be characterized in terms of the Total-Time-on-Test curve, see [14].

The concept of TTT transform has been extended and applied to different research fields, such as economics and actuarial sciences or biostatistics, see [15] and references therein for further details. In the field of reliability engineering the TTT curve has revealed as a very useful tool for aging characterization [15], model identification [16] and [17], hypothesis testing [18], [19], [20], stochastic ordering [12], age replacement policies in maintenance [21], structural reliability [22], among others. Recently [15] and [6] have listed some known characterizations of common aging notions in terms of TTT function and have also derived some new ones.

One of the advantages of the TTT curve is that it is confined to the compact interval $[0, 1]$ whereas the failure rate is not bounded in general. Given the relationship between the failure rate and the TTT transform, one can understand the shape of the failure rate function by exploring the TTT curve. In this paper, the scaled TTT plot is used to discover a possible aging tendency of an underlying distribution based on sample information. In particular, increasing failure rate (IFR), bathtub failure rate (BFR) and new better than used in expectation (NBUE) are considered.

Identification of models by testing monotonic and non-monotonic trends has been a matter of research for decades in reliability and maintainability, [23] and [24], where the property of non aging can also be interpreted as the so-called “as-good-as-new” condition. In particular, the interest has traditionally been put on testing exponentiality against aging alternatives (see [10] and [25] for a detailed discussion) and it continues being a subject of study nowadays, [26], [27], and [28] are some recent contributions. In the late 70’s and early 80’s several tests based on the TTT transform were proposed to test exponentiality against different aging trends ([29], [30], [16], [18], [19], [20]).

The contribution of this paper is twofold. On the one hand, a new estimator of the TTT-transform is proposed based on nonparametric statistics, more specifically, based on kernel smoothing techniques. To our knowledge, this is an innovative contribution to this area of Statistics. Although nonparametric smoothing techniques are very popular in related areas such as survival analysis, they are not very usual in reliability engineering where parametric methods have been traditionally preferred by the practitioners

for solving inference problems. One motivation is the following. From available data, the theoretical TTT transform is usually approximated by means of the TTT-plot, the empirical estimator. While the theoretical curve is an absolutely continuous function, the empirical curve is always discontinuous and may be viewed as a poor approximation of the true curve, among other reasons, because it is a step function and the derivative either equals zero or is not defined, which makes difficult to evaluate shape characteristics. Kernel smoothing avoids discontinuities in the empirical function.

The second contribution is a new method for assessing non-aging properties in the underling lifetime. The new proposal is a graphical test able to recognize aging trends from data. The main advantage, compared to existing tests, is that it allows identifying specific areas where discrepancies from non-aging are detected. In contrast, standard testing methods summarize the sampling information in the single p-value to decide on the adequacy of the model specified in the null hypothesis.

The paper is organized as follows. In Section 2 the Total-Time-on-Test transform is formally defined and some relevant properties are reviewed. Section 3 introduces local-polynomial estimators for the TTT-curve and its two first derivatives. Section 4 is devoted to SiZer map methodology. First, the general idea is exposed and then a new graphic tool is presented based on the SiZer map aimed to recognize aging trends in a lifetime by developing scale and space inferences about the TTT curve and some particular transformations of this curve. Finally, a graphical method for hypothesis testing is proposed. The good performance of the new graphical test is evaluated by an extensive simulation study and the method is applied to several real datasets in Section 5. Conclusions and future research interests are summarized in Section 6. Finally, some mathematical developments are included in the Appendix.

2. Preliminary

This section is devoted to some aging classes defined through the failure rate and/or the residual life and that are univocally described in terms of the TTT-transform ([16]).

2.1. Reliability classes based on aging notions

Let X denote a random lifetime with absolutely continuous distribution function, with survival function S , for any fixed $t > 0$ let X_t denote the

120 *residual lifetime* from time t , which represents the additional lifetime from t . The conditional survival function, given that $T > t$ is defined as $S_t(x) = S(t+x)/S(t)$, for all $x > 0$. The mean residual time is then defined as $\mu_t = \int_0^{+\infty} \frac{S(t+x)}{S(t)} dx$. Note that $\mu_0 = E[X] = \mu$. For a continuous random variable X , with density f , and survival function S , the corresponding *failure rate* or *hazard function* is defined as $h(t) = f(t)/S(t)$.

- 125 1. Increasing failure rate, *IFR*:
 X is *IFR*, if and only if, for all $x > 0$ fixed, $S_{t_1}(x) \leq S_{t_2}(x)$, and for all $t_1 < t_2$. In other words, the conditional survival function, S_t defined above is a non decreasing function in t . This condition can be also established in terms of the failure rate, saying that X is *IFR* if and
130 only if $h(t)$ is increasing in t .
2. Bathtub shaped Failure Rate, *BFR*:
 X is *BFR*, if and only if, its failure rate curve is divided into three regions: decreasing failure rate region, constant failure rate region, and increasing failure rate region.
- 135 3. New better than used in expectation, *NBUE*:
 X is *NBUE*, if and only if, $\mu_t \leq \mu$, for all $t > 0$; where μ_t , defined previously, denotes the expected residual life of a mechanism with distribution F and at the age t .

2.2. Total-Time-on-Test transform: Definition and relevant properties

140 Total time on test plots provides a useful graphical method for tentative identification of lifetime models. This concept is very important in applications in reliability analysis. When several units are tested for studying their life lengths some of the units would fail while others may survive the test period. The sum of all observed and incomplete life lengths is the total
145 time on test statistics. The plot of this statistic versus time is called the total-time-on-test plot. As the number of units on a test tends to infinity the limit of this statistic is called the total time on test transform (TTT). This concept was introduced by [31] and later studied by [2].

DEFINITION 2.1. Total-Time-on-Test statistic Suppose n items under test and successive failures are observed at $0 = X_{(0)} \leq X_{(1)} \leq X_{(2)} \leq \dots \leq X_{(n)}$, with $X_{(i)}$ the i -th order statistic from a lifetime random variable X with absolutely continuous distribution function F . Then the total time on

test statistic during the interval $(0, t)$ is defined as

$$\tau(t) = \sum_{i=1}^r X_{(i)} + (n - r)t,$$

provided that $X_{(r-1)} < t \leq X_{(r)}$.

DEFINITION 2.2. Total Time on Test transform Let X be a (non-negative) random variable with absolutely continuous cumulative distribution function F . The total time on test transform of X is defined as

$$\varphi(p) = \int_0^{Q(p)} (1 - F(t)) dt \quad (1)$$

150 where $Q(p) = F^{-1}(p)$, for $p \in [0, 1]$ denotes the corresponding quantile function.

When $E[X] < \infty$, this expectation can be obtained as $\mu = \int_0^{Q(1)} S(t)dt$, where $S(t) = 1 - F(t)$ denotes the survival function. Then the scaled TTT transform is defined as $\varphi(p)/\mu$, for $0 \leq p \leq 1$, which is scale invariant. In
155 the following, the notation $\varphi(p)$ is kept for the scaled TTT transform, and it is assumed that $\mu = 1$ since it does not imply any loss of generality.

2.3. Aging properties based on the TTT transform

The scaled TTT transform can be used to characterize different aging properties, see [2] and [14]. For F the exponential distribution, it can be
160 checked that $\varphi(p) = p$, for $0 \leq p \leq 1$. As mentioned above, based on a sample X_1, X_2, \dots, X_n one can construct the TTT plot, which will be closer to the scaled TTT curve as n tends to $+\infty$. The TTT plot is used as a tool for model selection, in the sense that when, for example, the TTT plot produces a cloud of points around the diagonal of the square unit, the exponential
165 distribution fits well of the underlying lifetime F , which implies constant failure rate. Other failure rate shapes can be recognized from an inspection of the TTT plot. A convex TTT curve corresponds with a decreasing failure rate (DFR); a concave TTT curve corresponds with an increasing failure rate (IFR). When the TTT plot describes a trajectory first convex and then
170 concave it indicates a bathtub failure rate shape and when it is first concave and then convex, it indicates a unimodal failure rate shape.

Let X be a lifetime with distribution function F and with finite mean μ . From the theorems given in [18], the above aging conditions can be expressed in terms of the TTT-curve as follows:

175 **PROPOSITION 2.1.** *TTT-curve characterization of aging*

1. F is IFR, if and only if, $\varphi''(u) \leq 0$, for all $0 < u < 1$;
2. F is BFR, if and only if, for some $u_0 \in (0, 1)$, $\varphi''(u)(u - u_0) > 0$, for all $0 < u < 1$;
3. F is NBUE, if and only if, $\varphi(u)/u \geq 1$, for all $0 < u < 1$.

180 Thus, one of the main objectives of this paper is to estimate TTT-curve as well as the first and second derivatives to search for aging trends.

3. Local polynomial estimation of the TTT-transform and its first and second derivatives

185 In this section a local-polynomial estimator for the TTT-transform directly formulated from an empirical estimation of the TTT-curve is suggested, that is, there is no need to estimate the quantiles to get an estimator of the TTT-transform.

3.1. Least-squares estimation of the Total-Time-on-Test transform

Let X_1, X_2, \dots, X_n be an independent and identically distributed random sample drawn from an absolutely continuous distribution function F with density f . Let $X_{(1)}, X_{(2)}, \dots, X_{(n)}$ denote the corresponding order statistics. Let us denote $p_i = \frac{i}{n}$ for $i = 1, 2, \dots, n$. An empirical (*naive*) estimator of the TTT-curve $\hat{\varphi}_{n,i}$, can be defined as follows

$$\hat{\varphi}_{n,i} = \sum_{j=1}^i \left(1 - \frac{j-1}{n}\right) (X_{(j)} - X_{(j-1)}), \quad (2)$$

190 for $i = 1, 2, \dots, n$, with $\hat{\varphi}_{n,0} = 0$. As can be seen $\hat{\varphi}_{n,n} = \bar{X}$, the mean sample statistics. Since the properties of the curve are not affected by scale changes, the curve can be confined to the interval $[0, 1]$ by first normalizing the data. In the following, without loss of generality, it is assumed that $\bar{X} = 1$.

Under a local-polynomial approach, for each estimation point $p_0 \in (0, 1)$, the TTT-transform $\varphi(p_0)$ is locally (in a neighborhood of p_0) approximated by a m th-degree polynomial function in the sense that for all $p \in (p_0 - h, p_0 + h)$ it holds that $\varphi(p) = \theta_0 + \theta_1(p - p_0) + \theta_2(p - p_0)^2 + \dots + \theta_m(p - p_0)^m$, for an appropriate bandwidth h .

The parameters of the model can be interpreted respectively as $\theta_0 = \varphi(p_0)$; $\theta_1 = \varphi'(p_0)$; and, in general, $\theta_k = \frac{\varphi^{(k)}(p_0)}{k!}$, for $k = 1, 2, \dots, m$. The

200 approximation above is valid locally if certain smoothness conditions on the true curve, in the sense of derivability, are assumed.

In particular, the three first coefficients provide the following estimates: $\widehat{\varphi}(p_0) = \widehat{\theta}$, $\widehat{\varphi}'(p_0) = \widehat{\theta}_1$, and $\widehat{\varphi}''(p_0) = 2\widehat{\theta}_2$, respectively. To this goal, the following least squares problem is formulated.

$$\begin{aligned} & \left(\widehat{\theta}_0, \widehat{\theta}_1, \dots, \widehat{\theta}_m \right)^\top = \\ & \arg \min_{(\theta_0, \theta_1, \dots, \theta_m)^\top} \sum_{i=1}^n \{ \widehat{\varphi}_{n,i} - \theta_0 - \theta_1(p_i - p_0) - \dots - \theta_m(p_i - p_0)^m \}^2 K_h(p_i - p_0), \end{aligned} \quad (3)$$

where $K_h(\cdot) = \frac{1}{h}K(\frac{\cdot}{h})$, with K a symmetric kernel function, and h the bandwidth parameter that controls the size of the window around the estimation point, p_0 , where the polynomial approximation is valid. After differentiating in equation (3), for $m = 2$ with respect to θ_j ($j = 0, 1, 2$), it is obtained a system of linear equations that can be written in matrix form

$$\begin{pmatrix} a_0 & a_1 & \cdots & a_m \\ a_1 & a_2 & \cdots & a_{m+1} \\ \vdots & \vdots & \ddots & \vdots \\ a_m & a_{m+1} & \cdots & a_{2m} \end{pmatrix} \begin{pmatrix} \theta_0 \\ \theta_1 \\ \vdots \\ \theta_m \end{pmatrix} = \begin{pmatrix} A_0 \\ A_1 \\ \vdots \\ A_m \end{pmatrix}; \quad (4)$$

where

$$A_r(p_0) = \sum_{i=1}^n (p_i - p_0)^r K_h(p_i - p_0) \widehat{\varphi}_{n,i}, \quad r = 0, 1, \dots, m; \quad (5)$$

and

$$a_l(p_0) = \sum_{i=1}^n (p_i - p_0)^l K_h(p_i - p_0), \quad l = 0, 1, 2, \dots, 2m. \quad (6)$$

205 In [21] the authors also consider a least-squares optimization problem based on the TTT-plot. They assume a Weibull model and, from a dataset, they estimate the shape parameter by minimizing the distance between the TTT-plot and the TTT-transform of the Weibull model. In this paper, a more general and versatile approach is considered, that is, the optimization
210 problem is formulated assuming no specific parametric form for the theoretical TTT-transform.

3.2. Local-quadratic estimator

For illustrative purposes, in the following, the data are fit locally using a 2-degree polynomial. However, it should be taken into account that it is convenient to increase the complexity of the model when interested in exploring the properties of the form through the second derivative. Detailed expressions for the estimators based on a local-cubic polynomial fit are given in the Appendix.

The least squares problem (3) is set for $m = 2$, and $A_r(p_0)$ are defined as in (5) for $r = 0, 1, 2$; and $a_l(p_0)$, for $l = 0, 1, 2, 3, 4$ as in (6). The estimator of the TTT-transform is denoted $\hat{\varphi}_h(\cdot)$.

The Cramer's rule provides an appropriate solution to the equations that leads to the estimation of the curve φ and its derivatives at a given p_0 , based on the quadratic fit as follows.

- The TTT-curve

$$\hat{\varphi}_h(p_0) = \hat{\theta}_0(p_0) = \sum_{i=1}^n \bar{K}_{0,h}(p_i - p_0) \hat{\varphi}_{n,i}, \quad (7)$$

where

$$\bar{K}_{0,h}(p_i - p_0) = \frac{(a_1 a_3 - a_2^2)(p_i - p_0)^2 + (a_2 a_3 - a_1 a_4)(p_i - p_0) + (a_2 a_4 - a_3^2)}{a_0 a_2 a_4 + 2a_1 a_2 a_3 - a_2^3 - a_0 a_3^2 - a_1^2 a_4} K_h(p_i - p_0).$$

- The first derivative

$$\hat{\varphi}'_h(p_0) = \hat{\theta}_1(p_0) = \sum_{i=1}^n \bar{K}_{1,h}(p_i - p_0) \hat{\varphi}_{n,i}, \quad (8)$$

where

$$\bar{K}_{1,h}(p_i - p_0) = \frac{(a_1 a_2 - a_0 a_3)(p_i - p_0)^2 + (a_0 a_4 - a_2^2)(p_i - p_0) + (a_2 a_3 - a_1 a_4)}{a_0 a_2 a_4 + 2a_1 a_2 a_3 - a_2^3 - a_0 a_3^2 - a_1^2 a_4} K_h(p_i - p_0).$$

- The second derivative

$$\hat{\varphi}''_h(p_0) = 2\hat{\theta}_2(p_0) = 2 \sum_{i=1}^n \bar{K}_{2,h}(p_i - p_0) \hat{\varphi}_{n,i} \quad (9)$$

where

$$\bar{K}_{2,h}(p_i - p_0) = \frac{(a_0 a_2 - a_1^2)(p_i - p_0)^2 + (a_1 a_2 - a_0 a_3)(p_i - p_0) + (a_1 a_3 - a_2^2)}{a_0 a_2 a_4 + 2a_1 a_2 a_3 - a_2^3 - a_0 a_3^2 - a_1^2 a_4} K_h(p_i - p_0).$$

3.3. Statistical properties of the estimator

230 This section is devoted to the local-quadratic case. Similar results for the local-cubic estimator can be derived and are sketched in the Appendix A.

The SiZer methodology involves the construction of confidence intervals around the target function and then it is needed to derive statistical properties such as mean and variance. First, expressions in (7)-(9) are rewritten as
 235 a linear combination of the order statistics $X_{(1)} \leq X_{(2)} \leq \dots \leq X_{(n)}$ so that each estimator is written in terms of the corresponding L -estimator. Then, in Appendix B the results in [32] help to obtain exact analytic expressions for the bootstrap moments.

The empirical estimator $\hat{\varphi}_{n,i}$ ($i = 1, \dots, n$) given in (2) can be expressed as

$$\hat{\varphi}_{n,i} = \sum_{j=1}^i \omega_{i,j} X_{(j)}, \quad (10)$$

where

$$\omega_{i,j} = \begin{cases} \frac{1}{n}, & j = 1, 2, \dots, i-1 \\ \frac{n-(i-1)}{n}, & j = i \end{cases} \quad (11)$$

These weights can be arranged in matrix form as

$$\mathbf{W} = \begin{pmatrix} 1 & 0 & 0 & 0 & \dots & 0 \\ \frac{1}{n} & \frac{n-1}{n} & 0 & 0 & \dots & 0 \\ \frac{1}{n} & \frac{1}{n} & \frac{n-2}{n} & 0 & \dots & 0 \\ \frac{1}{n} & \frac{1}{n} & \frac{1}{n} & \frac{n-3}{n} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{1}{n} & \frac{1}{n} & \frac{1}{n} & \dots & \frac{1}{n} & \frac{1}{n} \end{pmatrix}$$

Expressions for the estimators of the TTT-transform and its derivatives

240 as L-estimators can be obtained. Equations (10) and (7) lead to

$$\begin{aligned}\widehat{\varphi}_h(p_0) &= \sum_{i=1}^n \bar{K}_{0,h}(p_i - p_0) \sum_{j=1}^i \omega_{i,j} X_{(j)} \\ &= \sum_{i=1}^n \sum_{j=1}^i \bar{K}_{0,h}(p_i - p_0) \omega_{i,j} X_{(j)}\end{aligned}$$

and, re-ordering the terms inside the sums,

$$\widehat{\varphi}_h(p_0) = \sum_{j=1}^n \sum_{i=j}^n \bar{K}_{0,h}(p_i - p_0) \omega_{i,j} X_{(j)}. \quad (12)$$

Using matrix notation the above expression can be written as

$$\widehat{\varphi}_h(p_0) = \bar{\mathbf{K}}_{0,h}(p_0)^\top \cdot \mathbf{W} \cdot \mathbf{X}_{(\cdot)}, \quad (13)$$

where the vector of weights is denoted

$$\bar{\mathbf{K}}_{0,h}(p_0) = (\bar{K}_{0,h}(p_1 - p_0), \bar{K}_{0,h}(p_2 - p_0), \dots, \bar{K}_{0,h}(p_n - p_0))^\top,$$

and $\mathbf{X}_{(\cdot)} = (X_{(1)}, \dots, X_{(n)})^\top$ is the ordered sample.

Let us introduce the following notation

$$\boldsymbol{\mu} = (\mu_{(1)}, \mu_{(2)}, \dots, \mu_{(n)})^\top, \quad (14)$$

with $\mu_{(i)} = E[X_{(i)}]$, for $i = 1, 2, \dots, n$, is the vector of means of the order statistics; and,

$$\boldsymbol{\Sigma} = \begin{pmatrix} \sigma_{(1)}^2 & \sigma_{(12)} & \cdots & \sigma_{(1n)} \\ \sigma_{(12)} & \sigma_{(2)}^2 & \cdots & \sigma_{(2n)} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{(1n)} & \sigma_{(2n)} & \cdots & \sigma_{(n)}^2 \end{pmatrix} \quad (15)$$

with $\sigma_{(i)}^2 = \text{Var}(X_{(i)})$ and $\sigma_{(ij)} = \text{Cov}(X_{(i)}, X_{(j)}) = E[(X_{(i)} - \mu_{(i)}) \cdot (X_{(j)} - \mu_{(j)})]$, for $i, j = 1, 2, \dots, n$, $i < j$, is the covariance matrix.

Then, the variance of the estimator of the TTT-transform can be computed by

$$\text{Var}(\widehat{\varphi}_h(p_0)) = \bar{\mathbf{K}}_{0,h}(p_0)^\top \cdot \mathbf{W} \cdot \boldsymbol{\Sigma} \cdot \mathbf{W}^\top \cdot \bar{\mathbf{K}}_{0,h}(p_0). \quad (16)$$

Similar to (16) the corresponding expression for the first derivative of the TTT-curve can be obtained. Let us define the corresponding vector of weights

$$\bar{\mathbf{K}}_{1,h}(p_0) = (\bar{K}_{1,h}(p_1 - p_0), \bar{K}_{1,h}(p_2 - p_0), \dots, \bar{K}_{1,h}(p_n - p_0))^\top,$$

then it can be written

$$\hat{\varphi}'_h(p_0) = \sum_{j=1}^n \sum_{i=j}^n \bar{K}_{1,h}(p_i - p_0) \omega_{i,j} X_{(j)} = \bar{\mathbf{K}}_{1,h}(p_0)^\top \cdot \mathbf{W} \cdot \mathbf{X}_{(\cdot)},$$

and the variance is given as

$$\text{Var}(\hat{\varphi}'_h(p_0)) = \bar{\mathbf{K}}_{1,h}(p_0)^\top \cdot \mathbf{W} \cdot \boldsymbol{\Sigma} \cdot \mathbf{W}^\top \cdot \bar{\mathbf{K}}_{1,h}(p_0). \quad (17)$$

The second derivative of the TTT-curve

Finally, for the local-quadratic estimator of the second derivative of the TTT-curve, let us denote

$$\bar{\mathbf{K}}_{2,h}(p_0) = (\bar{K}_{2,h}(p_1 - p_0), \bar{K}_{2,h}(p_2 - p_0), \dots, \bar{K}_{2,h}(p_n - p_0))^\top,$$

and

$$\hat{\varphi}''_h(p_0) = 2 \sum_{j=1}^n \sum_{i=j}^n \bar{K}_{2,h}(p_i - p_0) \omega_{i,j} X_{(j)} = 2 \bar{\mathbf{K}}_{2,h}(p_0)^\top \cdot \mathbf{W} \cdot \mathbf{X}_{(\cdot)}.$$

Then, the variance is computed by

$$\text{Var}(\hat{\varphi}''_h(p_0)) = 4 \bar{\mathbf{K}}_{2,h}(p_0)^\top \cdot \mathbf{W} \cdot \boldsymbol{\Sigma} \cdot \mathbf{W}^\top \cdot \bar{\mathbf{K}}_{2,h}(p_0). \quad (18)$$

245 4. A graphic tool for evaluating aging trends

In this section, a novel method to graphically test certain aging properties of the underlying lifetime distribution given a sample of lifetime data is proposed. The graphical test is based on scale and space inference, which are explained in the following.

250 *4.1. Introduction to SiZer*

“SiZer” stands for “significant zero crossings of the derivatives” and was introduced by [33] and [34] as a powerful exploratory graphical tool for density and regression functions. This tool uses kernel smoothing to estimate the structure that underlies the data and plays with the smoothing parameter as a scale parameter to visualize the underlying characteristics in the function under study. The characteristics that “really are there”, that is, those that are not a mere artefact of the sample variability, are revealed through the construction of confidence intervals for the first derivative of the function. The main idea of SiZer is to consider the full family of smooths instead of the “true underlying curve”. The estimated curves under different smoothing scales may provide different information on the variation of the curve. Indeed, larger smoothing levels are helpful to find the global trend of the underlying curve and the small ones are useful to reflect the local features. There has been lots of literature on the research and applications of this method, for example, for time series analysis (see [35]), to compare the equality of regression curves [36], survival analysis [37], economic data analysis [38], ecological data analysis [39], internet traffic data analysis [40], etc.)

In its most well-known version, the reasoning underlying SiZer can be summarized as follows. At a bump, there is a zero-crossing of the derivative. Then, all estimated slopes with different bandwidths to its left are significantly increasing while all estimated slopes to its right are significantly decreasing. In its most well-known version SiZer relies on two plots. On the one hand, the so-called “family plot”, which is the representation of a family of nonparametric smoothers of the target function, indexed by the bandwidth parameter. On the other hand, the gradient “SiZer map”, which displays the scale and space inference about the first derivative. For each bandwidth, which corresponds to the scale, and each value in the support, which gives localization, a confidence interval for the first derivative is calculated and the signs are displayed on the map using a color code. The code and documentation can be downloaded from [41].

A generic black-and-white version of SiZer is explained, although frequently other representations can be found in the literature. Considering n_h scales and n_x localizations, each pixel in the $(n_x \times n_h)$ map is coded as white if zero is greater than the upper confidence bound, indicating significant decrease; black if zero is less than the lower confidence bound, indicating significant increase; dark gray if zero is within the confidence limits (no sig-

nificant increase or decrease); and gray indicating regions where the data are too sparse to infer significance. The structure in the data is highlighted by gray changes and a change from black to white means a significant bump.

Several versions and adaptations of SiZer have been proposed in the literature to account for other interesting features such as curvature. Specifically, there is the so-called “SiCon” map which is the counterpart of SiZer to display the scale and space inference about the second derivative. Thus, SiCon map is black for negative curvature (concave), white for positive curvature (convex), dark gray for zero curvature, and gray indicating regions where the data are too sparse.

4.2. Development of SiZer methods for examining the shape of the TTT-curve

In this paper, the general idea of SiZer map is adopted and a new graphical tool is developed that allows to evaluate different types of aging underlying the data by means of scale and space inference about the TTT curve and its two first derivatives. The method is denoted “TTT-SiZer” and it will rely on four plots: the TTT-plot and three color maps.

The first map is called “SiZer-0” map and is obtained by interpreting the sign of the confidence intervals constructed for a convenient transformation of the TTT curve. This map will be used later to evaluate the NBUE property. The second map is called “SiZer-1” map and is strictly the SiZer map describe above. That is, based on the first derivative of the target curve which is the TTT curve. This plot is just for control purposes. Recall that the TTT curve is obtained as the integral of a continuous positive function, therefore increasing. The SiZer-1 map should accordingly reflect it. The third map is called “SiZer-2” map and is the SiCon built from the inference about the second derivative of the TTT curve as it is mentioned above. This map is used to evaluate deviance from non-aging (exponentiality) in favor of strong aging properties as IFR or BFR, or their duals.

Let $g_k(p)$ denote a generic function, and SiZer- k map the corresponding color map. Specifically, define $g_0(p) = \varphi(p) - p$; $g_1(p) = \varphi'(p)$; and $g_2(p) = \varphi''(p)$.

Consider a grid of bandwidths (*scale*) and a grid of localizations in the interval $(0, 1)$ (*space*), which corresponds to the estimation window.

Each combination of bandwidth and localization determines one pixel of a two dimensional space which will be the support of the color map. For a given bandwidth, the local-polynomial estimator is constructed as explained

325 in Section 3. For a significance level $\alpha \in (0, 1)$ the computation of the variance given in Section 3.3 is used to build the corresponding confidence interval, that is

$$\left(\widehat{g}_{k,h}(p) - q_{1-\frac{\alpha}{2}} \sqrt{\widehat{V}(\widehat{g}_{k,h}(p))}, \widehat{g}_{k,h}(p) + q_{1-\frac{\alpha}{2}} \sqrt{\widehat{V}(\widehat{g}_{k,h}(p))} \right), \quad (19)$$

with $p \in (0, 1)$, and $k = 0, 1, 2$.

330 The interest is in determining whether 0 is inside the interval (19) or on the contrary, the interval is strictly positive or negative. To represent each situation a color code is used as follows. A pixel is white if the upper confidence bound is lower than 0; it is black if the lower confidence bound is greater than 0; and, it is dark gray if zero is within the confidence limits. Gray color represents regions with sparse data.

335 4.3. Motivating example

The versatility of *SiZer* for lifetime data analysis is shown through a simulated sample. Let us consider a bathtub shaped failure rate distribution. In particular, let us simulate a sample of size $n = 500$ from an additive Weibull model discussed in [42] with failure rate $r(t) = (b/a)(t/a)^{(b-1)} + (d/c)(t/c)^{(d-1)}$ for $a = 1; b = 5; c = d = 0.5$. This model is displayed in Figure 1.

345 The results of the TTT-SiZer analysis are shown in Figure 2. The top-left panel shows the empirical TTT-plot for these data. The plot suggests a change of sign in convexity properties of the curve thus revealing the characteristics of the underlying bathtub shaped failure rate. This is confirmed by the color maps which represent inferences about the TTT-curve as well as its first and second derivatives. The top-right panel presents the corresponding SiZer-0 map. In this case, it can be seen a change of color in the sense white to black indicating that the TTT-transform crosses the diagonal of the unit square from below, which is in accordance with a bathtub shaped failure rate while at the same time allows to arguing against the NBUE. The bottom-left panel presents the SiZer-1 map indicating positive sign of the first derivative, as expected since the TTT-curve is defined as a cumulative integral function. Finally, the bottom-right panel shows the SiZer-2 map which tells us about 355 the second derivative. This graph picks up the true features of the underlying hazard model. The plot shows that the hazard rate decreases significantly at the beginning (white color up to about the point 0.5). There is then a zero-crossing signaled by the dark gray color (between points 0.5 and 0.7),

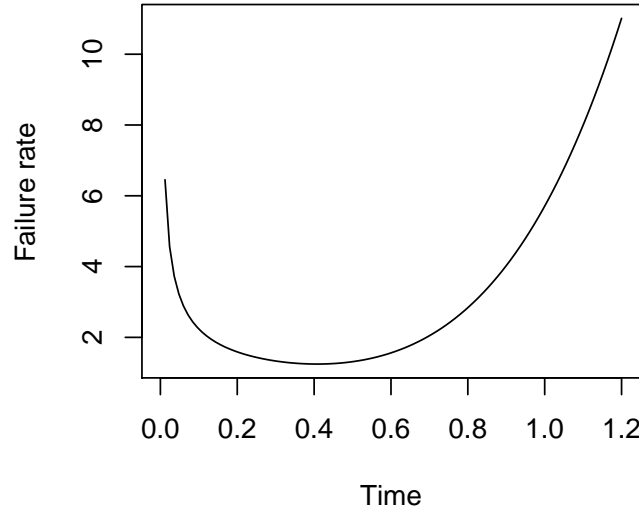


Figure 1: Bathtub shaped failure rate.

indicating that the hazard rate is constant. The hazard rate then increases
 360 to the point 0.95, as the black color indicates. This reveals a minimum of
 the hazard rate around 0.5.

It is worth to mention at this point that, although the same range of
 bandwidths is used for the three curves, it might not be the most appropriate.
 The second derivative implies the most complex estimation problem. More
 365 information is needed, meaning that bigger bandwidths are required. Smaller
 bandwidths increase variability. The resulting estimators are less efficient
 leading to wider confidence intervals. The wide dark gray area at the bottom
 of the plot in SiZer-2 shows this point.

4.4. Some important issues in the SiZer methodology

1. Effective sample size

The concept of effective sample size (ESS) is considered as defined by
 [33]. In this paper, an estimated slope is classified to be not enough

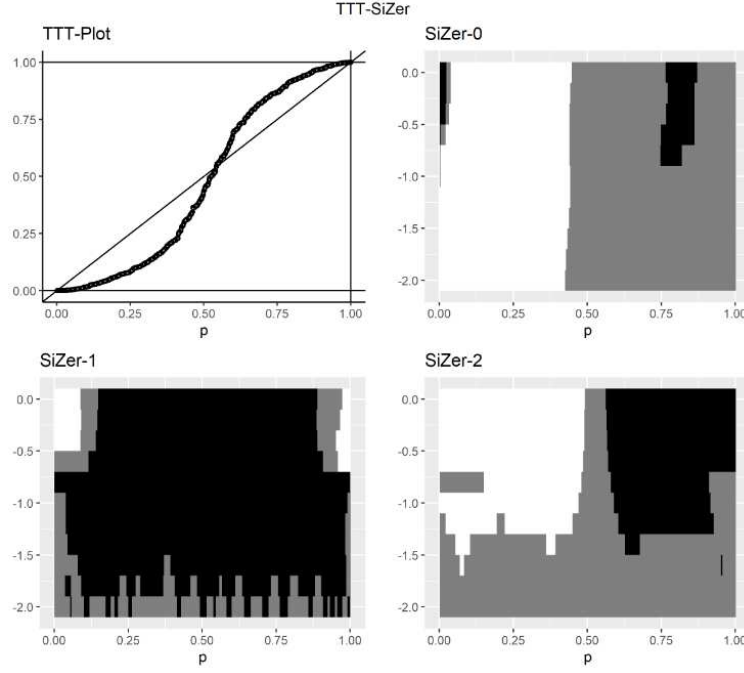


Figure 2: TTT-Sizer for a dataset from an additive Weibull model.

data if its ESS is less than or equal to 5,

$$ESS(p_0, h) = \frac{\sum_{i=1}^n K_h(p_i - p_0)}{K_h(0)}.$$

370

2. Quantile functions

Candidates for calculation of the quantile q include:

- Pointwise Gaussian quantiles: $q_1(h) = q_1 = \Phi^{-1}[1 - \alpha/2]$, with Φ the standard normal distribution function.
- Approximate simultaneous over p Gaussian quantiles: based on “number of independent blocks” [43], defined as

$$q_2(h) = \Phi^{-1} \left[\left(1 - \frac{\alpha}{2} \right)^{1/\{\theta(\Delta)d\}} \right],$$

where

$$\theta(\Delta) = 2\Phi \left\{ \frac{\Delta \sqrt{3 \log(d)}}{2h} \right\} - 1$$

375 with d the number of pixels in a row in the SiZer Map, Δ is the distance between two successive neighbouring locations p_0 . In [43] the quantity $\theta(\Delta)$ is defined as the clustering index that measures the level of dependency between pixels.

4.5. Examples: Two real cases in Reliability

In this section, the proposed graphic tool is applied to two real datasets. 380 The first dataset (Example 1) represents interoccurrence times of fatal accidents to British-registered passenger aircraft, 1946-1963, measured in number of days and listed in the order of their occurrence in time. The second dataset (Example 2) represents failure and running times (1000 cycles) of a sample of 30 units of a larger electrical system. The data have been taken from 385 Appendix B in [28], where new consistent and scale-free goodness-of-fit tests for the Exponential distribution are presented. After an exhaustive analysis of the two real cases, the authors conclude Exponential distribution is acceptable for the first case while not for the second one. Moreover, they point out that the proposed tests agree with the decisions suggested by different 390 exponentiality tests with proven good power performance. However, they note that, at the 5% level of significance, few of them fail to reject the null hypothesis for the second dataset. In Figure 3 only partial information provided by the SiZer analysis is reported, specifically the results based on inferences about the second derivative. On the top panel, Example 1 is analyzed. 395 The TTT-plot is displayed on the left side and the SiZer-2 map on the right. According to the arguments given in the former section, it can be concluded that the Exponential distribution fits well the data in this case. As for Example 2, a very different graph is produced so the Exponential distribution is clearly not admissible for the second case.

400 4.6. Hypothesis testing based on TTT-SiZer

In this section, a graphical test based on TTT-SiZer is derived to explore aging trends underlying in a given lifetime dataset. The null hypothesis (H_0) is “No aging”, that is, the underlying lifetime is assumed to be exponentially distributed. Different alternative hypotheses (H_1) are faced according to the 405 particular aging trend one is interested in. The kind of H_1 also determines the way the condition of “No aging” in H_0 is expressed. More specifically, a classic statistical testing problem can be settled as follows:

Let X be a random lifetime, one is interested in testing the null hypothesis

$$H_0 : X \text{ follows } \text{Exp}(\lambda) \text{ distribution, for some } \lambda > 0,$$

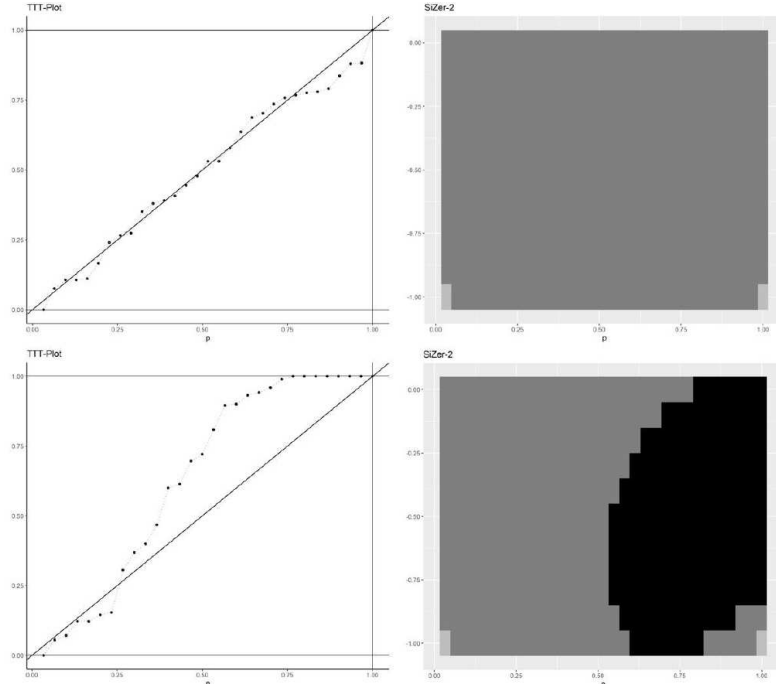


Figure 3: TTT-Sizer analysis of two real cases in Reliability.

against general alternatives based on a sample X_1, X_2, \dots, X_n of independent copies of X .

410 In order to solve the problem using the graphical test, the hypothesis is written in terms of the TTT-transform. In this sense, mainly the two following problems are considered

1. “No aging” *against* NBUE:

$$\begin{aligned} H_0 &: \varphi_X(p) = p, \text{ for all } p \in (0, 1) \\ H_1 &: \varphi_X(p) > p, \text{ for some } p \in (0, 1) \end{aligned} \quad (20)$$

2. “No aging” *against* IFR:

$$\begin{aligned} H_0 &: \varphi_X''(p) = 0, \text{ for all } p \in (0, 1) \\ H_1 &: \varphi_X''(p) < 0, \text{ for some } p \in (0, 1) \end{aligned} \quad (21)$$

415 The proposed graphic tool is composed of four plots: the TTT-plot and the three SiZer maps which are described below.

- SiZer-0: The first map is based on the sign of the following transformation of the TTT curve: $g_0(p) = \varphi(p) - p$. Then, the corresponding $(1 - \alpha)100\%$ confidence interval for $g_0(p)$ is considered, that is

$$\left[\hat{\varphi}_h(p) - q_{1-\frac{\alpha}{2}} \sqrt{\hat{V}(\hat{\varphi}_h(p))} - p, \hat{\varphi}_h(p) + q_{1-\frac{\alpha}{2}} \sqrt{\hat{V}(\hat{\varphi}_h(p))} - p \right],$$

420 for $0 \leq p \leq 1$.

- SiZer-1: The second map examines the sign of the first derivative, then define $g_1(p) = \varphi'(p)$. This map is built just for checking purposes. Since the TTT-transform is defined as the integral of a positive continuous function, it should be an increasing function, and so it should be displayed in the SiZer-1 map.

425

- SiZer-2: In this case, the sign of the second derivative of the TTT-transform is examined. Then confidence intervals for $g_2(p) = \varphi''(p)$ are computed. For $0 \leq p \leq 1$,

$$\left[\hat{\varphi}_h''(p) - q_{1-\frac{\alpha}{2}} \sqrt{\hat{V}(\hat{\varphi}_h''(p))}, \hat{\varphi}_h''(p) + q_{1-\frac{\alpha}{2}} \sqrt{\hat{V}(\hat{\varphi}_h''(p))} \right]. \quad (22)$$

In all cases, q is a proper quantile. The corresponding function $g_k(p)$, for $k = 0, 1, 2$ is significantly positive (negative) when both confidence limits are above (below) 0, and it is not significant when 0 belongs to the confidence interval.

430

The general procedure consists of rewriting the hypotheses in SiZer language. To explain it, let us focus on (21). The null hypothesis is equivalent to asserts that the SiZer-2 map underlying to the true distribution is completely dark gray. This one is called the *true* SiZer-2 map. The decision is to reject the null hypothesis in the case that the *empirical* SiZer-2, which is the one based on the data, displays a percentage of non-dark gray pixels above a pre-specified level.

435

This level is usually referred to as the type I error probability and it is denoted as α . This value is commonly taken as $\alpha = 0.05$.

The steps of our proposal are summarized in the following algorithms.

440 *Algorithm 2. Testing exponentiality against hazard-trend changes*

Define the *true* TTT-SiZer map according to an Exponential distribution.
Under this null hypothesis, SiZer-2 is completely dark gray.

- Step 1. Compute the sample mean \bar{X} and define $\bar{X}_i = X_i/\bar{X}$, for $i = 1, 2, \dots, n$.
Step 2. Construct the *empirical* SiZer-2 map as explained in Section 4 based
445 on $\{\bar{\mathbf{X}}_i; i = 1, 2, \dots, n\}$.
Step 3. Compare pixel by pixel the *empirical* SiZer-2 map with the correspond-
ing *true* SiZer-2 map and count the total number of pixels where the
color in the generated *empirical* map is not the same as in the *true*
map. Define the test statistic T_2 , as the percentage of non-dark gray
450 pixels in the empirical map, the reported value is T_2^0 .
Step 4. Use bootstrap methods to approximate the distribution of statistic T_2
under H_0 : Draw M samples of size n from the $Exp(1)$ distribution.
Construct the corresponding SiZer-2 maps and count for each the num-
ber of non-dark gray pixels. A bootstrap sample of T_2 , labelled T_2^* , is
455 obtained.
Step 5. Define the p -value as $p_{2,boot} = (1/M) \sum_{m=1}^M I\{T_2^{*,m} > T_2^0\}$, with $I\{\cdot\}$
an indicator function.

Reject the null hypothesis at a significance level of $\alpha \in [0, 1]$ when $p_{2,boot} < \alpha$.

Example 3. Aarset dataset, [44]

460 For a demonstration of the above testing method, let us consider the
dataset consisting of $n = 50$ failure times of electrical devices, available in
[44], page 107. The results provided by classical tests are given in Table 1,
columns 2-3. As suggested by the TTT-plot, the interest, in this case, is
to test exponentiality against BFR alternatives. The results of the TTT-
465 SiZer method have been implemented for the local-cubic estimator and are
presented in Figure 4.

Moreover, Algorithm 2 has been implemented for this data case. A total
of $M = 1000$ samples of size $n = 50$ according to H_0 have been simulated.
The reported p -value $p_{2,boot} = 0.044$ leads to the decision of rejecting Expo-
470 nentiality, as also is suggested by the majority of testing procedures reported
in Table 1. Looking at the whole group of plots in Figure 4 one can get more
information than the only provided by the p -value. As already mentioned,
the TTT-plot suggests the BFR condition for the underlying lifetime. This
idea is confirmed by looking at both SiZer-0. This graph displays a change

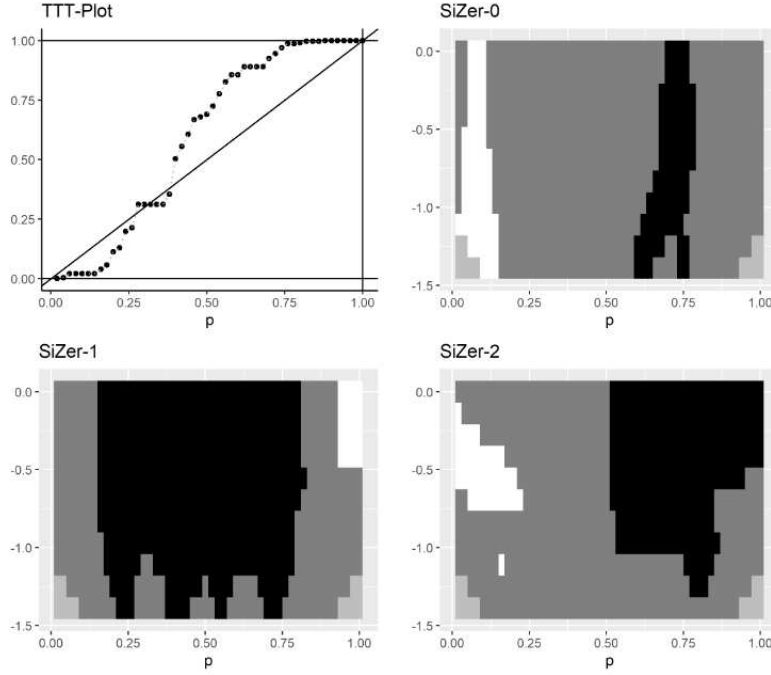


Figure 4: TTT-Sizer for Example 3: Electric devices failure times.

475 of sign from white to black for all bandwidths which means that the data
are not in accordance with the NBUE condition. On the other hand, looking
at the plot presented on SiZer-2, there is an evident change from white to
black meaning a clear change of trend of the hazard rate from decreasing to
increasing. So, the conclusion is that the data come from a BFR lifetime
480 distribution.

Example 4. Survival days of chronic granulocytic leukemia, [1]

The method has been applied to the dataset consisting of survival times,
in days from diagnosis, of 43 patients suffering from chronic granulocytic
leukemia. This case is considered to highlight the usefulness of our graphical
485 method against other classical non-graphical tests where the decision relies on
the value of a statistic and the corresponding p-value. Although, Algorithm
2 allows summarizing the testing information of the graphical test in the
value of a statistics, the true relevance of our procedure is that areas where
the null hypothesis is not supported by the data can be located, instead of

Table 1: Some Exponentiality tests implemented in package *exptest* [45] of program R.

	<i>Example 1. Reliability data</i>		<i>Example 2. Survival time data</i>	
Test [46]	Test Statistic	<i>p</i> - value	Test Statistic	<i>p</i> - value
Cox and Oakes	−3.388	0.709	12.171	0.148
Cramer-von Mises	0.519	1	0.149	1
Deshpande	0.708	0.528	0.729	0.127
Gini-statistic	0.411	0.031	0.426	0.097
Gnedenko <i>F</i> -test	2.236	0.005	1.316	0.373
Hollander- Proschan	0.209	0.007	0.225	0.125
Kocher	3.509	0.0004	2.327	0.019
Kolmogorov-Smirnov	0.191	0.005	0.162	0.054
Lorenz test	0.177	0.870	0.191	0.804
Shapiro-Wilk	0.040	0.996	0.0415	0.982

only rely our decision on a single value or p-value.

Classical tests lead to the decision of not rejecting exponentiality for this data case (see Table 1, columns 4-5). Moreover, Algorithm 2 has been implemented for the local-quadratic estimator. The test statistic reported a value of $T_2^0 = 0.091$ with a $p_{2,boot} = 0.068$. This also implies not rejecting H_0 . However, one should be cautious with this decision since it can appreciated a significant non-dark gray area on the left side of panel SiZer-2 that suggests an area of the interval $[0, 1]$ where TTT-curve is strictly negative convex, as can be seen from Figure 5.

Algorithm 3. Testing exponentiality against NBUE alternatives

Define the *true* TTT-SiZer map according to an Exponential distribution. Under this null hypothesis, SiZer-0 is completely dark gray.

- Step 1. Compute the sample mean \bar{X} and define $\bar{X}_i = X_i/\bar{X}$, for $i = 1, 2, \dots, n$.
- Step 2. Construct the *empirical* SiZer-0 map as explained in Section 4 based on $\{\bar{\mathbf{X}}_i; i = 1, 2, \dots, n\}$.
- Step 3. Compare pixel by pixel the *empirical* SiZer-0 map with the corresponding *true* SiZer-0 map and count the total number of black pixels in the generated *empirical* map, which means that the curve is strictly above the diagonal. Define the test statistic T_0 , as the percentage of black pixels in the empirical map, the reported value is T_0^0 .

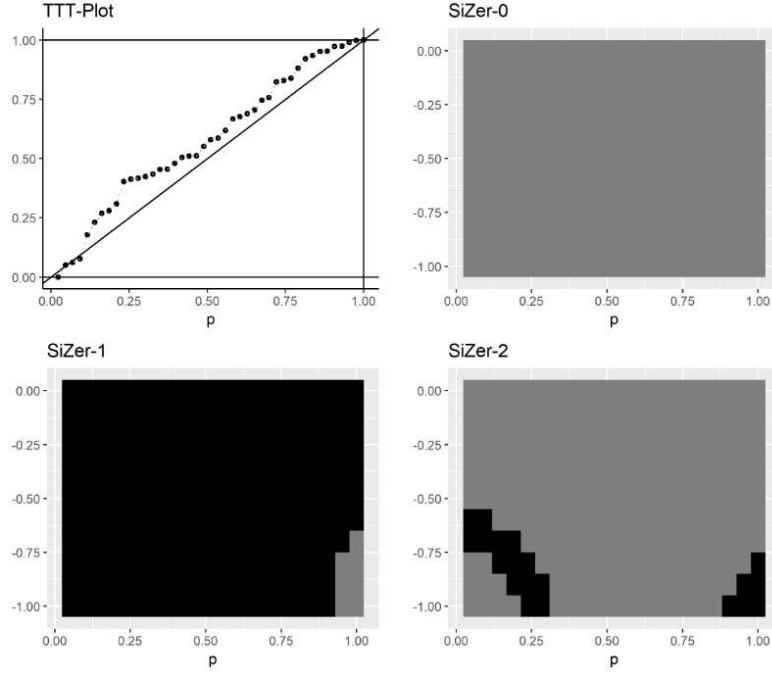


Figure 5: TTT-Sizer for Example 4: Survival days of chronic granulocytic leukemia.

Step 4. Use bootstrap methods to approximate the distribution of the statistic T_0 under H_0 : Draw M samples from the $Exp(1)$ distribution. Construct the corresponding Sizer-0 maps and count for each the number of black pixels, then a bootstrap sample of T_0 , labelled T_0^* , is generated.

Step 5. Define the p -value as $p_{0,boot} = (1/M) \sum_{m=1}^M I \{T_0^{*,m} > T_0^0\}$.

Reject the null hypothesis at a significance level $\alpha \in [0, 1]$ when $p_{0,boot} < \alpha$. To illustrate this method, consider the following example.

Example 5. Failure times of rear brakes, [13]

This dataset represents failure times for right rear brakes on D9G-66A Caterpillar tractors [13]. The null hypothesis of Exponential distribution is clearly rejected by the classical test, and the TTT-plot also points to this decision. The graphical test has been carried out using the local-cubic estimator and paying attention to the alternative hypothesis H_1 : “NBUE but not Exponential distribution”. In this case, the plot presented in SiZer-0 shows that data are in accordance with H_1 . Moreover, Algorithm 3 has

525 provided a value for the statistics $T_0^0 = 0.663$ with a value $p_{0,boot} = 0.000$, which suggests clear evidence in that sense.

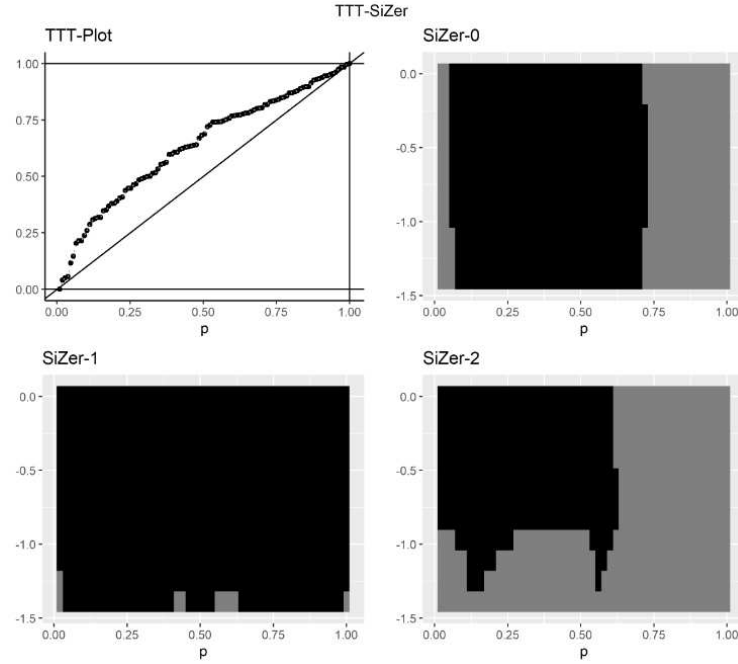


Figure 6: TTT-Sizer for Example 5: Failure times dataset of a brake-system.

5. Simulations

In this section, the performance of the graphical test is evaluated. The type I error of the test and the empirical power under different alternatives
530 are calculated.

5.1. Type I error

The type I error occurs when the graphical test rejects the true model under the null hypothesis. To evaluate the type I error of the graphical TTT-test, samples of size $n = 50, 100, 500$, and 1000 , from an Exponential
535 distribution with mean 1 are simulated.

The TTT-transform and its second derivative are estimated using the local polynomial estimators defined in Section 3, with the gaussian kernel.

The algorithm consists of simulating a sample of size n from the true model, then the local-polynomial estimate is calculated and the TTT-SiZer method is applied to compare the SiZer- j map (for $j = 0, 2$) with the corresponding true one.

The probability of committing this error is calculated following [47]. The null hypothesis is H_0 : *No aging* and the alternative is H_1 : *“Aging trend”*. Two different tests are performed. On the one hand, when the alternative is “NBUE but not Exponential”, aging trends are sought by inspecting the TTT-curve in the SiZer-0 map. Stronger conditions such as “IFR but not Exponential” can be elucidated by studying the SiZer-2 map. In any of the two cases, under the null hypothesis, the corresponding generated map should have only dark gray pixels. Let us focus on the SiZer-2 map case to explain the procedure to study the type I error.

As remarked above, under the null hypothesis that the TTT-curve is the diagonal of the unit square, the SiZer-2 map should have only dark gray pixels. This map is considered as the true one. The experiment is repeated $M = 1000$ times. For all the M simulated samples, the corresponding SiZer-2 maps are constructed and compared with the true map, pixel by pixel. For each sample, the total number of pixels where the color in the generated map is not the same as in the true map is recorded. The proportion of type I errors for each sample is this count divided by the total number of pixels in the map. M proportions of type I errors (one for each simulated sample) are obtained for each sample size. Table 2 presents summary statistics from the experiment and reports results for the two tests, that are for alternative NBUE and IFR, respectively.

Table 2: Summary statistics of the type I errors calculated from $M = 1000$ simulated samples, for the null hypothesis of H_0 : No aging. Columns 2-4 report the mean, the median and the quantile of order 0.75 for the proportions of type I error for the test with alternative H_1 : NBUE. Columns 5-7 report the mean, the median and the quantile of order 0.75 for the proportions of type I error for the test with alternative H_1 : IFR.

	<i>SiZer</i> – 0			<i>SiZer</i> – 2		
Sample size	Mean	Median	P_{75}	Mean	Median	P_{75}
50	0.011	0.000	0.000	0.036	0.000	0.017
100	0.014	0.000	0.000	0.033	0.001	0.026
500	0.012	0.000	0.004	0.028	0.008	0.027
1000	0.012	0.000	0.003	0.035	0.013	0.034

Table 2 shows that the mean of the proportions of type I error is under
565 5% for all sample sizes, as well as the median.

5.2. Empirical power

In hypothesis testing the power is defined as the probability of reject-
ing the null hypothesis when it is false. The probability of accepting the
null hypothesis when false is called type II error. To evaluate the power
570 of the graphical TTT-test, three different aging models and sample sizes
 $n = 50, 100, 500$, and 1000 are considered, as in the previous section. In
particular:

- IFR model: X_1 with Gamma distribution with shape parameter $sh = 5$
and mean $\mu = 1$;
- 575 • BFR model: $X_2 = \min\{W_1, W_2, W_3\}$, where W_j has Weibull distribu-
tion with scale $sc = 2.5$, and respectively, shape parameters given by
 $sh_1 = 3$, $sh_2 = 2$, and, $sh_3 = 0.5$;
- UFR model: X_3 with log-Normal distribution with parameters $E[\log(X_3)] =$
 -0.5 , and $Var(\log(X_3)) = 1$.

580 In all cases, the parameters have been chosen to have mean around 1 and
avoid scale adjustments of the TTT transform. A picture of the correspond-
ing hazards is given in Figure 7.

The TTT-transform and its first and second derivatives are estimated
using the local polynomial estimators defined in Section 3, with the gaussian
585 kernel. The TTT-SiZer method is applied to visualize the inference about
the three curves considering for each case the corresponding two-dimensional
space with $np \times nh$ pixels, respectively.

The algorithm now consists of simulating a sample of size n from the
true model, then the local-polynomial estimate is calculated and the TTT-
590 SiZer method is applied to compare the corresponding set of maps with the
true ones. The type II error occurs when the graphical test accepts the null
hypothesis under the alternative. Each model represents a different aging
trend in some way. Under the null hypothesis, the SiZer-2 map should have
only dark gray pixels. This map is the true one. The experiment is repeated
595 $M = 1000$ times. For each of the M simulated samples, the corresponding
maps are constructed and compared with the true map, pixel by pixel. For
each sample, the total number of pixels where the color in the generated map

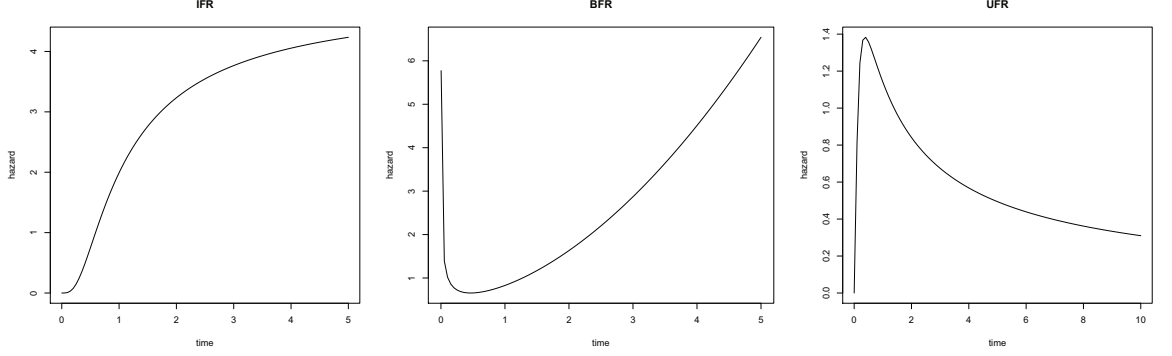


Figure 7: Hazard functions for the three aging models considered.

is the same as in the true map is recorded. The proportion of type II errors for each sample is this count divided by the total number of pixels in the map. M proportions of type II errors (one for each simulated sample) are obtained for each sample size. The empirical power is obtained as one minus this proportion. Table 3 presents the results of the experiment.

Table 3: Summary of empirical power calculated from $M = 1000$ simulated samples.

H_1	Sample size	Mean	Min.	Median	P_{75}	P_{95}	Max.
IFR model	50	0.746	0.035	0.771	0.805	0.861	0.908
	100	0.651	0.444	0.654	0.679	0.711	0.747
	500	0.517	0.461	0.518	0.529	0.544	0.560
	1000	0.557	0.521	0.558	0.567	0.580	0.589
BFR model	50	0.184	0.000	0.143	0.234	0.610	0.762
	100	0.243	0.000	0.221	0.285	0.528	0.647
	500	0.390	0.240	0.398	0.454	0.490	0.525
	1000	0.499	0.360	0.516	0.533	0.552	0.568
UFR model	50	0.050	0.000	0.008	0.043	0.340	0.670
	100	0.093	0.000	0.089	0.098	0.456	0.600
	500	0.305	0.006	0.350	0.403	0.445	0.495
	1000	0.430	0.157	0.448	0.471	0.490	0.506

Note that for sample sizes $n = 500, 1000$ the maps have been built taking in total 401×11 pixels, whereas for $n = 100, 51 \times 11$ pixels, and for $n = 50$, 21×11 pixels are considered in the maps, which means that the results are not fully comparable. Table 3 shows the good performance of our test given

that the results presented in the table imply a percentage of rejection is reasonable to high for almost all models and sample sizes. Especially when the alternative hypothesis is monotone. Only for the UFR case and small sample sizes, a small percentage of pixels allowing to detect the alternative hypothesis in the data are obtained. For the rest of the models and sample sizes, the graphical test displays wide areas in the corresponding plots properly recognizing the alternative hypothesis.

6. Concluding remarks

This paper has aimed to present a new procedure to explore lifetime data for discovering aging trends in the underlying life distribution.

A new estimator of the TTT-transform is obtained based on nonparametric statistics, more specifically, based on kernel smoothing techniques. Although nonparametric smoothing techniques are very popular in related areas such as survival analysis they are not very usual in reliability engineering where parametric methods have been traditionally preferred by the practitioners for solving inference problems. Although, the theoretical TTT transform is usually approximated from available data by means of the TTT-plot, which is a discontinuous curve while the theoretical curve is an absolutely continuous function. So, the empirical curve may be viewed as a poor approximation of the true curve, among other reasons, because it is a step function and the derivative either equals zero or is not defined, which makes difficult to evaluate shape characteristics. Kernel smoothing avoids discontinuities in the empirical function. Local-polynomial estimators have been constructed for the TTT-curve and its first and second derivatives. To obtain the properties of the estimators the moments of the order statistics have to be estimated and bootstrap methods have been considered for this purpose.

A graphic tool has been developed to test exponentiality against alternatives that represent non-constant trends in aging. This issue is not new in the reliability literature. Klefsjo in [18], where, the author, guided by the properties of the TTT-transform, provides a series of hypothesis tests to contrast the exponentiality against a wide range of aging alternatives. Also remarkable are the works of [30] and [44] where a test statistic based on the TTT plot, for testing if a random sample is generated from a life distribution with constant versus bathtub shaped hazard rate. The testing method proposed here is a graphical test able to recognize aging trends from data. The main advantage, compared to existing tests, is that it allows identifying specific

areas where discrepancies from non-aging are detected. In contrast, standard testing methods summarize the sampling information in the single p-value
645 to decide on the adequacy of the model specified in the null hypothesis.

This graphical test is developed through scale and space inference about the Total-Time-on-Test transform which is implemented by adapting the SiZer methodology to our context. Punctual as well as simultaneous confidence intervals have been constructed around each curve and for different
650 levels of smoothing. The graphical representation allows one to detect and confirm monotone aging trends and/or changes of tendency. Simulations and the comparison with other non-graphical tests show that the graphical test helps localize discrepancies of empirical data concerning a given hypothesized aging property. The extensive simulation study carried out as well as
655 the real cases discussed along the manuscript demonstrate that this proposal is interesting and has a high potential for reliability engineering in practice.

A natural extension of the method is to consider more general scenarios where censoring and/or other filtering schemes are present in the sampling mechanism.

660 **Acknowledgments**

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Appendix A. The local-cubic approach

It is convenient to increase the complexity of the model when interested in exploring shape properties through the second derivative. Thus it is proposed
670 to carry out the local fit by using cubic polynomials. After solving the equations in (4) with $m = 3$, taking the empirical estimator given in (2), the estimators of φ and its first and second derivatives can be written similar to Section 3.2 as follows.

Appendix A.1. The TTT-curve

675 First, some notation is given. Let \mathbf{A} be a square matrix of dimension $n \times n$.

For each $i, j = 1, 2, \dots, n$, denote $M_{i,j}$ corresponding *minor*, that is, the determinant of the sub-matrix obtained by deleting the i th row and the j th column of matrix \mathbf{A} . The corresponding *cofactor* is given by $\Delta_{ij} = (-1)^{i+j} M_{i,j}$.

The Cramer's rule provides an appropriate solution of the system of linear equations and the determinants are computed by cofactor expansions. Then the solution is written as

$$\tilde{\varphi}_h(p_0)(p_i - p_0) = \tilde{\theta}_0(p_0) = \sum_{i=1}^n \tilde{K}_{0,h}(p_i - p_0) \hat{\varphi}_{n,i} \quad (\text{A.1})$$

680 where the cubic kernel is expressed as

$$\begin{aligned} \tilde{K}_{0,h}(p_i - p_0) &= \\ &= \frac{\Delta_{11} + \Delta_{21}(p_i - p_0) + \Delta_{31}(p_i - p_0)^2 + \Delta_{41}(p_i - p_0)^3}{a_0\Delta_{11} + a_1\Delta_{21} + a_2\Delta_{31} + a_3\Delta_{41}} K_h(p_i - p_0) \end{aligned}$$

where the cofactors Δ_{ij} , $i, j = 1, 2, 3, 4$, are taken from matrix \mathbf{A} , that is,

$$\mathbf{A} = \begin{pmatrix} a_0 & a_1 & a_2 & a_3 \\ a_1 & a_2 & a_3 & a_4 \\ a_2 & a_3 & a_4 & a_5 \\ a_3 & a_4 & a_5 & a_6 \end{pmatrix}.$$

The local-cubic estimator can be seen as an L-estimator likewise the second-order case (see Section 3.3) so the statistical properties of the estimator can be studied, in particular, expressions for the moments are obtained next.

$$\tilde{\varphi}_h(p_0) = \sum_{i=1}^n \sum_{j=1}^i \tilde{K}_{0,h}(p_i - p_0) \omega_{i,j} X_{(j)},$$

which is also an L -estimator, with $\omega_{i,j}$ as in (11). Let us denote

$$\tilde{\mathbf{K}}_{0,h}(p_0) = \left(\tilde{K}_{0,h}(p_1 - p_0), \tilde{K}_{0,h}(p_2 - p_0), \dots, \tilde{K}_{0,h}(p_n - p_0) \right)^\top,$$

so the variance of the estimator of the TTT-curve using the local-cubic approach is

$$\text{Var}(\tilde{\varphi}_h(p_0)) = \tilde{\mathbf{K}}_{0,h}(p_0)^\top \cdot \mathbf{W} \cdot \Sigma \cdot \mathbf{W}^\top \cdot \tilde{\mathbf{K}}_{0,h}(p_0) \quad (\text{A.2})$$

685 for each $p_0 \in (0, 1)$. Equally the variance for the first and second derivatives of the local-cubic estimate can be obtained.

Appendix A.2. The first derivative

$$\tilde{\varphi}'_h(p_0) = \tilde{\theta}_1(p_0) = \sum_{i=1}^n \tilde{K}_{1,h}(p_i - p_0) \hat{\varphi}_{n,i}, \quad (\text{A.3})$$

where

$$\begin{aligned} \tilde{K}_{1,h}(p_i - p_0) &= \\ &= \frac{\Delta_{12} + \Delta_{22}(p_i - p_0) + \Delta_{32}(p_i - p_0)^2 + \Delta_{42}(p_i - p_0)^3}{a_0\Delta_{11} + a_1\Delta_{21} + a_2\Delta_{31} + a_3\Delta_{41}} K_h(p_i - p_0). \end{aligned}$$

Appendix A.3. The second derivative

Finally the second derivative, based on local-cubic approximation.

$$\tilde{\varphi}''_h(p_0) = 2\tilde{\theta}_2(p_0) = \sum_{i=1}^n \tilde{K}_{2,h}(p_i - p_0) \hat{\varphi}_{n,i}, \quad (\text{A.4})$$

690 where

$$\begin{aligned} \tilde{K}_{2,h}(p_i - p_0) &= \\ &= \frac{\Delta_{13} + \Delta_{23}(p_i - p_0) + \Delta_{33}(p_i - p_0)^2 + \Delta_{43}(p_i - p_0)^3}{a_0\Delta_{11} + a_1\Delta_{21} + a_2\Delta_{31} + a_3\Delta_{41}} K_h(p_i - p_0). \end{aligned}$$

Appendix B. Bootstrap moments of the order statistics

Following [32] the estimators above are considered as L-estimators and bootstrap techniques can be used to estimate the first two moments of the order statistics, that is, vector $\boldsymbol{\mu}$, given in (14), and the covariance matrix $\boldsymbol{\Sigma}$ given in (15).

Exact analytic expressions for these bootstrap mean and covariance matrix are obtained, as well as the corresponding estimators based on Monte Carlo resampling.

Appendix B.1. Exact analytic expressions

700 Let X_1, X_2, \dots, X_n be a sample of independent random variables with a common absolutely continuous distribution F , and let $X_{(1)} \leq X_{(2)} \leq \dots X_{(n)}$ be the order statistics.

First, define m th non-centered moment of the r th order statistics as (see [48])

$$\mu_{(r)}^{(m)} = E [X_{(r)}^m] = \frac{n!}{(r-1)!(n-r)!} \int_0^1 (Q(u))^m u^{r-1} (1-u)^{n-r} du, \quad (\text{B.1})$$

for $1 \leq r \leq n$, and with $Q(u) = F^{-1}(u)$ the quantile function. The interest is on the mean and the variance, then take $m = 1, 2$. As usual compute
705 $\sigma_{(r)}^2 = \mu_{(r)}^{(2)} - (\mu_{(r)})^2$.

The quantile $Q(u)$ can be replaced by $\hat{Q}(u)$. Given that $\hat{Q}(u) = X_{(j)}$ for $(j-1)/n < u \leq j/n$, the bootstrap estimator can be obtained

$$\hat{\mu}_{(r)}^{(m)} = \sum_{j=1}^n \int_{(j-1)/n}^{j/n} (Q(u))^m f_B(u) du dv = \sum_{j=1}^n X_{(j)}^m \int_{(j-1)/n}^{j/n} f_B(u) du, \quad (\text{B.2})$$

where $f_B(u) = \frac{n!}{(r-1)!(n-r)!} u^{r-1} (1-u)^{n-r}$ denotes the density function of a Beta distribution with parameters $a_1 = r$ and $a_2 = n - r + 1$. Then the conclusion is that the corresponding moment can be easily computed using the incomplete beta function, that is

$$\begin{aligned} \hat{\mu}_{(r)}^{(m)} &= \sum_{j=1}^n X_{(j)}^m \left[F_B \left(\frac{j}{n}; a_1 = r, a_2 = n - r + 1 \right) - \right. \\ &\quad \left. F_B \left(\frac{j-1}{n}; a_1 = r, a_2 = n - r + 1 \right) \right], \end{aligned}$$

710 where $F_B(x; a_1, a_2) = \frac{n!}{(r-1)!(n-r)!} \int_0^x u^{a_1-1} (1-u)^{a_2-1} du$.

For $1 \leq r < s \leq n$, the (1,1)-order moment can be defined as

$$\mu_{(rs)} = E [X_{(r)} X_{(s)}] = {}_n C_{rs} \int_0^1 \int_u^1 Q(u) Q(v) u^{r-1} (v-u)^{s-r-1} (1-u)^{n-s} du dv; \quad (\text{B.3})$$

where ${}_n C_{rs} = \frac{n!}{(r-1)!(s-r-1)!(n-s)!}$.

As above, replacing the quantile function by its empirical version the bootstrap estimator for the second-order moment can be obtained so the

double integral in (B.3) is therefore estimated as

$$\begin{aligned}\hat{\mu}_{(rs)} &= \sum_{i=1}^{n-1} \sum_{j=i+1}^n X_{(i)} X_{(j)} \int_{(i-1)/n}^{i/n} \int_{(j-1)/n}^{j/n} {}_n C_{rs} u^{r-1} (v-u)^{s-r-1} (1-v)^{n-s} dv du + \\ &+ \sum_{i=1}^n X_{(i)}^2 \int_{(i-1)/n}^{i/n} \int_u^{i/n} {}_n C_{rs} u^{r-1} (v-u)^{s-r-1} (1-v)^{n-s} dv du,\end{aligned}\quad (\text{B.4})$$

715 After a convenient change of variable ($v = u + w$, for $0 < w < 1$),

$$\begin{aligned}\hat{\mu}_{(rs)} &= \sum_{i=1}^{n-1} \sum_{j=i+1}^{n-1} X_{(i)} X_{(j)} \int_{(i-1)/n}^{i/n} \int_{(j-1)/n-u}^{j/n-u} {}_n C_{rs} u^{r-1} w^{s-r-1} (1-u-w)^{n-s} dw du + \\ &+ \sum_{i=1}^n X_{(i)}^2 \int_{(i-1)/n}^{i/n} \int_0^{i/n-u} {}_n C_{rs} u^{r-1} w^{s-r-1} (1-u-w)^{n-s} dw du,\end{aligned}\quad (\text{B.5})$$

The function inside the integrals can be interpreted in terms of a Dirichlet distribution of order 2, which describes the distribution of a random vector (U, W) according to the bivariate density function

$$f_D(u, w) = \frac{\Gamma(a_1 + a_2 + a_3)}{\Gamma(a_1)\Gamma(a_2)\Gamma(a_3)} u^{a_1-1} w^{a_2-1} (1-u-w)^{a_3-1} \quad (\text{B.6})$$

where $0 < u, w < 1$, and $0 < u + w < 1$, and $a_1, a_2, a_3 > 0$. Taking $a_1 = r$, $a_2 = s - r$, and $a_3 = n - s + 1$, the second order moments can be computed by means of the probabilities under a Dirichlet distribution. In other words, (B.5) is computed by

$$\begin{aligned}\hat{\mu}_{(rs)} &= \sum_{i=1}^n \sum_{j=i+1}^{n-1} X_{(i)} X_{(j)} Pr \left\{ \frac{i-1}{n} < U \leq \frac{i}{n}; \frac{j-1}{n} < U + W \leq \frac{j}{n} \right\} \\ &+ \sum_{i=1}^n X_{(i)}^2 Pr \left\{ \frac{i-1}{n} < U < U + W \leq \frac{j}{n} \right\},\end{aligned}\quad (\text{B.7})$$

720 with (U, W) random vector with joint density function as in (B.6).

Appendix B.2. Estimation of the moments by Monte Carlo simulation

Let $\{X_1, X_2, \dots, X_n\}$ denote a sample of independent random lifetimes identically distributed as X . The aim is to estimate the mean and moments of order 2 defined in the previous section by using resampling techniques. A

725 Monte Carlo simulation is proposed in the following algorithm.

Algorithm 1. Bootstrapped moments of the order statistics

Step 1. Draw with replacement a total of n items from the set $\{1, 2, \dots, n\}$, that is: i_1, i_2, \dots, i_n .

Step 2. For each i_j , take the corresponding X_{i_j} , for $j = 1, \dots, n$. Denote $X_{(1)}^* \leq X_{(2)}^* \leq \dots \leq X_{(n)}^*$ the resulting bootstrap order statistics sequence.

Step 3. Repeat Step 2 up to M times. Construct the $n \times M$ -dimensional matrix of the form

$$\mathbf{X}^* = \begin{pmatrix} X_{(1)}^{1*} & X_{(1)}^{2*} & \dots & X_{(1)}^{M*} \\ X_{(2)}^{1*} & X_{(2)}^{2*} & \dots & X_{(2)}^{M*} \\ \dots & \dots & \ddots & \vdots \\ X_{(j)}^{1*} & X_{(j)}^{2*} & \dots & X_{(j)}^{M*} \\ \dots & \dots & \ddots & \vdots \\ X_{(n)}^{1*} & X_{(n)}^{2*} & \dots & X_{(n)}^{M*} \end{pmatrix}$$

Step 4. Define the vector of bootstrap means $\hat{\boldsymbol{\mu}}^*$, with components

$$\hat{\mu}_j^* = \frac{1}{M} \sum_{m=1}^M X_{(j)}^{m*},$$

for $j = 1, 2, \dots, n$; and the bootstrap covariance matrix

$$\hat{\boldsymbol{\Sigma}} = (1/M) (\mathbf{X}^* - \hat{\boldsymbol{\mu}}^*)^\top (\mathbf{X}^* - \hat{\boldsymbol{\mu}}^*).$$

References

- [1] Bryson, M.C. and Siddiqui, M.M. **Some criteria for aging**. Journal of the American Statistical Association, 64 (328), (1969), pp. 1472-1483.
- [2] Barlow, R. E. and Proschan, F. *Statistical theory of reliability and life testing: Probability Models*. (1975) Holt, Rinehart and Winston.
- [3] Hollander, M. and Proschan, F. **Nonparametric concepts and methods in reliability**, In P. R. Krishnaiah and P. K. Sen (Editors), Handbook of Statistics, 4, (1984), pp. 613-655.
- [4] Deshpande, J.V., Kochar, S.C. and Singh, H. **Aspects of positive ageing**. Journal of Applied Probability, 23 (3) (1986), pp. 748-758.
- [5] Cao, J. and Wang, Y. **The NBUC and NWUC classes of life distributions**. Journal of Applied Probability, 28 (2), (1991), pp. 473-479.

- 745 [6] Franco-Pereira, A. and Shaked, M. **The total time on test transform and the decreasing percentile residual life aging notion**. Statistical Methodology, 18, (2014), pp. 32–40.
- [7] Navarro, J., Del Aguila, Y., Sordo, M.A. and Suárez-Llorens, A. **Preservation of reliability classes under the formation of coherent systems**. Applied Stochastic Models in Business and Industry, 30, (2014), pp. 444–454.
- 750 [8] Szymkowiak, M. **Characterization of distributions through aging intensity**. IEEE Transactions on Reliability, 67, (2018), pp. 446–458.
- [9] Szymkowiak, M. **Generalized aging intensity functions**. Reliability Engineering and System Safety, 178(C), (2018), pp. 198–208.
- 755 [10] Lai, C.D., and Xie, M. *Stochastic aging and Dependence for Reliability*. (2006), Springer.
- [11] Lillo, R.E. **Note on relations between criteria for aging**. Reliability Engineering and System Safety, 67, (2000), pp. 129–133.
- [12] Nair, N.U., Sankaran, P.G. and Balakrishnan, N. *Quantile-based reliability analysis*. (2013), Birkhauser.
- 760 [13] Barlow, R.E. and Campo, R. **Total time on test processes and applications to failure data analysis**. Reliability and Fault Tree Analysis, Edited by: Barlow, R.E., Fussell, J. and Singpurwalla, N.D. (1975) pp. 451–481.
- 765 [14] Bergman, B. and Klefsjo, B. **The Total Time on Test Concept and Its Use in Reliability Theory**. Operations Research, 32 (3), (1984), pp. 477–749.
- [15] Nair, N.U. and Sankaran, P.G. **Some new applications of the total time on test transforms**. Statistical Methodology, 10 (1), (2013), pp. 93–102.
- 770 [16] Klefsjo, B. **On aging properties and total time on test transforms**. Scandinavian Journal of Statistics, 9, (1982), pp. 37–41.

- [17] Rausand, M., and Hoyland, A. *System reliability theory: Models, Statistical Methods, and Applications*. Second edition (2004), John Wiley & Sons.
- 775 [18] Klefsjo, B. **Some tests against aging based on the total time on test transform**. Communications in Statistics - Theory and Methods, 12 (8), (1983), pp. 907–927.
- [19] Klefsjo, B. **Testing exponentiality against HNBUE**. Scandinavian Journal of Statistics, 10, (1983), pp. 65–75.
- 780 [20] Kochar, S.C. **Testing exponentiality against monotone failure rate average**. Communications in Statistics - Theory and Methods, 14 (2), (1985), pp. 381–392.
- [21] Zareitalab, A., Haghighi, H. S., Mansour, S., and Sajadieh, M.S. **A mathematical model for the joint optimization of machining conditions and tool replacement policy with stochastic tool life in the milling process**. The International Journal of Advanced Manufacturing Technology, 96, (2018), pp. 2319–2339.
- 785 [22] Lindqvist, B.H. and Samaniego, F.J. **Some new results on the preservation of the NBUE and NWUE aging classes under the formation of coherent systems**. Naval Research Logistics, 66, (2019), pp. 430–438.
- 790 [23] Kvaloy, J.T. and Lindqvist, B.H. **TTT-based tests for trend in repairable systems data**. Reliability Engineering and System Safety, 60 (1), (1998), pp. 13–28.
- [24] Viertava, J. and Vaurio, J.K. **Testing statistical significance of trends in learning, aging and safety indicators**, Reliability Engineering and System Safety, 94, (2009), pp. 1128–1132.
- 795 [25] Anis, M. **Tests of non-monotonic stochastic aging notions in reliability theory** Statistical papers, 55 (3) (2013), pp. 691–714.
- 800 [26] Sreelakshmi, N. Sudheesh, K.K, and Asha, G. **Quantile based tests for exponentiality against DMRQ and NBUE alternatives**. Journal of the Korean Statistical Society, 47 (2), (2018), pp. 185–200.

- [27] Izadi, M., and Manesh, S.F. **Testing exponentiality against a trend change in mean time to failure in age replacement.** Communications in Statistics – Theory and Methods, (2019) DOI: 10.1080/03610926.2019.1702693.
- [28] Cuparic, M., Milosevic, B., and Obradovic, M. **New L^2 -type exponentiality tests.** SORT, 43 (1), (2019), pp. 1–26.
- [29] Hollander, M. and Proschan, F. **Testing whether new is better than used.** The Annals of Mathematical Statistics, 43 (4), (1972), pp. 1136–1146.
- [30] Bergman, B. **On age replacement and total time on test concepts.** Scandinavian Journal of Statistics, 6, (1979), pp. 161–168.
- [31] Barlow, R. E. and Doksum, K.A. Isotonic test for convex ordering. Proceedings of the 6th Berkeley Symposium on Mathematical Statistics and Probability, 1, (1972) pp. 293–323, University of California Press.
- [32] Hutson, A.D. and Ernst, M. **The exact bootstrap mean and variance of an L-estimator.** Journal of the Royal Statistic Society, B. 62 (1), (2000), pp. 89–94.
- [33] Chaudhuri, P. and Marron, J.S. **SiZer for Exploration of Structures in Curves.** Journal of the American Statistical Association, 94 (447) (1999), pp. 807–823.
- [34] Chaudhuri, P. and Marron, J.S. **Curvature vs. Slope Inference for Features in Nonparametric Curve Estimates.** (2002) *Unpublished manuscript.*
- [35] Park, C., Hannig, J. and Kang, K.H. **Improved SiZer for time series.** Statistica Sinica, 19, (2009), pp. 1511–1530.
- [36] Park, C. and Kang, K.H. **SiZer analysis for the comparison of regression curves.** Computational Statistics & Data Analysis, 52 (8), (2008), pp. 3954–3970.
- [37] Marron, J.S. and de Uña Álvarez, J. **SiZer for length biased, censored density and hazard estimation.** Journal of Statistical Planning and Inference, 121 (1), (2004), pp. 149–161.

- [38] Pittau, M.G. and Zelli, R. **Exploring patterns of income polarization using siZer**. Journal of Quantitative Economics, 5, (2007), pp. 101–111.
- [39] Sonderegger, D.L., Wang, H., Clements, W.H. and Noon, B.R. **Using SiZer to detect thresholds in ecological data**. Frontiers in Ecology and the Environment, 7, (2009), pp. 190–195.
- [40] Park, C., Hernández-Campos, F., J. Marron, J.S. and Smith, F.D. **Long-range dependence in a changing Internet traffic mix**. Computer Networks, 48 (3), (2005), pp. 401–422.
- [41] Marron’s Matlab Software - J.S. Marron (Steve Marron) . *http : //marron.web.unc.edu/sample – page/marrons – matlab – software/*; 2020 [accessed 17 February 2020]
- [42] Xie, M. and Lai, C.D. **Reliability analysis using and additive Weibull model with bathtub-shaped failure rate function**. Reliability Engineering and System Safety, 52 (1), (1996), pp. 87–93.
- [43] Hannig, J. and Marron, J.S. **Advanced Distribution Theory for SiZer**. Journal of the American Statistical Association, 101 (474), (2006), pp. 484–499.
- [44] Aarset, M.V. **How to identify a bathtub hazard rate**. IEEE Transactions on Reliability, 36 (1) (1987), pp. 106–108.
- [45] Novikov, A., Pusev, R. and Yakovlev, M. Package ”exptest”. (2015) <https://cran.r-project.org/web/packages/exptest/>.
- [46] Ascher, S. **A survey of tests for exponentiality**. Communications in Statistics - Theory and Methods, 19 (5) (1990), pp. 1811–1825.
- [47] Rondonotti, V., Marron, J.S., and Park, C. **SiZer for time series: A new approach to the analysis of trends**. Electronic Journal of Statistics, 1, (2007), pp. 268–289.
- [48] Arnold, B.C., Balakrishnan, N. and Nagaraja, H.N. *A First Course in Order Statistics. Classics in Applied Mathematics*. (2008) New York: Wiley.

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