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Reliability of Repairable Valves: Analysis of Failure Times from Chemical Plants

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ABSTRACT
The non-homogeneous Poisson process (NHPP) is widely adopted to monitor reliability improvement during system development as well as to model the number of failures for complex systems. The most popular functional forms proposed in the literature to model NHPP intensity functionsare monotonicwith time. However, there are situation in which the use of monotonic intensity functions can be too restrictive.In this paper, a new Non-Homogeneous Poisson Process with a non-monotonic intensity function is presented. The model is tested to formulate the reliability of repairable valves that are used for critical functions in a chemical plant. The analysis isperformed by adopting a real set of time data that were collected during the first operative years of the plant. In general, similar applicative cases arise when a model is needed for the reliability of a complex system/plant in the early phase of the operative life. The model fits well all the analysed failure data sets, each corresponding to a specific type of valve.
Keywords: Failure mechanism; Intensity function; Model identification; Non Homogeneous Poisson Process; Cramèr-Von Mises Goodness-Of-Fit Test.

I. INTRODUCTION

As is known, theNHPP furnishes a good description ofrepairable systems subject to *minimal repairs* (i.e., the part repaired or substituted has a negligible effect on the system reliability) or systems experiencing reliability improvement (Duane, 1964; Crow,1974). Among the NHPPs, the power law process (PLP) (Cox and Lewis, 1966; Crow, 1974) isvery popular to model the reliabilitygrowth of repairable systems, which areeither deteriorating or improving with the operating time (i.e., the intensity is monotonic with theoperating time). However, it cannot be appropriately used when a non-monotonic trend in the number of failure is observed (e.g., early phase of new system’s operative life).

In particular, in Section 2,it is found unsuitable for modelling a real dataset of failure records of mechanical valves used for critical functions that has been collected during the first operative years of a chemical plant.In Section 3, a new Non-Homogeneous Poisson Process with a non-monotonic intensity function is presented. In Section 4, the parameters of the presentedmodel areestimated and the model is tested to formulate the reliability of the repairable valves considered in Section 2. In Section 5 concluding remarks are drawn in order to set up future directions of similar research.

II. PRELIMINARY RELIABILITY ANALYSIS

In order to attain economy of scale, many chemical plants are planned and built to be very large. Consequently, they involve very complex control systems with several thousands of components. Among these, a large number of mechanical valves have critical missions and give rise to a relevant reliability modelling problem (Soleimani et al., 2014). Valves are not standardised because their mission includes many functions —like flow control, flow arrest and pressure relief— as well as a wide range of working conditions. This variety of shape and size prevents one from observing large samples of duplicate valves in similar operating conditions.The valve data analysed in this paper are from a data collection activity carried out during the first operative years of achemical plant. The dataset covers many different types, manufacturers, sizes and media as well as a wide range of operational pressure and temperature. The several factors that affect the failure rate may be difficult to establish as remarked also by Bhattacharjee et al. (2003) in a similar study on nuclear power plant failure data. The valves consist of a pneumatically operated ram, that displaces fluid from the interior, and prevents the subsequent blockage due to solidification of the fluid itself.The available dataset includes records of the four factors (Table 1) that are utilized to group by the valves.

Table 1. Valve groups

Diameter d inches	**Medium**	**Temperature** °C	**Pressure**
(4-12)	steam or water	(130-351)	high or low

From a reliability point of view, the diameter is to be the most significant factor, since, in general, valves of unequal diameter are situated in different area/subsystems and thus encounter different environments, duties and applications. For example, all 7’’ diameter valves are mainly situated on low-pressure steam lines, whereas 5’’ valves are on bypass or drain lines with high pressure and water as medium. Then, in the following, each group will be identified by the diameter size *d* (in inches) of their valves. Failure time data are reported inTable 2 for each of the five groupsconsidered inTable 1. The observation period has been stoppedafter 1307 days ($t = t_c$). However, valve groups did not start to operate simultaneously, then astarting time delay (t_0) has to be considered for each group. For all the valves contained in each group, the data set records the chronologically ordered numbers of days (*t*) taken from the beginning of the observation period ($t = 0$) to the times when the interested valve shows its failure. Then,for each valve the actualrunning time is defined as the difference betweenthe calendar time andthetime delay t_0 of the corresponding group.For the managerial purposes of the plant, each group of valves is considered a unique repairable system. So, each valve failure is assumed to producea failure of the group.Moreover, only a negligible proportion of valves (with respect to the number of valves operating in the whole system) is replaced as soon as a failure occurs. Then, minimal repair policy can be also assumed (Maghsoodloo and Helvaci, 2014). A first study is carried out to assess whether the valve deterioration times come from a Homogeneous Poisson Process (HPP).

Table 2. Analysed groups of valves

Group d	**Time delay** t_0	**Medium**	**Temperature °C**	**Pressure**	**Total failures** n **// Total valves** m	**Laplace's statistic** u_L	***p*-value**
4	63	steam	347	high	29//8	-1.63	0.05
5	161	water	130	high	11//16	-1.67	0.05
7	0	steam	351	low	22//24	-1.53	0.06
9	0	steam	347	high	20//20	-1.77	0.04
12	133	steam	351	low	9//26	-1.45	0.07

Under the hypothesis of HPP, the timeintervals between successive failures are independent and identically distributed Exponential random variables and the Laplace’s statistic u_L rapidly approaches the standardised Normal deviate as the sample size increases (Hascher and Feingold, 1984; Ansell and Philips, 1994):

$$u_L = \frac{\frac{1}{n}\sum_{i=1}^{n} t_i - \frac{t_c - t_0}{2}}{(t_c - t_0)\sqrt{\frac{1}{12n}}} \qquad (1)$$

where t_i is the actual running timeto the *i*-th failure.

The values of the statistic u_L , reported inTable 2, are significantly negative in all cases; thatgives the evidence for rejecting an intensity function constant with the time.In addition, the Cramér-von Mises goodness-of-fit test to aPLP (Park and Kim, 1992) is also applied.

The Cramér-von Mises statistic is:

$$C_n^2 = \frac{1}{12n} + \sum_{i=1}^{n}\left[\left[\frac{t_i}{t_c - t_0}\right]^{\hat\beta} - \frac{2i-1}{2n}\right]^2 \qquad (2)$$

where $\hat\beta$ is the time-censored unbiased maximum likelihood estimate (MLE) of the shape parameter (Crow, 1990; Tobias and Trindade, 2012):

$$\hat\beta = \frac{n-1}{\sum_{i=1}^{n}\ln(t_c / t_i)} . \qquad (3)$$

The results reported inTable 4 show that the hypothesis of PLP could be rejected in three cases out of five, in spite of the high flexibility and the extensive practical use of this model.

Table 3. Days $t_i + t_0$ from the beginning of the observation period until the i-th failure

i	**Group** d				
	4	**5**	**7**	**9**	**12**
1	147	168	42	13	137
2	150	222	50	17	158
3	295	264	70	21	246
4	355	477	122	21	373
5	418	583	256	101	382
6	424	585	258	294	664
7	436	695	297	331	791
8	438	698	329	387	991
9	441	712	333	462	1260
10	470	798	369	597	
11	470	1045	387	602	
12	471		388	605	
13	471		424	633	
14	492		557	730	
15	494		617	761	
16	498		654	763	
17	579		662	778	
18	707		798	813	
19	709		1243	990	
20	709		1266	1156	
21	715		1266		
22	728		1276		
23	762				
24	762				
25	762				
26	798				
27	814				
28	991				
29	1213				

III. RELIABILITY MODEL

The lack of fitting of the PLP to all group data is probably due to an upside-down bathtub-shapedintensity function, inspired by the Aïvazian (1970) model proposed in a different context. Then the following very flexible s-shaped function is adopted to fit the mean function

$$M(t) = \frac{b\left[\exp(t^{1/3}) - 1\right]}{(a+b)\left[b + a\exp(t^{1/3})\right]} \qquad (4)$$

whose derivative provides the following intensity function:

$$z(t) = \frac{b\exp(-t^{1/3})}{3\,t^{2/3}\left[a + b\exp(-t^{1/3})\right]^2}. \qquad (5)$$

This function is infinite as t approaches zero and, apart from a very short initial time interval, shows an upside-down bathtub predominant shape (Figure 1).

IV. DATA ANALYSIS

Using the ratio i/m (between the observed number of failures by the actual running time t_i and the size of the respective group) as the natural estimator of $M(t_i)$ (Hartler, 1985; Nelson, 1998), we obtain points whose fitting by the model(4), via Least Square Method, provides the estimates of the two parameters *a* and *b*. The *a* and *b* estimates, obtained in this way, are reported inTable 5. The five fitted $M(t)$ models for $d = 4,5,7,9,12$ and those interpolated for $d = 6,8,10,11$ are reported in Figure 2. The estimated intensity functions(5)are reported in Figure 1.

V. CONCLUSIONS

Many different phenomena, occurring alternatively or concomitantly in real field, make the HPPs or monotonic-intensity NHPPs too restrictive to monitor/assess the reliability growth programs of complex systems/plants in the early phase of their operative life.A new Non-Homogeneous Poisson Process with a non-monotonic intensity functionhas been introduced in order to model the failure times of repairable valves that are used for critical functions during the first operative years of a new chemical plant. The graphs derived for different diameters appear to be a good tool for practical applications and for setting up future research. In particular, the statistical features of the proposed model and alternative parameter estimation procedures should be investigated. Moreover, additional parameters could be introduced in the model in order to achieve even more flexibility (e.g., by substituting the exponent 1/3 with a new parameter and/or by adding a scale parameter).

Table 4. Cramér-von Mises goodness-of-fit test to a PLP

Group d	**Unbiased MLE of** β	**Test statistic** C_n^2	**Critical value**	**Significance level**
4	0.95	0.63	0.33	0.01
5	0.59	0.45	0.32	0.01
7	0.75	0.39	0.33	0.01
9	0.61	0.25	0.22	0.05
12	0.48	0.29	0.21	0.05

Table 5. Least Square estimates (LSE) of the parameters of the proposed NHPP with intensity function(5)

Group d	**LSE of** a	**LSE of** b	**Coefficient of determination**
4	0.235	816.7	0.987
5	1.258	2535.6	0.976
7	1.160	1599.9	0.993
9	0.955	2900.4	0.975
12	3.313	1072.1	0.973

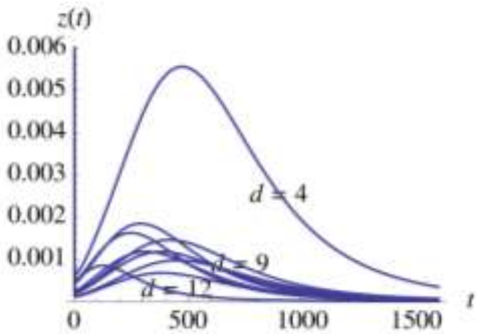

Figure 1. Five intensity functions (5) fitted to data (for valves of diameter $d = 4, 5, 7, 9, 12$) and four intensity functions interpolated (for valves of diameter $d = 6, 8, 10, 11$).

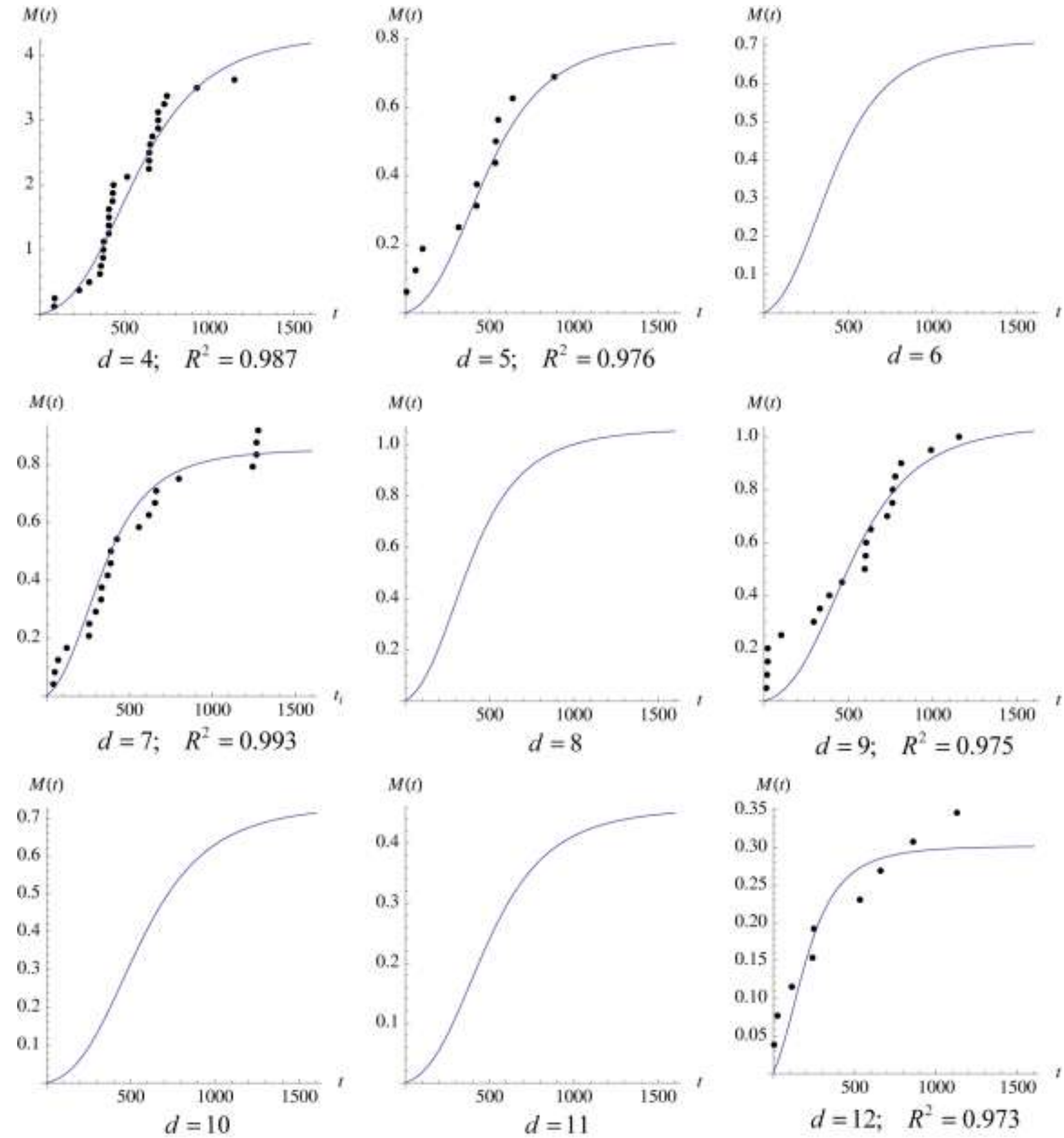

Figure 2. Five mean functions (4) fitted to data (with the corresponding coefficients of determination R^2) and four interpolated mean functions, for valves with respective diameter d .

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