Modelling the quality of maintenance of a protection system: a case study on isolation valves used in water distribution systems.

A. R. Alberti*, C. A. V. Cavalcante**, P.A. Scarf ***, A. L. O. Silva****

* *Departamento de Eng. de Produção, Universidade Federal de Pernambuco, Brazil: alexandre.emc091@gmail.com*
***Departamento de Eng. de Produção, Universidade Federal de Pernambuco, Brazil: cristiano@ufpe.br*
**** *Salford Business School, University of Salford, Manchester M5 4WT, UK: p.a.scarf@salford.ac.uk*
*****COMPESA, Companhia Pernambucana de Saneamento, Brazil*

Abstract. A hybrid inspection and replacement policy for a protection system is described by a mathematical model that incorporates a set of maintenance quality aspects. A three-state component failure model is assumed, with a defective state preceding failure. The quality of maintenance intervention is modelled by supposing that inspection may induce a defect and is subject to errors in the defective state judgement (false positives and false negatives). The quality of replacement is modelled by supposing that a component arises from a heterogeneous population, composed of weak and strong items. This paper presents a case study on isolation valves used in water distribution systems, that motivated the development of the model. We evaluate the impact of these quality aspects upon cost and production losses. A detailing of the context is presented, highlighting important aspects of the analysis, which should be observed when other studies are carried out in different contexts. We present the results in order to evaluate the impact of the quality aspects regarded, verify conditions that justify investment in higher quality maintenance, and obtain guidance on which aspects should be prioritized in the investment. Defect induction is found to be a key determinant of the cost-optimal policy.

1. Introduction

This paper presents a discussion about a case study on isolation valves carried out at a Brazilian sanitation company. This case study motivated the development of a new model to evaluate the impact of different aspects of maintenance quality on the performance of protection systems, which was recently presented in Alberti et al. (2018). Here, our objective is present a discussion about the case study accomplishment, highlighting important aspects of the analysis, which should be observed when other studies are carried out in different contexts. Some results of an application are present in order to show how the model can be used to obtain some guidelines for decision-making in maintenance.

2. The case study

Isolation valves play an important role in a water distribution system by enabling the isolation of certain segments in the system, which is necessary in some cases such as repair of broken pipes or confinement of contaminants within a controlled area (Jun et al., 2007). Walski (1993) defined “segment” as the smallest area in a water distribution system for which supply can be interrupted with the closing of the valves without affecting the rest of the system.

Due to its operation characteristics, isolation valves can be classified as a protection system, that is, a system for which operation is only required in the case of a specific demand. In that case, demands can be understood as any event that requires the isolation of a segment in the distribution network. Two types of demands are specifically highlighted in the literature: leaks or related preventive measures, and water contamination (Jun et al., 2007; Giustolisi and Savic, 2010). Goulter and Coals (1986) suggested a Poisson distribution with parameter λ (failures/km/year) as a probability distribution that better represents the occurrences of pipeline breakdowns. In regards to water contamination events, a Poisson distribution is assumed to also represent them well since those are occasioned by external and potentially random factors.

When a demand event occurs and the valves required are fully functional, the isolation of the segment involved is done without delay, leaving only a limited number of clients without service and avoiding greater damage to the region. On the other hand, when a demand occurs and any of the isolation valves required fail, a new containment plan is needed and requires the isolation of adjacent segments, leaving a greater number of clients without service for a longer period.

The damage caused by pipeline breakdowns can be significant depending on the operational pressure of the segment and the failure of an isolation valve can make matters worse due to the greater time needed to carry out containment plans, thus contributing to greater waste of water, more damage to surrounding structures potentially leading to erosion. It is even more critical to control contamination events, which have a greater impact on cost and service disruption. Failure of the isolation system can lead to contaminants being spread to more extensive areas, contributing to costlier economic damages, as in the case of substances that can damage the network and clients' infrastructure, or even magnify the effects of sabotage actions.

We can see that the impact resulting from an unmet demand can be considerably negative, which justifies the concerns with isolation valve maintenance planning. Next, some information obtained from an investigation about failure aspects and maintenance practices is presented.

2.1 *Failure aspects*

An isolation valve is considered to be failed when it is not possible to close it completely to stop water flow through it. As it is common with mechanical equipment, the valve's physical condition or "state" declines over time due to a number of factors such as fatigue, corrosion, wearing of material, or accumulation of debris. The deterioration rate depends on the valve and its specific operational context (Marlow, Beale and Mashfort, 2012). In our case study, we discovered that the most failure prone component is the reduction mechanism of the valve's activation system, its criticality is due to the fact that it wears off faster and is more sensitive to factors related to maintenance quality. Such components are used in valves of great nominal diameter and high operation pressure.

In practice, it is noted that before failure, the equipment presents a malfunctioning state, that is, even though it can fulfill its role, it shows signs that should serve as a warning of imminent failure such as, resistance when turning the valve's lever and/or small passing of water. Such valve functioning information can be gathered through inspections thus, the delay time modelling becomes very useful for describing failures in this context (Marlow, Beale and Mashfort, 2012; Christer, 1999).

2.2 *Maintenance*

Since the reduction mechanism that activates isolation valves is critical, the main focus of our analysis is the replacement of this component in special. Because it is a component with a high deterioration rate compared to others, and is greatly affected by maintenance quality aspects (especially when it comes to defect induction), it can be presumed that a maintenance policy defined based in its characteristics is capable of serving the system well as a whole. Thus, preventive and corrective maintenance has to entail the substitution of the valve's reduction mechanism, and other activities that are done with the purpose of improving the state of the equipment as a whole and restoring it to a like-new state.

Due to safety concerns, it is not possible to perform maintenance on the isolation valve while it is under normal operation conditions. Therefore, it is necessary to interrupt water flow by isolating the surrounding region. In that case, maintenance of the isolation valve system causes the main system to be partially unavailable, and it is plausible to assume that the system's activation will not be required during that time. That stands in contrast to the example presented by Berrade, Cavalcante and Scarf (2012), where protection system maintenance does not lead to the unavailability of the main system; however, there is the risk of a demand not being met by the protection system while in maintenance.

The quality of the maintenance service may influence the valve's performance: if maintenance is performed incorrectly, or with poor quality materials, the valve can became more vulnerable to premature failure with a short life span (this aspect is classified as bad installation).

2.3 *Inspection*

The only purpose of inspections is to identify the equipment's working status. The inspection procedure is done in the following manner at the company in which the case study was conducted: an inspector tries to close an isolation valve and verifies, through pressure gauges downstream, if the water flow was interrupted.

In this case, the inspection does not cause the protection system to be unavailable and the impact on the operation of the main system is negligible.

Some important observations were made:

(1) The pressure gauges show pressure differences when water flow is high enough to fill the duct's transverse section, which happens when the valve is failed. Small quantities of passing water are not detected, making it difficult to identify a defective state.

(2) The perception of the resistance when closing a valve (a characteristic of defective valves) varies among inspectors, depending on personal physical strength. Nonetheless, it is possible to tell for sure when a valve cannot be fully closed (failed valve).

(3) The use of tools such as levers to close the valves more easily is common practice. That practice increases the torque applied, but the inspector may end up using more force than necessary and damage the components of the activation mechanism of the valve, accelerating wear and tear of the component.

By making these observations, we concluded that the quality of the inspection influences the accuracy of the judgement of the valve's functioning status, besides potentially contributing to valve malfunction.

As seen in items (1) and (2), it can be concluded that there is no error in judgement when it comes to identifying signs of failed state; however, the inspection is subject to error in judgement when identifying the defective state. Besides that, as seen in item (3), a poor quality inspection can lead to defects.

2.4 *The model*

Based on these observations, we developed a delay time model for a single component protection system, which regards the maintenance quality aspects aforementioned:

- In order to model the replacement quality, we assumed that the components come from a heterogeneous population made out of strong and weak items, with a mix parameter p indicating the percentage of weak items (Scarf et al., 2009).
- To model inspection quality, we considered the probabilities w of a false positive (false alarm when the valve is fully functional) and q of a false negative (as approached by Berrade, Cavalcante and Scarf, 2012). Therefore, we assume that there is a probability r of inducing defect in a good working valve (as approached by Scarf and Cavalcante, 2012).

We considered a hybrid inspection and replacement policy similar to the one suggested by Vaurio (1999), which advises performing M inspections with time interval T between them such that, when an inspection finds a component in defective or failed state, its replacement for a new unit is arranged and in the occasion of the M-th inspection, replacement is indicated regardless of its state.

The model was presented in Alberti et al. (2018).

3. Application

For the application, we consider as decision criterion the cost-rate (C_∞) obtained as function of the maintenance policy, additionally we present as an auxiliary criterion the loss-rate (Sh_∞ - long-run production loss per unit time), which here represents the quantify of water that is not delivered.

3.1 *Specification of the parameters*

To apply the model, we studied an isolation valve in a water distribution network that is installed in a high-pressure pipeline, located in an easily accessible site. Also, the segments adjacent to that valve cover a region that is at high risk for contamination. The parameters were estimated based on expert knowledge obtained from the engineers of the network operator and maintainer.

There are premature failures in approximately 10% of the valves installed due to poor installation, or items that return to the company's inventory after a poor maintenance. Therefore, we established p=0.1. Weibull distributions were used to distinguish the X (time to defect arrival) and H (delay time) distributions (characteristics of gear reducers), with the parameters displayed in Table 1.

In the initial scenario observed in the case study, we found a low probability of a false positive occurring followed by a high probability of a false negative occurring, while the probability of a defect induction was low, albeit not significant. In that way, we estimated the following values for the variables that characterize the quality of the maintenance: $w = 0.05$, $q = 0.3$ and $r = 0.05$.

Table 1 – Probability distribution parameters of X and H.

Variable	**Scale parameter**	**Shape parameter**
X – weak components	$\eta 1 = 1$ year	$\beta 1 = 2$
X – strong components	$\eta 2 = 4$ years	$\beta 2 = 3$
H	$\eta 3 = 0.5$ year	$\beta 3 = 1$

An isolation valve is subject to demands coming from the different segments adjacent to it: when there is a need to isolate a segment, the adjacent segment can also be affected depending on the state of the valve. Each segment has their specific rates of demand occurrences and the consequences associated with it are also different in each case. For a direct application of the model presented, we simplified the scenario by regarding the valve as a protection system subject to two kinds of demands and by assuming that the consequences of each demand, depending of its functional state, are constant and known. The value used to characterize the consequences of the demands, met or not, may be an average of what is actually seen.

Therefore, concerning operations, we consider that demands due to leaks occur on average once every 120 days ($\mu_1 = 3.042$ demands/year), while demands resulting from contaminations occur on average once every two years ($\mu_2 = 0.5$ demands/years). If a demand due to leakage occurs and the valve is functional, a region with an average daily consumption of 25.000 m³ of water (D_1) is without supply for 1 day ($T1_m$), but if the valve fails, a greater region with daily consumption of 50.000 m³ (D_2) is without supply for 2 days ($T1_u$). On the other hand, if a demand due to contamination occurs and the valve is fully functional the time without supply is 2 days ($T2_m$), and if the valve fails, 4 days ($T2_u$). To maintain the valve, it is necessary to interrupt the supply to a region with a daily consumption of 50.000 m³ (D_3) for 1 day ($S_p = S_d = S_f$). Besides that, as observed in subsection 3.2: $S_i = 0$.

The costs required for the model were established based on the cost of preventive replacement, so that c_p = 1 un. (quantity not specified in monetary units). The remaining costs were then specified in the following way: $c_i = 0.04$ un., inspection cost is significantly lower than preventive replacement, but it is not insignificant due to the cost of transportation to the valve's location. With regards to replacement costs: $c_d = 1{,}4$ un. and $c_f = 2$ un., it is plausible to consider these as being different because we are considering the cost of refurbishing the component to return it to the company's inventory, which varies according to its state ($c_f > c_d > c_p$). The extra costs resulting from a unmet leakage demand is $CUD_1 = 20$ un., and the extra costs resulting from a unmet contamination demand is $CUD_2 = 50$ un., these values take into consideration the direct costs of the containment and the impact in terms of clients left without water supply.

3.2 *Results and discussion*

The model is an approximation to reality, and to obtain the most suitable values for the maintenance quality parameters can be a difficult activity. Thus, a complete analysis of results obtained from de model has to be carried out, in order to obtain some guidelines for decision-making in maintenance. In this section, we present a possible way to realize this analysis.

First, we aimed to analyze the effect of the variation of the maintenance quality parameters on the definition and performance of the optimal maintenance policy. Beside this, we aimed to evaluate if worth to adopt a policy that advises the replacement in case of identification of a defective state. Some results are presented in Table 2.

From the results, we can conclude that, given the level of inspection quality, this practice is not advantageous, so it is more advisable to adopt a non-inspection preventive replacement policy, even if quite conservative, with little use of the useful component's life. The results were more sensitive to variation of *r*, what evidence that, if there is some uncertainty about the value of this parameter, it can be better to consider the scenario more conservative. Another trend observed is that the practice of inspections becomes more relevant the greater the percentage of weak items in the population of components (*p*).

In the lines 13 and 14 we consider a policy where the replacement is advised only when the failed state is identified (for this, it is sufficient to set $w = 0$ and $q = 1$, that is, not "perceiving" a defective state). From the results, we can see that it is better to consider the policy as presented previously. Furthermore, from the lines 15 and 16, it gets evident that mistakes can be made if the maintenance quality aspects considered are ignored.

Table 2 - Comparison of optimal policies for various values of the quality parameters. T in years, C_∞ in un., Sh_∞ in $10^5 m^3$ (adapted from Alberti et al., 2018).

	Case	Quality parameters				Optimal policy				
		p	w	q	r	M	T	MT	C_∞*	Sh_∞
1	Base case	0.10	0.05	0.30	0.05	1	0.785	0.785	1.856	1.659
2	Worse *p*	0.20	0.05	0.30	0.05	24	0.151	3.624	2.134	1.425
3	Best *p*	0	0.05	0.30	0.05	1	1.239	1.239	1.072	1.419
4	Worse *r*	0.10	0.05	0.30	0.10	1	0.785	0.785	1.856	1.659
5	Better *r*	0.10	0.05	0.30	0.03	20	0.162	3.240	1.644	1.353
6	Better *r*	0.10	0.05	0.30	0.01	15	0.184	2.760	1.253	1.314
7	Best *r*	0.10	0.05	0.30	0	17	0.178	3.026	1.051	1.288
8	Worse *w*	0.10	0.10	0.30	0.05	1	0.785	0.785	1.856	1.659
9	Best *w*	0.10	0	0.30	0.05	1	0.785	0.785	1.856	1.659
10	Worse *q*	0.10	0.05	0.50	0.05	1	0.785	0.785	1.856	1.659
11	Best *q*	0.10	0.05	0	0.05	20	0.178	3.560	1.805	1.371
12	Best *w* and *q*	0.10	0	0	0.05	25	0.146	3.650	1.656	1.295
13	Ignoring defects, better *r*	0.10	0	1	0.01	14	0.133	1.862	1.687	1.321
14	Ignoring defects, best *r*	0.10	0	1	0	20	0.109	2.180	1.309	1.264
15	Perfect inspection	0.10	0	0	0	20	0.164	3.280	0.818	1.197
16	Perfect maintenance	0	0	0	0	15	0.192	2.880	0.749	1.201

The model also can be used to demonstrate the benefit of investment in higher quality maintenance, as in the analysis presented in Table 3.

Table 3 - An analysis of the benefit of investment in higher quality maintenance. T in years, C_∞ in un., Sh_∞ in $10^5 m^3$ (adapted from Alberti et al., 2018).

	Case	Quality parameters					Costs			Optimum policy				
		p	w	q	r	c_i	c_p	c_d	c_f	M	T	MT	C_∞	Sh_∞
1	Base case	0.10	0.05	0.30	0.05	0.04	1	1.40	2	1	0.785	0.785	1.856	1.659
2	Improve classification	0.10	0.01	0.10	0.05	0.05	1	1.40	2	24	0.151	3.624	1.816	1.314
3	Improve classification	0.10	0.01	0.10	0.05	0.06	1	1.40	2	21	0.161	3.381	1.879	1.312
4	Reduce defect induction	0.10	0.05	0.30	0.02	0.08	1	1.40	2	13	0.207	2.691	1.662	1.324
5	Reduce defect induction	0.10	0.05	0.30	0.03	0.08	1	1.40	2	13	0.203	2.639	1.864	1.344
6	Improve inspection	0.10	0.01	0.10	0.01	0.12	1	1.40	2	11	0.244	2.684	1.448	1.251
7	Improve inspection	0.10	0.01	0.10	0.02	0.12	1	1.40	2	12	0.229	2.748	1.645	1.263
8	Improve inspection	0.10	0.01	0.10	0.03	0.12	1	1.40	2	12	0.224	2.688	1.837	1.281
9	Reduce weak items	0.05	0.05	0.30	0.05	0.04	1.10	1.54	2.20	1	0.954	0.954	1.670	1.546
10	Reduce weak items	0.05	0.05	0.30	0.05	0.04	1.50	2.10	3	1	1.042	1.042	2.082	1.506
11	Joint improvement	0.05	0.01	0.10	0.01	0.12	1.50	2.10	3	11	0.255	2.805	1.648	1.237

The analysis shows that the investment in higher quality maintenance can present a good cost benefit in the long term. The best results are obtained with investment in inspection quality, especially when focused on reducing the level of defect induction.

4. Conclusion

In this paper we discuss an interesting, real problem that motivated the development of a new model to evaluate the impact of maintenance quality aspects on the performance of a protection system. We bring some details of the case study in order to present the elements considered to build the model.

Through the application, we show how the model can be used to obtain important guidelines for decision-making in maintenance. From the results, we are able to answer some questions: what maintenance quality aspects have the greatest impact on the system's performance? Is it worth to invest in higher quality maintenance? Which aspects must be prioritized in that investment? The level of defect induction during inspections has the most significant impact on the performance of the maintenance policy, and its impact becomes even more prominent when combined with judgement errors made during inspections. By investing in higher quality maintenance, it is possible to arrive at a more economical scenario in the long term. That investment should be directed mainly towards improving inspection quality, especially when it comes to reducing defect induction. Furthermore, if efforts to reduce judgement errors are included, even greater results can be achieved.

In our case study, defect induction was a frequently mentioned topic by those interviewed; however, a clearly identified perception, and that can be translated into reliable estimates, cannot always be verified. Hence, the application of techniques to investigate trends that affect the system performance can be useful.

Acknowledgements

The work of Cristiano Cavalcante has been supported by CNPq (Brazilian Research Council). The work of Alexandre Alberti has been supported by FACEPE (Foundation for Science and Technology of the State of Pernambuco). The work of Phil Scarf has been supported by the College of Science, King Saud University, Saudi Arabia.

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