DETERMINING THE SIZE OF ISOLATION SEGMENTS IN DRINKING WATER DISTRIBUTION SYSTEMS

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Abstract

This paper introduces a method how to come to a best practise for segment size of a distribution system to be isolated during an outage based on calculation of the customer minutes lost (CML) including the effect of valve failure. It shows that smaller distribution segments (and hence more valves) are needed when the value of water service is high, the pipe failure rate is high, the time to repair breaks is high, and the reliability of isolation valves is low. Using the values in this study, which is oriented toward practices in the Netherlands, the desired number of household customers per segment is on the order of 50 to 80.

1 Introduction on valve reliability and isolation segments

Drinking water distribution networks (DWDN) are an important part of infrastructure. They consist of multiple types of assets of which pipes and valves are the most common ones. The function of valves in the DWDN is twofold:

- blocking isolation segments in case of a pipe failure;
- controlling flow in the DWDN.

While designing a DWDN drinking water companies have to consider the placement of isolation segments. Engineers have to decide where to place valves and how large isolation segments should be designed (in terms of connections and length).

The function of valves in the DWDN and a rational design of isolation segments is not trivial since the DWDN has often a complex (meshed) structure as the DWDN grew in an organic way. Guidance on valve placement in the USA has been around for over a century: "They [valves] can be placed at any desired distance apart but one on each line at each corner, or at intervals of 500 to 700 ft [150 to 220 m] where blocks are longer than this, is probably as close as it is generally desirable to place them." and "…no accident will require cutting out of service more than 500 ft of main in high value district or 800 ft [240 m] in other segments" (Folwell, 1926). Numerous regulatory agencies have similar standards. In North American systems, the usual situation is 10-20 connections per segment. In the Netherlands common practice used to be 20-50 connections per segment, however, there are no uniform standards which relate valve placement and segment size. With new insights into network design (Vreeburg et al., 2009) and more cost awareness, including the costs of valve maintenance (Blokker et al., 2011), the isolation segments of new (post 2010) DWDNs seems to be more around 100 connections. To study the influence of segment size, specific designs were made for Ypenburg with even larger numbers of connections.

Several methods are available in literature in which consider cost and the effect of valve placement on the network performance using optimization algorithms (Creaco et al., 2010; Giustolisi and Savic, 2010) while other methods focus more on criticality analyses based on segmentation of networks (Kao and Li, 2007; Walski et al., 2006). Reliability of DWDNs is often quantified considering the network segmentation (Walski, 1993) and the likelihood of a pipe failure in a certain segment. The reliability of valves is not considered in these methods, which means that the valve reliability is implicitly assumed to be 100%. The practical consequence of this assumption is that segments will always be isolated by closing the valves serving as boundaries to these segments. Since valves can fail in various ways (Trietsch and Vreeburg, 2005) ignoring valve reliability can lead to underestimating the effect of a pipe failure. In case of pipe failure (or planned maintenance) the affected segment is isolated by closing the segment isolation valves. For a looped DWDN the water supply in the adjacent isolation segments will be continued, which minimizes the inconvenience for customers. It is assumed that a security of supply (i.e. if transport mains fail, there is still enough pressure to supply e.g. 75% of a maximum demand) and continuity of supply (i.e. the isolation of a single segment does have a limited effect on surrounding connections) is ensured during the design phase by considering pipe diameters, pipe connectivity through loops as well as the smart placement of valves. If one or more valves – which should isolate the segment – do fail, one or more adjacent segments need to be closed to isolate the incident in the DWDN. Failure reports in the Netherlands show a valve reliability roughly between 0.7 and 0.95 (van Thienen et al., 2011; Vreeburg, 2012). Assuming a segment with 2 valves (A and B) the likelihood P_f of (any) valve failure is equal to:

$$P_f = 1 - R_A \cdot R_B \qquad [1]$$

where R_A and R_B equal the reliability (1-probability of failure) for respectively valves A and B. Under the assumption that all valves in a segment have the same probability of failure p and reliability R, equation [1] can be generalized for a segment with N valves:

$$P_f = 1 - R^N \qquad [2]$$

Substituting the probabilities mentioned above (0.7; 0.95) this means that a the probability of any valve failure – and thus, more inconvenience during an incident than for the customers in the segment itself – varies between 10 and 51% for a segment consisting of 2 valves and between 19 and 76% for a segment consisting of 4 valves.

The robustness of DWDNs can be improved by optimizing the design of valve locations while taking into account the risk of valve failure. The risk of valve failure is determined by the probability of failure multiplied by the effect of a water outage due to valve failure. Designing optimal segments – in terms of costs – mitigates the risk of valve failure on the effect side (Figure 1) for a given segment size. The probability of valve failure can be quantified by valve inspections, from which the results can give insight into failure mechanisms of valves and valve reliability (Trietsch and Vreeburg, 2005). Effective valve maintenance mitigates the failure probability (Marlow et al., 2012; van Thienen et al., 2011), which is mainly important for valves whose malfunctioning will lead to a large effect. This effect can be quantified with CAVLAR® (Blokker et al., 2011) which quantifies the effect (contribution) of valve malfunction on the water outage (number of affected connections and customer minutes lost). CAVLAR® is a software tool which was developed by KWR Watercycle Research Institute to optimize valve maintenance by ranking valves based on their influence on network performance (in case they fail). CAVLAR® is available as OptiValves within the Watershare® programme.

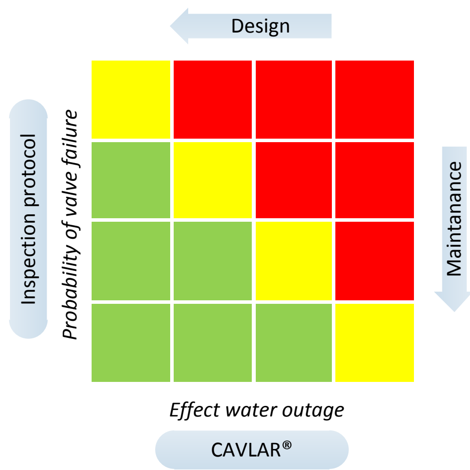

Figure 1 Risk matrix for asset management of valves.

The focus of this paper is on the design of networks and its influence on the effect of valve failure. This paper describes a method for designing optimal sized isolation segments including the risk of valve failure. Additional to the method description the outcomes of a real case study (Vogelaar and Pieterse-Quirijns, 2013) are discussed.

2 Method for optimal sized isolation segments in DWDNs

2.1 Iterative process optimization of segment design

One of the design parameters in deciding on valve locations in the DWDN is the number of connections in an isolation segment (segment size). An optimal size of isolation segments can be determined by evaluating the cost of several DWDN designs consisting of different segment sizes, i.e. number of connections per segment. Balancing the costs for construction and maintenance on the one hand and the value of the expected number of interruptions per customer on the other, an optimum (minimum cost scenario) can be found (Figure 2).

To optimize the segment design by focussing on total cost the three groups of costs mentioned in Figure 2 (Valve CAPEX, valve OPEX, cost for water outage) have to be quantified.

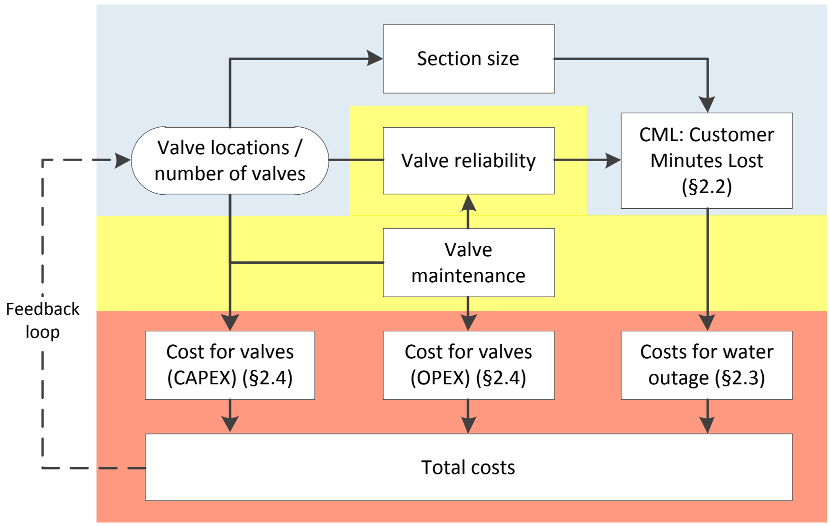

Figure 2 Method for design of optimal sized isolation segments in DWDNs. The blue part represents the quantification of effect, the yellow part the quantification of valve reliability (1-probability of failure) and the red part represents the costs.

2.2 CAVLAR: quantification of expected interruption time for segments including valve failure

The interruption of water service is measured in Customer Minutes Lost (CML), which is determined by the average outage time (in minutes) per year per customer. This performance indicator is part of the benchmark of the Dutch drinking water companies (Blokker and Geudens, 2005). The total CML for an isolation segment is defined as:

$$CML_i = I_i f_i \, T \qquad [3]$$

where I_i is the impact for segment i, f_i the probability of water outage in segment i (number of incidents per year) and T the duration time. The possible effect of decreasing pressure during shutdown is ignored here. The probability of a water outage could be estimated through evaluation of all pipes in an isolation segment and their corresponding pipe failure frequencies:

$$f_i = \sum_{n=1}^{N} p_n \, L_n \qquad [4]$$

where N equals the number of pipes in a segment, p_n the failure probability (failures·km^{-1}·year^{-1}) for pipe n and L_n the length of pipe n (km). p_n can be estimated from pipe failure data. For this paper data from USTORE was used, which is the Dutch national database of failures of drinking water pipes (Kwakkel et al., 2013).

A pipe failure leads to water outage when valves are closed. As valves are not 100% reliable, the effect of valve failure on CML is taken into account when determining the desired number of valves per segment. The impact I during an incident of water outage is a risk factor which contains the contribution of all segments which are directly or indirectly affected by the incident. The directly affected segment is the segment wherein the pipe failure occurs. In case of valve failure the adjacent segments are indirectly affected by the pipe failure in the hit segment. CAVLAR® calculates all possible options (M_i) of valve failure events for every segment i. M is defined as:

$$M_i = \sum_{v=1}^{V} \binom{V}{v} \qquad [5]$$

where V equals the number of valves serving as boundary of segment i. Assuming a pipe failure in segment i CAVLAR® calculates the impact of every valve failure scenario m for segment i from which the total impact I_i per segment can be derived using:

$$I_i = \sum_{m=1}^{M_i} q_m\, a_m \qquad [6]$$

where q_m equals the probability of one valve failure event m (or combination of failing valves) and a_m the number of affected connections in the segment adjacent to the 'hit' segment for the failure event m. In the Netherlands data about the number of connections per segment (a_m) can be derived by open data or client information systems of drinking water companies.

After calculation of I_i for the first order adjacent segments, CAVLAR® continues to calculate the contribution of the second order adjacent segments on the impact – assuming a valve failure in the first order adjacent segment. This process continues until a given lower limit q_{min} (e.g. 10^{-5}) for the probability q_m is exceeded. After calculation of the contributions ($I_{i,m}$) of all failure events M_i (which have a probability $q_m > q_{min}$) on the impact (I_i) the CML of segment i can be calculated using equation [3]. After calculation of all CML values for all segments the CML for the whole DWDN is defined as the sum of all CML values divided by the total number of connections:

$$CML_s = \frac{\sum_{i=1}^{S} CML_i}{\sum_{i=1}^{S} a_i} \qquad [7]$$

2.3 Quantification of costs

The cost for water outage is difficult to determine. According to calculations from a single Dutch water company – which are based on the threshold to which costs for pipe failure are commercially acceptable – the cost for one CML was estimated as a range of 0.20 – 0.30 €·CML^{-1}.

During the model study an interval cost of 0.10 – 0.30 €·CML^{-1} was used, which means a cost range 900 – 2700 € for a segment containing 50 connections and an average water outage duration of 180 minutes. Costs for installation of valves (Capital Expenditures or CAPEX) and valve inspections (Operational Expenditures or OPEX) were estimated as 1500 €·valve^{-1} and 50 €·inspection^{-1} respectively. This estimation was based on numbers provided by Dutch drinking water companies (2013). In this approach the cost of water outage is assumed to be linearly correlated with the duration of the interruption. However, the effect of an outage on customers is fundamentally different than purely based on volume of water. The initial outage causes a lot of concern. As the duration increases, the concern only increases marginally with time. Putting this into a monetary value would lead to something like:

$$total\ cost = C + cT^{b} \qquad [7]$$

where C equals the overall cost for any interruption, T the duration of an outage, b a shape factor and c the cost for one CML, with C being much larger than $T^{b}\cdot c$ unless the duration is multiple days. b would be less than 1. A customer survey is required to establish proper values in this equation. Because C is a constant and increases the total (absolute) cost, but not so much the influence of failing valves (and thus the number of valves, or the number of customers in an isolation segment) on the minimum (i.e. relative) cost. The cost of contamination is not a design issue here, but deserves a risk approach (see e.g. (Blokker et al., 2014) where the risk of infection needs to be decreased by good hygienic practice during work, reducing number of pipe failures, boil water advice, network design, and only in the last instance valve placement. We prefer to leave this discussion out of the current paper.

2.4 Valve reliability and maintenance

Valve failure could be made explicit in five ways (Trietsch and Vreeburg, 2005; van Thienen et al., 2011):

- cannot be found within 5 minutes;
- cannot be positively identified (i.e. maps and practice do not line up) within 3 minutes;
- cannot be accessed within 5 minutes (sometime may need to jackhammer through asphalt to get to top of valve box that has been paved over);
- cannot be turned within 2 minutes (sometimes it takes an hour to clean out valve box[1]);
- cannot be closed.

Drinking water companies in the Netherlands perform valve inspections to ensure the functionality of important valves. The extent to which valve maintenance is related to valve reliability is part of current research and depends on the failure mechanism. Some mechanisms (e.g. ‘valve box filled with debris which must be removed’, ‘cannot be operated and uncertain as to whether open or closed’) can be related to processes in time (e.g. ageing). However, other failure mechanisms (e.g. ‘cannot be find, ‘cannot be accessed’) are probably influenced by processes which are not necessarily time related, e.g. road replacement, vehicle parked on box with no way to move vehicle. In past research a correlation was found between valve maintenance and valve reliability (van Thienen et al., 2011; Vreeburg, 2012) these numbers are used in the model.

2.5 General relation between CML and valve reliability

As shown in eq. [3-7] the CML_s depends on CML values of all individual segments in the DWDN and their specific parameters for valve reliability. To enable the calculation of an (average) value for optimal segment size forces a simplification in the form of a direct relation between the CML_s and the valve reliability. This relation was derived using the following steps:

- creation of a variety of DWDNs for one case study area (Ypenburg);
- calculation of CML_s values for every DWDN for a range of valve reliabilities (0.7 – 1.0) using CAVLAR;
- derivation of a general relation between valve reliability and CML_s using a power function.

[1] In which case during unplanned work, the next valve will be used. Planned maintenance may give time to clean the valve box.

The study area (Ypenburg: Figure 3) was manually cut into smaller redesigned parts to create networks consisting of isolation segments with approximately 50, 100, 150, 200 and 250 connections per segment (Yp2-Yp6: Table 1).

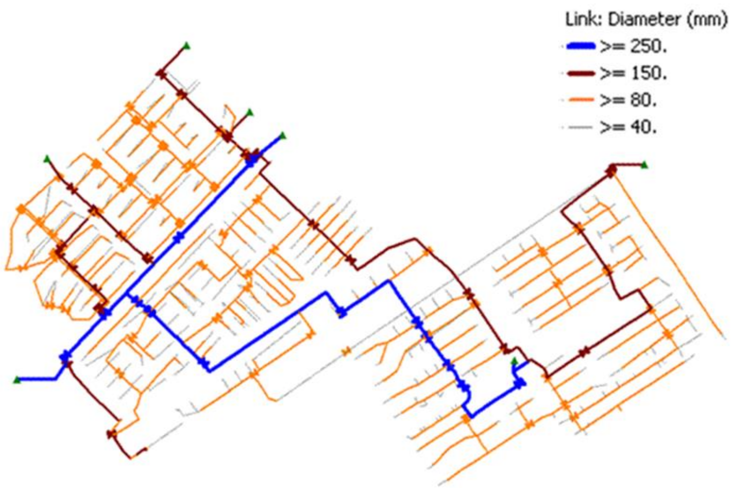

Figure 3 Ypenburg study area (Yp1); DWDN consisting of 5757 connections, 46.9 km of pipe, 75 connections/isolation segment (on average).

Table 1 Network segment characteristics.

Network name	**Av. num. connections per segment**	**Av. num. valves per segment**
Yp1 (default; Figure 3)	75	3.10
Yp2	48	2.43
Yp3	73	2.66
Yp4	90	2.41
Yp5	148	2.41
Yp6	186	2.32

Using CAVLAR® values for CML_s were calculated for networks Yp2 to Yp6 using different values for the valve reliability R (0.7 – 1.0; Figure 4) assuming an average pipe segment failure rate p_n of 0.04 failures·km^{-1}·year^{-1} and an interruption time of 180 minutes for an incident.

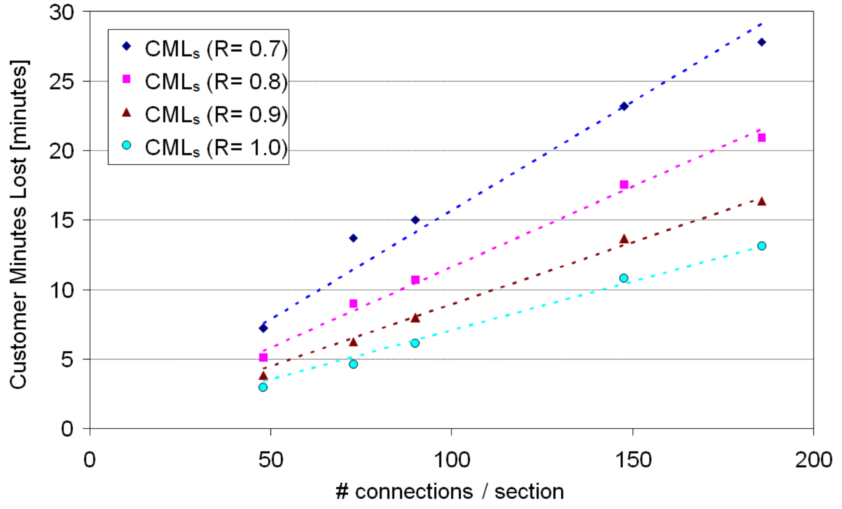

Figure 4 CML_s values calculated for five different network layouts (Yp2 – Yp6); assuming different values (0.7 – 1.0) for R (valve reliability).

The general relationship between CML_s and the valve reliability is based on a power function:

$$\widehat{CML_s} = aSR^p \qquad [8]$$

where $\widehat{CML_s}$ represents the derived CML_s value for the DWDN, S is the number of segments, R equals the average valve reliability, p is a shape factor which is fitted based on the outcomes of the CAVLAR study (Figure 4) and a is a constant which represents outage duration, variation of segment sizes in the DWDN and failure probability:

$$a = V\overline{f}D \qquad [9]$$

V is a variation factor which represents the variation of segment sizes around the average segment size, $\overline{f}$ the average probability of a water outage (determined by the average segment length $\overline{L}$ multiplied by the average pipe failure rate $\overline{p}$) and D the average duration of this outage.

Since the variation factor V and shape factor p are based on CAVLAR study for Ypenburgh, the numbers for these factors (and thus, the outcomes of eq. [7]) are only valid for cases which are comparable with the Ypenburg network. This means that a DWDN has a comparable average number of valves per segment (3.10) and a comparable connectivity expressed in the variation factor V. For Ypenburg V equals 1.17 and p equals -2.23.

3. Results for Ypenburg case

The method proposed in paragraph 2 was applied on the DWDN of Ypenburg (Figure 3) using the parameters and system characteristics as described in Table 2.

Figure 5 shows the results of Ypenburg optimization for multiple scenarios of interruption cost and valve reliability. A valve reliability of 0.9 leads to a smaller segment size (50 – 150 connections) than a valve reliability of 1.0 (100– 250 connections).

Table 2 Values for input parameters and system characteristics for DWDN of Ypenburg.

Parameter	**Value**	**Unit**
Total number of connections	5757	-
Total network length	46.9	km
Total number of valves	77	-
Average probability of failure (Dutch average).	0.04	failures·km^{-1}·year^{-1}
Average interruption time	180	minutes·event^{-1}
Valve reliability	0.9 – 1.0	-
Valve inspection interval	3 – 0.5	year
Valve CAPEX	1500	€·valve^{-1}
Valve OPEX (inspection)	50	€·inspection^{-1}
Deprecation time	50	year
Interest rate	4%	-
Cost of water outage	0.10 – 0.30	€·minute^{-1}·connection^{-1} (= €·CML^{-1})

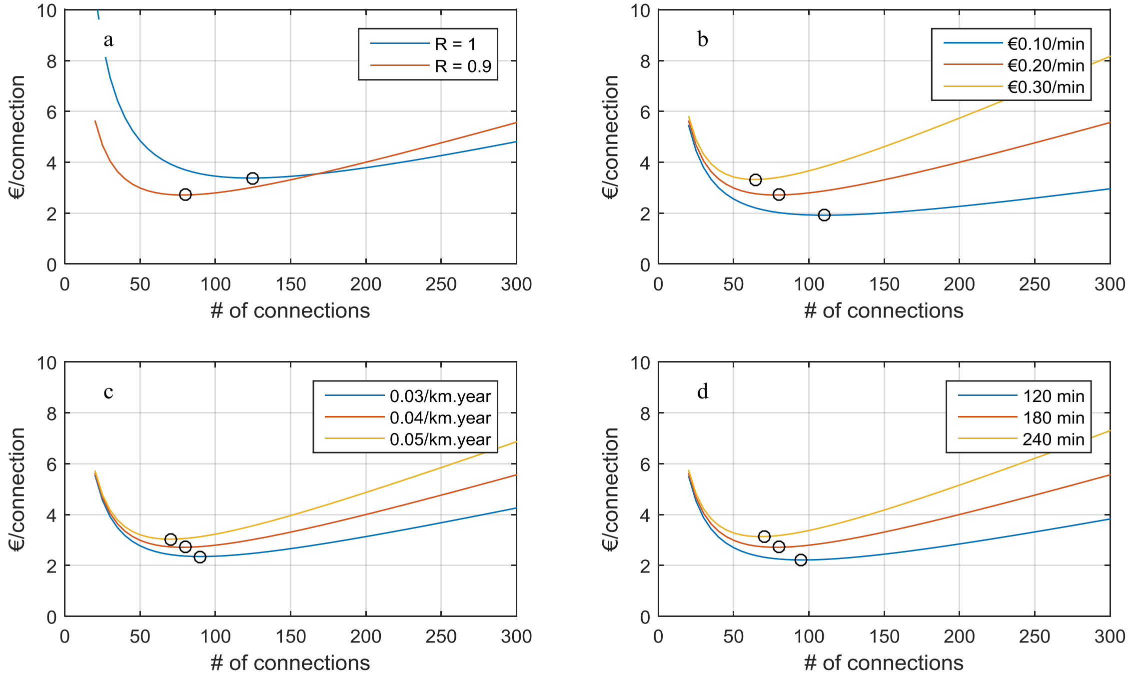

Figure 5 Sensitivity test for cost per connection, the minimum cost is shown with a black circle; a) valve reliability = 0.9 - 1.0 (with inspection interval of 3 and 0.5 years); b) OLM cost is €0.10 - €0.30 per minute; c) pipe failure rate is 0.03 – 0.05 per km per year; d) repair down time is 120 – 240 minutes.

The sensitivity test shows that for a large optimum segment size, the valve reliability should be high, the cost per CML should be low, the pipe failure rate should be low, and the repair time should be short. Along with these parameters leading to a larger optimum segment size, the cost decreases for most of these parameters, except for the valve reliability. A higher valve reliability comes at a cost.

4. Discussion

A method was developed to determine best practise size for isolation segments in DWDN design. The proposed method can be used for all types of DWDN. An optimal segment size of 50 – 100 household connections was found assuming a valve reliability of 0.9, an average failure rate of 0.05 failures$\cdot$km$^{-1}\cdot$year^{-1} and an outage cost of 0.20 €$\cdot$CML^{-1}. These failure rate and reliability numbers are (on average) representative for the situation in the Netherlands. One should notice that a higher failure rate (e.g. 0.5 failures$\cdot$km$^{-1}\cdot$year^{-1}) or longer duration (e.g. 480 minutes) will lead to much smaller isolation segments (30-50 connections; Figure 6).

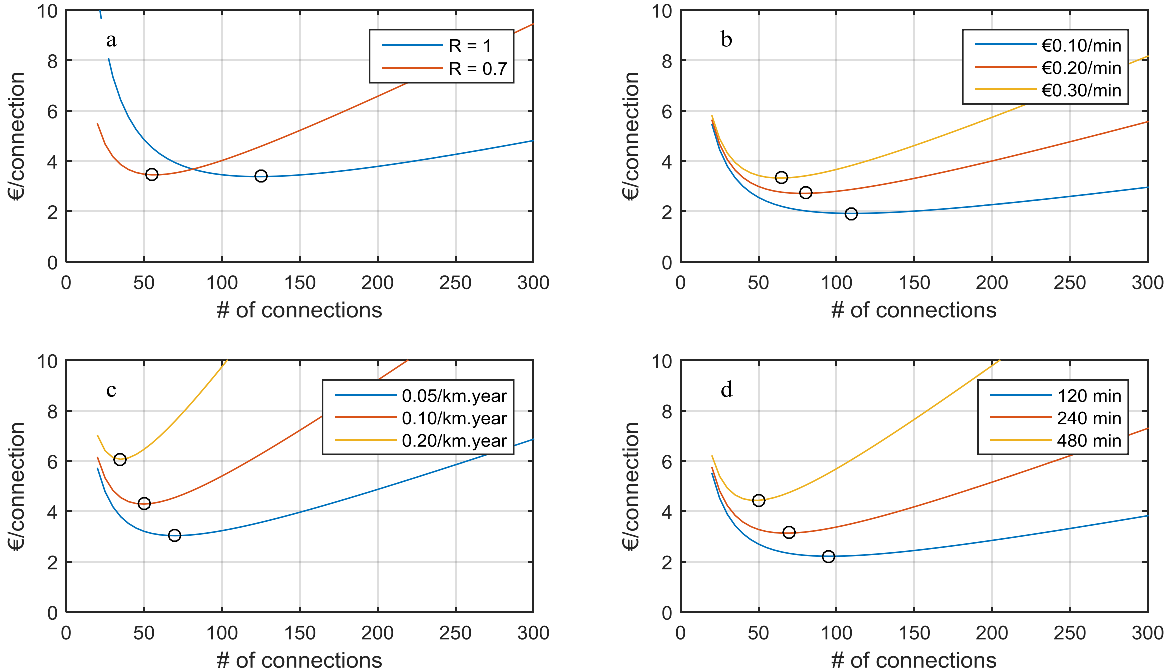

Figure 6 Sensitivity test (using high numbers) for cost per connection, the minimum cost is shown with a black circle; a) valve reliability = 0.7 - 1.0 (with inspection interval of 5 and 0.5 years); b) OLM cost is €0.10 - €0.30 per minute; c) pipe failure rate is 0.05 – 0.2 per km per year; d) repair down time is 120 – 480 minutes.

The model results show the importance of valve reliability. Various models and software programs assume the valve reliability to be 100%, which does not hold in practice. Incorporating a valve reliability less than 100% results in isolation segments which are (at least) 50 – 100 household connections smaller compared to a situation with 100%-reliable valves. To compensate for failing valves, more valves need to be placed. Not only for mitigating the effect (CML) of failing valves but also for reason of cost optimization.

The method described in this paper was used by drinking water company Brabant Water to develop a workflow for design of isolation segments. The study performed by Brabant Water showed that the optimal isolation segment size does not depend only on the total number of connections, but also on the total length of a segments. This outcome resulted in a differentiated company specific optimal segment size: 80 connections·segment^{-1} (with a 40 – 120 bandwidth) for urban areas and 50 connections·segment^{-1} (with a 25 – 75 bandwidth) for rural areas.

The method described in this paper can be used to determine an average optimal segment size and includes the effect of valve failure. To count for investment cost (CAPEX) for valve placement, interruption time and failure rate average numbers were used. In reality these numbers will vary with pipe diameter and the location of a segment in the DWDN. The method can be used to derive the average optimal segment size and does therefore not fully reflect the variation of segments.

A cost of water outage equal to 0.20 €·minute^{-1}·connection^{-1} was used. However, in reality the cost for water outage is probably not linear with time, since there is a consumer surplus in the fact that there is no drinking water delivery at all. Therefore, a surplus cost parameter has to be applied in model studies involving cost for water outage. This surplus parameter has no effect on the best practice segment size described in this paper, only on the total cost value. However, the rationale that the cost for water outage is non-linear could be used to optimize the maintenance of current DWDNs by better maintenance of valves of segments which have a higher probability of a failure event (due to ageing pipes).

Future work on this topic will consist of the combination of optimization algorithms and the effect of valve failure. Another important topic for future work is formed by a broader modelling of the effect of valve failure. In the current CAVLAR methodology for calculation of the effect of valve failure, only the CML is used which is based on the number of connections in a segment (see eq. [3-7] in paragraph 2.2). In reality not only the number of connections is of interest, also possible presence of vulnerable customers (e.g. hospitals, nursing homes, etc.) in a segment is important.

Further research on valuing the cost of water outage is highly recommended, e.g. by evaluating the costs of past outages. Next to this it would be valuable to research the relation between the approach presented in this paper and the derivation of design parameters such as the number of valves per segment and the number of valves per intersection (Walski, 2011).

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