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Risk Assessment and Development of Maintenance Strategy for Pipe Rehabilitation Using WDNetXL

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Abstract

This paper shows potential application of mechanical reliability analysis in WDNetXL in a risk-based asset management applied to a distribution network in Norway. Evaluation of hydraulic importance of the network's pipe segments, based on quantification of pressure deficiency and unsupplied customer demand during simulated service interruptions, allows risk assessment on individual pipe level with the inclusion of statistical information about break rate of the pipe. From risk assessment of individual pipe, a priority ranking for pipe rehabilitation can then be developed. Such an approach should benefit the rehabilitation planning by highlighting criticality of a specific pipe and its impact on the service of the network. This approach can also be extended to evaluate the risk reduction reached once the rehabilitation plan is executed.

1 Introduction

Most water utilities in Norway have not developed a long-term rehabilitation strategy, nor do they systematically explore their options for maintaining or upgrading the water distribution network. At best, a list of most urgent rehabilitation projects is established and work proceeds along this list of projects that are on the list if funds are available and the budget is not cut by other investment needs such as repair of unforeseen pipeline damage. There is a large potential for avoiding this rather reactive approach and for improving the efficiency of water network rehabilitation. Network information systems provide a rich source of information that should be used in a proactive approach to network rehabilitation.

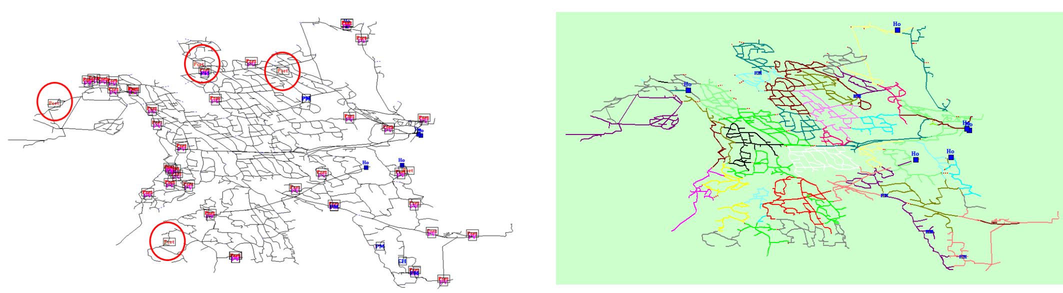
As pointed out in Oslo Municipality Water Supply Masterplan of 2015-2030 (Krogh et al., 2015), the main emphasis is in two-fold: to ensure sufficient water supply for the growing city of Oslo and to reduce the dependency on Maridalsvannet as the main raw water source and water treatment plant

Oset. In terms of providing water in sufficient quantity, one of the main measures is to reduce physical leakage and the ambition is to reduce the leakage level from 40% to 20% of the total water production. Pipe rehabilitation is one of the focuses as deterioration of the distribution network also influences the leakage level. It is set in the masterplan that pipe rehabilitation should target at least 1.2%/year of the total pipe length. Thus, it is of utmost importance to pinpoint the potential pipe(s) to be monitored and prioritized. This process must be conducted in a careful manner to ensure correct use of resources and, most importantly, to safeguard the main objectives of the water supply as stated in the masterplan. E3WDM (Efficient, Effective, Economic Water Demand Management) project, funded by Regional Research Funds in Norway (RFF) and City of Oslo, Agency for Water and Wastewater Services (Oslo VAV), considers a risk-based analysis to assist the water utility in Norway in planning the rehabilitation project of the distribution network.

2 Methodology

2.1 Basic Information of "E3 Network"

The distribution network used in this study (Figure 1), referred to as "E3 Network" in this paper, is a part of Oslo's water distribution network and comprises of 5440 nodes (5 reservoirs and 1 tank), 5812 pipes (108 closed pipes, 16 pumps, and 44 pressure control valves-PCV), and 102 pipe segments. The basic hydraulic model was calibrated by assessing the model parameters of background leakage to reproduce similar network behavior as that of the original EPANET model supplied by Oslo VAV. The initial background leakage was calculated to be around 27%, which was consistent with the value reported in the EPANET model. With the RRTC setting as depicted in Figure 1a, a further background leakage reduction to ~25% was achieved.



(a) (b)

Figure 1: a) Overview of E3 Network with RRTC, the red circles indicate locations of control nodes for RRTC, and b) Pipe segments resulted from isolation valves analysis

2.2 Mechanical Reliability Analysis in WDNetXL

WDNetXL has the capability to perform mechanical reliability analysis of the entire water distribution system considering pipe or nodal failure. For this type of analysis, pressure driven analysis (PDA) is preferable because a hydraulic system component failure generally causes a pressure-deficient condition for customer demands. Mechanical reliability function in WDNetXL analyses the hydraulic system behavior in terms of nodal pressure deficiency and unsupplied customer demand. The function considers each failure event in an extended period simulation (EPS). Eqs. 1 and 2 are used to evaluate the level of unsupplied demand and nodal pressure deficiency, respectively.

$$UN_{i,e,t} = 1 - \frac{d_{i,e,t}^{act}}{d_{i,0,t}^{req}} \qquad \forall i \in n_n \quad \forall e \in n_e \quad \forall t \in [1, T] \tag{1}$$

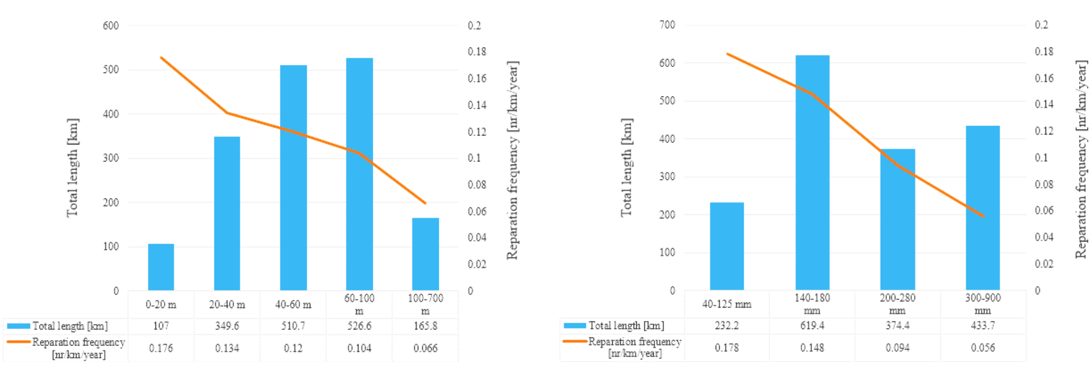
$$PR_{i,e,t} = 1 - \frac{p_{i,e,t}^{act}}{p_{i,0,t}^{normal}} \qquad \forall i \in n_n \quad \forall e \in n_e \quad \forall t \in [1, T] \tag{2}$$

In Eqs. 1 and 2:

UN = fraction of unsupplied customer demand
d^{act} = actual customer demand computed in PDA
d^{req} = required customer demand
PR = fraction of nodal pressure reduction with respect to normal conditions
p^{act} = actual nodal pressure computed in PDA
p^{normal} = nodal pressure in normal conditions
i, e, t = subscripts representing i-th node, e-th failure event, and time t of EPS simulation of period T; e=0 represents the normal condition
n_n = number of nodes
n_e = number of events

2.3 Pipe Break Rate Data

Break statistics data of the network pipes was supplied by Oslo VAV (Geleta, 2015; Kropp, 2014). In this paper, the break rate (λ [breaks/km/year]) for all pipes in Oslo's distribution network was assessed from pipes grouped in diameter and length (Figure 2). The failure statistics was based from Norwegian pipe database Gemini VA/Geo VA in period from 1976 to 2014. This data was assumed representative for E3 Network given that the pipes in E3 Network are the subset of the overall network. No classification based on pipe materials nor installation year was included in the analysis, since such data for E3 Network was unavailable. This was certainly a key challenge for the analysis; however, this will not deter the applicability of the risk-based asset management method proposed in this paper.



(a) (b)

Figure 2: Failure rate represented by reparation frequency of pipes in Oslo distribution network grouped by a) length and b) diameter

2.4 Method of Risk Assessment and Rehabilitation Strategy

The consequence of dividing the network into pipe segments dictates that all pipes belonging to the same pipe segment will be assigned the same hydraulic importance. Thus, the results from mechanical reliability analysis will be more meaningful if such a hydraulic importance can be assigned to individual pipe within the segment. The inclusion of failure statistics becomes very useful in this respect and, in turn, allows valuation of consequence, risk probability and overall risk of individual pipe in the risk assessment step (Figure 3).

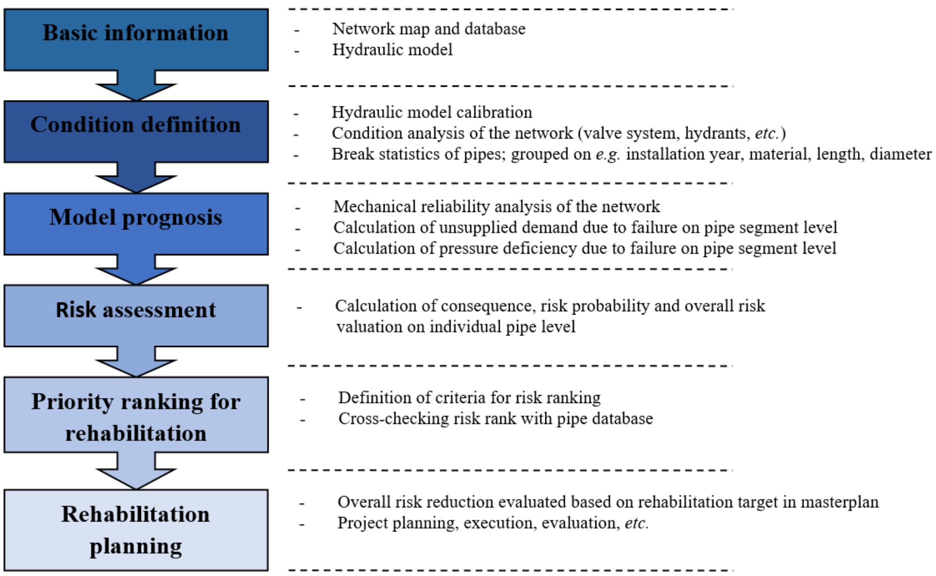


Figure 3: Workflow of risk-based asset management

In the priority ranking for rehabilitation step, unsupplied demand and pressure deficiency were chosen as the two main elements for risk valuation. Given the discussion in the preceding paragraph, it is not only interesting to quantify the hydraulic importance of each individual pipe, but moreover to quantify the risk that each pipe possesses in terms of causing one of the detrimental conditions. Risk assessment of individual pipe in this paper was quantified by incorporating the break rate λ in the calculation (Figure 4). Two break rates were available: λ based on diameter groups (λ_D) and pipe length groups (λ_L), and in addition a combination of the two lambdas (*i.e.* $\lambda_{DL} = \lambda_D * \lambda_L$) were viewed as a joint probability of the two groups and, thus, gave a total combined risk based on the two break rate groups. This paper also attempts to evaluate overall risk reduction based on pipe rehabilitation target stated in the masterplan *i.e.* 1.2% of total length per year (Krogh et al., 2015) applied to the priority ranking for the pipe rehabilitation.

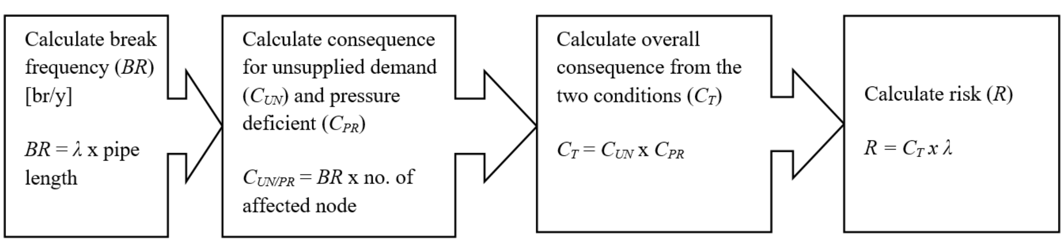


Figure 4: Procedure of risk quantification applied to each λ value

3 Results and Discussion

3.1 Model Prognosis of Failure Events

Mechanical reliability analysis was done by systematically closing each of the pipe segments and calculating the pressure deficiency and unsupplied demand. Hence, the ID number of failure event also represents the ID number of the pipe segment being simulated. To determine whether a node is experiencing an unsupplied demand or pressure deficiency condition was based on comparison between the demand and pressure values at a failure event and normal event (*i.e.* normal functioning of the network in extended period simulation in WDNetXL). It is important to infer that some nodes can exhibit one of the detrimental conditions (unsupplied demand or pressure deficiency) or both conditions simultaneously. For the analysis in this paper, if the ratio of the values between the two events exceeded 0.5 (*i.e.* 50% change compared to values at normal event), then it was concluded that the node exhibited a detrimental condition. This criterion is, of course, rather arbitrary and can be refined.

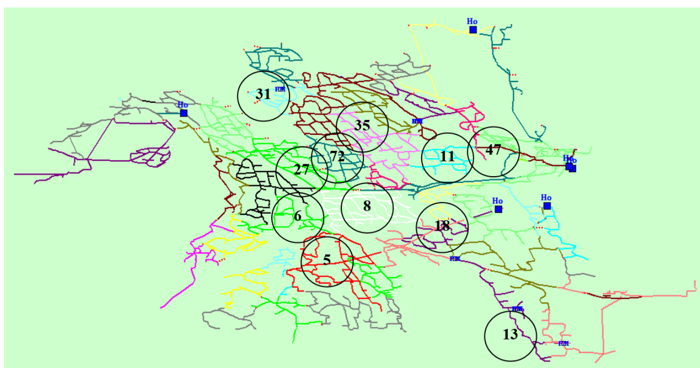


Figure 5: Locations of the failure events and pipe segments in E3 Network listed on top-10 failure events

Rank	Unsupplied demand		Pressure deficiency	
	Failure event	**Number of affected nodes**	**Failure event**	**Number of affected nodes**
1	8	1592	8	2345
2	6	1098	6	1845
3	47	792	47	1105
4	72	792	72	1105
5	11	787	35	1075
6	35	787	11	1070
7	18	621	31	1063
8	13	611	13	987
9	5	604	18	985
10	27	525	5	883

Table 1: List of top-10 failure events corresponding to the number of affected nodes

Figure 5 shows the location of pipe segments/failure events with the highest number of affected nodes both in terms of unsupplied demand or pressure deficient condition. The number in each circle corresponds to the ID number of failure event/pipe segment simulated in the hydraulic model. The top-10 failure events for each detrimental condition are listed in Table 1. It is interesting to see the dynamics in the ranking. This implies that each pipe segment possesses a distinct hydraulic importance and can affect the distribution network in different manners depending on the failure events simulated. For example, failure event no. 27 that ranks 10th in terms of failure events causing unsupplied demand is absent on the list of failure events causing pressure deficiency.

3.2 Risk Assessment of Individual Pipe and Pipe Rankings

Table 2 shows exemplary risk calculation done for the longest pipes in E3 Network following the procedure explained in Figure 4. Observe that the number of affected nodes with unsupplied demand is always lower than that with pressure deficiency. Consequently, C_{PR} values are always higher than C_{UN} indicating that the network is more prone to pressure deficiency. This can be viewed as the direct consequence of pressure management to reduce background leakage as modelled by WDNetXL. With lower pressure on the network, the pressure becomes closer to the pressure limit for correct service (p^{ser}). Thus, the effect of screening criterion as described in Section 3.1 must, however, be revisited in order to assess its sensitivity in affecting the outcome of this method.

Pipe ID	Length [m]	Diameter [mm]	Failure event no.	*UN*	*PR*	λ_D [br/km/y]	*BR* [br/y]	C_{UN}	C_{PR}	C_T	R_D
5071	1552.4	800	16	67	148	0.056	0.0869	5.8	12.9	74.9	4.2
3834	1286.1	220.4	24	167	234	0.094	0.1209	20.2	28.3	571.2	53.7
3637	804.6	600	18	621	985	0.056	0.0451	28.0	44.4	1241.8	69.5
2111	594.1	300	45	59	103	0.056	0.0333	2.0	3.4	6.7	0.4
327	565.2	600	18	621	985	0.056	0.0317	19.7	31.2	612.8	34.3

Table 2: An excerpt of risk calculation for the longest pipes in E3 Network (*UN*, *PR*, and R_D represent number of affected nodes with unsupplied demand, pressure deficiency, and risk based on λ_D, respectively)

From the results of risk calculation in the preceding section, one can rank the pipes according to their hydraulic importance *i.e.* pipes with highest risk to promote detrimental conditions if service is interrupted. Figure 6 shows the risk ranking of the pipes based on the three different failure rates assigned in the calculation of the risk. The figure shows only the top 20 pipes to show the clear trend of the points.

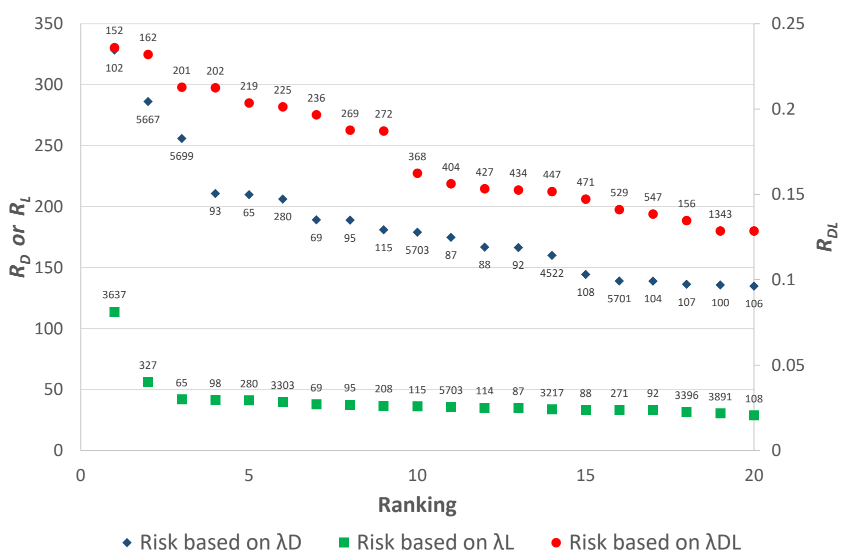


Figure 6: Priority rankings based on different failure rate definitions

As seen from the figure, the rankings show a more dynamic trend than that of the previous list when discussing the failure events with most affected node (Table 1). In this case, λ really is the determining factor of the individual pipe's hydraulic importance. Table 3 crosschecks the risk values against the failure events that the pipes belong. For risk calculation based on λ_D and λ_L, the predominant failure events (no. 8 and 13) are listed previously in Table 1. However, pipe segments *i.e.* no. 21 (*UN*: 47 *PR*: 103) and 36 (*UN*: 108 *PR*: 137) that are not considered important due to low number of affected nodes become predominant if λ_{DL} is used. This exercise highlights the many factors to consider in the decision-making. What is useful from this exercise is the fact that the importance of specific pipes depends on the criteria imposed. The analysis would be more conclusive if pipe installation year and material are also considered. Figure 7 shows the locations of the pipe segments within E3 Network that render important when analyzing the risk using λ_{DL}.

Rank	λ_D			λ_L			λ_{DL}		
	Pipe ID	R_D	Failure event	Pipe ID	R_L	Failure event	Pipe ID	R_{DL}	Failure event
1	102	328.4	8	3637	113.8	18	152	0.236	36
2	5667	286.1	8	327	56.2	18	162	0.232	21
3	5699	255.9	8	65	41.8	8	201	0.213	27
4	93	210.7	8	98	41.6	8	202	0.212	27
5	65	209.8	8	280	41.1	8	219	0.204	36
6	280	206.2	8	3303	39.8	8	225	0.201	8
7	69	189.2	8	69	37.7	8	236	0.197	21
8	95	188.9	8	95	37.7	8	269	0.188	8
9	115	181.0	8	208	36.8	8	272	0.187	8
10	5703	178.9	8	115	36.1	8	368	0.162	27
11	87	174.8	8	5703	35.7	8	404	0.156	35
12	88	166.8	8	114	35.2	8	427	0.153	18
13	92	166.4	8	87	34.9	8	434	0.153	18
14	4522	160.0	13	3217	33.5	18	447	0.152	37
15	108	144.4	8	88	33.3	8	471	0.147	37
16	5701	139.0	8	271	33.2	8	529	0.141	32
17	104	138.9	8	92	33.2	8	547	0.139	32
18	107	136.3	8	3396	31.5	8	156	0.135	36
19	100	135.7	8	3891	30.4	8	1343	0.129	48
20	106	134.8	8	108	28.8	8	1344	0.129	39

Table 3: Crosschecking ranking list with the failure event number

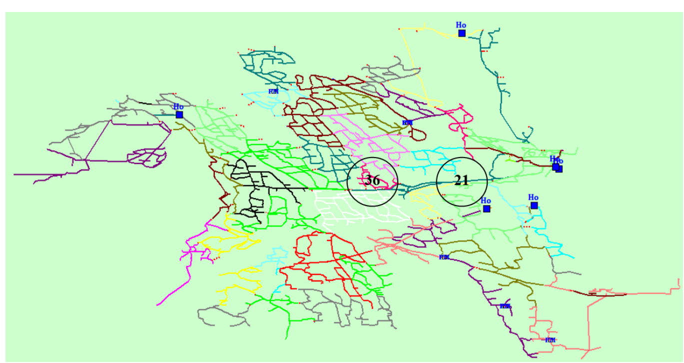
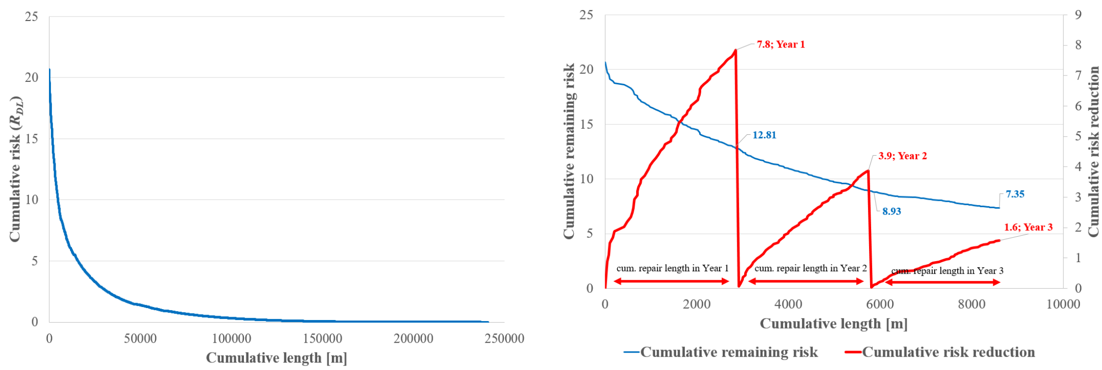


Figure 7: Priority rankings based on different failure rate definitions

3.3 Rehabilitation Planning for Risk Reduction

Figure 8a shows the cumulative risk (R_{DL}) based on the pipe ranking expressed in cumulative pipe length. The risk value used in this exercise is calculated using λ_{DL}. The cumulative value peaks at cumulative length equal to zero that principally represents total risk if no rehabilitation program is implemented. On contrary, the cumulative risk starts decreasing if rehabilitation program is executed, and this is limited either by the available budget or, in this example, by the rehabilitation length goal. In theory, the cumulative risk is equal to zero if all the pipes in E3 Network are rehabilitated.



(a) (b)

Figure 8: (a) Cumulative risk based on pipe rank as a function of pipe length in E3 Network and (b) Cumulative risk reduction evaluated based on the target rehabilitation length in the masterplan calculated for a 3-year rehabilitation program

Figure 8b shows analysis of cumulative risk reduction in a 3-year rehabilitation program evaluated based on the target rehabilitation length in the masterplan (1.2% of pipe length/year). The x-axis in the figure is a blow up of x-axis in Figure 8a marking a 3-year cumulative pipe length being rehabilitated. Indeed, such a rehabilitation planning is not as straight forward as suggested in this example. However, this section is meant to put emphasis on its potential application in the rehabilitation-planning phase with respect to the risk-based asset management principle discussed in this paper. The red line in the graph represents cumulative risk reduction up to the point where the yearly cumulative length is equal to 1.2% x the total length of pipe. As seen from the graph, at the end of Year 1, if the rehabilitation program based on the priority ranking is implemented, the cumulative risk reduces by almost 40% from 20.65 to 12.81 (corresponding to cumulative risk reduction of 7.8). In Year 2, the cumulative risk reduces further from 12.81 to 8.93 (cumulative risk reduction of ~3.9), so on and so forth.

The analysis should be extended owing to the type of rehabilitation to be executed. Pipe rehabilitation does not always mean a complete replacement of a pipe but can also be a simple pipe repair or renovation (*e.g.* coating or lining). If the simpler pipe repair is necessary, then it will spare the length of pipe to be rehabilitated. Thus, it is noteworthy in many respects if the x-axis in Figure 8 is represented by the cumulative budget since the cost of rehabilitation depends also on the type of pipe to be rehabilitated, cost of work, *etc.*

4 Conclusions

This paper shows potential application of mechanical reliability analysis in WDNetXL in a risk-based asset management, specifically in evaluation of hydraulic importance of pipe segment. The risk assessment on individual pipe level is made possible with the inclusion of statistical information about break rate of the pipe. From risk assessment of individual pipe, a priority ranking can then be developed. Such an approach should benefit the rehabilitation planning by highlighting criticality of the pipe and its impact to the service of the network. This approach can also be extended to evaluate the risk reduction reached once the rehabilitation plan is executed.

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