Article

Rehabilitation Planning of Water Distribution Network through a Reliability – Based Risk Assessment

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Abstract: The management of existing water distribution system (WDS) is challenged due to ageing of infrastructure, population growth, increasing of urbanization, climate change impacts and environmental pollution. Therefore, there is a need for integrated solutions that support decision makers to plan today the potential interventions, considering the possible consequences and variations in the mid and long term perspective. This research study is part of a more comprehensive project, where advanced hydraulic analysis of WDS is coupled with a dynamic resources input-output analysis model. The proposed modelling solution could be used for the optimization of the performance of a water supply system while also considering energy consumption and environmental impacts, therefore, providing a robust support tool for the management of water supply systems also in the stage of intervention planning. This work presents a possible application of the proposed method in pipe rehabilitation/replacement planning, based on which the network mechanical reliability is maximized while minimizing, at the same time, the risk of unsupplied water demand and pressure deficit evaluated at nodal level, under given economic constraints.

Keywords: Water distribution; Management; Mechanical Reliability; Risk Assessment

1. Introduction

According to an EPA report [1] "System rehabilitation is the application of infrastructure repair, renewal, and replacement technologies to return functionality to a drinking water distribution system or a wastewater collection system". The process of intervention planning and prioritization is a function of network's current condition assessment, the extent of critical repair needs, the availability of funding for rehabilitation work options, and the ability to inspect and assess the condition and deterioration rate of each element [2]. Asset management activity and life cycle analysis drive the broad activities that determine system-wide planning.

Among the potential alternatives for leakage reduction, asset replacement is quite expensive compared to active leakage control (ALC) and pressure management (PM). However, cases where the condition of the underground assets is so poor ALC and PM not provide a sustainable solution. A well-managed water loss programme should always include a budget for selective replacement of mains and/or service pipes specifically to reduce leakage and the cost of ALC, if PM is no longer a feasible option to mend the situation. [3].

Knowing when, where and how to rehabilitate pipes requires a good knowledge of the system performance, its conditions and the availability of decision support systems for rehabilitation planning.

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The present study describes a replacement planning approach based on mechanical reliability to minimize unsupplied water demand and pressure deficit.

1.1. Reliability theory applied to water distribution system

The definition of reliability is not unique but depends on the specific field in which it is applied and therefore it is more correct to use this term in a general sense to indicate the overall ability of a system to perform its function [4]. The mechanical and electrical complex systems are the main sectors where the theory of reliability found the initial application and only later was applied to hydraulic systems that exhibit some analogues aspects with those of the production, transport and distribution. Reliability is commonly defined in regard to engineering systems, among other definitions, as "the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered" [5]. This comprises the concept of probability, adequate performance, time and operating conditions [6].

InWDSs, several types of reliability can be defined, in theory one for each set expected function of an asset or of the entire network. However, the literature has mainly focused on the concepts of mechanical and hydraulic reliability. The mechanical reliability can be defined as the probability that a component (new or repaired) experiences no structural failures during the time interval from time zero to time t (0, t). The hydraulic reliability refers to the probability that a water distribution pipe can meet a required water flow level at a required pressure at each nodal demand [7].

Walsky [8] observed that the topic of reliability is integrated to all parts of decision related to WDS design, operation and maintenance, even though most evaluations of reliability tend to focus on the design of the system. If the WDS has a sufficient redundancy to deliver water and is able to perform the expected function even for aged infrastructure, it is therefore considered reliable. Moreover Kanakoudis et al. [9, 10], observed that reliability is the most commonly performance indicators used as maintenance priority criterion.

The reliability analysis could be used to identify repair works on existing system [11] considering various random factors such as user demand, mechanical failures, roughness indices, that could affect the performance or in the expansion of existing networks [12] where the reliability is to be maximized with the support of computer models.

Among the existing models to analyse the reliability of a water distribution system, WDNetXL [13-14] is a system tool that through the "*Management module*" enables reliability analysis of the network by three specific functions: Reliability One Failure, Reliability Multiple Failure and Hydraulic Reliability. The first two functions analyse hydraulic behaviour of a WDS by simulating single or multiple pipe or node failures/disconnections. Hydraulic Reliability performs the analysis of the network hydraulic behaviour while varying the boundary conditions such as pipe hydraulic resistances, pipe background leakages, nodal customer demands, nodal free-orifice demands, and their combinations.

Reliability One-Failure function, which was used in this study, investigates all failure scenarios generated by disconnection of single pipe or node from the network. Given that a pipe may represent a device, a pipe failure can be also associated as a device failure. The reliability indicators proposed are based on two parameters: unsupplied demand and pressure deficit. Both parameters are assessed from the failure events considered in Reliability One Failure function in a pressure driven, extended period simulation [15], and associated with Isolation Valve system (IVS) that disconnects the failed pipe or node from the rest of the network [16-17].

Therefore, the study of WDS behaviour resulting from the failure events can be considered a mechanical reliability analysis. The break rate λ that represents the number of break per kilometre per year, is a common parameter associated with the mechanical reliability analysis. It is dependent on many factors such as installation year, pipe corrosion, diameter, break type, pipe material, seasonal variation, soil environment, break history, pressure, land use and pipe length [18]. Consequently, to consider these factors individually in order to obtain a prevision of the expected break rate is a rather difficult task.

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Break rate is case specific and therefore, it is advisable to calculate it at a cohort level through an analysis of the historical break data related to the specific network. Otherwise, it is also possible to use formulae taken from the literature from a similar case study.

The break rate is assessed for different pipe cohorts defined by similar characteristics and grouped to have a representative statistical sample. Afterwards, the specific number of breaks per year is evaluated for each pipe by multiplying λ with the individual pipe's length.

2. Methodology

Figure 1 depicts the adopted methodology. The analysis starts with the creation of the hydraulic model for the specific case study in WDNetXL environment [13-14]. Mechanical reliability is done by running simulations in "Reliability One Failure" function that evaluate the hydraulic behaviour in term of nodal pressure and customer demand impacts after each failure event. The specific contribution of this study is to couple failure statistics with a risk based ranking of pipes for rehabilitation by using the reliability indicators calculated from WDNetXL simulation results. Each part of the workflow will be explained in the following subparagraphs.

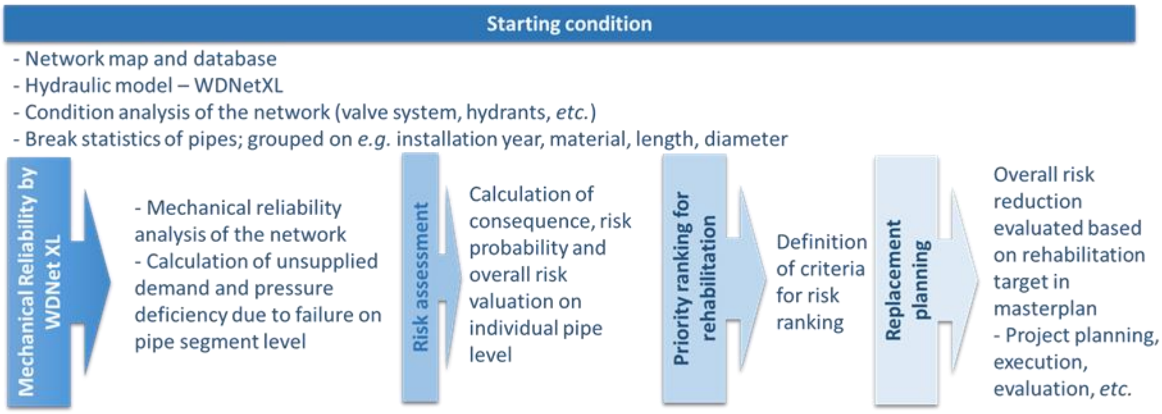

Figure 1. Workflow adopted in this study

2.1 The reliability indicators implemented in WDNetXL

The literature demonstrates that many indicators exist to evaluate the performance of a water distribution system developed by agencies like the International Water Association (IWA), the American Water Works Association (AWWA), Asian Development Bank, (ADB); National Research Council (NRC), National Water Commission (NWC), Office of the Water Services (OFWAT), World Bank (WB). Moreover, more researchers have also studied, improved and implemented these indicators [19-20-21-22-23].

As suggested by several authors (among others, Gupta and Bhave [24]; Gargano and Pianese [25]; Tanymboh et al. [26]) reliability is calculated by using performance indicators on the basis of the ratio between volumes actually delivered during the evaluation period and the volume required at a given node. It was also suggested a performance indicator relative to pressure, defined taking into account the ratio between the minimum pressure value and pressure required [27].

After the failure of each pipe or node of the network, the WDNetXL model assesses in extended period simulation (EPS) two indicators relative to customer demand (UN) and pressure (PR) evaluated at node level. They depend by actual value of demand and pressure after a failure event and are compared with those in a normal condition, i.e. condition in which no failure occurs. UN and PR are defined as [28]:

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

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

Where:

- i, e and t are subscripts indicating respectively the i-th node, the e-th failure event and the time t of the EPS during time interval T; $e=0$ stays for normal condition;
- d^{act} and p^{act} are the actual customer demand computed in PDA using the Wagner's model [29] and actual nodal pressure evaluated in PDA or DDA. d^{requ} is the required customer demand varying over time;
- p^{normal} is the nodal pressure in normal conditions computed varying over time;
- n_n and n_e are the number of nodes and events, respectively;

It is clear that in normal condition d^{act} and p^{act} are equal or close to d^{requ} and p^{normal}. Thus, the corresponding fractions $\frac{d^{act}}{d^{requ}}$ *and* $\frac{p^{act}}{p^{normal}}$ are close to unity giving the indicators UN and PR are equal to or close to zero. This means that there is small or no deficiency between the supplied and required values and the condition of the i-th node are 'good'. If a failure is imposed, the values of d^{act} and p^{act} are no longer equal or close to d^{requ} and p^{normal}. Thus, $\frac{d^{act}}{d^{requ}}$ *and* $\frac{p^{act}}{p^{normal}}$ give a value that are less than unity. This means there is a deficiency between the supplied and required values. Therefore, UN and PR values would be larger than zero. The larger values of UN and PR represent the worse condition of unsupplied demand and pressure deficit. Note that for isolated nodes e.g. due to valve shutdowns d^{act} and p^{act} are null and the corresponding fraction UN and PR are unitary.

Based on UN and PR evaluated by WDNetXL Management module, the results are then elaborated in a risk analysis for the nodes in the network affected by each failure event. This enables classification of pipes based on the risks they impose to the performance of WDS should a failure occurs to them. The extended period simulation is done on hourly basis for 24-hour simulation period. Considering each node for the specific failure event, the maximum value that represents the worse condition for that node in the day is registered.

A value of UN and PR >= 0.5 is chosen to define a critical situation in which the demand and pressure are less than the 50% of the normal condition. This value is arbitrary and can be chosen specifically by the decision makers.

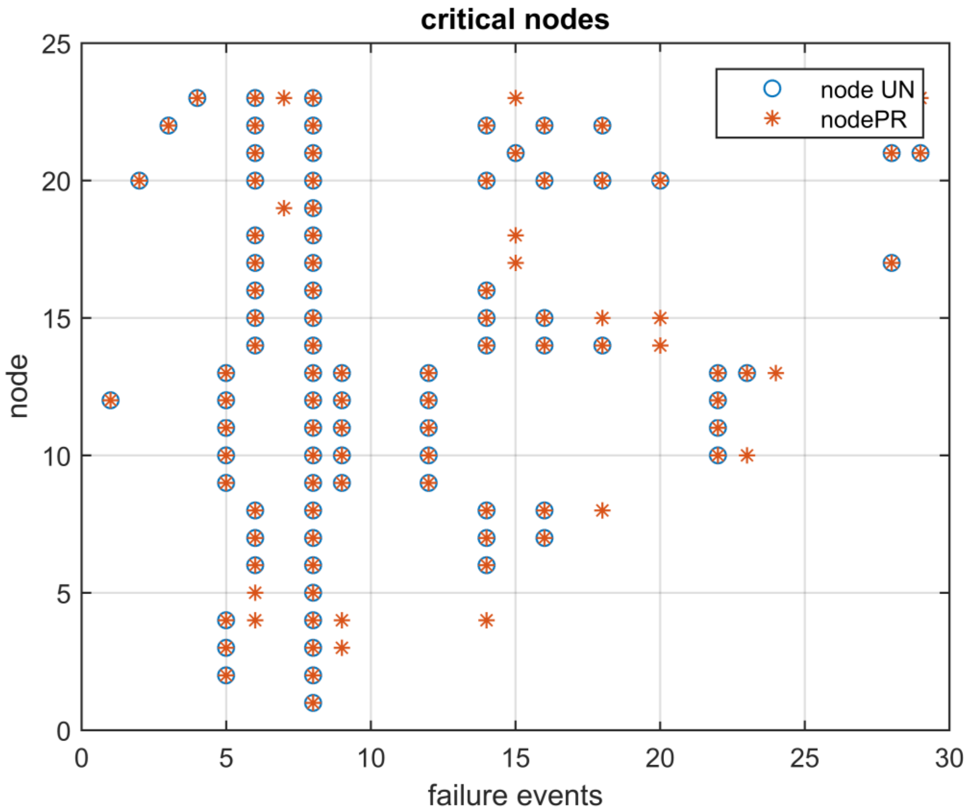

Figure 2. Example of a scatter plot of critical nodes that are affected by each failure event, identifiable by node ID

Figure 2 depicts a visualization of critical nodes after each failure event. At this stage, the methodology ranks failure events in term of the number of affected nodes from two indicators, UN and PR.

The use of IVS helps to isolate parts of the network creating segments, i.e. the smaller portions of a distribution system.

By performing network segmentation, one can assume that a failure event related to a specific pipe segment deals with all pipes belonging to the same pipe segment and, therefore, the same hydraulic importance is assigned to these pipes belonging to that specific pipe segment.

2.2 Risk assessment approach

Risk methodologies are intended to evaluate risks associated with the existing system and possible intervention options, and to contribute to the understanding of how decisions can contribute to meeting performance targets. Multi-criteria decision analysis (MCDA) methods need to be used for aggregation and ranking tasks. Decision criteria can be used in parallel metrics of risk as well as of performance and cost. Risk values, crossing probability scenario and their consequences, will be passed to the MCDA to provide a possible ranking for competing alternatives.

There are many definitions of risk and risk management. The definition sets out in ISO 31000 and in ISO Guide 73, is that risk is the “effect of uncertainty on objectives”. In order to assist with the application of this definition, Guide 73 also states that an effect may be positive, negative or a deviation from the expected, and that risk is often described by an event, a change in circumstances or a consequence and by the associated likelihood of occurrence. It is important to underline that the term likelihood refers to the chance of something happening, whether defined, measured or determined objectively or subjectively, and described using general terms or mathematically (such as a probability or a frequency over a given time period). For example, Kanakoudis [30] had associated the probability of a failure occurrence with the magnitude of the failure impacts in the

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Significance Index introducing 'a methodology for the hierarchical planning in place and time of the preventive maintenance policy in water supply network'.

In this study, the risk assessment is performed by combining the probability for each pipe to break with the consequence induced at nodes in terms of unsupplied demand (UN indicator) and pressure deficit (PR indicator).

Therefore, the risk associated to each pipe p-th after a failure event is defined as:

$$risk_p = \lambda * C_{tot_p} = frequency * consequence \tag{3}$$

Where:

- λ represents the frequency of break in a year;
- $C_{tot_p} is\ the\ overall\ consequence_p = C_p^{UN\ dem} * C_p^{PR};$ (4)
- $C_p^{UN\ dem}$ is the consequence in term of $UN_{dem} = break\ rate_{norm\ p} * n_{critical\ nodes\ UN};$ (5)
- C_p^{PR} is the consequence in term of PR $= break\ rate_{norm\ p} * n_{critical\ nodes\ PR};$ (6)
- p subscript indicating the p-th pipe;

The combined probability and consequence for each pipe for all failure events is depicted in a risk matrix as in Figure 3. Figure 4 is another example in which the pipes are ranked according to risk value sorted in descending order. The visualizations help support decision makers to decide the risk reduction measure to adopt should be more preventive (reduce the probability for the event to happen) or protective (mitigate consequences).

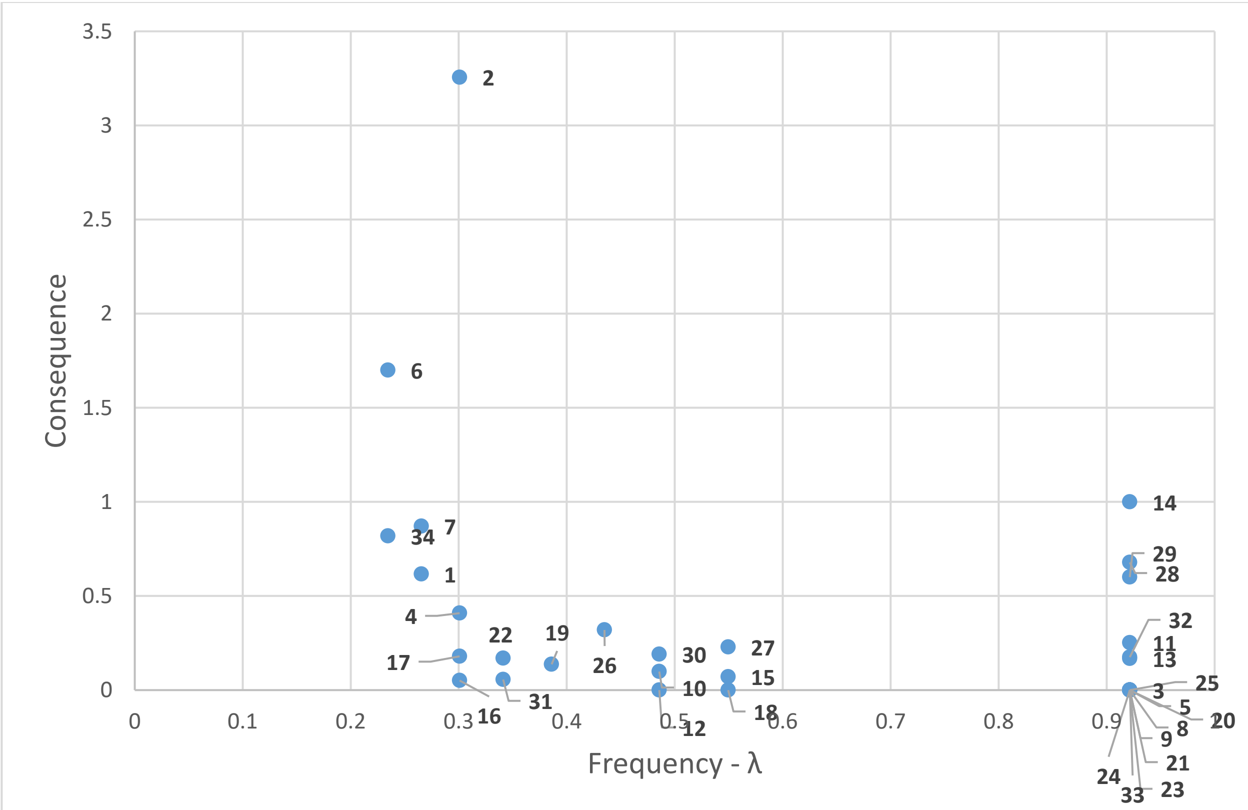

Figure 3. Frequency of break and relative consequence

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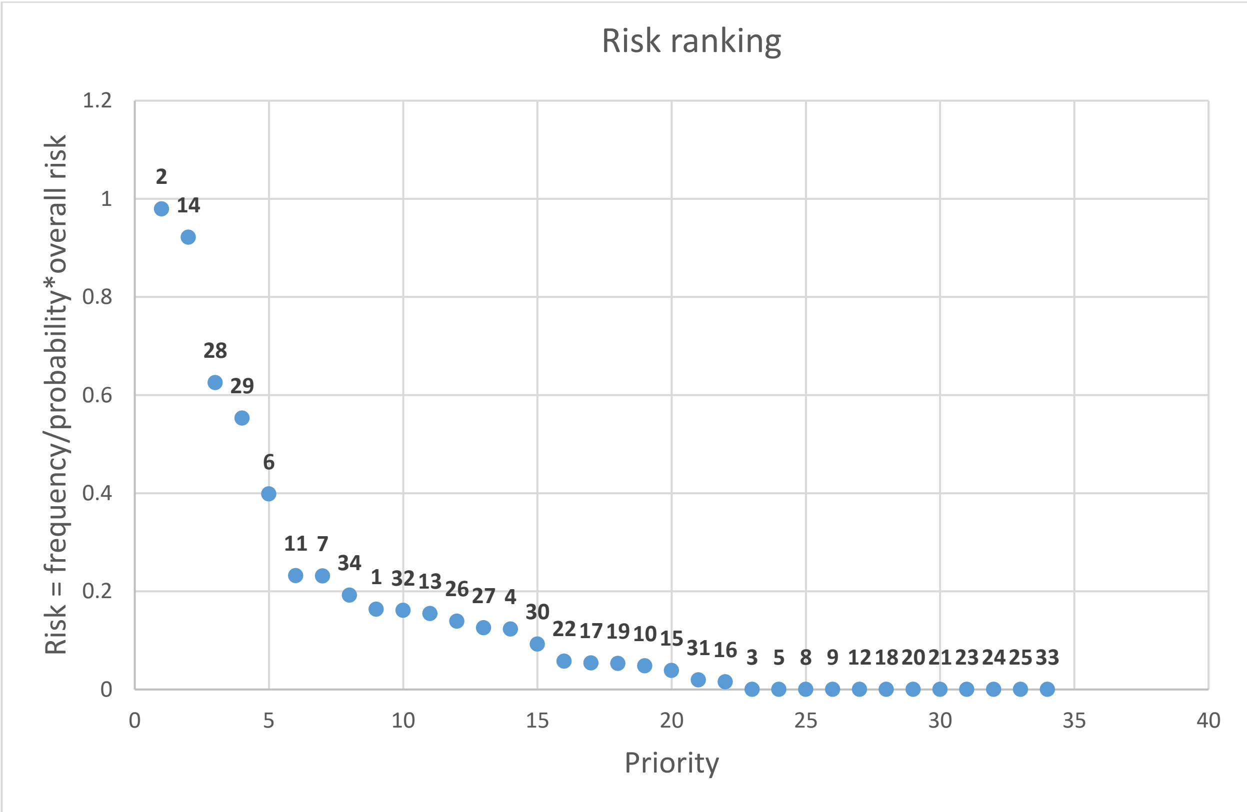

Figure 4. Risk values sorted in descending order

2.3 Replacement Planning

The prioritization and selection of the intervention options require the adoption of a MCDA methodology. The objective is to minimize the residual risk, after rehabilitation of a given pipe to ensure maximum reliability for example for a given annual investment.

The methodology therefore ranks pipes with the objective of minimum residual risk, maximum reliability for optimal fit of the available budget.

The cumulative direct cost is defined as:

$$cum\ cost_p \ = \ cost_p \ + \sum_{k=1}^{p-1} cum\ cost_k \qquad (7)$$

Where:

- p depicts the p-th pipe;
- $cost_p$ is the direct cost of the p-th pipe;
- $\sum_{k=1}^{p-1} cum\ cost_k$ is the cumulative sum of the direct costs of pipes until pipe p-1.

The **cumulative risk reduction,**$cum\ risk\ reduction_p$, is evaluated considering the risk sorted in descending order:

$$cum\ risk\ reduction_p \ = \ risk_p \ + \sum_{k=1}^{p-1} cum\ risk\ _k \qquad (7)$$

Where:

- $risk_p$is the risk associated to the p-th pipe;
- $\sum_{k=1}^{p-1} cum\ risk\ reduction_k$ is the cumulative sum of the risks of pipes until pipe p-1

The **residual risk** is evaluated as:

$$residual\ risk_p = \max(risk\ reduction) - cum\ risk\ reduction_p \qquad (8)$$

Given a fixed annual investment budget for each intervention of rehabilitation (an annual investment budget for each intervention of rehabilitation is fixed and) , the remaining budget is

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assessed and used to fit further interventions minimizing the actual residual risk and provide maximum service.

Figure 5 shows an example of the analysis of cumulative risk reduction evaluated based on a specific budget. The cumulative residual risk curve (pointed in blue) is based on the pipe ranking expressed in cumulative pipe cost. The red line curve represents the cumulative risk reduced up to the point where the direct cost of pipes to replace is covered by the investment budget (the vertical line in grey).

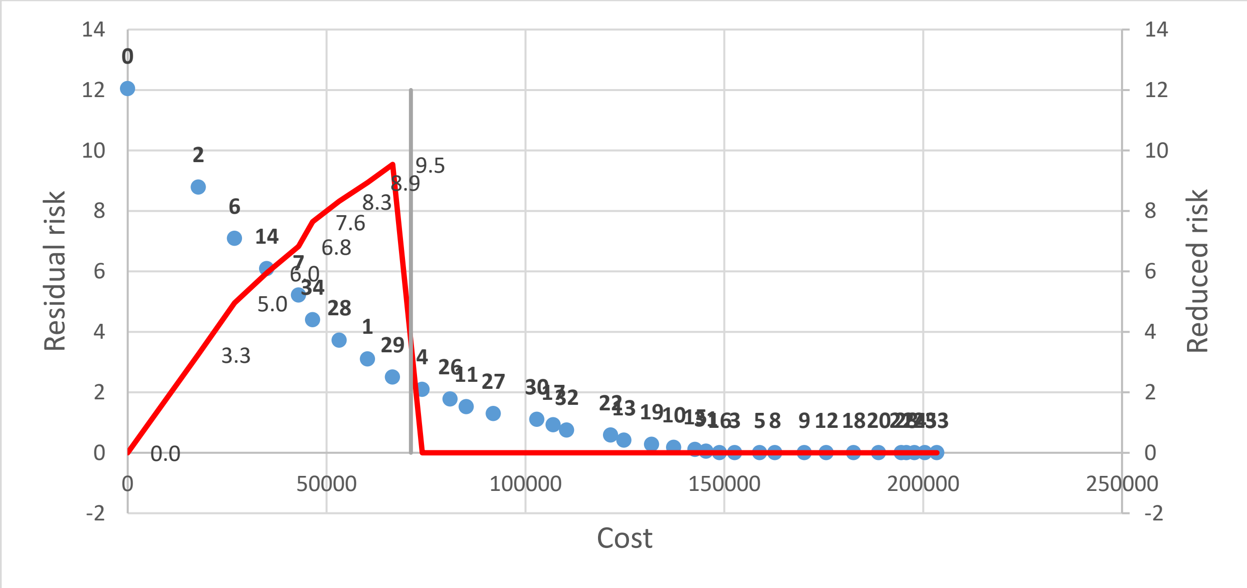

Figure 5. Example of cumulative risk reduction evaluated based on the target of a specific budget

The cumulative residual risk value peaks at cumulative cost equal to zero, representing the total risk if no replacement program is implemented. The cumulative risk starts decreasing if replacement program is executed and this is limited by the available budget or for example by a target length of pipe rehabilitation/replacement. In theory, the cumulative risk is equal to zero if all pipe in the network are replaced.

3. Case study – Laives

The methodology described above has been applied to the Laives network, a town in the province of Bolzano, Italy. It serves about 18000 customers and spreads from the districts of San Giacomo in the south of Bolzano until the industrial area of Laives. The three interconnected districts subdivide the network are San Giacomo, Pineta and Laives. Each of these districts has a tank supplied by wells or springs.

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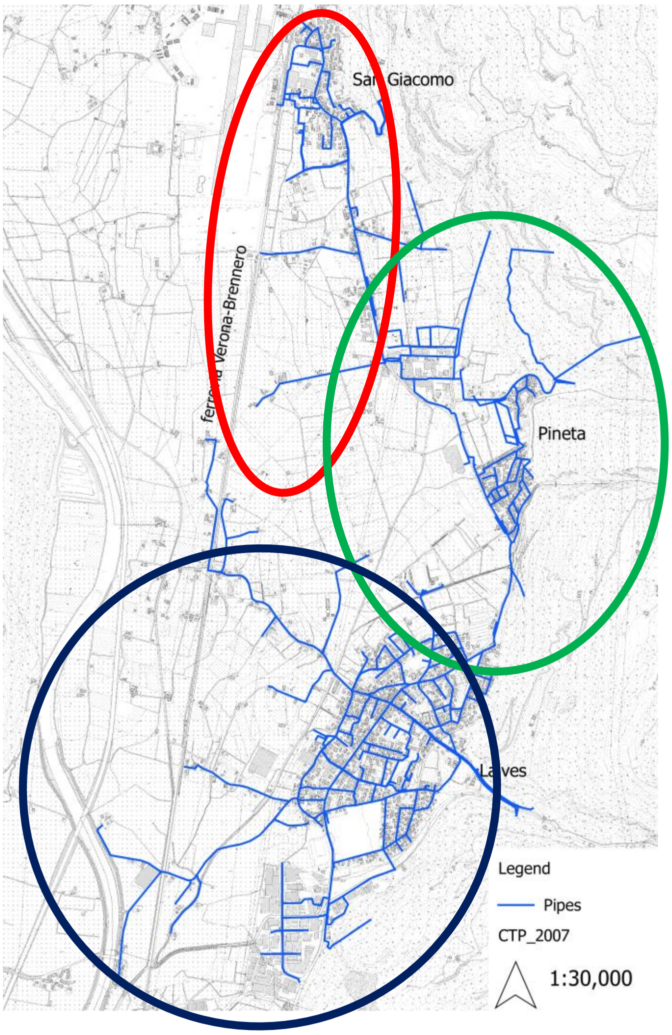

Figure 6. Laives network and relative districts

Pipes materials that characterize the network are ductile iron that cover more less the 58% of pipes, mild steel 37% and a low percentage of PE (4%) and PVC (1%).

The Laives network is modelled using WDNetXL system tool and is characterized by 375 nodes and 439 pipes of which 18 are really valves and pumps. Some of the pumps present in the network work with different regimes during the hours of the day to save energy. To simulate this, parallel pumps are added working in a different range of hours and with distinct levels in the tanks.

In this paper, the mechanical reliability analysis considered in WDNetXL *Management module* is the 'Pipe Failure' type that evaluates the impacts of closure of a particular isolation valve system/pipe segment to unsupplied demand and pressure deficiency. The mechanical reliability simulation, considering an ‘N-rule’ valve system, that assume two valves for each pipe trunk, returns 379 failure events; each corresponds to a specific segment in the Laives Network.

4. Results and discussion

The scatter plot of nodes that are affected by each failure event is reported in the Figure 7. Some of the nodes exhibit unsupplied demand (UN), pressure deficiency (PR) or both conditions simultaneously.

The results of the first simulation show that the majority of the worst condition registered at nodes are of pressure deficit (PR) type, rather than of unsupplied demand (UN) type. This is because the PR indicator take a reference value of the nodal pressure in the normal condition, (p^{normal}) that for the Laives network is characterized by a generalized high level of pressure distribution, much higher than the 30-40 m of water column usually required.

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Therefore, a new simulation was performed by lowering the reference value down to the minimum pressure level for users defined by regulation of the province of Bolzano, which is of 40 meters water column (see figure 7). In the following, the PR indicator is presented with subscript "ser" to indicate the reference value is the service pressure (PRser).

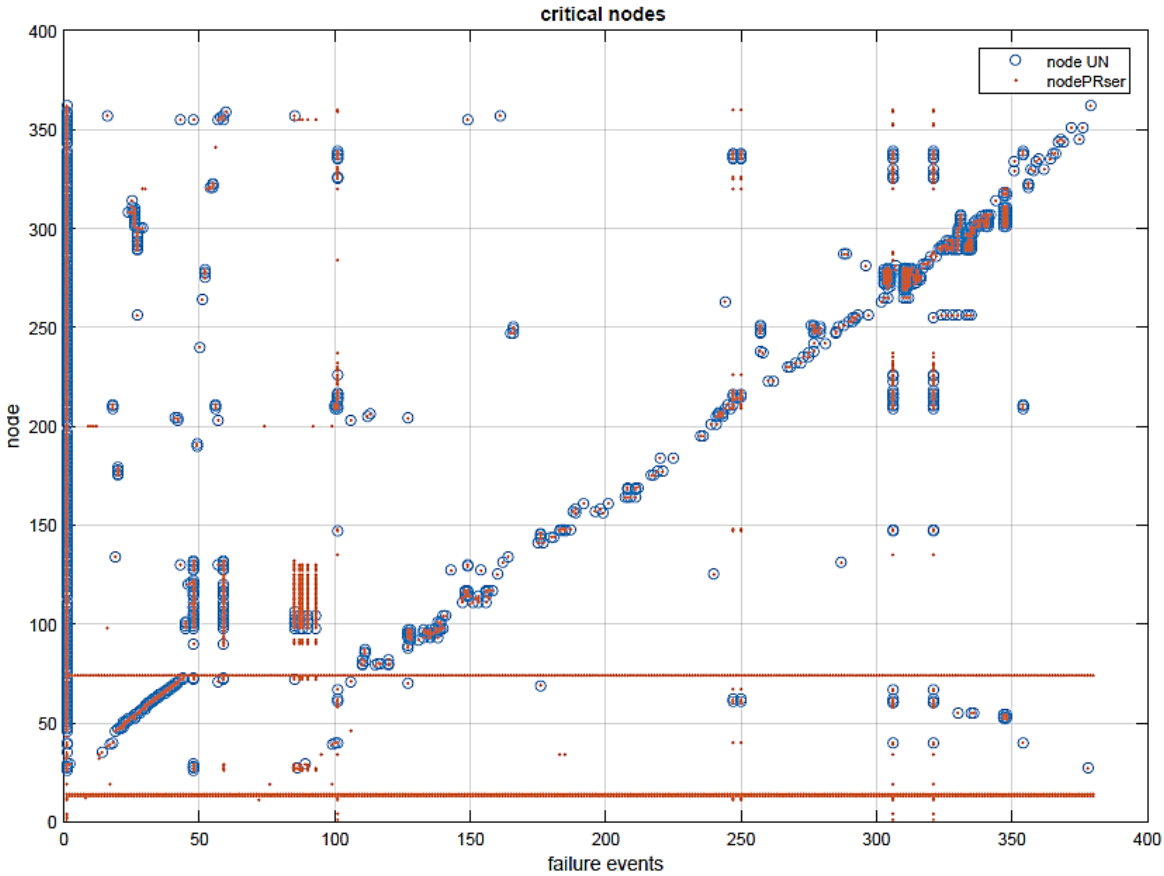

Figure 7. Scatter of node ID's that are affected by each failure event – Laives

Table 1 reports the top 10 events ranked based on the number of affected node from the simulation and the location of the five common failure events in the network is shown in Figure 8. It is interesting to observe the different ranks of failure events that lead to highest number of nodes affected by UN and PR. In addition, for example the last five failure events causing UN are absent on the list of failure events causing PR.

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

	Unsupplied demand		*Pressure deficit (reference value PRser)*	
rank	**Failure event**	**Number of affected nodes**	**Failure event**	**Number of affected nodes**
1	**48**	34	**306**	54
2	**59**	29	**321**	54
3	**321**	29	**59**	45
4	**306**	28	**101**	42
5	**101**	20	**85**	40
6	**347**	16	**87**	37
7	**348**	16	**90**	37
8	**335**	14	**88**	35
9	**26**	13	**93**	35
10	**310**	13	**48**	34

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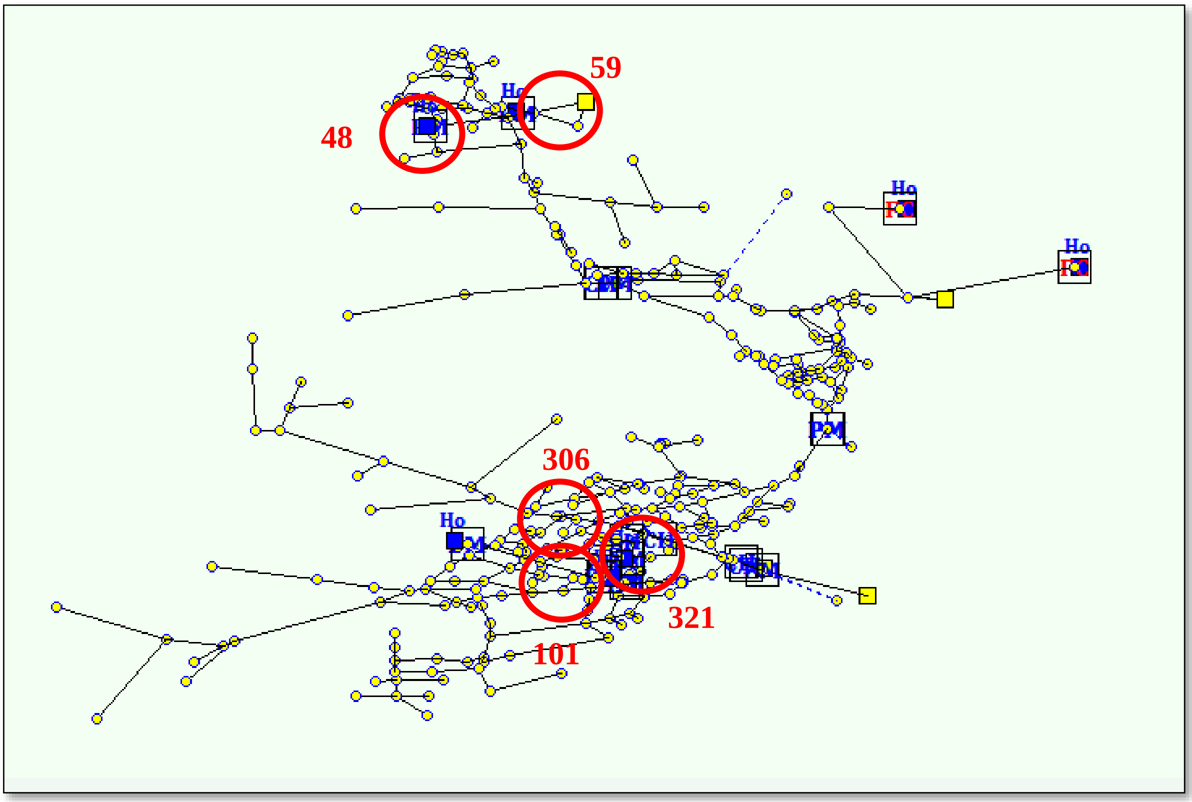

Figure 8. Location of the five common failure events

Table 2 shows an extract of risk calculation for some pipes of the network. One can observe that the number of affected nodes with unsupplied demand are lower than that with pressure deficiency. Consequently, the consequence in term of unsupplied demand, $C_p^{UN\ dem}$, and consequence in term of pressure deficit, C_p^{PRser} are affect by these differences.

Table 2. An extract of risk calculation

failure event	Pipe ID	Length	UN	PRser	λ	break	break norm	C_p^{UNdem}	C_p^{PRser}	$C_{\_tot}$	risk
87	**32**	41.62	4	37	0.601	0.025	0.028	0.112	1.035	0.116	0.070
88	**33**	53.37	2	35	0.601	0.032	0.036	0.072	1.255	0.090	0.054
90	**34**	19.36	4	37	0.601	0.012	0.013	0.052	0.482	0.025	0.015
93	**35**	28.63	2	35	0.601	0.017	0.019	0.038	0.674	0.026	0.016

Figure 9 shows the ranking of portion of pipes (the first twenty pipes exhibiting highest risk) in term of risk; the corresponding risk values are reported in Table 3 with the relative values of λ and C_{tot}. The list of failure events in Table 1, compared with the list of the first twenty pipes ranked following the risk evaluation in Table 3, shows that only three of the predominant failure events in Table 1 appear in the ranking list. This is due to the effect of λ acting as ranking weight.

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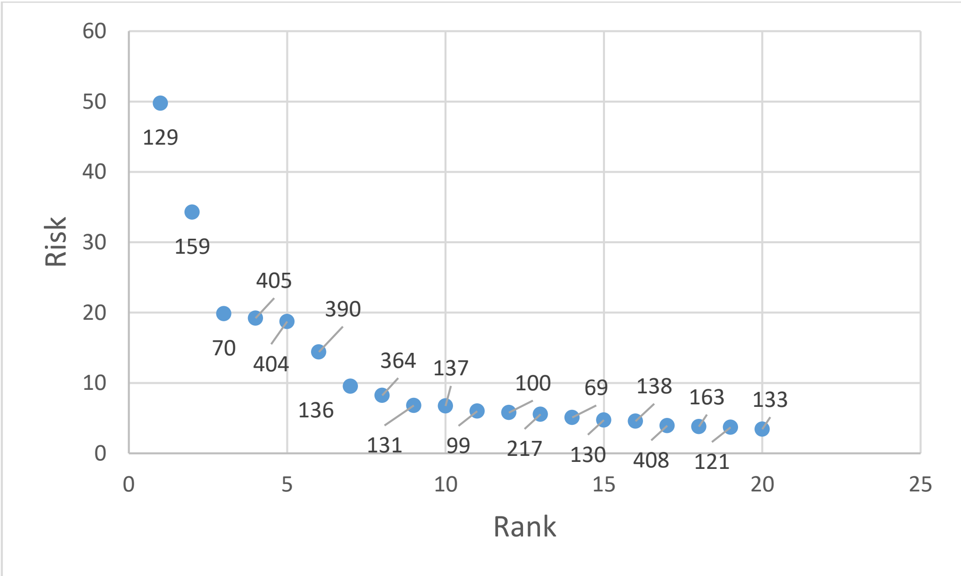

Figure 9. Priority ranking of the first 20 pipes

Table 3. Ranking list of the first 20 pipes with the failure event number

rank	*failure event*	*pipe ID*	λ	C_{tot}	*risk*
1	312	**129**	1.164698	42.71896815	49.75472
2	328	**159**	1.164698	29.4251172	34.27139
3	27	**70**	0.921421	21.52369527	19.83238
4	59	**405**	0.601952	31.91113549	19.20899
5	59	**404**	0.601952	31.12305147	18.7346
6	48	**390**	0.728958	19.76419825	14.40727
7	52	**136**	1.164698	8.184900227	9.532941
8	135	**364**	1.164698	7.065763846	8.229484
9	305	**131**	0.728958	9.332392247	6.802922
10	52	**137**	1.496754	4.497545577	6.731719
11	42	**99**	1.164698	5.14500632	5.992381
12	42	**100**	1.164698	4.966474288	5.784445
13	247	**217**	0.921421	6.021586638	5.548415
14	27	**69**	0.921421	5.53121004	5.096572
15	304	**130**	1.164698	4.058647449	4.7271
16	313	**138**	0.921421	4.96502344	4.574876
17	48	**408**	0.728958	5.395299548	3.932946
18	27	**163**	1.164698	3.258599588	3.795286
19	321	**121**	0.728958	5.067614029	3.694078
20	315	**133**	1.164698	2.94751094	3.432961

Figure 10 shows the cumulative risk calculated for all pipes in the network. By replacing particular pipes in Table 3 will lead to reduction of risk proportional to the risk imposed by the pipes. The cumulative value peak at zero represents the total risk if no replacement program is implemented.

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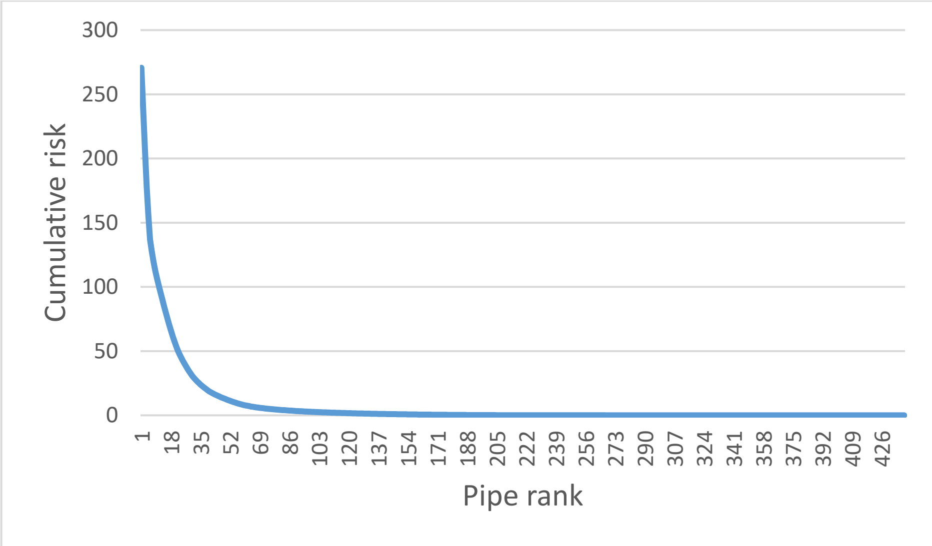

Figure 10. Cumulative risk based on pipe rank

The ranking of pipes could be driven by other constraint than cost, as for instance the requirement set by regional authorities on rehabilitation targets to be met. In the case of Laives, the target replacement rate is 2.5% of pipe network/year [31], which corresponds to substitute about 10 pipes a year.

Considering this alternative constraint, an additional analysis was performed and the results are presented in Figure 11. The x- axis is a blow up of x- axis in Figure 10. This section is meant to put emphasis on its potential application in the replacement-planning phase with respect to the risk asset management principle discussed in previous section. The red line represents cumulative risk reduction up to the point where the number of pipes to replace is equal to 10. Following the replacement program, as seen from the graph, the cumulative risk reduces by almost 66% from 313.41 to 106.34 (corresponding to cumulative risk reduction of 207.07).

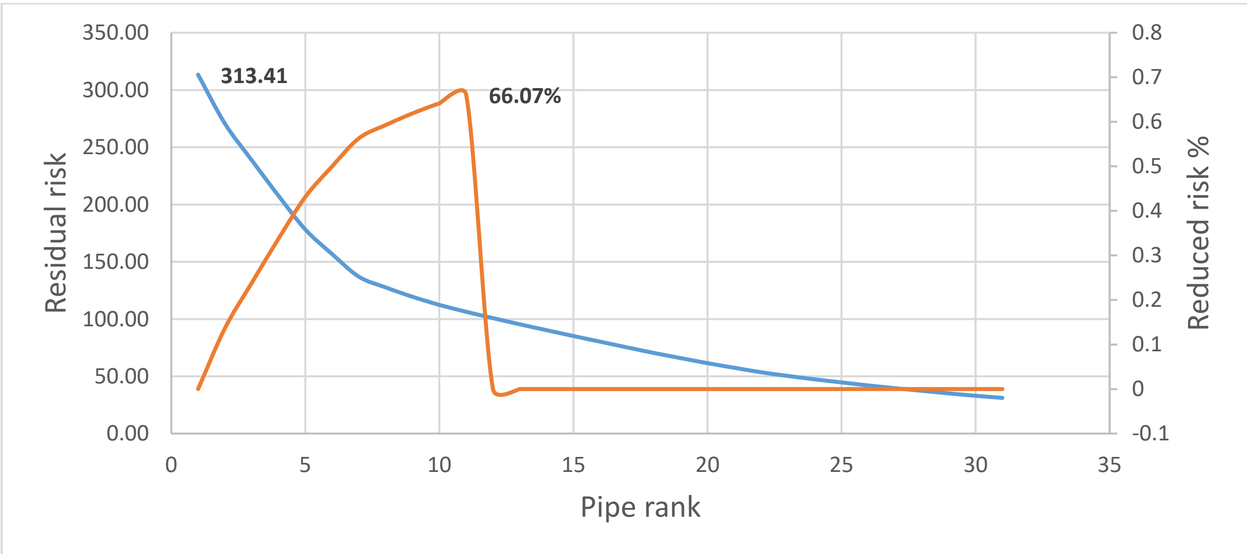

Figure 11. Cumulative risk reduction evaluated based on the target replacement percentage pipe in the masterplan calculated for the first year

5. Conclusions

Many factors like aging of infrastructure, population growth, increasing of urbanization but also more recent factors such as climate change and environmental pollution require a change in the management of the WDS. This paper, born by a more comprehensive project of optimization of the performance of a water supply system, presents an application in the rehabilitation/replacement planning starting from a mechanical reliability analysis in WDNetXL. The association of statistical information of pipe break rate (λ) allows the risk assessment at individual pipe level that could be used to develop a pipe replacement priority ranking. An application of the method to the network of Laives, a town in province of Bolzano is presented highlighting the effect of λ that acts as the ranking weight. This approach can also be extended to evaluate the risk reduction reached once the replacement plan is executed.

Limiting factor in this study has been the data availability for break rate calculation. To develop good pipe replacement plan, the real break rate with a minimum of 10 year pipe break history should be considered. Anyway, the results obtained demonstrate that the presented methodology could be a useful tool to support the decision in the rehabilitation/replacement planning.

The 'map' of the pipes that need replacement evaluated with the specific break rate to plan the intervention of the year, has to be updated in the following year with a break rate that takes into account the data of the passing year. At the same time, it will be interesting to observe the results obtained with a break rate that considers factors like age and materials of pipe and not only the pipe diameter. Actually, the ongoing research considers the age factor and its influence to a long-term planning by observing the ranking list over time.

For each replacement, the main constraint considered was the direct cost, but it is possible to evaluate the energy consumption and the CO_2 emissions connected with this kind of operation using the integrated modelling approach, as will be also addressed by this study, i.e. by incorporating MCDA.

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