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Article

Rehabilitation planning of water distribution network through a reliability – based risk assessment

Marianna D'Ercole [1],*, Maurizio Righetti [1], Gema Raspati [2], Paolo Bertola[3] and Rita Maria Ugarelli[4]

[1] Faculty of Science and Technologies, Free University of Bozen, 39100, Italy;
[*] Marianna.Dercole@natec.unibz.it; Tel.: +39 3200421938
[2] *SINTEF Byggforsk SINTEF Building and Infrastructure, Trondheim, Norway;*
[3] *University of Trento, 38123, Italy;*

[4] *Dep. of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, Norway.*

Abstract: The management of existing water distribution system (WDS) is challenged by 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, while taking into account the effect of these factors in the mid and long term. The paper is part of a more comprehensive project, where advanced hydraulic analysis for WDS is coupled with a dynamic resources input-output analysis model. The proposed modeling solution can be used to optimize the performance of a water supply system while considering also the energy consumption and consequently the environmental impacts. Therefore, as a support tool in the management of a water supply system also in the intervention planning. Here a possible application is presented for rehabilitation/replacement planning while maximizing the network mechanical reliability and minimizing risk of unsupplied demand and pressure deficit, 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". Its planning and prioritization are driven by the current condition of the system, the extent of critical repair needs, the availability of funding for rehabilitation work, and the ability to inspect and assess the condition and deterioration rate of each element of the system [2]. Asset management activity and life cycle analysis drive the broad activities that determine system-wide planning.

Asset replacement is an expensive option for reducing leakage compared to active leakage control (ALC) and pressure management (PM). However, in some systems, the condition of the underground assets is so poor that ALC and PM are not sustainable solutions. A well-managed water loss programme should always include a budget for selectively replacing mains and/or service pipes specifically to reduce leakage and the cost of ALC, when further pressure management to remedy the situation is not a feasible option. [3].

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

This paper presents a replacement planning approach based on the minimization of unsupplied demand and pressure deficit from pipes more prone to break.

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1.1. Reliability theory applied to water distribution system

The theory of reliability was developed at first to study mechanical and electrical complex systems and only later was applied to the hydraulic system that for some aspects presents similarity with those for the production, transport and distribution of energy. One of the common definition of reliability is: "reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered" that comprises the concepts of probability, adequate performance, time and operating conditions [4].

In water distribution systems, several types of reliability can be defined, in theory one for each set expected function of an asset or of the entire network. However, literature has mainly focused on the concepts of mechanical and hydraulic reliability. The mechanical reliability can be defined as the probability that the component experiences no structural failures during the time interval (0, *t*) from time zero to time *t*, given that it is a new one or repaired at time zero. While 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 demand node [5].

Walsky [6] observed that the topic of reliability is integrated to all part of decision regarding water distribution system design, operation and maintenance, even if most evaluations of reliability tend to focus on the design of the system. When the water distribution system has a sufficient redundancy to deliver water, even if the infrastructure has aged, it means that is able to provide the expected function and therefore it is reliable.

The reliability analysis could be used also to identify repair works to be carried out on existing system as in Gargano et al. [7] considering most of the various random factors such as user demand, mechanical failures, roughness indices, etc. that could affect the performance and in the expansion of existing networks where the reliability is to be maximized [8] with the support of computer models.

Between the existing models to analyze the reliability of a water distribution system, WDNetXL is a system tool that through the *"Management module"* consent to analyze the reliability of the network by three specific functions: Reliability One Failure, Reliability Multiple Failure and Hydraulic Reliability. The first two functions analyze the WDN by simulating the network hydraulic behavior assuming single or multiple failure /disconnection of each single pipe or node. Hydraulic reliability performs the analysis of the network hydraulic behavior varying the boundary conditions such as pipe hydraulic resistances and/or pipe background leakages and/or nodal customer demands and/or nodal free-orifice demands.

The WDNetXL Management module through the Reliability one-failure function, which was used in the methodology presented below, investigates all failure scenarios generated by the disconnection of each single pipe or node into the network: given that the pipe may represent a device, the failure of the pipe can be the failure of a device. The reliability indicators proposed are the fraction of unsupplied demand and of pressure deficit. They are calculated making an estimation in pressure driven simulation and in extended period [9], associating an Isolation Valve system to disconnect the pipe or node failed from the rest of the network [10-11].

Therefore, as shown, it is done a mechanical reliability analysis studying the behavior of the WDS after the break or disconnection of each single pipe or node into the network that often is associated to the study of break rate λ, the number of break per kilometre per year. It depends by many factors such as: installation period, corrosion, diameter, break type, pipe material, seasonal variation, soil environment, previous break, pressure, land use and pipe length [12]. Consequently, trying to consider each of these factors to obtain a prevision of the expected break rate becomes quite difficult, also considering that the urban surrounding have changed continually from the first laid of water pipes.

Break rate is case specific, therefore it is recommended to calculate it, at cohort level, through an analysis of the historical break data related to the specific network, to have more representative results, if data are available. Otherwise, it is possible the use of formulae taken from the literature trying to find a case study similar as much as possible.

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

3. Methodology

The adopted methodology is explained below through the workflow depicted in figure 1. The analysis starts with the creation of the hydraulic model for the specific case study in the WDNetXL environment [13-14]. Mechanical reliability is assessed by running the "Reliability one failure" function that evaluate the hydraulic behavior in term of unsupplied demand and pressure deficit after the break simulation of each pipe or node. By using the reliability indicators calculated with the WDNetXL, the specific contribution of this study consists in coupling a risk based ranking of pipes for rehabilitation with failure statistics. Each part of the workflow will be explained in the following subparagraphs.

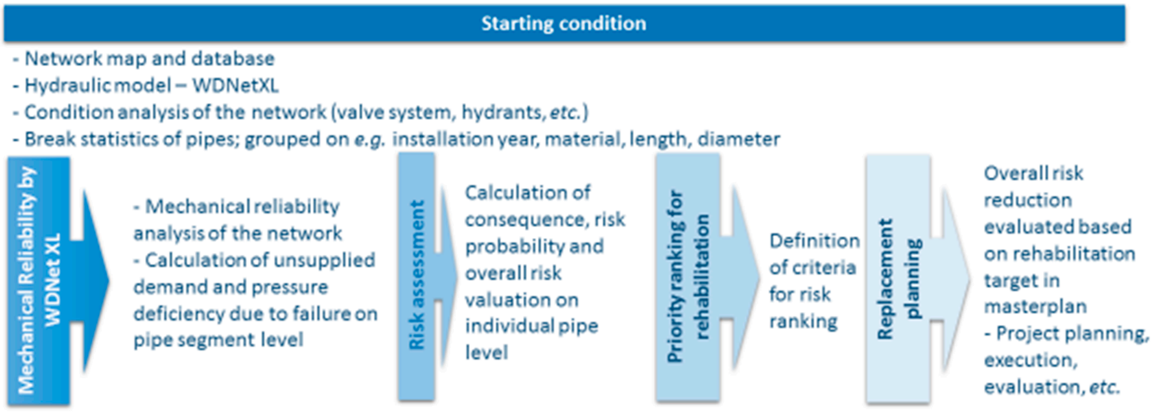

Figure 1. Workflow adopted

3.1 The reliability indicators implemented in WDNetXL

The indicators evaluated in extended period simulation (EPS) after the failure of each pipe or node of the network are UN and PR calculated in term of unsupplied demand and pressure deficit at node level. They depend by actual value of demand and pressure, calculated with respect to demand required and pressure evaluated in normal condition.

UN an PR are defined as:

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

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

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 and actual nodal pressure evaluated in PDA or DDA. Note that for node of separated portion of the hydraulic system due to valve shutdowns d^{act} and p^{act} are null and the corresponding fraction UN and PR are unitary;
- d^{requ} is the required customer demand varying over time;
- p^{normal} is the nodal pressure in normal conditions computed varying over time;

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- n_n *and* n_e are the number of nodes and events, respectively;

Studying the value that these indicators can assume, it is possible note that the parameter that can change is the actual customer demand for the fraction of unsupplied customer demand, d^{act} ,and the respective actual nodal pressure for the fraction of nodal pressure reduction, p^{act}.

When d^{act} and p^{act} are equal to or tend towards d^{requ} and p^{normal}, the corresponding fractions $\frac{d^{act}}{d^{requ}}$ *and* $\frac{p^{act}}{p^{normal}}$ assumes a value equal to or that tends towards the unit. The indicators UN and PR are equal to or tend towards zero that means that there is not variation and the condition of the *i*-th node are 'good'. If d^{act} and p^{act} are equal to or tend towards zero, $\frac{d^{act}}{d^{requ}}$ *and* $\frac{p^{act}}{p^{normal}}$ assumes a value equal to or that tends towards zero that means that UN and PR tend towards the unit, therefore a big reduction referring to the d^{requ} and p^{normal}. The *i*-th node results in worse condition.

Starting from these indicators evaluated by WDNetXL Management module, the results were elaborated to make a risk analysis of the nodes affected by each failure events and which specific node is in worse condition. Therefore, the number of node in worse situation after each specific failure event was evaluated.

The indicators are evaluated for each hours of the time period that is 24 hours. 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, defines a critical situation at which the demand and pressure are minor than the 50% of (referring on) the standard value. (It is possible change this limit depending by the preference of the decision makers).

Consequently, next step consists in the identification of the critical nodes after each failure event occurs and eventually visualize them as depicted in figure 2 with a general example.

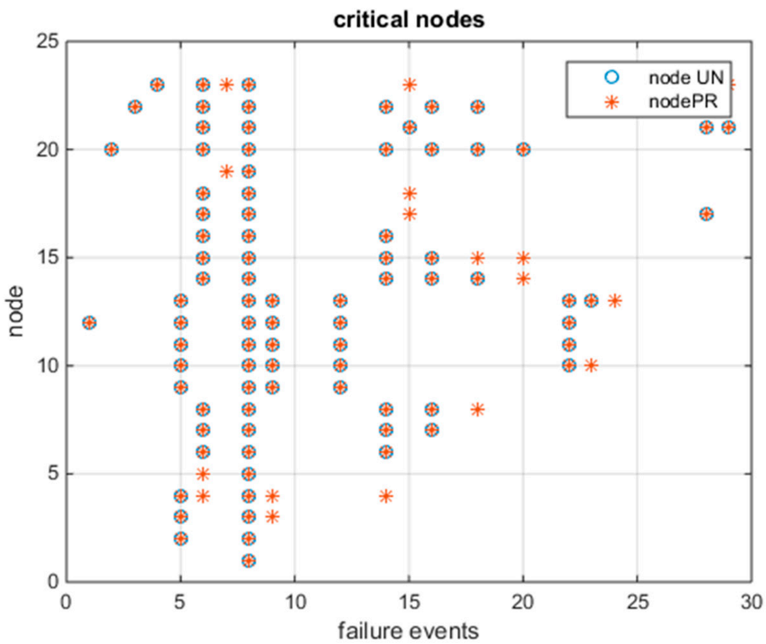

Figure 2. Example of a scatter plot of critical nodes that are affected by each failure events, identifiable by ID

At this stage, the methodology ranks failure events in term of number of nodes affected obtaining two vectors, one in terms of unsupplied demand the other in terms of pressure deficit.

The use of IVS helps the disconnection of part of the network creating segments, the smallest portions of a distribution system.

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

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3.2 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. Multicriteria 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 asof performance and cost. Risk values, crossing the scenario probability with its consequences, will be passed to the MCDA to provide a possible ranking for competing alternatives.

The risk assessment here is performed by combining the probability for each pipe to break with the consequence induced 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:

$$risk_p = \lambda * C\_tot_p = frequency * consequence \quad (3)$$

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 can be depicted in a risk matrix as in figure 3, to better visualize what most influence risk for the given pipe (probability or consequence or both equally). The results support deciding if the risk reduction measure to adopt should be more preventive (reduce the probability for the event to happen) or protective (mitigate consequences).

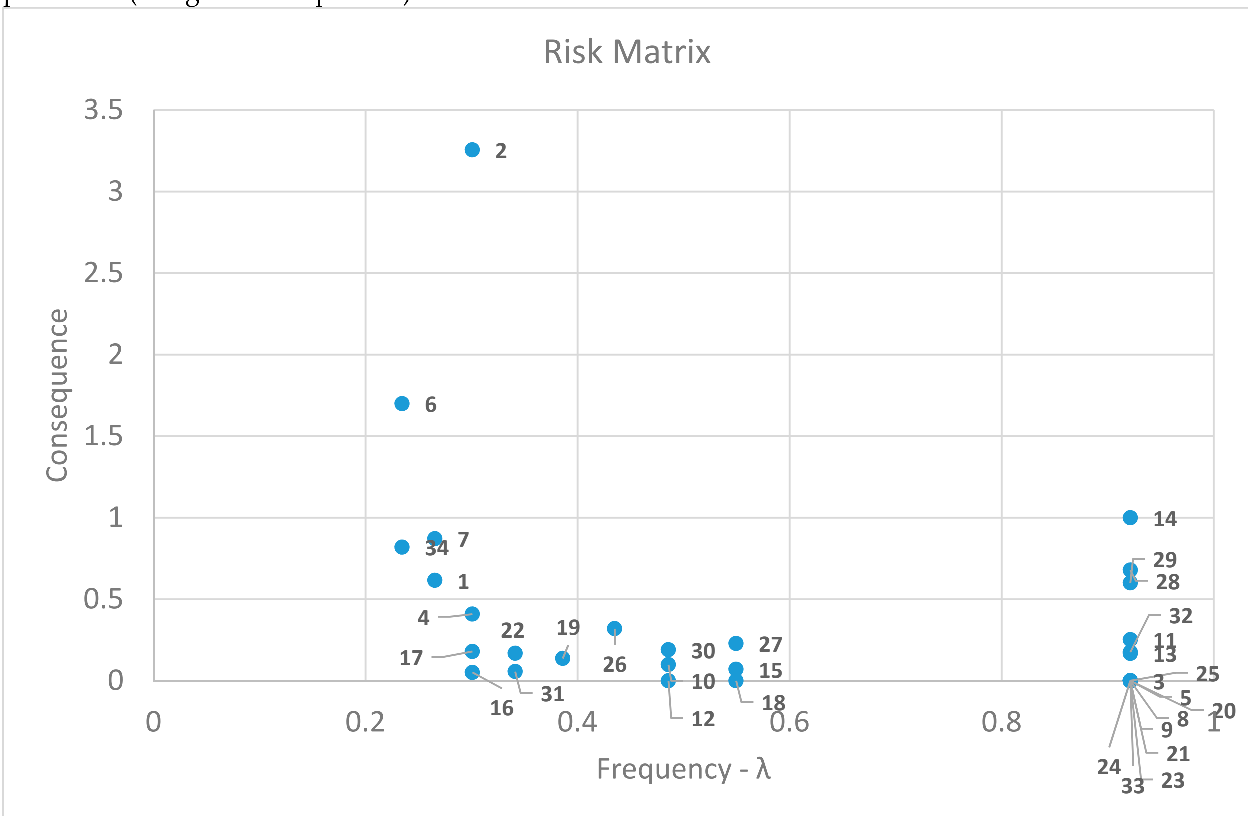

Figure 3. Example of a graph which reports frequency of break and relative consequence

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The figure 4 is another example in which the pipes of the WDS are ranked according to risk value sorted in decreasing way: this ranking can give the priority of intervention to be applied.

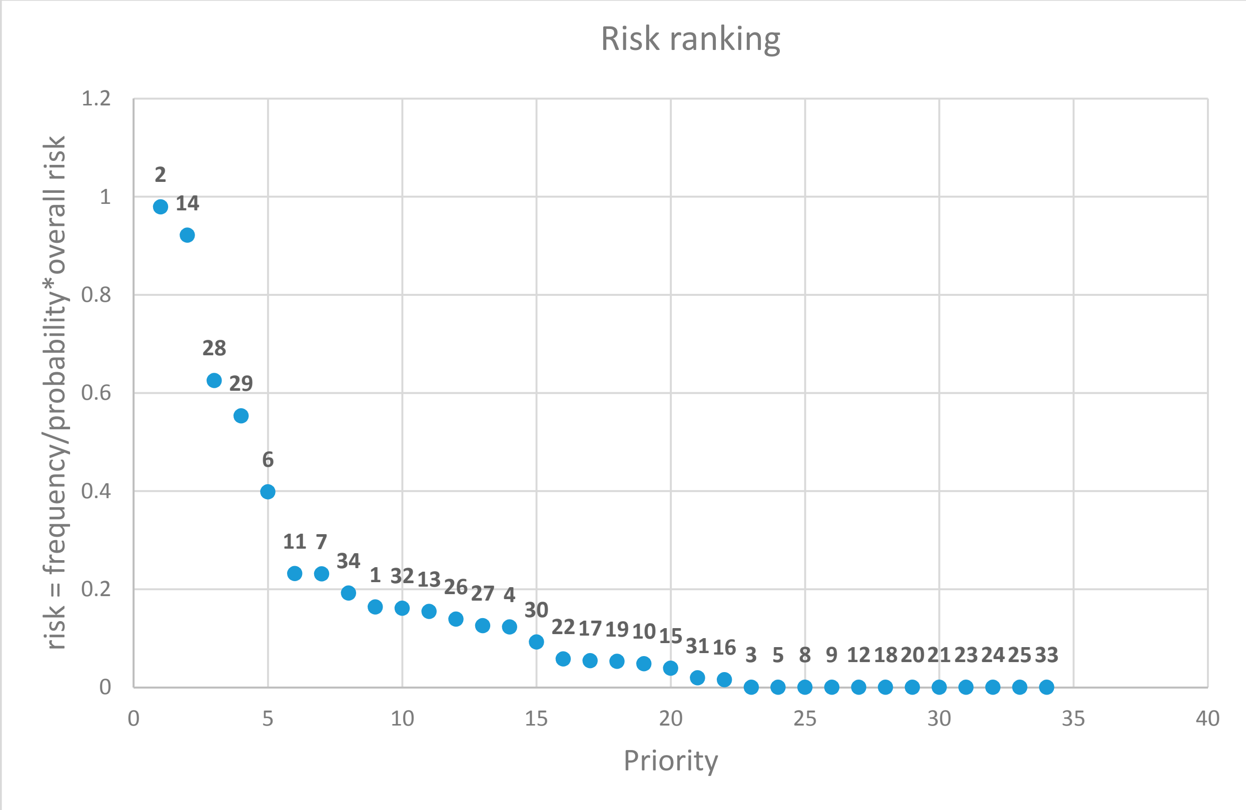

Figure 4. Risk values sorted in decreasing way

3.3 Replacement Planning

In order to prioritize the interventions a MCDA methodology has to be adopted to select intervention options. The objective is to minimize the residual risk, after rehabilitation of a given pipe to ensure maximum reliability 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:

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

Where:

- p depicts the p-th pipe;
- $cost_p$ is the direct cost of the p-th pipe;
- $\sum_{k=1}^{p-1} cum\ cost_{p-1}$ 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 decreasing way:

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

Where:

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

The **residual risk** is evaluated as:

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

Given a fixed annual investment budget, for each intervention of rehabilitation, the remaining budget is assessed and used to fit further interventions to minimize the actual residual risk and provide maximum service.

The figure 5 shows an example of the analysis of cumulative risk reduction evaluated based on a specific budget: the cumulative remaining risk curve is based on the pipe ranking expressed in cumulative pipe cost. The red line represents cumulative risk reduced up to the point where the direct cost of pipes to replace is covered by the investment budget.

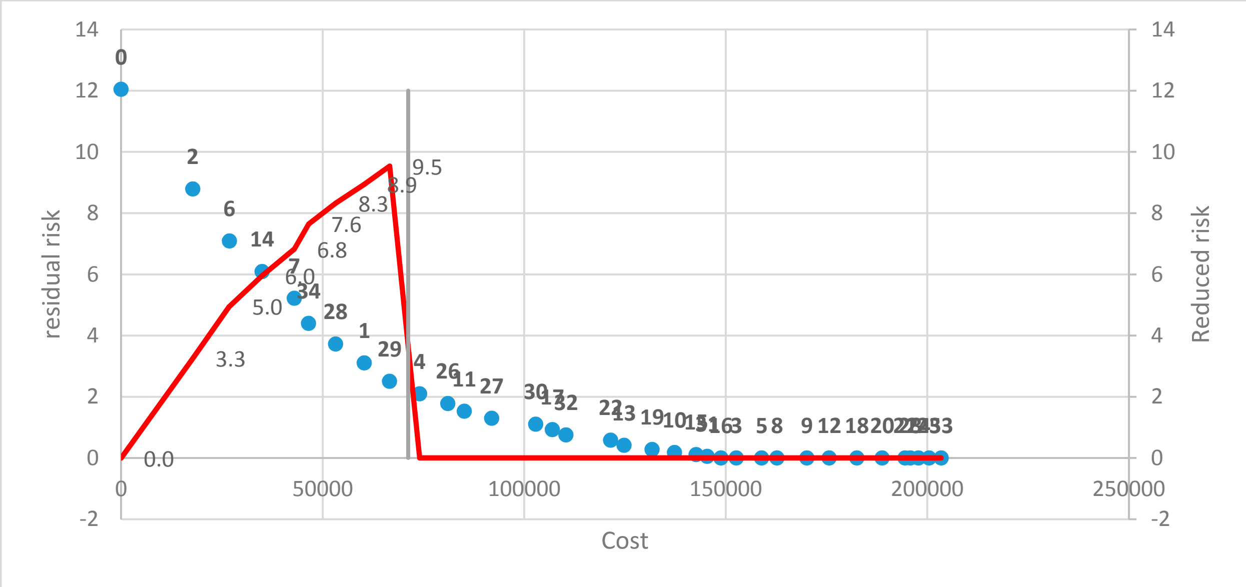

Figure 5. Example of cumulative risk reduction evaluated based on the target of a specific budget remaining/reduced risk for a fixed budget

The cumulative 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 length goal. In theory, the cumulative risk is equal to zero if all pipe in the network are replaced

4. 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 users and spread from the districts of San Giacomo in the south of Bolzano until the industrial area of Laives. Three districts interconnected subdivide the network: San Giacomo, Pineta and Laives. Each of these districts have a tank charged by wells or springs.

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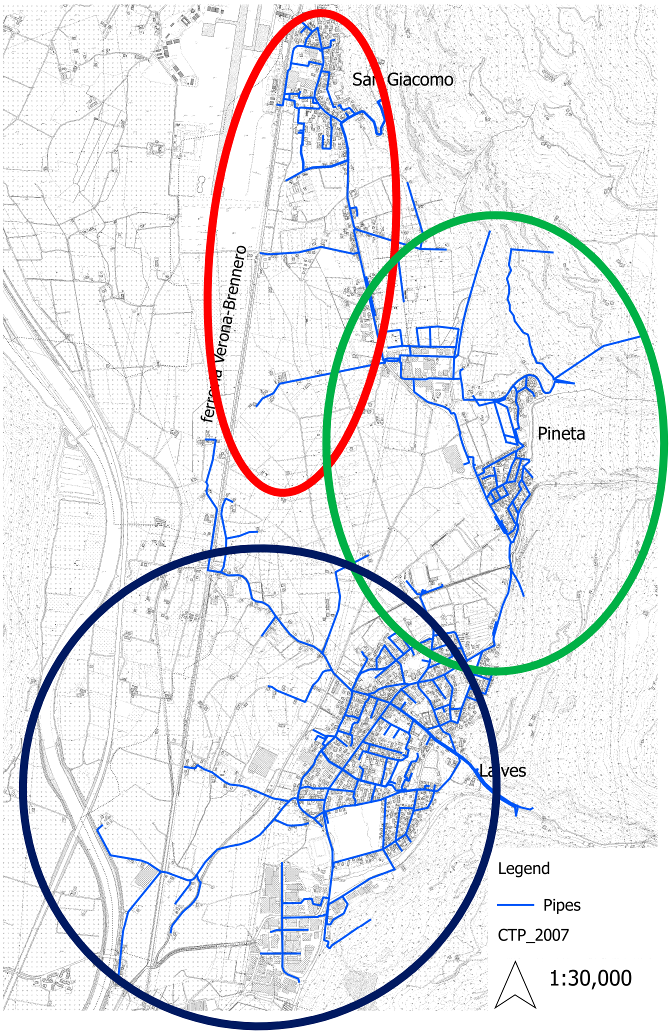

Figure 6. Laives network and relative districts

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 through 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 a different regime during the hours of the day to save energy therefore, to simulate this, parallel pumps are added working in a different range of hours and with distinct levels of the tanks.

In this paper, the mechanical reliability analysis considered for the simulation 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 is assuming two valves for each pipe trunk, returns 379 failure events; each corresponds to a specific segment in the Laives Network.

5. Results and discussion

In this section are reported the results obtained applying the methodology explained above to the Laives case study.

The scatter plot of nodes that are affected by each failure event is reported in the figure 7: some of nodes can result in unsupplied demand, pressure deficiency condition or both conditions simultaneously.

The results of a first simulation show that the most part of the worst condition registered at nodes are of pressure deficit (PR) type, rather than of unsupplied demand (UN) type. This because the PR indicator take as reference value the nodal pressure in normal conditions, p^{normal}, that for the

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Laives network is characterized by a generalized high level of pressure distribution in normal working conditions, much higher than the 30-40 m of water column usually required.

Therefore, a new simulation was performed by lowering the reference value for pressure, 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 will present the subscription "ser" to indicate that in the formulation is take as reference value the service pressure (PRser).

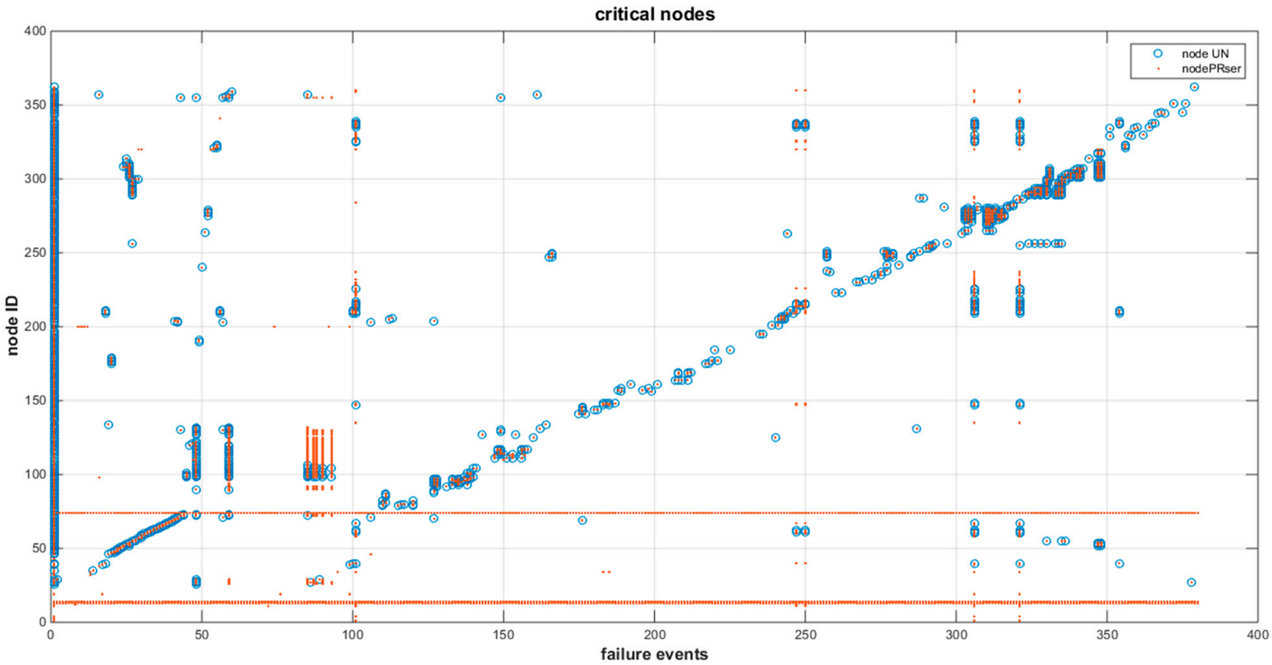

Figure 7. Scatter of node ID's that are affected by each failure event – Laives

The table 1 reports the top 10 events ranked based on the number of affected node from the simulation and the location in the network of the five common failure events is shown in the figure 8.

Table 1. List of top 10 failure event corresponding to the number of affected node

	Unsupplied demand		*Pressure deficit (reference value PRser)*	
rank	**Failure event**	**Number of affected node**	**Failure event**	**Number of affected node**
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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It is interesting to observe in table 1 the different rank between the unsupplied demand and pressure deficit condition. In addition, for example the last five failure event causing unsupplied demand are absent on the list of failure events causing pressure deficiency.

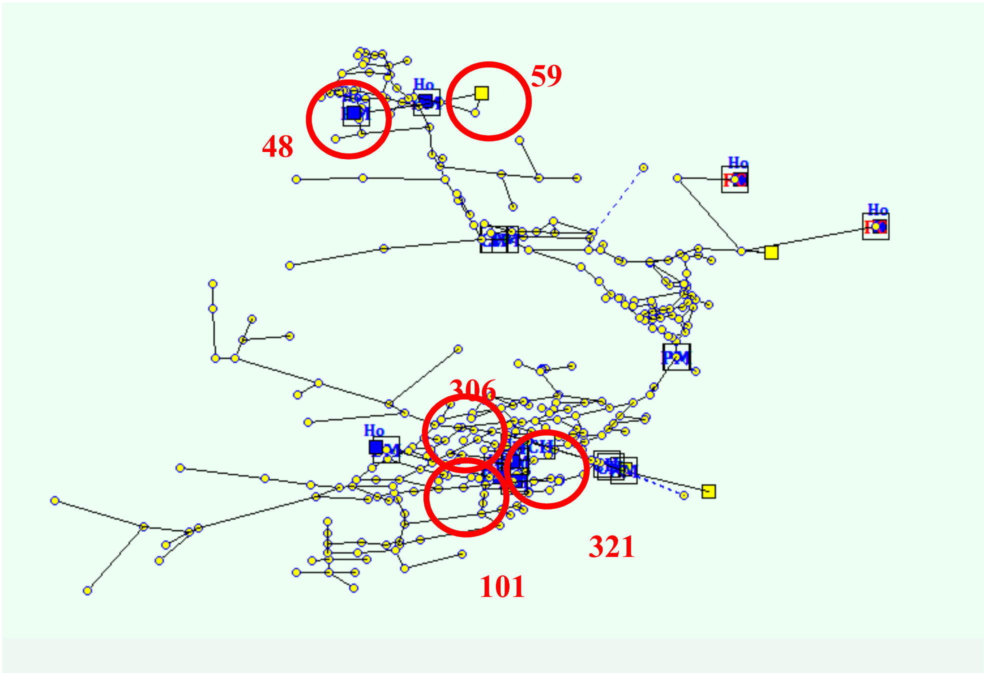

Figure 8. Location of the five common failure events

Table 2 shows an extract of risk calculation for some pipe of the network, where it is possible 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, $C_p^{UN\ dem}$ values, and consequence in term of pressure deficit, C_p^{PRser} values, feel the effect of 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 a portion of pipes (the first twenty pipes at highest risk) in term of risk, the corresponding risk values are reported in the table 3 with the relative values of λ and C_{tot}.

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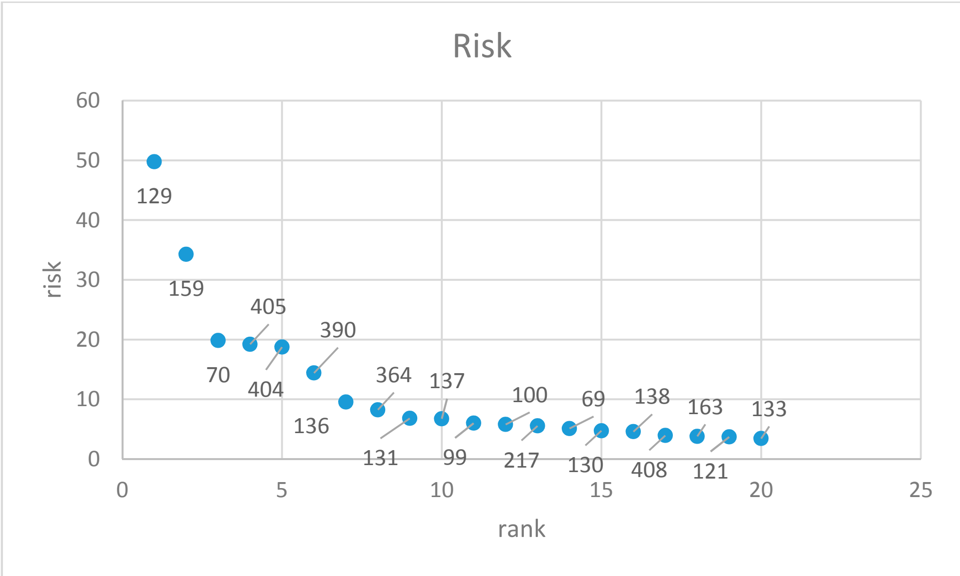

Figure 9. Priority ranking of the first 20 pipes

By comparing the list of failure events in table 1, with the list of the first twenty pipes ranked following the risk evaluation in table 3, only three of the predominant failure event of table 1 result in the ranking list, due to the effect of λ acting as ranking weight.

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

The figure 10 shows the residual risk as reduction of the cumulative risk while replacing the ranked pipes. The cumulative value peak at zero represents the total risk if no replacement program is implemented. On the contrary, the cumulative risk starts decreasing if replacement program is executed the risk reduction is optimized based on the annual investment.

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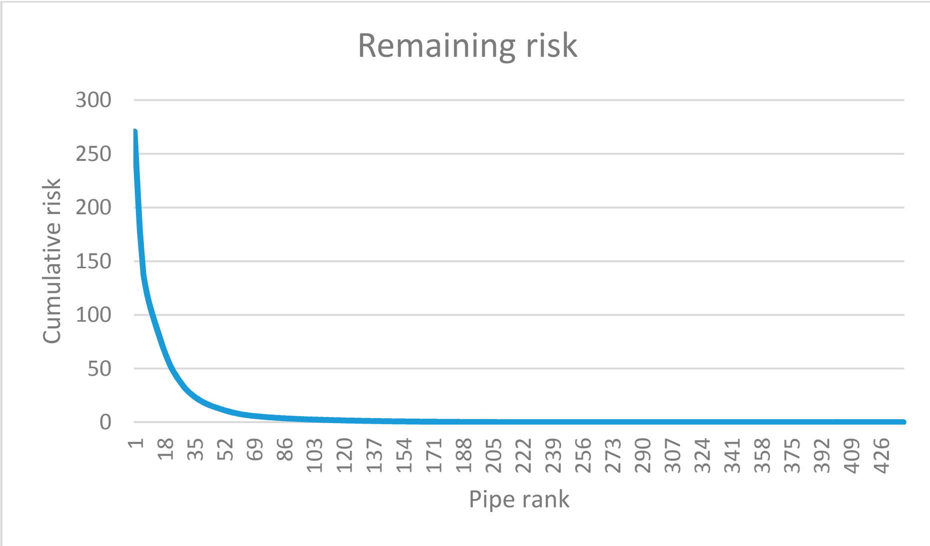

Figure 10. Cumulative risk based on pipe rank

The ranking of pipes could be driven by other constraint than cost, as for instance a requirement 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, which corresponds to substitute about 10 pipes a year.

Considering this alternative constraint, an additional analysis was performed and results are presented in fig 11. The x- axis is a blow up of the x- axis in the 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 before. The red line represents cumulative risk reduced 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).

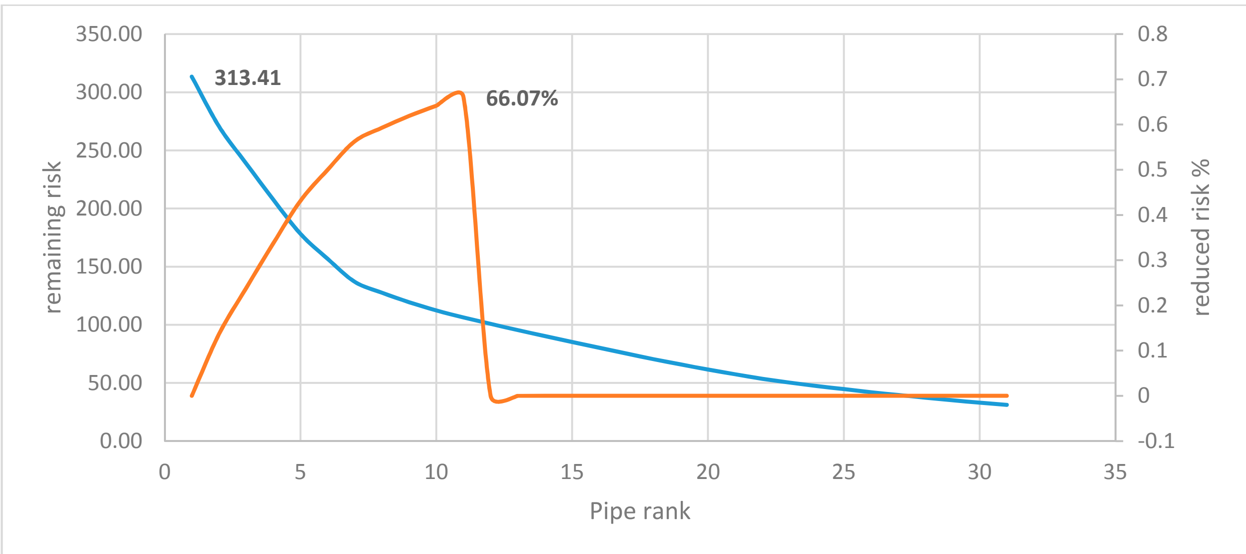

Figure 11. Cumulative risk reduction evaluated based on the target replacement percentage pipe in the masterplan calculated for the first year

6. Conclusions

Many factors like aging of infrastructure, population growth, increasing of urbanization but also more recent factors of climate change and environmental pollution require a change in the management of the WDS. The 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 allows the risk assessment at individual pipe level that can be used to develop a pipe replacement priority ranking. It is shown an application to the network of Laives, a town in province of Bolzano, highlighting the effect of break rate, λ acting as 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 plan the possible intervention of replacement, it will be better consider the real break rate of the network evaluated at least with the story break of a minimum of 10 year. The 'map' of the pipe that need to be replaced evaluated with the specific break rate to plan the intervention of the year, have to be uploaded the following year with the break rate that take into account the data of the last year passed. Those parameters linked, in a sense, to the 'new' and 'old' state of pipes needs to change too. At the same time it will be interesting observe the results obtained with a break rate that considers also the age of pipe and materials not only the diameter. Actually, the research is going on to consider the age factor and its influence for a long term planning seeing how change the ranking list in time period.

For each replacement, the 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 modeling approach, the research project from which this paper was born. Therefore a MCDA to include the environmental costs is actually developing.

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