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Optimal valves operation in WDNs to improve the resilience under critical scenarios

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Bridging Science to Practice

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Samenvatting

Annalisa Gentile (Universita Degli Studi di Cassino e del Lazio Meridionale) heeft tijdens haar afstuderen *Gondwana* ingezet om de veerkracht van leidingnetwerken te beoordelen en optimaliseren door afsluiters te manipuleren. Hiervoor is onderzoek verricht naar verschillende doelfuncties en crisisscenario's. De benadering is toegepast op het leidingnetmodel van Helmond-Mierlo (Brabant Water). De resultaten laten zien dat het mogelijk is om de veerkracht van een leidingnetwerk te verbeteren door afsluiterstanden te veranderen. Hiermee kan, bijvoorbeeld, het aantal getroffen klanten worden geminimaliseerd. Dit is tevens een startpunt om ook de locatie van afsluiters in een leidingnetwerk te optimaliseren.

De samenwerking met de Universita Degli Studi di Cassino e del Lazio Meridionale heeft bijgedragen aan het verder uitwerken van de benadering rondom de optimalisatie van de veerkracht van leidingnetwerken tijdens crisisscenario's. Daarnaast heeft het ook de mogelijkheid geboden om een niet KWR-onderzoeker te laten werken met de tool *Gondwana*, en de tool ook zo internationaal bekend(er) te maken.

UNIVERSITA' DEGLI STUDI DI CASSINO E DEL
LAZIO MERIDIONALE

DIPARTIMENTO DI INGEGNERIA CIVILE E MECCANICA

CORSO DI LAUREA MAGISTRALE IN
INGEGNERIA DELL'AMBIENTE E DEL TERRITORIO

TESI DI LAUREA MAGISTRALE IN IDRAULICA AMBIENTALE

Optimal valves operation in WDNs to improve the resilience under critical scenarios

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A mia madre e mio padre.

ABSTRACT

Le reti di distribuzione idrica hanno come obiettivo quello di fornire l’acqua agli utenti in qualsiasi momento, in buona quantità e qualità, anche durante uno scenario critico, come la rottura di una condotta. In seguito ad un evento di rottura, infatti, la portata erogata all’utenza potrebbe essere inferiore all’effettiva domanda in funzione del deficit di pressione. In questi casi è fondamentale intervenire sulla rete di distribuzione, risolvendo nel minor tempo possibile il guasto e ripristinando il corretto funzionamento della rete. Nel tempo che intercorre tra il momento della rottura e la riparazione della condotta, gli utenti si troveranno in condizioni di deficit: in questi casi assume un aspetto importante la gestione della rete attraverso la regolazione di valvole e pompe, il cui funzionamento può essere regolato per minimizzaare il danno all’utenza.

Nel presente studio è stata sviluppata una metodologia atta a massimizzare la qualità del servizio idrico durante uno scenario di rottura delle condotte, andando ad attuare una gestione ottimale delle sole valvole di intercettazione. Tramite questa gestione si rende la rete più resiliente, e quindi meno soggetta a creare significativi deficit di domanda nel caso in cui avviene la rottura di una tubazione.

La selezione delle valvole su cui agire negli scenari critici è stata effettuata attraverso la risoluzione di un problema di ottimizzazione che sfrutta un algoritmo genetico implementato nel software Gondwana, sviluppato dal KWR (Olanda), un software di ottimizzazione delle reti di distribuzione idrica.

Il caso studio qui riportato riguarda la rete di distribuzione idrica a servizio delle città di H. e M., in Olanda, con una popolazione servita di 100 000 abitanti, sulla quale sono presenti circa 900 valvole con stato aperto. Per ogni scenario di rottura studiato sono state utilizzate tre diverse funzioni obiettivo che volgono a minimizzare il deficit di domanda all’utenza ed è stata considerata solamente la condizione di picco della domanda. E’ stato inoltre considerato il caso in cui l’1% delle valvole, nella condizione iniziale, si trovano in uno stato diverso da quello considerato, e quindi sono chiuse. Ciò accade nel momento in cui, nelle operazioni di manutenzione, l’operatore dimentica di riposizionare la valvola nello stato originale.

Per entrambi i casi e per ogni scenario sono stati contati i nodi e gli allacci alle utenze che non si trovano più in una condizione di deficit dopo il processo di ottimizzazione: questa indagine

permette di avere una visione più realistica sul miglioramento che questa metodologia va ad attuare.

Sono state inoltre ricavate le valvole più utilizzate nelle operazioni di gestione ottimale durante un caso critico: queste sono le valvole più importanti della rete, sulle quali il Gestore deve prestare maggiore attenzione dal punto di vista della manutenzione.

La metodologia presentata può rappresentare un utile strumento operativo per gli enti gestori dei servizi idrici.

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1 INTRODUCTION

1.1 FRAMEWORK OF THE SUBJECT

A Water Distribution Network (WDN) is made up of nodes, pipes and other hydraulic components such as pumps, reservoirs, valves and tanks. Its main goal is to supply water at sufficient pressure and quantity levels to all users, even during a critical scenario, such as pipe failures.

When a critical scenario occurs, the flow supplied to the user is not equal to the requested demand, but rather, is related to the pressure: a demand deficit will occur in the network due to the fact that the requested user demand turns out to be higher than the supplied demand in a scenario failure. In such cases there is a need to rehabilitate the system by minimizing the deficit from the moment of failure to the moment the problem is solved. This may be carried out via an optimal operation to the network, that is, by modifyng the components that could be operated to ensure a minimal disservice to the customers.

The components of a network that could be operated are the valves and the pumps. In the present work, a methodology which improves the quality of the water service during a critical scenario is studied, by using an optimal valves management, in the absence of pumps. Those operations make the network more resilient, and thus less likely to create big deficit scenarios when a pipe failure occurs.

The operated valves are the isolation valves, considering only the open or closed statuses. The selection of valves to operate is carried out by solving an optimization problem using a genetic algorithm implemented in Gondwana, a software developed in KWR (The Netherlands) by van Thienen & Vertommen, a generic optimization tool for drinking water distribution networks.

The real WDN studied in this work, serves the cities of H. and M., in the Netherlands, and comprises almost 900 valves with an open status. For each failure scenario three different objective functions were used in order to minimize the demand deficit, taking into consideration the peak demand condition. Furthermore, the case with 1 % of closed valves was investigated in order to take into account the case when the valves are not in their original status.

The proposed methodology is useful for water companies in managing the operation of their networks during critical scenarios, creating a more resilient network.

1.2 LITERATURE REVIEW

Many definitions for resilience have been proposed over the years by different authors in literature. According to Makropoulos, et al. (2018) the definitions, even if they come from different standpoints, have some common ground since the resilience is a property of the system as a whole and also a key property for the sustainability of any system.

The first definition of resilience comes from Holling (1973), defining the resilience in a natural system as the amount of disturbance that a system can withstand without changing self-organized processes and structures.

In the engineering field, resilience has been used as a reliability indicator alongside other surrogate reliability indicators such as the entropy (Tanyimboh & Templeman, 2000) and the modified resilience (Prasad et al., 2003). Previously, the evaluation of the reliability of a WDN was made by direct estimation with stochastic reliability assessments, which required a high computational effort, due to the various scenarios to be considered and the complexity of the real networks. Some of these direct indicators were developed by Gargano & Pianese (2000), Tanyimboh et al. (2001), Ciaponi (2009), Creaco & Franchini (2012). Then, with the objective to reduce the computational time, reliability has been often expressed using indirect indices.

Subsequently, numerous studies have taken place in order to understand which of the above-mentioned surrogate measures is the most appropriate to better characterize the full reliability of the network. From the cases studied by Tanyimboh et al. (2011), with a multi-objective genetic algorithm that maximizes the flow entropy for a multiple operating conditions for any given network, results the entropy is the best surrogate measure, while, from Greco et al (2012) who compared entropy and resilience for measuring the robustness of a WDN, the best indirect reliability measure is the resilience. Moreover, Creaco et al. (2014) investigated and compared the entropy and resilience index to find out which of them was better to characterize the full reliability of the network in the design phase with a multi-objective optimization, performed in order to minimize costs and maximize reliability, with the result that indices based on energetic concepts represent a better compact estimate of reliability than entropy.

In 2005, the World Conference on Disaster Reduction (WCDR) highlighted the importance of the term resilience in the context of disaster scenarios and many authors who based their work on the general framework provided by Bruneau, et al. (2003), proposed new methods to quantify resilience. Cimellaro et al. (2010) proposed an evaluation of the disaster resilience based on dimensionless analytical functions related to the variation of functionality during a period of interest, obtaining a useful tool for disaster assessment in structural engineering.

Some techniques that study the system's robustness and susceptibility to damage are the graph methods which emphasize the significant role of the topology in system performance while ignoring some system component data like direction of flow: in particular, Yazdany & Jeffrey (2012) used the graph theory to improve system robustness and resilience. Later, Herrera et al. (2016) included the hydraulic attributes of the WDN in the graph theory.

Cimellaro et al. (2015) worked on a resilience index to help engineers evaluate the performance of a WDN in case of catastrophes. It is based on three indices: the number of users with a temporary lack of water, the water level in the tank and the water quality. The results show the importance of the partition of the network into districts to reduce the lack of service.

An important contribution to solve the optimization problems has been given from many programming methods, like linear programming, dynamic programming, enumeration techniques, heuristic methods and evolutionary techniques. Prasad et al. (2003) considered a multi-objective function described by the minimization of network cost and maximization of the network resilience, obtaining a set of Pareto-optimal solutions in the search space and confirming the superiority of the network resilience based approach.

The system resilience, in a context of mechanical failures, has been investigated by Ayala-Cabrera et al. (2017), exploring a pipe burst event and two palliative scenarios to mitigate the event. The results showed that a correlation with the location of the event and, the exclusive isolation of the affected pipe, is a better palliative action than the isolation of the surrounding area, with an increase of the network resilience of 71%.

Interesting methods have been studied during the 1st international WDSA/CCWI 2018 Joint Conference: Sweetapple et al. developed a methodology for the resilience assessment called “global resilience analysis”, used in exceptional conditions, based on a “stress-strain” concept; Paez et al. investigated the correlation between surrogate reliability measures in real size WDN, showing resuts that all Power-based indices, including resilience, are highly correlated between them, instead of Entropy-based measures; Meng et al. studied a framework for the optimization of the placement of new valves to improve the system resilience without entailing excessive costs.

In “A resilience assessment method for urban water systems”, Makropoulos, et al. (2018) worked on a toolbox for developing a resilience profile graph, based on a scenario planner, which allows the consideration of different situations, and a Urban Water Optioneering Tool (UWOT), which simulates the demand at arbitrary time steps and multiple network scales, obtaining a good method in continuous development.

As previously said, the resilience index can either be viewed either as a designing tool with the target of high resilience and low investment, or as an operation tool to consider how an existent networks should be operated under crisis scenarios. This last one will be considered as the main theme of this work since, the resilience assessment of an existing WDN, is currently a hot topic in the water research field. With this purpose, the resilience can be defined as *the ability of a system to maintain and adapt its operational performance in the face of failures and other adverse conditions* (Herrera, et al., 2016).

1.3 STRUCTURE OF THE THESIS

The thesis is composed of six chapters.

The first chapter is the *Introduction*, relative to the framework of the subject and the literature review, to ensure an easier comprehension of the thesis.

The second chapter talks about how to *evaluate the performance of a WDN*. Performance assessment methods are explained in order to understand why it is important to include the resilience index in the analysis of a critical situation in a WDN. Furthermore, an explanation about optimization algorithms, specially genetic algorithms, is provided.

The third chapter intoduces the *case study*, a WDN located in the Netherlands which supplies water to almost 100 inhabitants.

The fourth chapter describes the *methodology* used in this work. The process of evaluating and improving the resilience index of a WDN, using the software Gondwana, is explained step by step.

In the fifth chapter the *results* are presented, in terms of improvement of the resilience index, saved nodes and saved connections.

The last chapter is about the *conclusions* and the following research steps in this field.

2 PERFORMANCE EVALUATION OF THE NETWORKS

2.1 INTRODUCTION

In the literature many methods in assessing the performance of a network have been proposed. The main purpose is to find compelling methods applicable in the operational field.

There are two main directions in the performance evaluation of a network: the first has the objective to evaluate efficacy, efficiency and cost with some performance indicators obtained by elaboration of collected data in a data-base, and the second one aims to evaluate the hydraulic performance of the networks. In the following paragraphs a short explanation of the two ways of evaluations is provided.

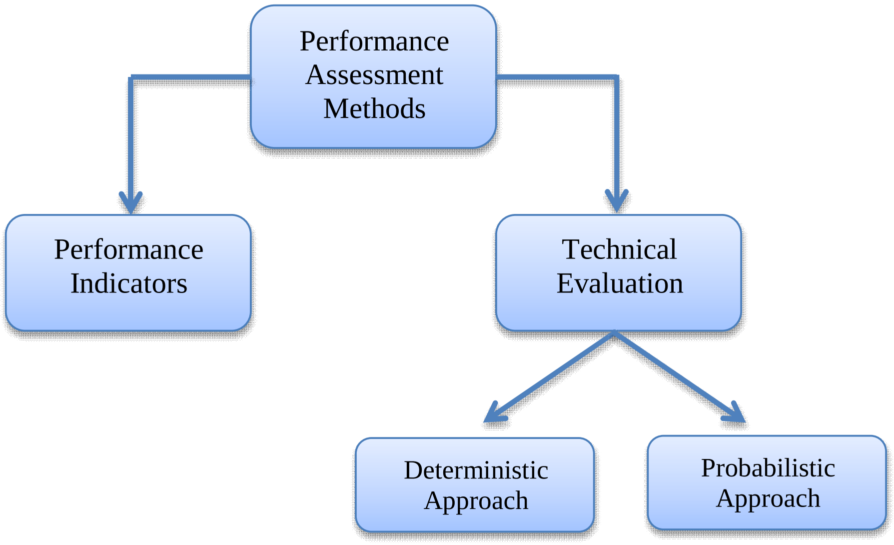


Figure 1. Performance assessment methods

2.2 TECHNICAL EVALUATION OF THE WDN

The first category includes all the methods which allow us to carry out a technical performance assessment of the WDN, but not the water service. In fact, the main expectation from a WDN is to supply quality water with the correct quantity in order to satisfy the user's demand. However, in this case, only the hydraulic aspects will be taken into account since the quality aspects are usually studied independently in respect to others. The target of the analysis is to evaluate wheth , and eventually in which measure the requested performance will be satisfied with a limited number of working conditions, which are the design conditions. This analysis may be carried out through two different approaches:

- Deterministic approach, which sole verifies if the design conditions are satisfied;
- Probabilistic approach, which evaluates the performance of the system under many different scenarios, which are not normally taken into account in the design conditions.

2.2.1 Deterministic Approach

The deterministic analysis is nowadays the most used method to assess the performance of a WDN or a WDN element: it consists in the evaluation of the capacity of the system to satisfy the user demand under specific conditions.

In the case of a real distribution network it consists of a hydraulic verification, allowing the whole plan component to be available, and thus assumes three different cases:

- Peak demand considered during the day of maximum consumption;
- Fire protection;
- Failure of one or more primary pipelines.

If these cases all networks are verified and can be considered as adequate. Howecer, it can also be considered inadequate so remedial actions must be found.

This approach has some limitations such as:

- The lack of consideration of many scenarios together with the fact that it is impossible to associate a probable number of occurrences on the scenarios taken into account;
- It will only provide an “adequate judgment”, therefore it is not possible to compare situations.

2.2.2 Probabilistic approach

The reliability theory was born during the II World War and was significantly developed during the following years. Now it is used in the productive and scientific field and is based on some important concepts which are vital in order to know how to apply this theory.

First of all, it is essential to define the *unreliability F(t)*, that is the inability of a system to completely fulfill the function for which it is designed due to mechanical failures. It can be defined as:

$$F(t) = \int_0^t f(t)dt$$

where *f(t)* is the probability of a collapse at time *t*.

On the other hand, the *reliability R(t)* of a system is the probability that the system will fully carry out its performance in the given period of time [0,t], therefore, the out of service will occur after this period. The reliability and the unreliability are two parametres which are incompatible and exhaustive, so the reliability can be defined as:

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)dt$$

The reliability evaluation is carried out by taking into account information which is not always available, regarding the failures that the system may have during its entire lifetime, therefore it is essentially a statistic evaluation of the performance indices obtained with hydraulic simulations of the system and taking into consideration different scenarios, each with its probabilistic value of occurance.

In the definition, the factors which can determante failure situations in the system are introduced as;

- *Mechanical factors*, which are failures like interruptions in the energy supply or out of service of components (pipes, valves, etc.);
- *Hydraulic factors*, which are random variations (in time and space) of the demand, pipe roughness coefficients, internal pipe diameters, etc.

In the literature there are many methods to set the problem, some include only the mechanical failures, some only the hydraulic failure, some both. The main problem is the simulation time, which take long computational time for the convergence, and that’s why several authors introduce some simplifications with the aim of reducing the computation time.

2.3 PERFORMANCE INDICATORS

These methods have the purpose of evaluating the water services in terms of efficacy, efficiency and cost, resulting from the plants, the physical and socio-economic context of the users and the operational practices followed by the water company.

To describe the performance of a WDN different indexes mentioned in the literature can be adopted. The most used indexes are resilience, reliability, vulnerability and robustness which are good quantitative indexes use to verify the choices taken into account in the design phase or in the mainternance and rehabilitation of an existent hydraulic infrastructure, related to the uncertain of the future operation conditions.

The evaluation system is constructed on an index which describes an aspect on the WDN, like demand, pipe type, pipe age, diameters, pressures, instant of the failure, etc., acquirable from direct measurement carried out by the water company or from the archives documentation. Relating the parameters to the actual functioning condition through elementary mathematic structures, a new parameter will be obtained in order to quantify the performance of the network. The obtained value then will be compared with some thresholds in order to obtain a measure of the performance.

This is certainly an easy and quick way to evaluate the performance of the networks for water companies, but it still remains general and unable to identify all the specific aspects of the system.

2.3.1 Resilience Index

One of the most used performance indexes is the resilience index, which has the aim of exploring the system during a perturbation, trying to identify the magnitude of the potential impact generated by a specific disturbance. The fact that the WDN are vulnerable infrastructures with all sorts of threats, from the aging of the system components to natural disasters like earthquakes and flood, right through to terrorist and recent cyber-physical attacks, has led water utilities to find a system which guarantese the strength and safety of their WDN. Therefore, it becomes important to assess the resilience of a network. Originally, the reisilience index was used in the design phase of a WDN, but lately it is mostly used for the restoring an existing network, changing its operational conditions after a critical scenario.

2.3.1.1 *The resilience index in the design phase*

The first resilience definition (Todini, 2000) is related to the hydraulic head surplus at the network nodes compared to the minimum required head under normal operating conditions; this head surplus represents the "energy storage" which can be dissipated under critical operational conditions such as segment isolations (which cause an increase in head losses), thus avoiding that the water supply to users is affected (Fortunato, et al., 2012). It is defined starting from the overall hydraulic power entering the network, P_{tot}, given by:

$$P_{tot} = \gamma \sum_{k=1}^{n_r} Q_k \cdot H_k$$

where Q_k and H_k are the flow entering the network and the head at the k-th reservoir, or supply point, respectively, n_r is the number of reservoirs supplying the network, and Υ is the specific gravity of water.

The hydraulic power dissipated by the water flowing through the network, P_{int}, is given by the difference of P_{tot} and the total hydraulic power provided to the users, P_{ext}, which is expressed by the following equation:

$$P_{ext} = \gamma \sum_{i=1}^{n_n} q_i \cdot h_i$$

where h_i and q_i respectively are the actual head and the supplied flow at the i-th node and n_n is the number of nodes of the system.

The maximum hydraulic power thatmay be dissipated within the system while meeting minimum heads constraints at the network nodes $h_{i\,min}$ in order to meet the required demand, is given by:

$$P_{int\,max} = P_{tot} - \gamma \sum_{i=1}^{n_n} q_i \cdot h_i$$

Resilience index, I_r, is eventually defined as:

$$I_r = \frac{P_{int\,max} - P_{int}}{P_{int\,max}} = 1 - \frac{P_{int}}{P_{int\,max}} = \frac{\sum_{i=1}^{n_n} q_i \cdot (h_i - h_{i\,min})}{\sum_{k=1}^{n_v} Q_k \cdot H_k - \sum_{i=1}^{n_n} q_i \cdot h_{i\,min}}$$

The Todini resiliece index was futher developed, modified and adapted to different cases. Among these, the *modified resilience index*, $I_{r\,mod}$, (Prasad, et Al., 2003) may be mentioned, since it is an upgrade of the Todini index which takes into account the uniformity of the pipes connected to each network node and the *entropy function*, *E*, (Tanyimboh & Templeman, 2000) which is connected to the uncertainty of the paths that bring water to each network node.

2.3.1.2 The resilience index in the rehabilitation phase

According to many authors, a common way to estimate the resilience index is with the ratio between the volume of water provided W_E and the volume of water requested by the users W_R:

$$R = \frac{W_E}{W_R}$$

This definition can be applied either in the global scale of the problem or in the local scale at the node, with the advantage of being a simple index directly connected to performance conditions. In this case, the probabilistic aspect of the problem is not considered.

In this work, a performance indicator based on the consumer demand satisfaction rate is considered in order to quantify the degree to which a water distribution network continues to perform under stress. The *demand satisfaction rate*, DSR_s, is defined as the ratio between the total available water that can be delivered to the consumer, Q_s, under scenario s, and the total water that is required by the consumer under normal circumstances, D, (Creaco, et al., 2015):

$$DSR_s = \frac{Q_s}{D} = \frac{\sum_i^{ND} q_{i,s}}{\sum_i^{ND} d_i}$$

where, d_i is the demand at each node of the network, i, and $q_{i,s}$ is the actual delivered water to node i in each scenario s. This indicator is in fact the same as the volumetric reliability metric proposed in Makropoulos et al. (2018).

2.4 HYDRAULIC MODELLING OF A WDN

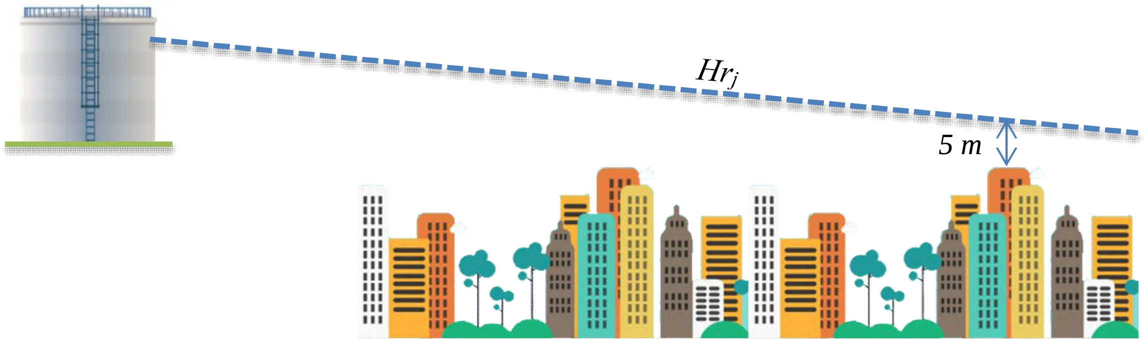


Figure 2. Piezometric line in Demand Driven Method

One of the main task is to evaluate the flows when the nodal pressure falls below a minimum required level, and so the flow will be significantly reduced. The evaluation model used assumes that nodal outflows are fixed and are satisfied regardless of network pressures, so they suppose that the outflow, in every j node, Q_j is equal to the requested flow Qr_j, with the hypothesis of a sufficient head H_j, which is unknown. This model, which is used in current engineering practice, is called *Demand Driven Method* (DDM), and this leads to correct results only when the hydraulic verification of the network is positive, i.e. when the nodes head H_j in node j is greater or equal to the requested head Hr_j to satisfy the demand, i.e. the minimum head to allow flow to the nodes.

The nodal pressure condition is fully satisfied, according to the Italian rules, when in every node, but mostly on the least favorably placed node, the head is $H_j \geq Hr_j$, where Hr_j is given by the height of the building plus the headloss in the building pipeline plus the minimum pressure of 5 m on the tap in the hours of maximum consumption and minimum level in the reservoir.

Moreover it is required $H_j < 70\ m$, which represent the 7 atm pressure that a tap and the internal pipes of houses can allow in Italy, in the hours of minimum consumption and maximum level in the reservoir.

In these conditions every users will be able to get water at his tap at good pressure. This kind of approach has been satisfying since the aim of the evaluation has been to verify the good design of a network.

When some critical events, like mechanical and hydraulic failure or excess demand, occur, the pressure can be lower than the minimum requested in some critical node, so $H_j < Hr_j$. Although some node may be able to satisfy their demands, others may meet the demand partially while the rest, if the pressure is below the threshold, may fail and may not provide any water at all: it results that the flow Q_j assigned as outflow at the critical nodes are not compatible with the head values H_j obtained.

Figure 3.Piezometric line in Pressure Driven Method

In this case, a different approach is requested, named *Pressure Driven Method* in the literature (PDM), which identifies the solutions not only for the hydraulic equations, but also for the relationship between head and outflow:

$$Q_j = f(H_j)$$

Taking into account this relationship, will make the simulation result more realistic and allow us to obtain a better evaluation of the reliability index.

The main problem of the PDM is the definition of the relationship between the outflow Q_j and the pressure h_j (directly related to the head H_j) since this depends on many factors like the dimensions and the configurations of the network and the spatial distribution of the taps. The evaluation of these elements turns out to be so difficult dueto their huge variability which requires information which is not always available: this means that the relationship could be only evaluated, in the hydraulic verifications, with some simplified formulas.

The methodology has two fixed head benchmarks:

- *Hmin*$_j$, minimum head value, below which there is no supply;
- *Hr*$_j$, head value required to satisfy the user demand.

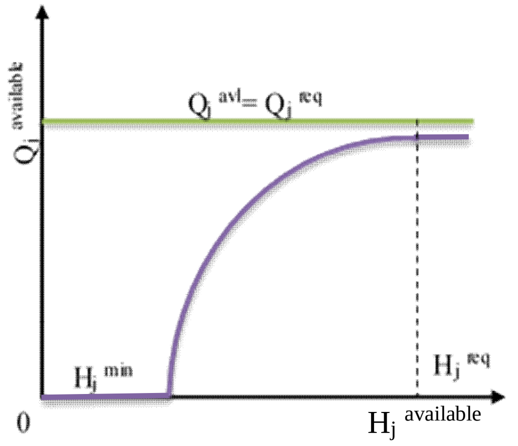


Figure 4. Demand driven function in green and Pressure driven function in purple

For the evaluation of the discharge delivered in a node, many expressions have been developed in the literature, which can lead to many different solutions, representing a problem for the methodology.

In this work, the supplied water flow at each node is a function of the nodal head and it is given by Wagner, et al., 1988:

$$q_{i,s} = \begin{cases} 0 & if\ H_{i,s} < H_{i,0} \\ d_{i,s}\left(\dfrac{H_{i,s} - H_{i,0}}{H_{i,min} - H_{i,0}}\right)^{\gamma} & if\ H_{i,0} \leq H_{i,s} < H_{i,min} \\ d_{i,s} & if\ H_{i,s} \geq H_{i,min} \end{cases}$$

where, $H_{i,s}$ is the actual head at node i and scenario s, $H_{i,0}$ is the minimum head to allow any flow to the node, and $H_{i,min}$ is the minimum head to fully satisfy nodal demand. The exponent γ is usually set to 0.5 (Creaco, et al., 2015).

Another problem is the fact that the numerical methods for the solution of the system hardly leads to a convergence due to the particular structure of the relationship $Q_i = f\ (H_j)$. That is why in the recent past, several packages like EPANET have been extended to include the possibility to run a PDM, with an easy methodology and fast results.

2.5 OPTIMIZATION PROBLEM

During the operational phase, the WDN is subject to a great flow variability, in time and space, caused by different user demand. Furthermore, we shall consider social costs directly connected to a missed water supply, which represents a penalty produced by the inadequacy of the system to satisfy the users request assuming a minimum head value in the nodes.

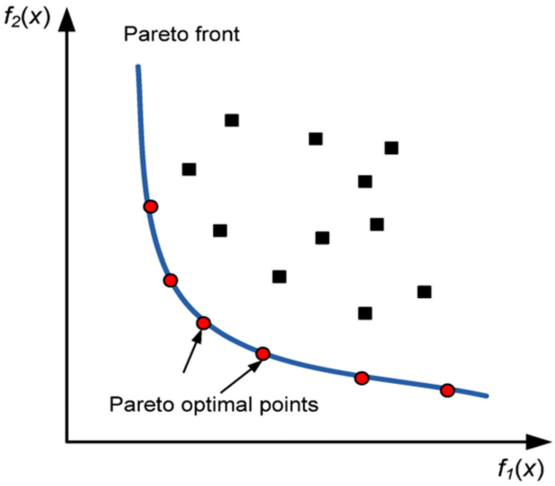


Figure 5. Pareto front

With the purpose of solving these problems, in the last years many available optimization algorithms mainly based on the research of the minimum or maximum of a function, called *objective* have been used. Other frequently used approaches are the *multi-objective functions*, which allow to make a final choice which turns out to be a good compromise between different aspects, even though they are in contrastbetween each other.

The problem of the optimal operation starts with a set of equations and inequalities, which represent some constraints for the variables involved in the problem, and if the solution exists, it aims to find it as if it were unique, so the objective function assumes the minimum or maximum value. In the case of a multi-objective function, all the solutions called *pareto optimal* are researched, in which the optimal together with other criteria must be found

The objective function can take into account some aspects like the network cost, ordinary and non-ordinary operation costs, the network resilience and even social costs, connected to the inability of the network to satisfy its users.

The operational problem of a WDN is normally carried out by assigning:

- The network topology, i.e. a set of nodes, links and tanks;
- The user demand distribution;
- The minimum head value for the nodes.

With this set of input information, assigning a scenario of failures , an optimal set of open/closed valves that will make the system more resilient has to be found even when a pipe failure occurs

2.5.1 Optimization Algorithm

In the past years, numerous methodologies based on the research of the minimum of the objective function, have been developed. In particular, the optimization problem may be resolved with:

- Exact Optimization (EO), including methods based on “Linear programming” and “Non-linear programming”;
- Heuristic Optimization (HO), including methods based on “Evolution Algorithms”(EA), “Simulated Annealing” (SA) and “Tabu Search” (TS).

One of the methods in the heuristic optimization class is the one with the *“Genetic Algorithms”* (GA), based on natural selection, which is well adapted to the amount of solutions to be examinated and with the non-linearity of the optimization problem.

This implement the evolution model, which is able to simulate the capacity to adapt to single individuals in an environment where a selection takes place. In particular, a genetic algorithm, starts with an initial population, which becomes better generation by generation (as the humans evolve) and where the individuals are characterized with strings, named *chromosomes*, composed by numbers, called *genes*.

Generally speaking, his method evolves with these phases:

1. Generation of the population;
2. Fitness calculation of individuals, which depends on the objective function;
3. Selection, with the aim to obtain a better fitness;
4. Genetic variations, in particular recombination and mutation;
5. Repetition of the steps from 1 to 5 till convergence in the optimal point (Figure 6).

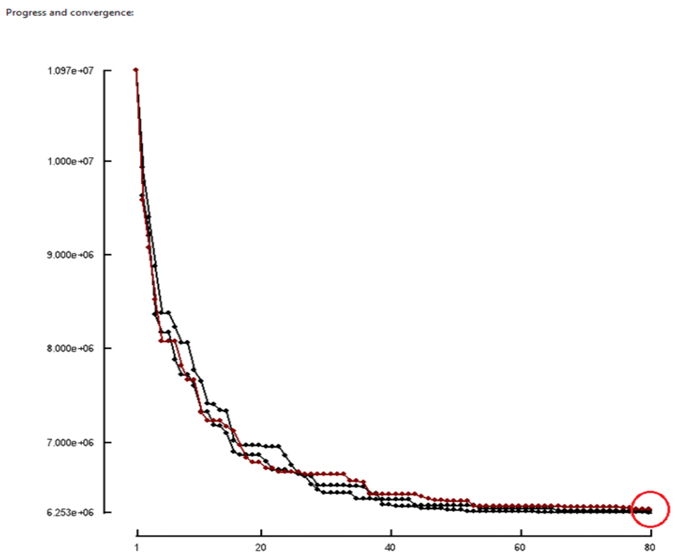


Figure 6. Convergence to the optimal point (Vertommen & van Thienen, 2015)

The structure of a genetic algorithm can be represented in the following diagram:

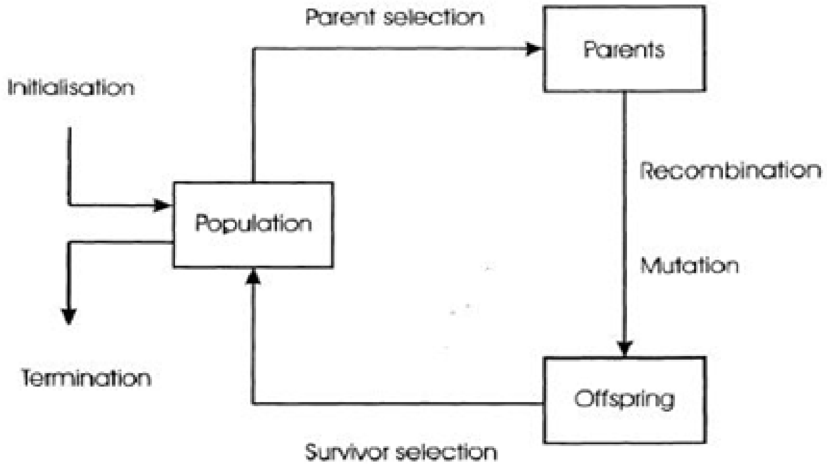


Figure 7.Representation of the GA process

1. ***Representation***: this represents the connection between the algorithm and the real problem, creating a population which better describes the characteristics of the problem.
    a. ***Binary representation***: it's the easiest case, where the individuals are represented with two numbers, 0 or 1;
    b. ***Representation with integers***: when the value of genes are known, it is better to represent the individual with a string of numbers where each number is connected to a characteristic of the gene;
    c. ***Representation with floating numbers***: used when there is the need for a more accurate representation;
2. ***Evaluation***: This is the function which describse requirements for adaptation which an individual must satisfy, called fitness function or, in the optimization problem, is called objective function.
3. ***Population***: it is made up of the set of individuals, with fixed dimensions, it is the main subject of the algorithm because it changes, evolves and improves the fitness aiming to the minimum of the function. Otherwise, the individuals are static entities which are born and die with certain characteristics that do not change during their existence.
4. ***Parent selection***: it is the selection based on fitness parameters, between individuals who become parents during reproduction, thus giving life to a new generation. In addition, it is based on the survival mechanism of the strongest individuals, i.e. higher

quality solutions are preferred rather than the ones with a lower level of fitness since they will lead to better generations. This does not permit a block of the algorithm among local optimals, but helps to find the global optimal.

   a. ***Rank***: the elements are ordered and chosen according to the value of the fitness function;
   b. ***Tournament***: a fixed number of individuals is casually extracted from the population and the individual with the best fitness will be chosen
   c. ***Truncation***: the solutions are ordered according to the fitness function and some of them (p=1/2, 1/5, etc.) are selected and reproduced 1/p times.

5. ***Genetic variations***: with the aim to generate new different individuals, they are:
   a. ***Recombination***: two individuals with good characteristics create one or more individuals with combined characteristics from their parents. This operator is called *crossover*, it is stochastic because of the casualty of their parents' characteristics, and probabilistic because there is a fixed probability of occurence.
      i. ***K-point crossover***: the most used are the one-point and two-point crossover;

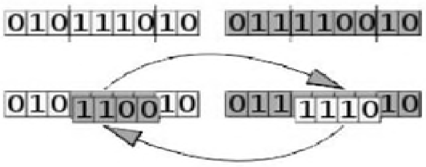


Figure 8. Two-point crossover

      ii. ***Uniform crossover***: a couple of chromosomes are casually chosen and the genes are switched among them with a given probability of occurence
   b. ***Mutation***: when applied, it changes the value of the individual. It is unitary, as this works only on a single individual to produce a different one, and stochastic, because of the casualty of the variations. This operator permits the exploration of each different candidate in order tofind the solution, avoiding the fact of remaining blocked in a local minimum. With a fixed probability of occurence, the mutation can be:
      i. ***Random resetting***: every gene can be substituted with a random value;
      ii. ***Creep mutation***: a little value is added to or subtracted from the gene.
6. ***Survivor selection***: This is the final selection which enables to choose which of the individuals will survive and will generate in the next generation.

   a. ***Total cancellation***: the generation is totally erased and replaced with a new one:
   b. ***Age based***: each individual has a maximum number of generations for survival during the creation of new generations;
   c. ***Fitness based***: based on the value of the fitness function
      i. ***Replace the worst***: the worst individual generated will be erased;
      ii. ***Elitism***: keep trace of the best individuals and copy them in the next generations. If the generated child does not turn out to be fit, it will be cancelled but the parent will remain.

An important aspect is the terminator conditions, which establish when the algorithm elaboration must end. It is obvious to think that the algorithm will stop when the global optimal value has been found, but there are no guaranties that this value will be reached in a finished time: for that reason it is important to set some parameters to respect in order to stop the elaboration.

The most common options are:

- Maximum CPU time used;
- Total number of evaluations of the fitness function reached;
- Missing increment of the fitness function in a given time period;
- The variability of the population is lower than a given benchmark.

2.5.2 Objective Function

The target of an optimization problem lies in finding the minimum or maximum objective function, called the global optimum, which is the optimal solution among all possible solutions.

This means that the determination of the global optimal solution to a problem may only be obtained through the use of exhaustive enumeration techniques, i.e., we can be sure about what the best solution is only by testing all possoble solutions .Regarding problems with a large solution space, as is mostly the case in problems related to water distribution networks, testing all solutions becomes unfeasible. Heuristics models, like GAs, provide an answer to these situations.

The GA’s complex procedures aim to resolve optimization problems, i.e. they research the maximum or the minimum of a function when this is too complex to be quickly resolved with analytic techniques. As a matter of fact, the genetic algorithm selects the best solutions and rearranges them with different methods in order to let them evolve towards the global optimum (maximum or minimum of the function), but it is not guaranteed that the global optimum will be reached it can also evolve in a local optimum.

The set of strings, with a fixed length, represent the solution space of the problem and each string represents a candidate solution of the problem. Generally, the objective function can be represented by the following expression:

$$F = \left(f(x_1, x_2, \dots, x_n)\right)$$

Using this function for each gene g_i of the initial population P(t=0), a value of the function is associated

$$F_i = F(g_i)$$

which represents the capacity of the individual to resolve the problem. Once the evaluation of the initial population is concluded, another population is generated P(t+1), with the chromosomes with higher fitness levels, applying the genetic variations, such as crossover and mutation, leading to a new set of solutions.

These techniques are interative methods that quickly find a good enough solution to a complex large problem. Not all solutions are tested, but only the ones with highest fitness. This means that these methods converge to an optimal solution, however, that there is no guarantee that this solution is the global optimum. The solution can be a local optimum, i.e., a solution that is optimal within a neighboring set of candidate solutions:

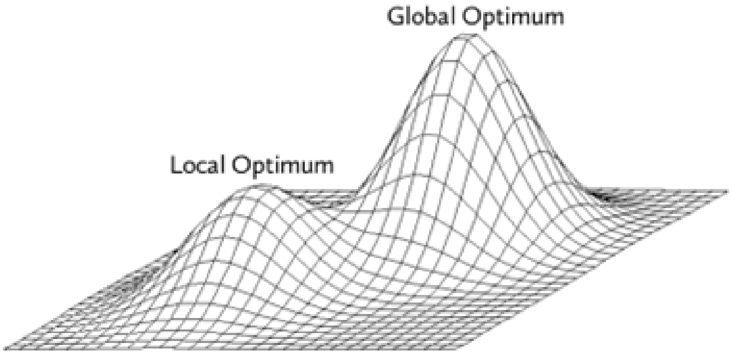


Figure 9. Representation of a local and a global optimum (Vertommen & van Thienen, 2015)

When a genetic algorithm is used, finding the best objective function is one of the main aspects; numerous parameters may be changed in an optimization problem, but they will not lead to a worst optimization just as a wrong fitness function may.. Ideally, a good objective function must be regular and flat in order to have chromosomes with a good fitness all within the same space. However, for many optimization problems it is not possible to build the function in that way, and frequently leads to finding plenty local optimum instead of the global.

An adequate choice of parameters' values are also important in order to give way to a broad search of the solution space while also converging to good solutions in reasonable time. Population size, crossover and mutation rates. A the number of function evaluations for instance, play an important role in this aspect.

A poor choice of values for these parameters can lead the algorithm to an endless search in the solution space, or can lead the algorithm to converge too quickly to a local optimum. The choice of parameters is problem specific and therefore a challenging task.

2.5.3 Computational time

In an optimization problem it is considered a good result when, by repesatedly carrying out the same simulation, they converge to the same result but it is not certain that the final result is the global optimum because the GA can remain blocked in a local optimum (Figure 5).

This result is not easily reached due to a lot of generation are needed for every simulation, prolonging the computational time. On the other hand, a simulation without plemty of generation may give different results for every simulation, with a bad quality for the optimization.

3 CASE STUDY

3.1 TERRITORIAL LOCATION

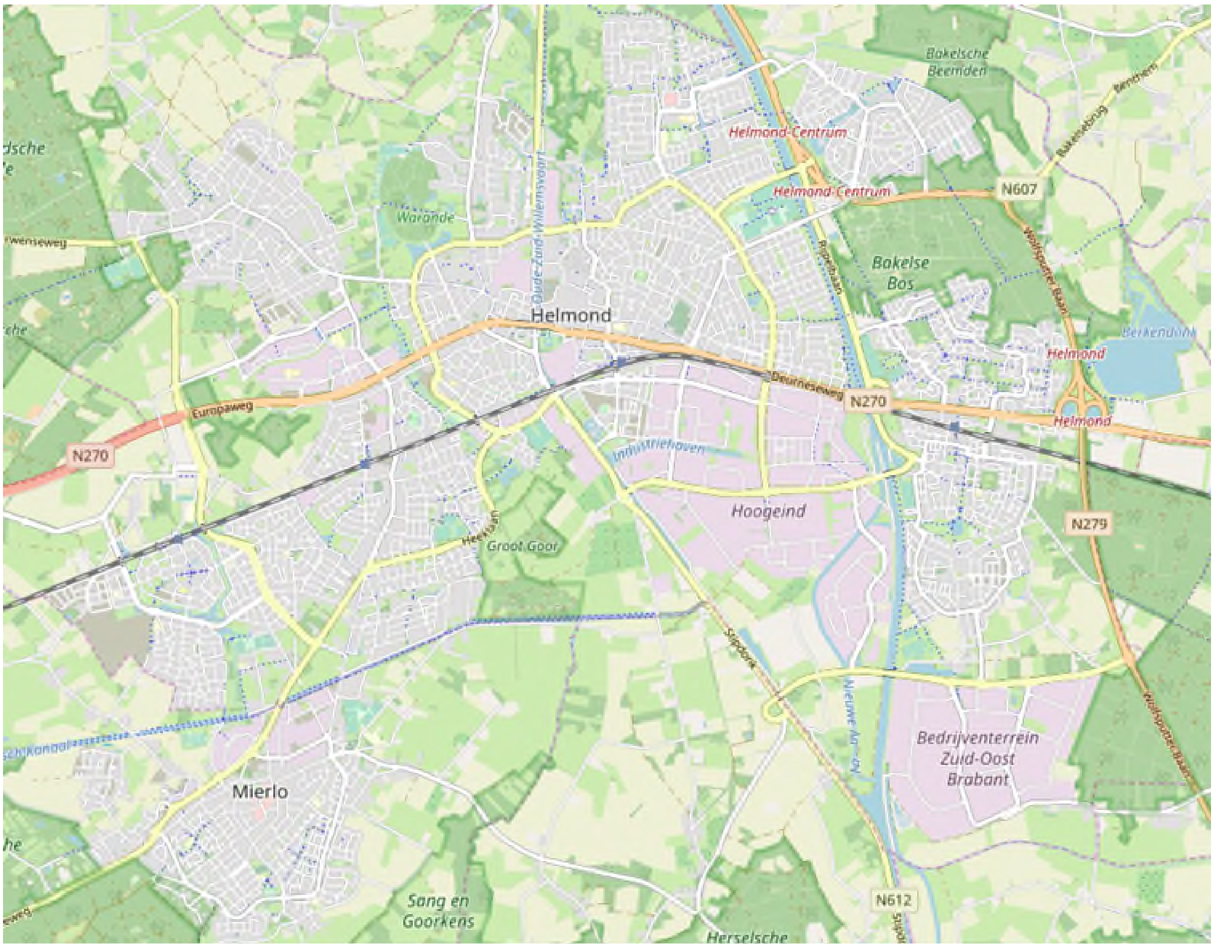


Figure 10. Location area served by the WDN

The WDN object of the study is to serve the cities of H. and M. (in Figure 10), part of the Eindhoven Metropolitan Region, in the province of Noord-Brabant, southern Holland. The Eindhoven Metropolitan Region comprises of 21 municipalities in the Eindhoven agglomeration, with a total area of 1 457.81 km^2 (Figure 11. Eindhoven Metropolitan Region Figure 11).

The city of H. covers a surface of 54.75 km^2, made up of 53.23 km^2 of land and 1.52 km^2 of water. The territory is flat and is situated at 18 m above sea level. The population is a total of 91 524 inhabitants (January 2019) with a given population density of 1.719/km^2.

The city of M. is smaller than H., with about 10 thousand inhabitants and covers an area of 18.09 km^2.

In total, the WDN in serves approximately 100 thousand people.

Figure 11. Eindhoven Metropolitan Region

3.2 THE WDN

The WDN of H. and M. is represented with an EPANET model, in Figure 12**Error! Reference source not found.**. The properties of the network can be seen in Table 1. The network is supplied by 5 reservoirs, situated in the north-east area of the territory at a height of 60 m a.s.l., and they furnish a total discharge of 31272 m^3/day. The elevation varies between 15 - 23 m.

Table 1. Properties of the WDN of H. and M.

Number of Junctions	5096
Number of Reservoirs	5
Number of Tanks	0
Number of Pipes	4311
Number of Pumps	0
Number of Valves (all open)	891

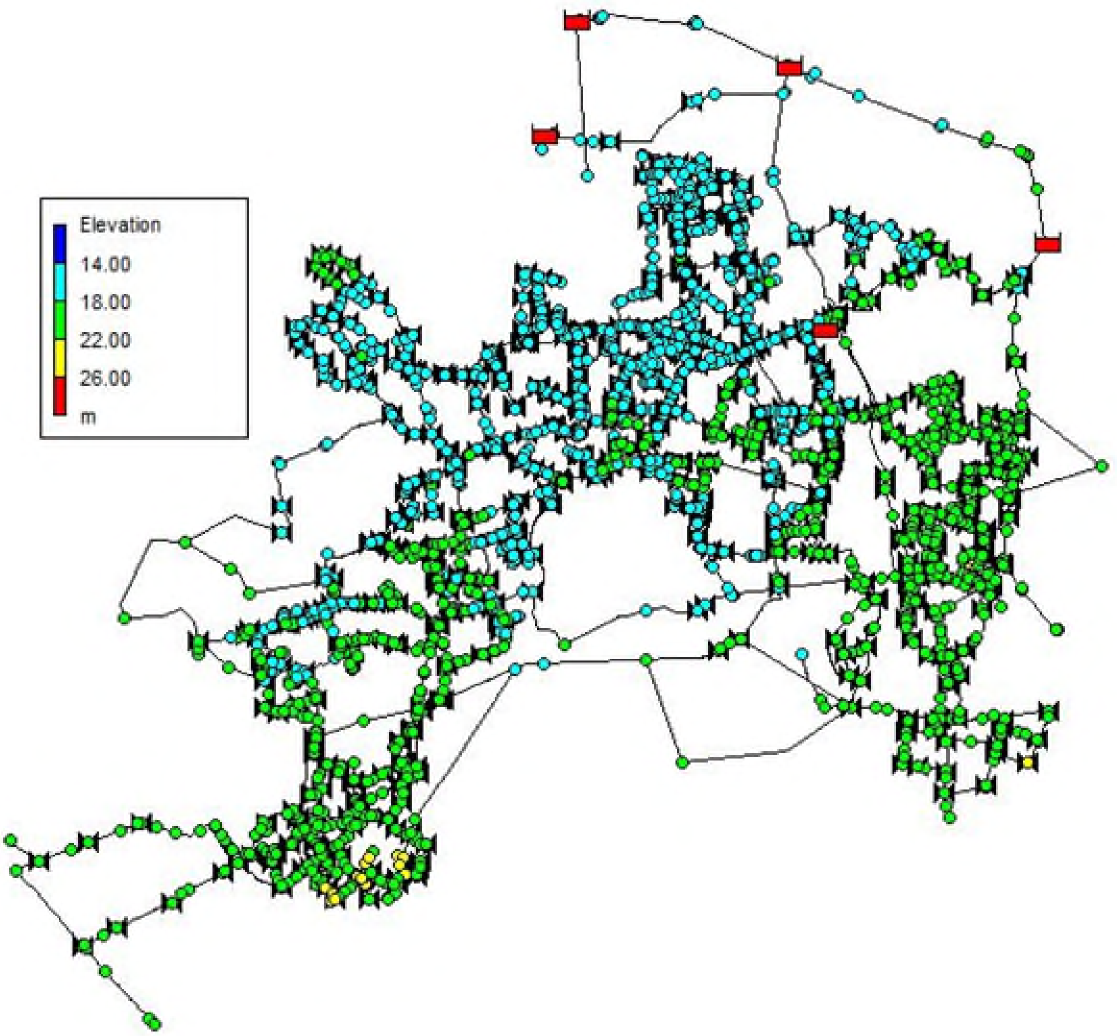


Figure 12. EPANET model of the WDN of H. and M. The reservoir are highlighted in red, the elevation is represented for the nodes.

It is important to highlight that all the valves present in the WDN have an open status. The system is highly looped in the center and in the border with new expansion zones. The WDN is mainly composed of pipes in plastic material, steel and concrete. Table 2 reports the corrisponding roughness coefficient, length and percentage of the length of the pipes made up of the same material. In Figure 13 is shown the distribution of the materials in the WDN.

Table 2. List of materials and their corresponding percentage of lenght

Materials	***Roughness [mm]***	***Lenght [km]***	***%***
Plastic materials	0.05 – 0.06	161.80	78%
Steel	0.1 – 0.2	33.27	16%
Galvanized iron	0.5	1.81	1%
Concrete	2 - 5	9.87	5%

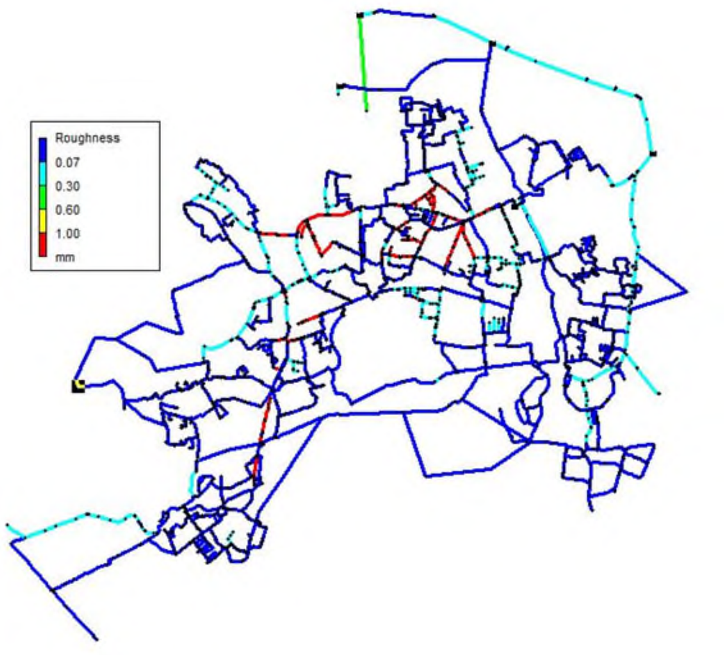


Figure 13. Distibution of the materials in the WDN

Looking at Figure 14, it is clear that the pipes which compose the WDN are mainly made of plastic material, however, a small portion is madeof steel which corresponds to the portions of pipes connecting one reservoir to the other, and concrete.

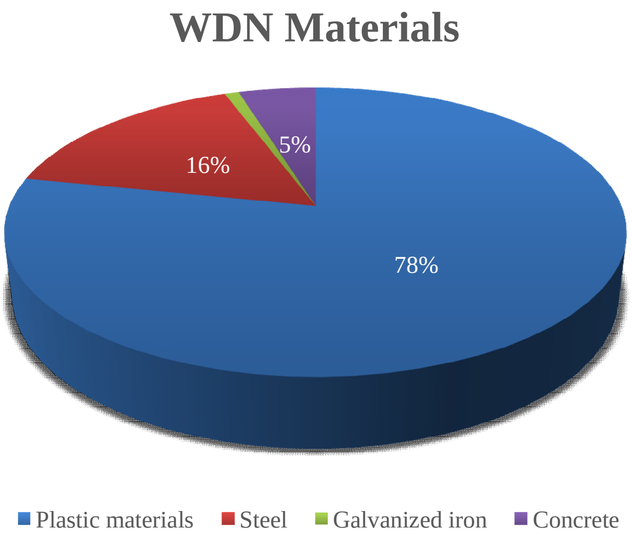


Figure 14. Percentage of the pipe materials

The diameters vary between DN 80 and DN 600 (Figure 15), where generally the pipes with an higher diameter represent the main pipes of the network that deliver the water from the reservoirs to the residential area, while the lower diameters form the loops of the network from where the connections to the users start.

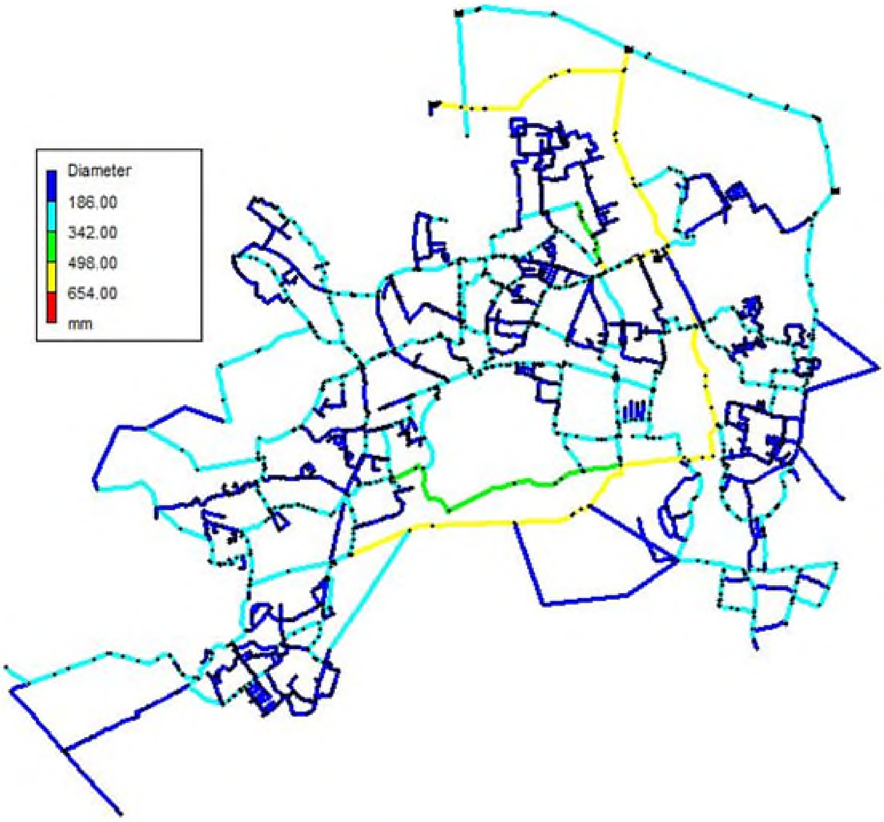


Figure 15. Distribution of the diameters in the WDN

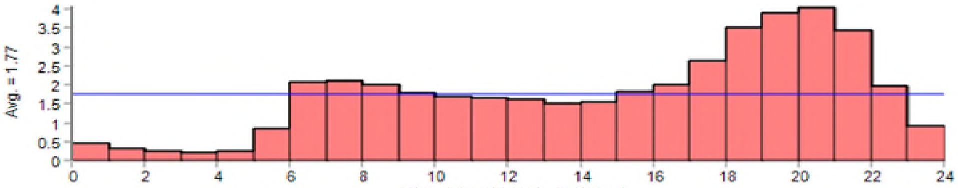
Table 3 represents the range of diameters used in the network with the corresponding length and percentage of the length of the diameters.

Table 3. Diameters of the WDN and corresponding lenght

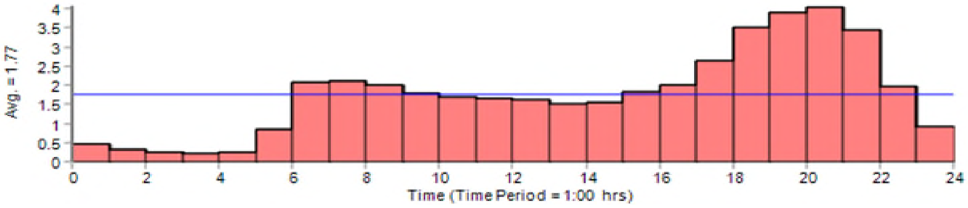
Range of diameters [mm]	**Length [km]**	**%**
80-100	54.21	26.22%
100-300	134.29	64.95%
300-600	18.25	8.83%

In this network are also present three demand pattern in order to simulate the variation of demand during the day. They have an hydraulic time step of 1 hour and they are shown in Figure 16.

Residential demand



New expansion zone



High consumption demand

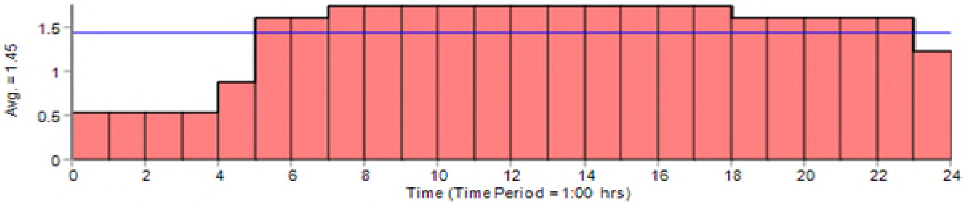


Figure 16. Demand patterns for the WDN of H. and M.

The three demand patterns simulate the demand for three different types of residential homes: among them the most used pattern is the "residential" one, representing 99% of the nodes, while the "new expansion zone" and "high consumption demand" are used only for 1% of the nodes. Even if the latter represent only 1% of the nodes, they are the ones with an higher base demand thus they represent the most critical nodes in case of a failure scenario.

4 METHODOLOGY

4.1 INTRODUCTION

In this work, a methodology aimed at improving the network resilience in critical scenarios was developed.

The methodology may be summarized in two steps:

I. A critical scenario is created with an out of service pipe and the current situation of the parameters of the water distribution network are evaluated;
II. The valve statuses are changed in order to reach an improvement in the resilience index.

With the purpose of taking into account a more critical scenario, in addition to the evaluation of the resilience index in a network with all open valves, as it is in reality, also the case with 1% of closed valves in the same network was studied, considering the fact that water companies believe this is the percentage of valves which are not in their original status.

Furthermore, the number of nodes and connections were no longer affected by the critical scenarios after the optimization process were estimated this which giving a more realistic view to the level of improvement reached with the following methodology.

4.2 VALVES IN CRITICAL SCENARIOS

Due to the fact that pipe failures occur in the drinking water distribution system, the isolation of parts of the network become essential to ensure supply continuity to the rest of the network and to minimize the effect of disruption on customers. In those critical scenarios, valves play an important role, in fact, in changing their operational status, it is possible to minimize the demand deficit caused by the critical scenarios.

In this work, in order to reach a high resilience in the water distribution network in an emergency situation, the valves statuses are changed by the numerical algorithm used in Gondwana. Moreover, a scenario with 1% of closed valves has been studied because the Dutch water companies admit that is 1% of the valves are not in their original status. Valves can fail for many reasons when they need to be closed: a broken valve stem or other mechanical problems (e.g. rounded operating nut), or the inability to locate the valve (e.g. cover paved over), or the inability to turn/reach the valves due to an obstruction (e.g. a blocked valve box) (Liu, et Al., 2017).

4.2.1 Type of valves

The most used valves in water distribution networks can be categorized as:

- ***Isolation valves***, used to isolate a section for maintenance and repair and are located so that the isolated areas will cause a minimum of inconvenience to other service areas. The maintenance of the valves is one of the major activities carried out by a utility. Many utilities have a regular valve-turning program in which a percentage of the valves are opened and closed on a regular basis. It is desirable to turn each valve of the system at least once a year. The implementation of such a program ensures that water can be closed off or diverted when necessary, especially in the case of an emergency, and furthermore, that valves have not been inadvertently closed. The most used are *gate valves* or *butterfly valves*.

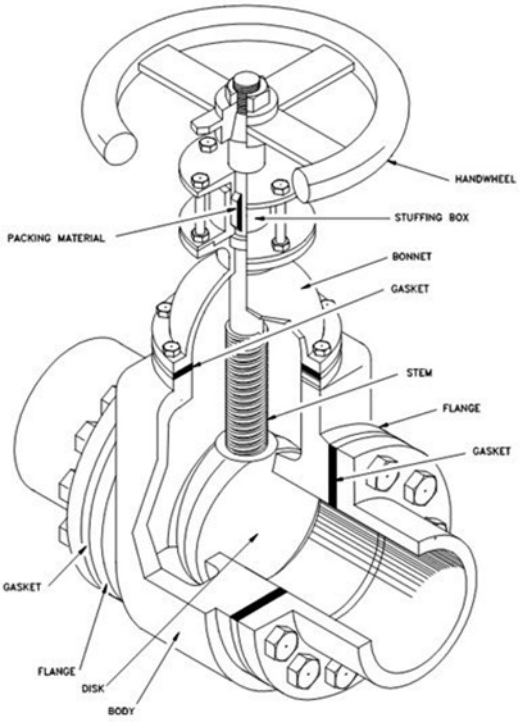


Figure 17. Gate valve

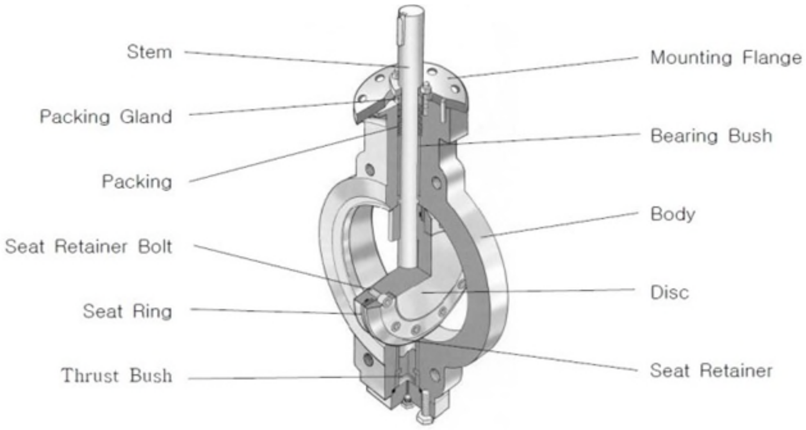


Figure 18. Butterfly valve

- ***Control valves***, are used to control the flow or pressure in a distribution system. They are normally sized based on the desired maximum and minimum flow rates, the upstream and downstream pressure differentials, and the flow velocities. Typical types of control valves include *pressure-control valves*, *flow-control valves*, *float valves* and *check valves*.

Due to the fact that control valves are more expansive in cost and regulations than isolation valves, in present research only isolation valves are taken into consideration. Furthermore, every valve can have a degree of openness but in this case, only the boolean variables, open and closed, were used.

4.3 SCENARIOS

A network can be defined as resilient if it has a good degree of continued performance under disturbance. This means that must be taken into account the influence of the future scenarios, that cannot be estimated by simple parameter sensitivity or even extrapolations of historic parameters. The infinite different future scenarios are open ended and complex.

In this work the scenarios studied concern a pipe failure in each scenario. Just because the future scenarios are unknown, every pipe of the WDN can fail, so a complete analysis of the problem should simulate *n* scenarios for *n* pipe present in the network. Due to the fact that the computational times weren’t as short to take into account every single pipe of the WDN, an empirical approach was used to select the ruptures.

4.4 GONDWANA

With the aim of providing a useful tool for the optimization of WDN, van Thienen & Vertommen (2015) developed a generic software platform “Gondwana”, which is currently being further developed. Lately, a resilience index has been inplemented based on the demand satisfaction rate, purposed by Creaco et al. (2014), which quantifies the capability of a network to deliver water under critical events, taking into account pressure-driven demand, and therefore the impact that the event has on the consumer.

4.4.1 The software

GONDWANA stands for *Generic optimization tool for network design add operation* (van Thienen & Vertommen, 2015), and is an optimization platform designed to address optimization problems in the framework of Drinking Water Distribution Systems.

The core idea of the optimization platform lies in the fact that any parameter that describes part of a hydraulic network model or its operation, and which is marked by the user as a degree of freedom, can be automatically changed by the software. An evaluation of the resulting network design is then performed in the context of the prescribed objective(s). Several inputs and components are required for any algorithm to update a network design towards an optimum. The required inputs are the hydraulic model itself, a list of decision variables, one or more objectives and boundary conditions. The required components are a hydraulic simulation function or program, an optimization algorithm, and a function which evaluates the performance of the design in terms of the optimization objective(s).

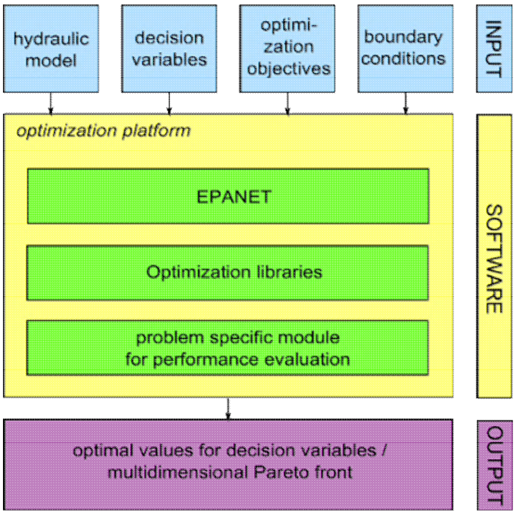


Figure 19. Gondwana Process (Vertommen & van Thienen, 2015)

Table 4 summarizes the different tab pages in which Gondwana is organized together with their corresponding functionality. The different tab pages are interlinked and elements defined in one tab may be selected in other tabs.

Table 4. Sections in Gondwana (Vertommen & van Thienen, 2015)

Tab	**Description**	**Functionality**
Network	Initiation of optimization problem definition.	→ Loading initial EPANET problem file; → Definition of node and link selections; → Initiation of problem definition wizard for predefined problems.
Scenarios	Definition of multiple types of scenarios.	→ network modification scenarios; → nodal demand scenarios; → contamination scenarios.
Dataset	Definition/import/export of additional data.	→ specific restrictions (not dependent of simulation results); → data lists; → roughness coefficient.
Decision variables	Selection of single or multiple sets of decision variables.	→ Available sections and parameters; → Application to node and/or link selections defined on the Network tab.
Objective	Definition of single or multiple optimization objectives.	→ Application to node and/or link selection defined on the Network tab; → Inclusion of data defined on the Requirements tab; → Application of scenarios defined on the Scenarios tab.
Constraints	Definition of one or more sets of constraints.	→ Application to node and/or link selection defined on the Network tab; → Inclusion of data defined on the Requirements tab; → Application of scenarios defined on the Scenarios tab; → Choice of enforce or penalty constraints; → Linking of constraints to specific objectives defined on the Network tab.
Optimization	Selection of optimization process parameters.	
Run	Scheduling and running of optimization problems.	→ Interactivity during computations; → Parallel processing; → Visualizing convergence curves and evolving Pareto front.
Results	Visualization and export of optimization results.	

4.4.2 Input data in Gondwana

A total of 18 critical scenarios have been considered. Each critical scenarios assumes that one pipe in the network is out of service. In order to make a selection of these pipes different parameters such as the diameter and length, the highest flow and the proximity to the node with the highest base demand were considered. Table 5 summarizes the length and diameter of the considered pipes. Figure 20 illustrates the location of the pipes in the network:

Table 5. Considered pipe ID's in Gondwana for the different critical scenario's and corresponding , length and diameter

Scenario	Pipe ID in Gondwana	Pipe ID in EPANET	Length [m]	Diameter [mm]
1	2	X12315.lungend01	1066.05	152
2	13	X12315.X13508	1001.13	593.30
3	25	X13841.brandv01	945.07	190
4	1	X14026.X07530.1	523.94	376.60
5	20	X08402.X07917	430.75	125.00
6	7	X12079.X00027a	763.37	190
7	4	X09786.X14769	734.96	296.6
8	17	X08181.X13053	1262.51	104
9	5	X06417.X06424	864.62	593.30
10	3	X14280.X11910	548.16	296.6
11	19	X07737.X07735	833.29	200.00
12	16	X00370.X06749	974.71	593.30
13	21	lungend01.X08125	1776.89	104
14	24	X02169.X08124	263.46	188.19
15	9	X14776.X12641	2000	237
16	11	brandv01.brandv02	1161.86	152
17	26	brandv04.brandv02	510.89	190
18	27	X14061.X10869	501.1	593.3

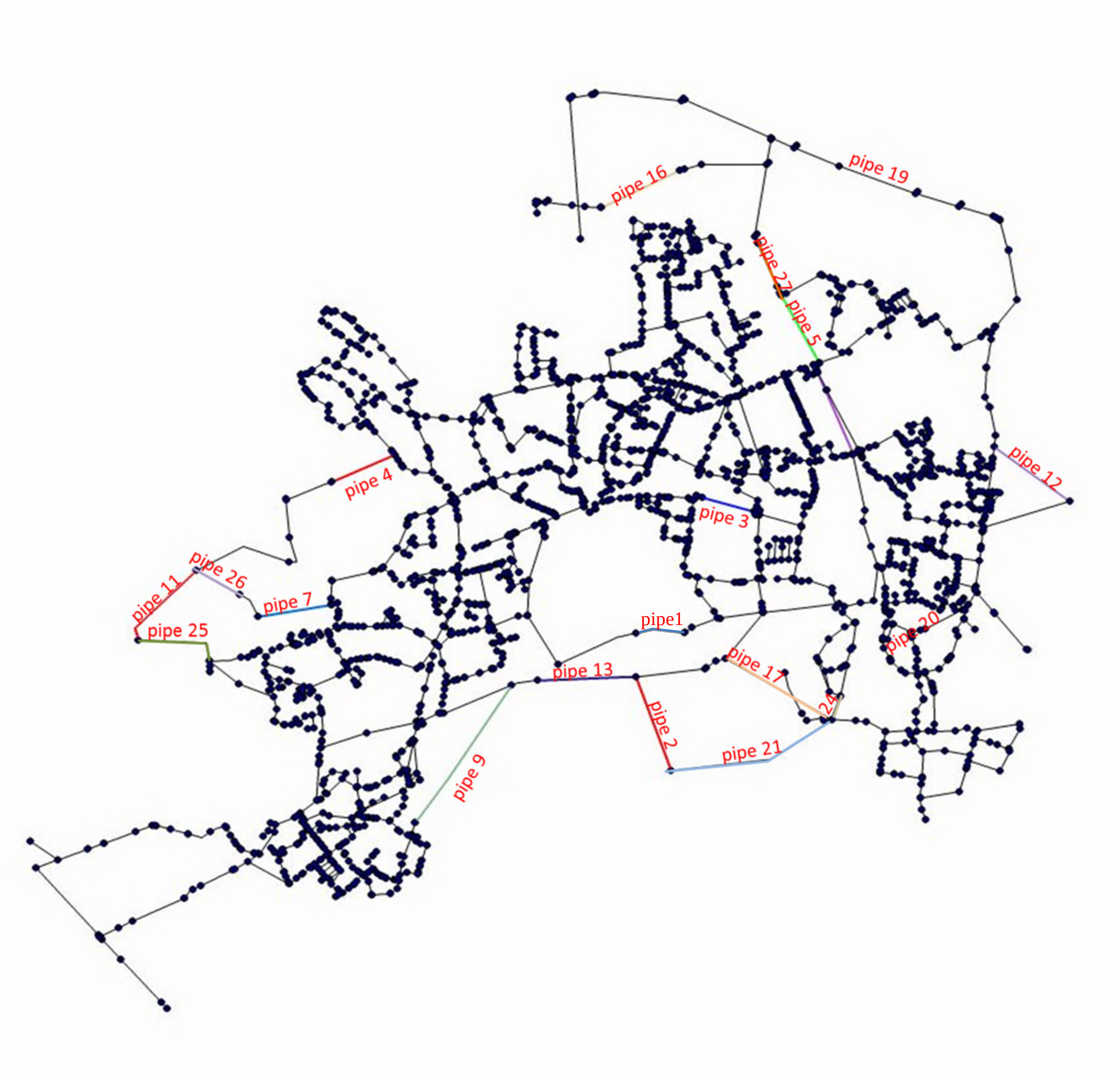


Figure 20. Location of the considered pipes in the network of Helmon-Mierlo (pipe ID in Gondwana)

It is assumed that the events take place during an entire simulation period (00:00 – 24:00). In real-life situations it is important to consider the actual start time of an event and its duration, and compute the resilience in this time period. A critical pressure, $H_{i,min}$, equal to 20 meters is considered for the computation of the pressure delivered demand. This means that for nodes with a pressure below 20 meters, the volume of water that is actually delivered is less than the demand, and is determined through a pressure driven simulation of the network.

4.5 OPTIMIZATION ALGORITHM

The following process was performed in order to investigate whether it is possible to improve a network resilience under critical scenarios by changing its operational mode;

1. The critical scenarios are created by changing to zero the diameter of the pipe that fails.
2. The demand satisfaction rate is determined for each scenario without changing valve statuses (current valve statuses) in order to get the initial resilience index of the WDN;
3. The valve statuses are changed with the numerical optimization technique implemented in Gondwana and the resilience index is again computed in order to minimize the demand deficit. This step is repeated in order to find the valve settings that maximize the demand satisfaction rate. For optimization, different objective functions were considered:
    a. Minimization of the total demand deficit;
    b. Minimization of the demand deficit at the node with the highest demand deficit;
    c. Minimization of the highest demand deficit in the simulation period for each node.

4.5.1 Step 1: Initial situation

Once the out of service pipe is selected, the performance of the initial situation, i.e. without changing valves status, is obtained by setting the optimization parameters to zero and computing only one generation. The initial situation is computed in Gondwana, instead of EPANET, in order to be able to run the model as pressure driven, which is necessary to obtain the desired demand satisfaction rates.

Table 6 summarizes some examples of the obtained results for each node of the network, and for each time step in the simulation period:

Table 6. Example of the data exported from Gondwana

Nodes	Node requested demands d_i	Node demands $q_{i,s}$	Node demand deficit $d_i - q_{i,s}$	Node demand satisfaction DSR_s
k010	0	0	0	-1
k030	0.0307853	0.03068585	9.9448E-05	0.99676964
X00002	0	0	0	-1
X00003	0	0	0	-1
(…)				

From the “node demand satisfaction”, which represents the resilience index, it is possible to get the unsatisfied demand for each node: value 1 means that the requested demand is equal to the delivered demand, otherwise there will be the ratio between the requested and delivered demand, as explained in the DSR equation .

Evaluating the results for all time steps in the simulation period, it is possible to obtain the node with maximum unsatisfied demand for every time step. In Table 7 an example of the results considering an out of service pipe.

Table 7. Unsatisfied demand for scenario 1 (pipe 2 out of services)

Hours	Max unsatisfied demand
0	7.38%
1	7.27%
2	7.20%
3	7.18%
4	7.94%
5	12.02%
6	19.50%
7	19.80%
8	19.07%
9	16.81%
10	16.03%
11	15.49%
12	15.14%

13	14.69%
14	14.79%
15	17.35%
16	19.04%
17	26.23%
18	29.60%
19	46.44%
20	47.74%
21	26.91%
22	18.47%
23	9.91%

The maximum unsatisfied demand occurs during the peak hour at 20:00, therefore it is also possible to note in the demand patterns in Figure 16. Demand patterns for the WDN of H. and M For this reason, only the peak hour was studied.

4.5.2 Step 2: Optimization of the network during the critical scenarios

In this step the valve statuses are changed in order to reach an optimal valve status which leads to an improved network with less demand deficit.

4.5.2.1 The objective functions

The evaluation is performed in Gondwana, allowing us to choose the different parameters related to the optimization problem. In this case, three different objective functions have been used in order to select the function that provides the best improvement:

- The first objective function considered in the optimization is the *sum* of the demand deficit, which optimizes the total demand deficit summed over all nodes of the network and all time steps of the simulation period:

$$min \sum_{t} \sum_{i=1}^{n} \frac{\sum_{i}^{ND} q_{i,s}}{\sum_{i}^{ND} d_i}$$

  Where $q_{i,s}$ is the available water that can be delivered under a critical scenario and d_i is the water required by the consumers under normal circumstances.

- The second objective function considered in the optimization process is the “*maximum network*”, which minimizes the demand deficit at the nodes of the network with maximum demand deficit in each time step:

$$min \sum_{t} \frac{q_{nmin,s}}{d_{nmax}}$$

  Where $q_{n\,min,s}$ is the minimum flow available under a critical scenario and d_{nmax} is the maximum water required by the consumers under normal circumstances.

- The last objective function considered is “*maximum element*” which optimizes the maximum demand deficit of each node of the network evaluated over the entire simulation period:

$$\min(max_t \frac{q_{nmin,s}}{d_{nmax}})$$

Where $q_{n\ min,s}$ is the minimum flow available under a critical scenario and d_{nmax} is the maximum water required by the consumers under normal circumstances.

The considered optimization parameters for the genetic algorithm are summarized in Table 8.

Table 8. Considered optimization parameters for the genetic algorithm in Gondwana

Population size (number of individuals)	200
Initialization	Current values
Selector	Tournament
Elitism rate	10%
Terminator	50 generations
Uniform mutation rate	0.001
Crossover rate (one point crossover)	0.95

Exporting again all the results from Gondwana, as shown in the example in Table 9, relative to the objective function “sum”, it is possible to assess the unsatisfied demand after the optimization process. What has been taken into consideration in each step is the maximum percentage of unsatisfied demand before the optimization and the maximum percentage of unsatisfied demand after the optimization among nodes. The improvement was then calculated by calculating the difference between those two values:

Table 9.Unsatisfied demand before and after the optimization for each time step for pipe 2 out of service

Time step	**Start**	**Optimized**	**Difference**
0	7.38%	7.38%	0.00%
1	7.27%	7.27%	0.00%
2	7.20%	7.20%	0.00%
3	7.18%	7.18%	0.00%
4	7.94%	7.94%	0.00%
5	12.02%	12.01%	0.01%
6	19.50%	19.50%	0.00%
7	19.80%	19.80%	0.00%
8	19.07%	19.07%	0.00%
9	16.81%	16.81%	0.00%
10	16.03%	16.03%	0.00%
11	15.49%	15.49%	0.00%

12	15.14%	15.14%	0.00%
13	14.69%	14.69%	0.00%
14	14.79%	14.79%	0.00%
15	17.35%	17.25%	0.10%
16	19.04%	19.04%	0.00%
17	26.23%	26.22%	0.00%
18	29.60%	29.59%	0.01%
19	46.44%	28.07%	18.37%
20	47.74%	24.47%	23.27%
21	26.91%	26.91%	0.00%
22	18.47%	18.51%	0.00%
23	9.91%	9.91%	0.00%

The column “difference” shows the improvement between the initial situation and the optimized situation, where the valve statuses have been changed to minimize the total demand deficit.

Since the maximum demand deficit in the initial situation and in the optimized situation may not correspond to the same node, each node was also compared between the initial situation and the optimized situation, thus, for every time step, the node with the maximum improvement has been obtained i.e. the one with the most critical condition, as reported in Table 10:

Table 10.Maximum optimization per node per time step

Time step	Optimization per node
0	0.03%
1	0.01%
2	0.01%
3	0.01%
4	0.01%
5	0.08%
6	0.39%
7	0.40%
8	0.37%

9	0.29%
10	0.27%
11	0.26%
12	0.25%
13	0.22%
14	0.23%
15	0.32%
16	0.37%
17	0.59%
18	0.92%
19	18.37%
20	26.57%
21	0.80%
22	0.36%
23	0.08%

5 RESULTS

5.1 OBJECTIVE FUNCTIONS COMPARISON

Table 11 summarizes the results in terms of percentage of improvement of the demand satisfaction rate for considered scenario and each objective function.

Table 11.Result comparison between the three objective functions

pipe out of service	*Initial situation*	*Objective function*					
	Critical Hour: 20	**Sum**		**Max Network**		**Max element**	
	Unsatisfied demand	**max opt time step**	**max opt node**	**max opt time step**	**max opt node**	**max opt time step**	**max opt node**
2	47.74%	23.27%	24.05%	23.16%	26.57%	23.22%	24.23%
13	37.43%	1.03%	2.66%	0.86%	1.11%	0.00%	1.26%
7	31.37%	0.41%	0.41%	0.41%	0.41%	0.60%	0.60%
25	29.28%	0.53%	0.68%	0.55%	0.55%	0.01%	0.10%
1	26.26%	0.23%	0.24%	0.40%	0.47%	0.49%	0.62%
11	25.58%	0.00%	0.35%	0.36%	0.38%	0.35%	0.92%
9	25.25%	0.00%	0.35%	0.17%	0.37%	0.12%	0.75%
26	25.18%	0.34%	0.36%	0.00%	0.22%	0.32%	0.47%
3	25.17%	0.25%	0.89%	0.00%	1.14%	0.43%	0.92%
4	25.04%	0.34%	0.48%	0.00%	0.50%	0.00%	0.02%
27	24.87%	0.51%	0.67%	0.33%	0.36%	0.33%	0.36%
5	24.86%	0.33%	0.36%	0.32%	0.47%	0.19%	0.34%
17	24.85%	0.33%	0.36%	0.00%	0.35%	0.19%	0.34%
12	24.85%	0.00%	0.22%	0.32%	0.77%	0.19%	0.34%
20	24.85%	0.42%	0.56%	0.00%	0.22%	0.00%	0.01%
16	24.85%	0.00%	0.30%	0.16%	0.47%	0.00%	0.01%
19	24.85%	0.18%	0.62%	0.32%	1.05%	0.24%	0.92%
21	24.82%	0.00%	0.35%	0.00%	0.35%	0.34%	1.26%
24	24.78%	0.00%	0.26%	0.00%	0.26%	0.26%	0.93%

The scenarios have been ordered from the higher initial unsatisfied demand to the lower, thus, for pipe 2 out of service, there will be the most critical scenario, while for pipe 27 out of service, there will be the mildest scenario, with a small initial unsatisfied demand.

For each pipe considered to be out of service, the initial unsatisfied demand is always higher than 20% during the peak demand hour however, after the optimization process, this is a lower value due to the fact that some valves have been closed to reach the minimum demand deficit, i. e. the minimum resilience index.

As we can see, every scenario was improved, for example, from the result obtained when pipe 2 was out of service, with an initial unsatisfied demand of 47.7% and an optimization in terms of demand satisfaction rate of more than 20% for all of the considered objective functions used.

Table 12 shows the numbers of valves closed for each scenario and objective function. On average the objective function “maximum element” tends to close more valves than the other two objective functions.

Table 12. Number of closed valves for each scenario and objective function

	Objective Functions		
Pipe out of service	*Sum*	*Maximum Network*	*Maximum Element*
2	5	6	8
13	3	4	8
7	2	5	4
25	8	4	5
1	2	4	2
11	3	3	6
9	3	4	3
26	7	6	7
3	4	4	6
4	3	4	1
27	5	6	2
5	4	4	7

17	3	3	7
12	3	4	4
20	6	4	5
16	4	4	5
19	3	6	5
21	3	3	3
24	3	3	4
Average	4	4	5

With the aim of comparing the three objective functions and understanding which performs better than others, in improving the resilience of a network, a graphical representation of the improvement of the demand satisfaction at each time step of the simulation period has been drawn, for each of the pipes considered to be out of service.

The obtained graphs, reported in the appendix, show that there is no objective function that clearly performs better than others, but their performance seems to be dependent on the considered case. In some cases, the functions give the same results.

5.2 MOST OPERATED NODES

In order to find out which are the most operated valves in the WDN, and keep them under control to make sure they will work well during the years, the valves that occur to be the most closed during a critical scenario were counted. Table 13 shows the most operated valves using the objective function sum, in Table 14 using the objective function maximum network and in Table 15 using the maximum element, always taking into account all the critical scenarios.

Table 13. Most operated valves with the objective function sum

Sum

Valve ID	81-82	253-254	839-840	1217-1218	1857-1858	2001-2002	3101-3102	6723-6724	7361-7362
Use	5	5	9	2	7	3	5	7	2

Table 14. Most operated valves with the objective function Maximum network

Valve ID	57-58	81-82	253-254	839-840	1857-1858	2001-2002	3101-3102	6723-6724
Use	2	7	2	11	7	4	5	10

Table 15. Most operated valves with the objective function Maximum element

Valve ID	81-82	83-84	253-254	835-836	839-840	2395-2396	2769-2770	4127-4128	4611-4612	4785-4786	7275-7276
Use	5	5	3	4	11	5	8	8	3	3	3

When the need to close a valve occurs, the case may be that it does not work due to insufficient maintenance and aging. The most operated valves are those that Water Companies have to maintain the most in order to have a working network when a critical scenario occurs.

5.3 CONVERGENCE CURVE

Bearing in mind the purpose of finding out whether there is a set of closed valves in which the simulation converges for the same critical scenario, two simulations with thousands of generations were run in Gondwana for the most critical scenario (pipe 2 out of service).

Table 16. Optimization parameters for the convergence for pipe 2 out of service

Optimization parameters	
Population size	200
Initialization	Current values
Selector	Tournament
Terminator	3000 generations
Uniform mutation rate	0,001
Crossover rate	0,95

Looking at the convergence curve in Figure 21, which represents the solutions of the objective function, thus closing a set of valves for each generation, it is possible to note that the convergence is already reached before 600 generations, in fact the algorithm returns the same solutions from the 600th generation right up to the end. Furthermore, the objective function is a curve without the regular aspect of a corvergence curve, but the solutions form some “steps” as generations progress.

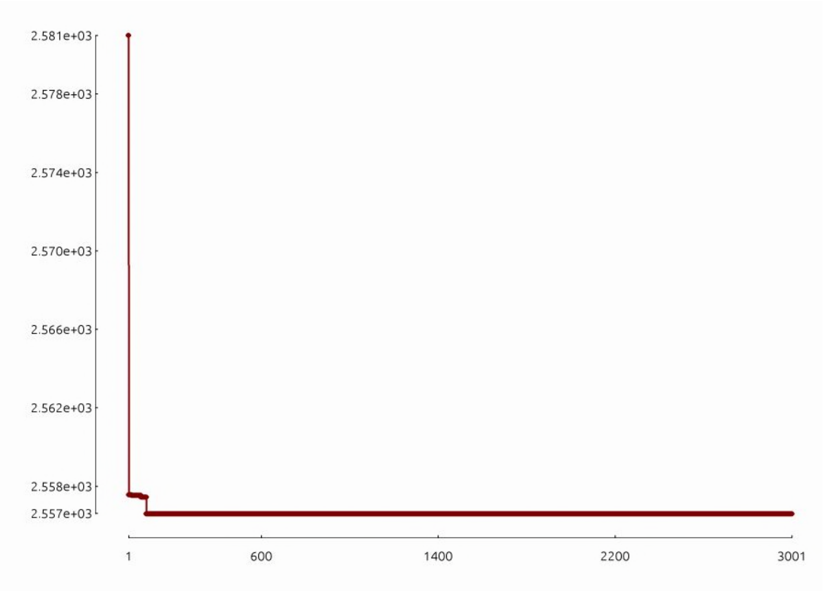


Figure 21. Convergence curve for pipe 2 out of service, with 3000 generations

Considering the results from the two simulations, it is possible to see that each one of them leads to a different set of closed valves ino order to improve the resilience of the network, with only two closed valves in common (Table 17):

Table 17. Set of closed valves from the 3000 generations simulations

Simulation 1	*Simulation 2*
X00081.X00082.1	X00839.X00840.1
X02507.X02508.1	X02507.X02508.1
X02545.X02546.1	X03099.X03100.1
X03027.X03028.1	X04127.X04128.1
X03099.X03100.1	X04173.X04174.1
X03101.X03102.1	X04843.X04844.1
	X06723.X06724.1

An interesting aspect of these simulations is to observe the improvements in terms of unsatisfied demand, as shown in Table 18:

Table 18. Percentage of improvement in the 3000 generations simulations for scenario 1, pipe 2 out of service

Simulation	*Initial Unsatisfied demand*	*Optimized*	*Difference*	*Optimization per node*
1	47.74%	24.49%	23.25%	26.58%
2	47.74%	24.50%	23.23%	27.28%

In both cases the simulations have reached the same level of improvement, either in time steps or in the node. This means that in a network with almost 900 valves, different sets of closed valves lead to the same improvement, thus guaranteeing different ways of ensuring the water supply in critical scenarios.

5.4 CRITICAL NODES

By exporting the results from Gondwana it is possible to see which are the nodes with higher unsatisfied demand in the initial situation, thus the most affected node from the critical scenario.

Looking at the results in Table 19, the most influenced node is “brandv02”, corresponding to the pattern describing the new expansion node demand. In general, the nodes which corrispond to this pattern are the most affected and have the higher base demand.

Table 19. Critical node for each scenario and corresponding pattern and base demand

Pipe out of service	*Critical Node*	*Pattern*	*Base Demand [m^3/h]*
2	lungend01	New expansion zone	11.608334
13	X14321	Residential demand	0.023217
7	brandv04	New expansion zone	12.769166
25	brandv01	New expansion zone	7.545417
1	brandv02	New expansion zone	4.062917
11	brandv02	New expansion zone	4.062917
9	brandv02	New expansion zone	4.062917
26	brandv02	New expansion zone	4.062917
3	brandv02	New expansion zone	4.062917
4	brandv02	New expansion zone	4.062917
27	brandv02	New expansion zone	4.062917

5	brandv02	New expansion zone	4.062917
17	brandv02	New expansion zone	4.062917
12	brandv02	New expansion zone	4.062917
20	brandv02	New expansion zone	4.062917
16	brandv02	New expansion zone	4.062917
19	brandv02	New expansion zone	4.062917
21	brandv02	New expansion zone	4.062917
24	brandv02	New expansion zone	4.062917

5.5 THE NUMBER OF NODES WITH INSUFFICIENT DEMAND

A way to estimate the number of customers affected by the critical scenario, were considered to be the nodes in which the demand was not satisfied.

In order to verify whether there is an improvement in terms of the number of nodes with insufficient demand, the above number of nodes with unsatisfied demand give threshold before and after the optimization has been counted.

Different thresholds of unsatisfied demand have been investigated. The number of nodes with an unsatisfied demand higher than 30%, 25%, 20% and 15% before and after the optimization have been counted. Based on the count, calculating the difference between the initial value and the optimized value, the percentage of optimized nodes for each scenario and each threshold has been obtained.

Table 20 shows the results in terms of the percentage of saved nodes, i.e. the percentage of nodes no longer affected by the critical scenario.

Table 20.Percentage of improved nodes after the optimization process

Demand deficit	30%			25%			20%			15%			10%		
pipe out of service	***Before***	***After***	***% saved nodes***	***Before***	***After***	***% saved nodes***	***Before***	***After***	***% saved nodes***	***Before***	***After***	***% saved nodes***	***Before***	***After***	***% saved nodes***
2	1	0	***100%***	1	0	***100%***	215	213	***1%***	872	850	***3%***	1496	1480	***1%***
13	457	342	***25%***	815	803	***1%***	998	984	***1%***	1097	1089	***1%***	1603	1556	***3%***
7	2	2	***0%***	4	4	***0%***	238	230	***3%***	851	848	***0%***	1496	1491	***0.3%***
25				13	3	***77%***	276	227	***18%***	852	843	***1%***	1510	1497	***1%***
1				21	21	***0%***	434	408	***6%***	916	915	***0.1%***	1620	1615	***0.3%***
11				2	2	***0%***	255	255	***0%***	852	852	***0%***	1508	1508	***0%***
9							387	387	***0%***	897	897	***0%***	1508	1508	***0%***
26							240	218	***9%***	853	848	***1%***	1506	1491	***1%***
3							307	250	***19%***	877	864	***1%***	1525	1515	***1%***
4							240	221	***8%***	853	848	***1%***	1506	1492	***1%***
27							245	226	***8%***	855	850	***1%***	1507	1495	***1%***
5							243	226	***7%***	853	850	***0.4%***	1507	1494	***1%***
17							243	226	***7%***	850	847	***0.4%***	1506	1493	***1%***

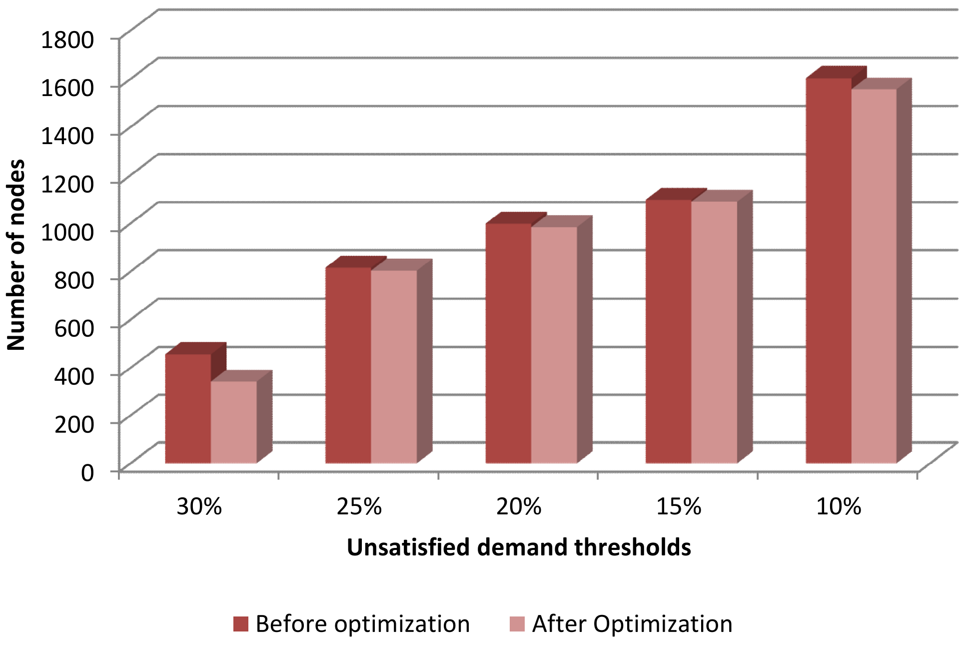


Figure 22. Node comparison between initial situation and optimization with different unsatisfied demand thresholds for scenario 2, pipe 13 out of service

Looking at the single scenario, as shown in Figure 22, the percentage of optimized node above the given threshold is higher in the case of a high unsatisfied demand. For scenario 2, with pipe 13 out of service, 25% of the nodes which were affected by the critical situation, have been saved for an unsatisfied demand above 30%.

Table 20 shows the result in terms of the percentage of improved nodes for each of the unsatisfied demand thresholds. Generally, the optimization has saved a good percentage of nodes with unsatisfied demands, especially for the most critical scenarios, where there is an high unsatisfied demand.

As represented in Figure 23, and considering all the critical scenarios, on average 53% of the nodes with an unsatisfied demand above 30% have been saved after the optimization, 37% of the nodes with unsatisfied demand above 25% have been saved after the optimization a minimum percentage of node have been saved for lower percentage of initial unsatisfied demand. This means that a good level of optimization, in terms of nodes that supply water even in a critical scenarios, is reached.

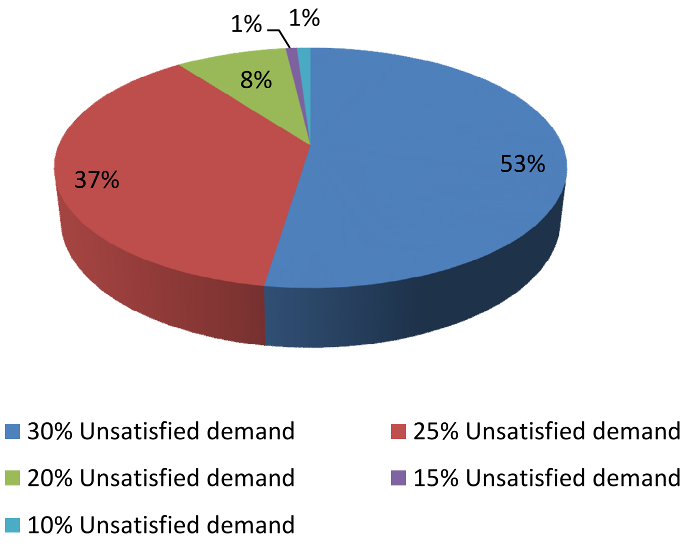


Figure 23. Percentage of the number of nodes saved after the optimization for each unsatisfied demand threshold

5.6 NUMBER OF CONNECTIONS WITH INSUFFICIENT DEMAND

An interesting point of view is to investigate the number of connections, i.e. the number of users that will be able to have the supply after the optimization of the network in the critical scenarios. Thanks to the water companies which are able to provide the number of connections for each node, it is possible to trace back the number of connections affected by the critical scenarios and the ones no longer affected , after the optimization. This represents a different point of view, compared to the number of nodes with insufficient demand, because in the WDN it is possible to either have nodes with a large number of connections or nodes with few connections: if one of the nodes in the first category is affected by the critical scenario a large amount of users will not be able to have the water supply, creating an unsatisfactory situation.

In order to do this, the number of connections with unsatisfied demand above a given threshold before and after the optimization, have been counted. Different thresholds of unsatisfied demand have been investigated. The number of connections with an unsatisfied demand with higher than 30%, 25%, 20% and 15% before and after the optimization have been counted, and then, calculating the difference, it is possible to obtain the percentage of connections that are able to supply water in the critical scenario studied.

Table 21. Percentage of connection saved after the optimization process

Demand deficit	30%			25%			20%			15%			10%		
Pipe out of service	***Before***	***After***	***% Connections saved***	***Before***	***After***	***% Connections saved***	***Before***	***After***	***% Connections saved***	***Before***	***After***	***% Connections saved***	***Before***	***After***	***% Connections saved***
2	1	0	***100%***	1	0	***100%***	742	739	***0.40%***	2607	2551	***2%***	4843	4808	***1%***
13	1484	1148	***23%***	2522	2457	***3%***	998	984	***1%***	3346	3342	***0.12%***	5077	5018	***1%***
7							815	767	***6%***	2565	2548	***1%***	4841	4829	***0%***
25				21	0	***100%***	887	768	***13%***	2568	2560	***0.31%***	4871	4837	***1%***
1				53	53	***0%***	1319	1269	***4%***	2847	2846	***0.04%***	5178	5150	***1%***
11							822	822	***0%***	2568	2568	***0%***	4859	4859	***0%***
9							1201	1201	***0%***	2726	2726	***0%***	4855	4855	***0%***
26							817	749	***8%***	2577	2550	***1%***	4859	4829	***1%***
3							992	856	***14%***	2672	2623	***2%***	4899	4886	***0%***
4							816	746	***9%***	2577	2550	***1%***	4859	4835	***0%***
27							826	756	***8%***	2585	2562	***1%***	4867	4841	***1%***
5							824	756	***8%***	2577	2562	***1%***	4867	4839	***1%***
17							824	756	***8%***	2565	2541	***1%***	4859	4835	***0%***

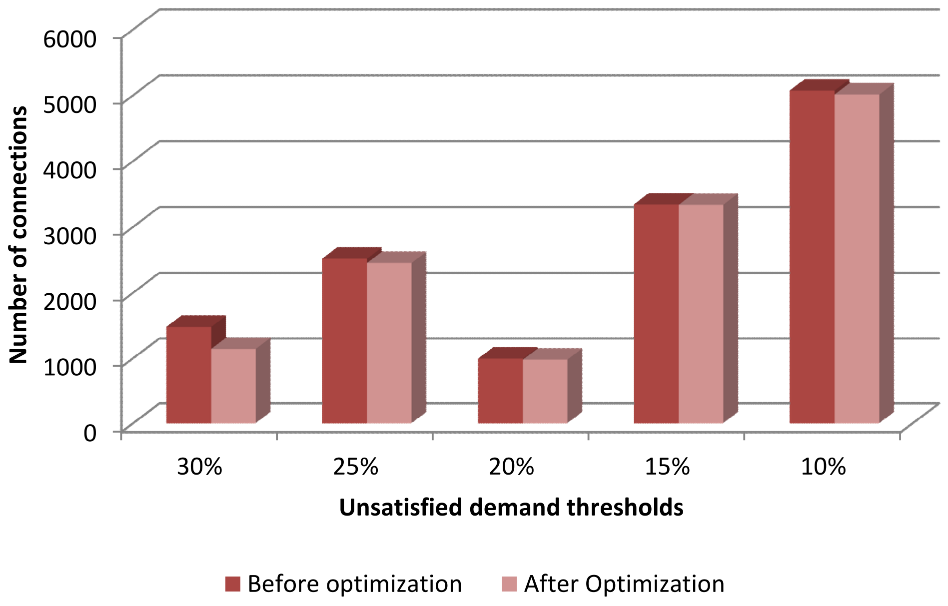


Figure 24. Connections comparison between initial situation and optimization with different unsatisfied demand thresholds for pipe 13 out of service

Looking at Figure 24, referred to scenario 2, with pipe 13 out of service, a big improvement is noticed in terms of saved connections for high thresholds of unsatisfied demand. Considering the nodes with an initial unsatisfied demand of 30%, after changing the valve statuses, 23% of them are able to supply water in the critical scenario studied, thus saving 336 connections out of 1484.

Table 21 shows the result in terms of the percentage of improved connections for each unsatisfied demand threshold. As can be seen, the number of saved connections may vary in accordance with the different scenario studied, but on the whole, good results are achieved for an higher percentage of unsatisfied demand.

A particular case can be seen in scenario 1, pipe 2 out of service: the critical node, with the highest demand deficit represenst a new expansion zone, thus it is represented with only one connection even if it supplies water to more users in the future. This means that in this case, in 30% of initial unsatisfied demand, there is an uncountable number of connections that will be saved in the future but are however unavilable available in the present time.

5.7 CLOSED VALVES SCENARIO

When the registstered status of the valves is different to the real status, the impact of a pipe failure may be harder than the scenario with all the open and available valves. With the aim to analyze scenarios in which the valves are in a wrong status, four different scenarios with a little percentage of 1% of closed valves have been studied. The status may not be the same as the one registered either if an operator fogest to set the valves in their original status, or if they are out of service. Those four combinations of closed valves have been generated with a Monte Carlo simulator and every pipe failure scenario has been studied. The combination of the closed valves can be found in the appendix.

In Figure 25 and Figure 26, from the “Run” section in Gondwana, it is possible to see the convergence curves of the studied scenarios: each of them starts with high value of the objective function so during the evaluation of new generations, the value lowers, converging to the combination of open/closed valves that lead to a better value of the objective function.

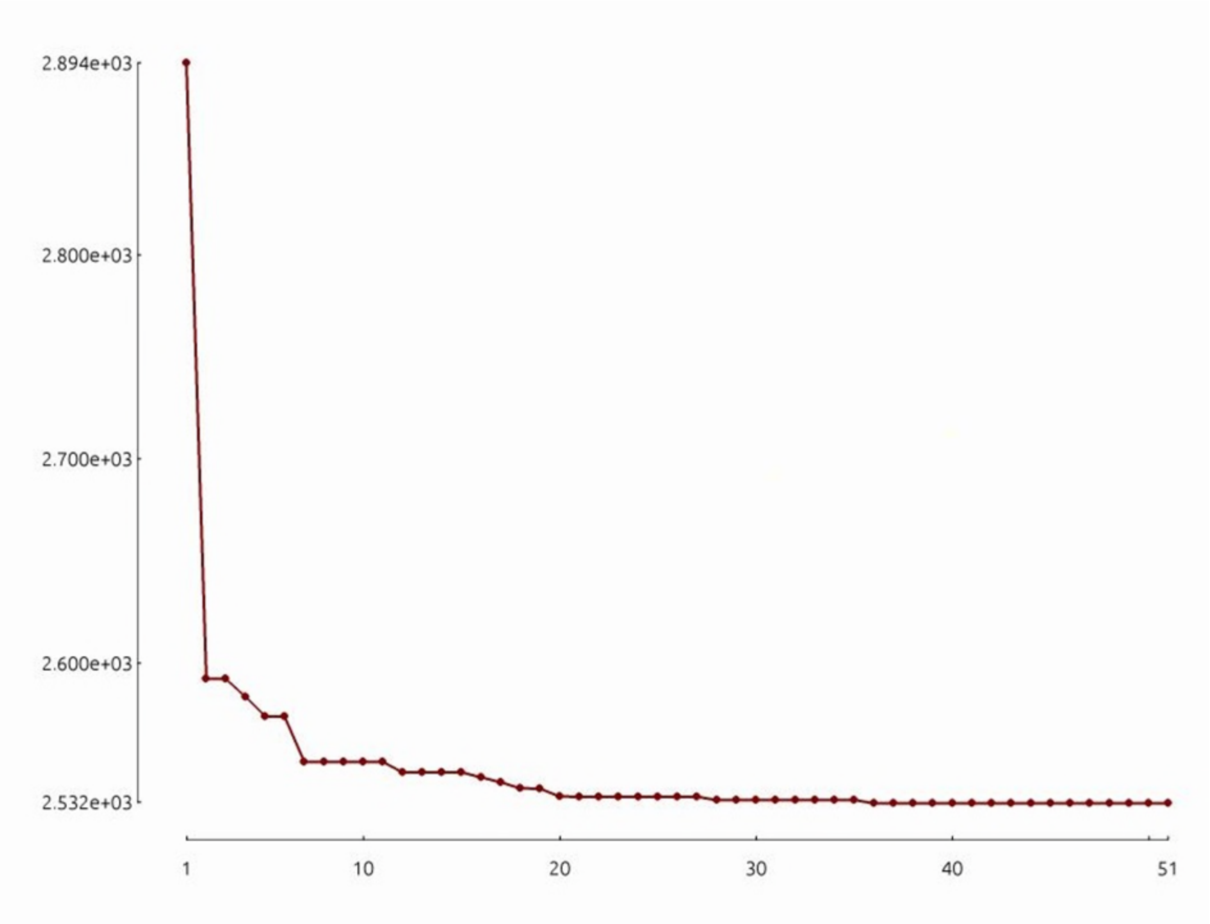


Figure 25. Convergence curve for pipe 7 out of service, with closed valves combination 1

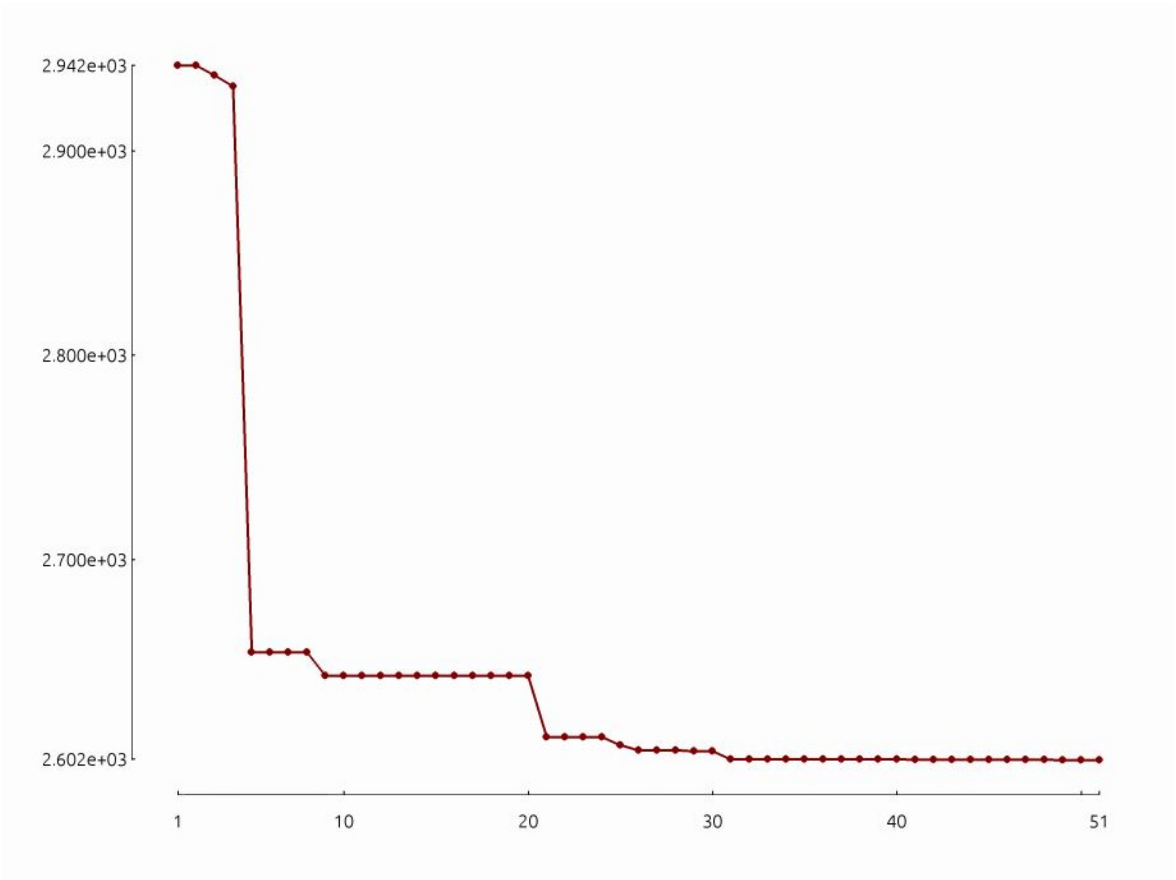


Figure 26. Convergence curve for pipe 1 out of service, with closed valves combination 4

The initial unsatisfied demand was evaluated for each scenario and with all the combinations of closed valves so comparing it with the condition of all open valves, it is possible to observe an increase in unsatisfied demand since it is to be expected in a more critical situation.

Then, the unsatisfied demand was compared between the initial condition and the optimized condition, where the valves statuses have been changed. For each time step, the maximum value of unsatisfied demand in the initial condition was subtracted from the maximum value of unsatisfied demand at the end of the process thus obtaining the maximum optimization in time step. Since this last value does not refer to one node alone, the difference between the unsatisfied demand at the start and at the end has been carried out in each node and the maximum value has been taken into account, representing the maximum optimization in the node.

In the following tables it is possible to see the result from the optimization in terms of unsatisfied demand, for each critical combination of closed valves.

In each table, for pipe 2 and 13 out of service, which represent the most critical situations due to the high unsatisfied demand produced, it has not been possible to obtain results because of the pressure driven code implemented in Gondwana, which works well for a limited difference of pressure produced by the critical scenarios.

Table 22. Results for valves combination 1

	Initial condition (peak hour)	**Objective function: Sum**	
pipe out of service	**Unsatisfied demand**	**max opt time step**	**max opt node**
2	negative pressure		
13	negative pressure		
7	33.11%	2.05%	3.77%
25	31.00%	1.94%	3.86%
1	27.97%	1.88%	3.55%
11	27.47%	1.98%	3.83%
9	27.18%	2.03%	3.81%

In Table 22 a good improvement is noted in terms of unsatisfied demand, reaching, with the first combination of the closed valve, almost 4% for the most critical nodes. The most critical scenario is with pipe 7 out of service, with 33.11% of unsatisfied demand, but this value is reduced after the optimization process of 3.77% in the critical node, in the peak hour.

Table 23. Results for valves combination 2

	Initial condition (peak hour)	**Objective function: Sum**	
pipe out of service	**Unsatisfied demand**	**max opt time step**	**max opt node**
2	negative pressure		
13	negative pressure		
7	31.08%	0.01%	2.16%
25	29.63%	0.56%	2.161%
1	26.52%	0.43%	2.159%
11	25.94%	0.45%	2.16%
9	25.94%	0.45%	2.16%

Furthermore, in this case, considering the second combination of closed valves, a good improvement for each critical node is shown in Table 23, reaching optimization in terms of an unsatisfied demand of 2.16%. The most critical scenario is with pipe 7 out of service, with 31.08% of unsatisfied demand, but this value is reduced after the optimization process of 2.16% in the critical node, in the peak hour.

Table 24. Results for valves combination 3

	Initial condition (peak hour)	**Objective function: Sum**	
pipe out of service	**Unsatisfied demand**	**max opt time step**	**max opt node**
2	negative pressure		
13	negative pressure		
7	32.58%	0.70%	2.09%
25	30.71%	1.64%	4.54%
1	30.32%	4.22%	9.62%
11	27.17%	1.68%	4.53%
9	26.73%	1.58%	4.55%

In Table 24 the results for the optimization process with the third closed valves combination are shown. The most critical scenario is with pipe 7 out of service, with 32.58% of unsatisfied demand, but this value is reduced after the optimization process of 2.09% in the critical node, in the peak hour. Further improvement may be seen in the scenario with pipe 1 out of service, where an improvement of 9.62% is reached.

Table 25. Results for valves combination 4

	Initial condition (peak hour)	**Objective function: Sum**	
pipe out of service	**Unsatisfied demand**	**max opt time step**	**max opt node**
2	negative pressure		
13	negative pressure		
7	32.74%	1.67%	4.70%
25	30.83%	1.71%	4.76%
1	30.39%	4.30%	9.80%
11	27.28%	1.80%	4.76%
9	26.92%	1.77%	4.78%

5.7.1 Number of nodes with insufficient demand

In order to verify whether an improvement is found in terms of the number of nodes with insufficient demand, the number of nodes with unsatisfied demand above a given threshold before and after the optimization have been counted.

Different thresholds of unsatisfied demand have been investigated. The number of nodes with an unsatisfied demand higher than 30%, 25%, 20% and 15% before and after the optimization have been counted. From that count the difference between the initial value and the optimized value has been obtained, so for the percentage of optimized node for each scenario and each threshold.

Considering Table 26, which shows the number of nodes saved after the optimization, for the closed valves configuration 1, we can note further improvemnets in terms of unsatisfied demand. A good percentage of saved nodes are reached for each level of unsatisfied demand, with a higher percentage for the most critical situations.

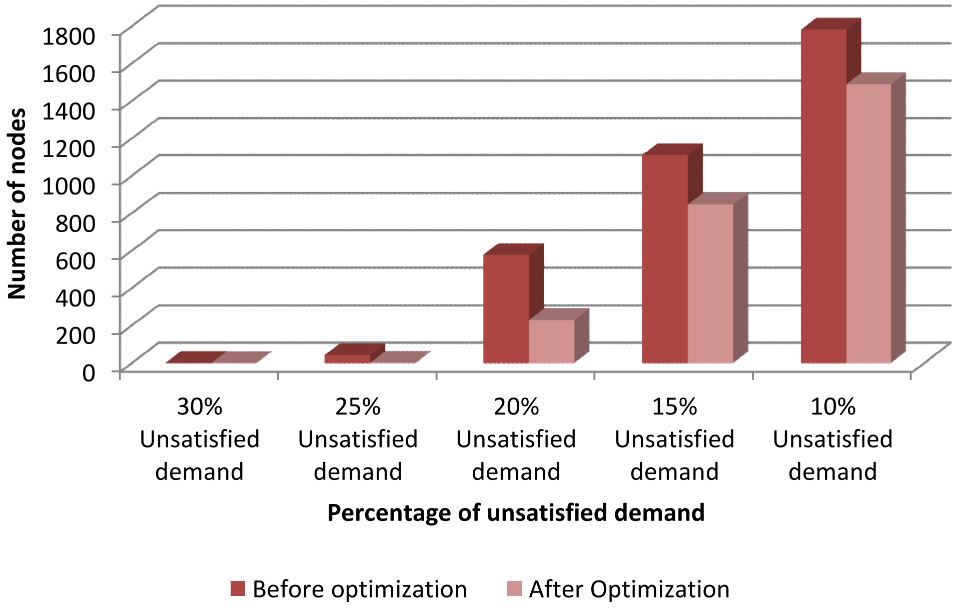


Figure 27. Number of nodes before and after the optimization process, for scenario 3, pipe 7 out of service, with closed valves combination 1

Table 26. Number of nodes with insufficient demand before and after the optimization for closed valves combination 1

Closed valves combination 1

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	3	2	33%	43	4	91%	579	231	60%	1111	849	24%	1783	1492	16.3%
25	1	0	100%	73	9	88%	558	258	54%	1115	851	24%	1783	1506	16%
1				85	21	75%	711	417	41%	1153	916	20.6%	1887	1616	14.4%
11				39	2	95%	595	234	61%	1117	852	24%	1788	1508	16%
9				54	2	96%	687	363	47%	1122	894	20%	1783	1506	16%

Table 27. Number of nodes with insufficient demand before and after the optimization for closed valves combination 2

Closed valves combination 2

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	2	2	0%	4	4	0%	233	231	1%	851	849	0.2%	1502	1492	0.7%
25				4	4	0%	290	258	11%	850	850	0%	1494	1494	0%
1				9	9	0%	434	417	4%	915	915	0.0%	1613	1613	0.0%
11				2	2	0%	294	238	19%	850	850	0%	1494	1494	0%
9				2	2	0%	294	238	19%	850	850	0%	1494	1494	0%

Table 28. Number of nodes with insufficiente demand before and after the optimization for closed valves combination 3

Closed valves combination 3

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	3	3	0%	34	14	59%	426	319	25%	968	902	7%	1656	1587	4.2%
25	1	0	100%	72	9	88%	427	258	40%	969	851	12%	1671	1506	10%
1	2	0	100%	244	21	91%	813	417	49%	1177	916	22.2%	1665	1614	3.1%
11				31	2	94%	442	235	47%	973	870	11%	1668	1523	9%
9				27	2	93%	599	364	39%	1000	894	11%	1661	1507	9%

Table 29. Number of nodes with insufficient demand before and after the optimization for closed valves combination 4

Closed valves combination 4

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	3	2	33%	42	4	90%	467	231	51%	995	849	15%	1626	1492	8.2%
25	1	0	100%	54	9	83%	452	267	41%	991	854	14%	1637	1509	8%
1	2	0	100%	269	21	92%	842	417	50%	1201	916	23.7%	1624	1614	0.6%
11				37	2	95%	478	238	50%	998	852	15%	1633	1506	8%
9				34	2	94%	634	362	43%	1012	907	10%	1633	1495	8%

In Figure 27, the gap between the nodes is seen between the initial situation, that is, without the changed valve statuses, and also after. The number of saved nodes is higher than the previous situation, where a pipe failure was simulated with an initial condition of all open valves.

For closed valves combination 2, in Table 27, a great improvement is not noted as in other combinations, in fact the maximum percentage of optimized nodes is 19%, and for a high percentage of unsatisfied demand there are no improvements at all. In this situation maybe more generations were needed in order to reach a discreet improvement in the WDN.

For closed valves combinations 3 and 4, in Table 28 and Table 29, the results of the improvement in terms of unsatisfied demand are shown. Those results show the greatest percentage of improvements of the three studied combinations, thus reaching almost 100% above the 25% of unsatisfied demand.

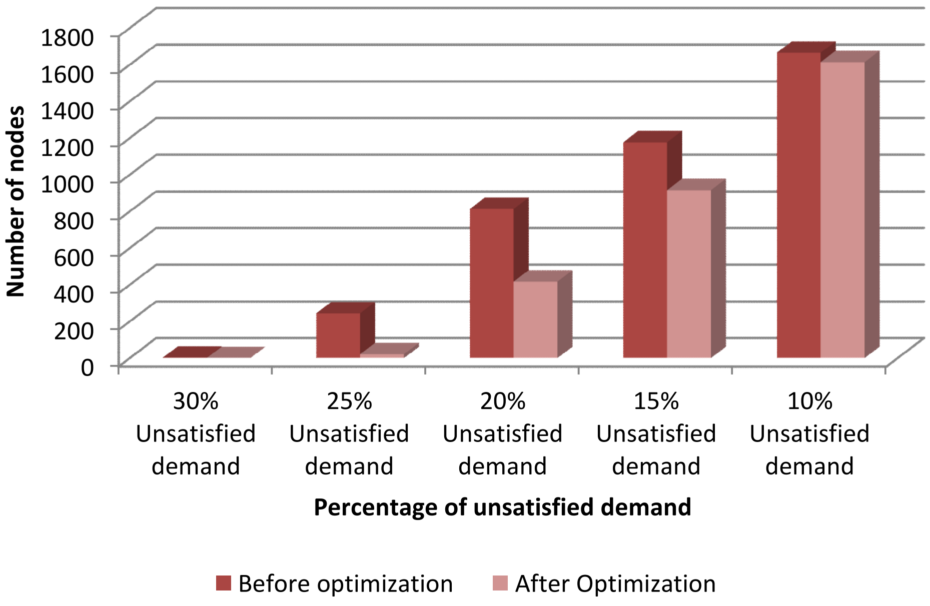


Figure 28. Number of nodes before and after the optimization process, for pipe 1 out of service, with closed valves combination 3

Looking at the Figure 28, a single scenario for the closed valves combination 3 is studied. It is possible to see the high level of improved nodes between the initial situation and the optimized one, where valves statuses have been changed. This enables the water supply to reach many more nodes in a critical situation.

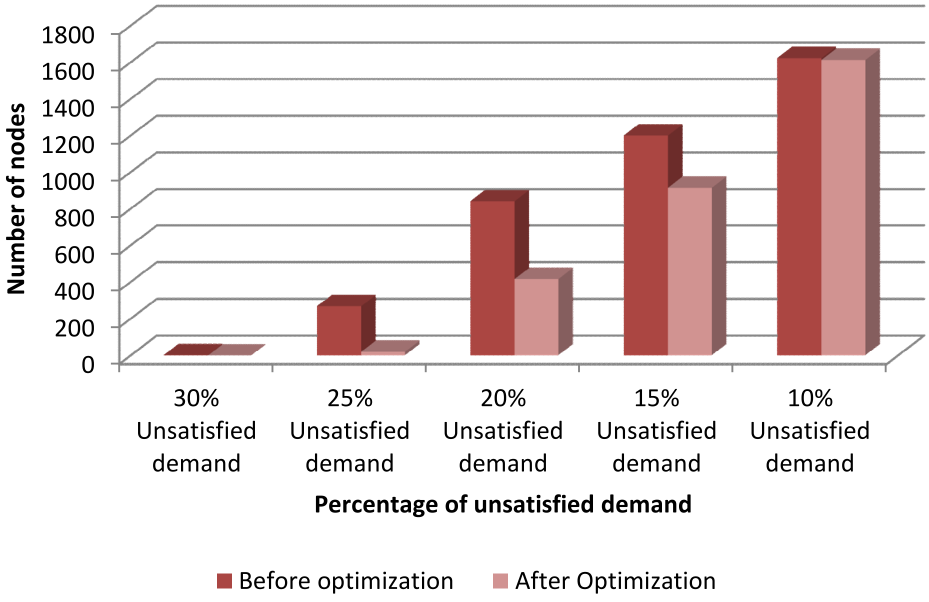


Figure 29. Number of nodes before and after the optimization process, for pipe 1 out of service, with closed valves combination 4

Considering all the four studied cases, a good level of improvement of the WDN in a critical situation has been reached. As can be seen, through observing the percentage of each level of unsatisfied demand, the higher number of saved nodes corresponds to a higher level of unsatisfied demand. As a matter of fact, looking at Figure 30, on average, almost 40% percent of the nodes saved are those with 25% of unsatisfied demand, while a good percentage are reached for the other thresholds.

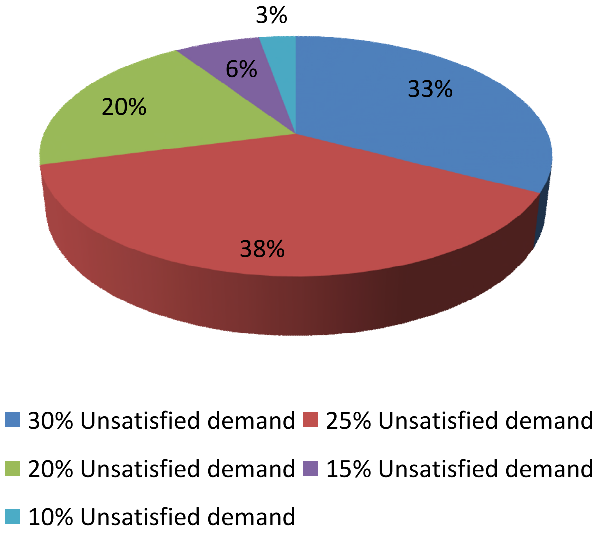


Figure 30. Percentage of the number of nodes saved after the optimization for each unsatisfied demand threshold

5.7.2 The Number of connections with insufficient demand

The number of connections with unsatisfied demand above a given threshold before and after the optimization have been counted. Different thresholds of unsatisfied demand have been investigated. The number of connections with an unsatisfied demand higher than 30%, 25%, 20% and 15% before and after the optimization have been counted, and then, calculating the difference, it is possible to obtain the percentage of connections that can supply water in the critical scenario studied.

Also in this case it is possible to see a great improvement resulting from this method. Table 30, Table 31, Table 32 and Table 33 show the results in terms of the percentage of improved connections for each unsatisfied demand threshold. As can be seen, the number of saved connections may vary in accordance with the different scenario studied, but overall, good results are achieved for an higher percentage of unsatisfied demand.

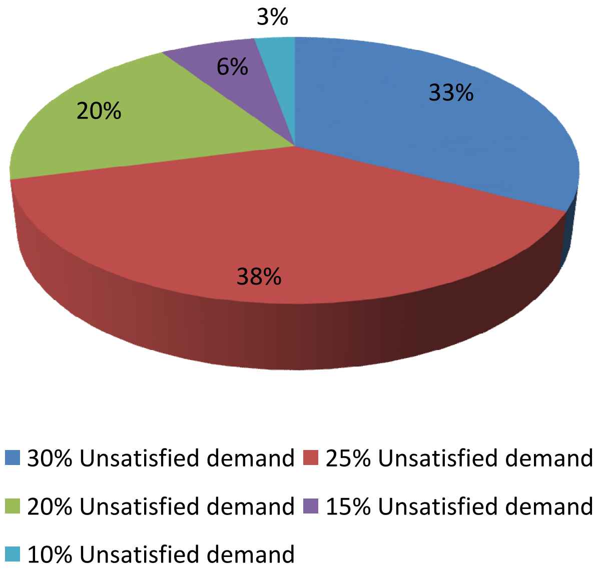


Figure 31. Percentage of the connections saved after the optimization for each unsatisfied demand threshold

As can be seen in Figure 31 most of the saved connections are those with a higher percentage of unsatisfied demand in the initial situation: in fact 38% of all the saved connections had a 30% of initial unsatisfied demand, but in this case, also the other theresholds of unsatisfied demand have a good improvement in terms of connections saved with the optimization process.

Table 30. Number of connections before and after the optimization for closed valves combination 1

Closed valves combination 1

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	9	9	0%	594	12	98%	6527	2664	59%	12242	9528	22%	20536	16845	18%
25	3	0	100%	929	68	88%	6473	2984	54%	12302	9551	22%	20536	16886	18%
1				1043	325	69%	8174	4674	43%	12722	10193	20%	21497	18482	14%
11				575	9	98%	6861	2656	61%	12327	9554	22%	20568	16914	18%
9				974	9	99%	8125	4503	45%	12330	10150	18%	20536	16890	18%

Table 31. Number of connections before and after the optimization for closed valves combination 2

Closed valves combination 2

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	9	9	0%	12	12	0%	2672	2664	0%	9503	9528	0%	16851	16845	0%
25				12	12	0%	3388	2984	12%	9500	9500	0%	16844	16882	0%
1				68	68	0%	4868	4674	4%	10167	10167	0%	18462	18462	0%
11				9	9	0%	3548	2765	22%	9553	9553	0%	16860	16860	0%
9				9	9	0%	3548	2765	22%	9553	9553	0%	16860	16860	0%

Table 32. Number of connections before and after the optimization for closed valves combination 3

Closed valves combination 3

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	9	9	0%	502	121	76%	4878	3697	24%	10821	9941	8%	19234	18296	5%
25	3	0	100%	924	68	93%	4873	2984	39%	10820	9551	12%	19330	16886	13%
1	9	0	100%	2711	325	88%	9299	4674	50%	13610	10193	25%	19154	18466	4%
11				511	9	98%	5103	2662	48%	10831	9693	11%	19352	17054	12%
9				408	9	98%	7065	4509	36%	11132	10150	9%	19226	16911	12%

Table 33. Number of connections before and after the optimization for closed valves combination 4

Closed valves combination 4

Demand deficit	30% Unsatisfied demand			25% Unsatisfied demand			20% Unsatisfied demand			15% Unsatisfied demand			10% Unsatisfied demand		
pipe out of service	Before	After	%	Before	After	%	Before	After	%	Before	After	%	Before	After	%
7	9	9	0%	589	12	98%	5353	2664	51%	11058	9528	14%	18658	16845	10%
25	3	0	100%	708	68	90%	5286	3091	42%	11056	9606	13%	18727	16922	10%
1	9	0	100%	3059	325	89%	9482	4674	51%	13730	10193	26%	18579	18466	1%
11				567	9	98%	5549	2765	50%	11090	9554	14%	18670	16911	9%
9				483	9	98%	7311	4499	38%	11324	10285	9%	18646	16718	10%

6 CONCLUSIONS AND RECOMMENDATIONS

In the present work, the possibility of an improvement of the resilience of a water distribution network changing the valves status was investigated.
The analysis was performed on a real case study: the water distribution network of the cities of H. and M., in the Netherlands. The possibility of an improvement of the resilience of the network was demonstrated, mainly in the peak hour, reaching 23% of improvements in a node with 47% of unsatisfied demand. This is obtained closing, on average, 4 valves, thus does not imply a large amount of work in closing the valves in the case of a critical scenario and permits to react rapidly. Since the study was developed using a Dutch network, which is characterized by small variations in pressure, due to the flat territory which is typical of the Netherlands, and the overdimensioned and highly looped design, there is a lower percentage of unsatisfied demand, thus a lower percentage of improvement.

Another important aspect of this methodology lies in the fact that it is possible to see which are the most operated valves: this could help Water Companies to check which valves are to be kept under control and given maintenance in order to have a well functioning network in the event of a failure.
The huge improvement given to this methodology can be seen in the number of nodes and connections saved, which gives a realistic idea of the number of users that may be saved in a critical situation.

The three different objective functions studied in this work have been able to improve the resilience index but one is no better than the other, in fact, two different behaviours can be distinguished in the graphs: either the objective functions have reached the same level of improvement, or one function may be better than the other but is not always the same. Above all, the three objective functions work well, so only one can be choosen that is based on the objective that the water companies wishes to reach.

Considering the simulations with thousands of generations, it is vital to emphasize that the same level of improvement in a WDN can be reached with different sets of closed valves.

This is significant the water company may decide which set of valves to close in a critical situation.

Another great aspect is found in the case with 1% of closed valves, where we note that even with a more citical situation, the method works well. Indeed, comparing the results between the real case, with all open valves, and the case with closed valves in the initial situation, we find a vast improvement in both cases. In addition, in this case the number of nodes and connections which are no longer affected by the demand deficit were counted, finding a good number of users which were served with a good water supply thanks to the fact that same valves were opened or closed.

For further studies, proving the methodology on a network subdivided into DMA's is suggested , where the reliability is decresed due to the closure of boundary valves. Also a less resilient network may be interesting to study, like, for example, the Italian WDNs, usually characterized by high pressure differences.

It might be interesting to discover whether a higher improvement may be reached with another objective function, therefore, an interesting future study might be to investigate other diverse objective functions and compare them with those already studied.

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8 APPENDIX

8.1 COMBINATIONS OF CLOSED VALVES

In the following images there are the locations of the set of closed valves used to simulate the occurance of valves not in their original status.

- Closed valves combination 1

Figure 32. Combination of closed valves 1

- Closed valves combination 2

Figure 33. Combination of closed valves 2

- Closed valves combination 3

Figure 34. Combination of closed valves 3

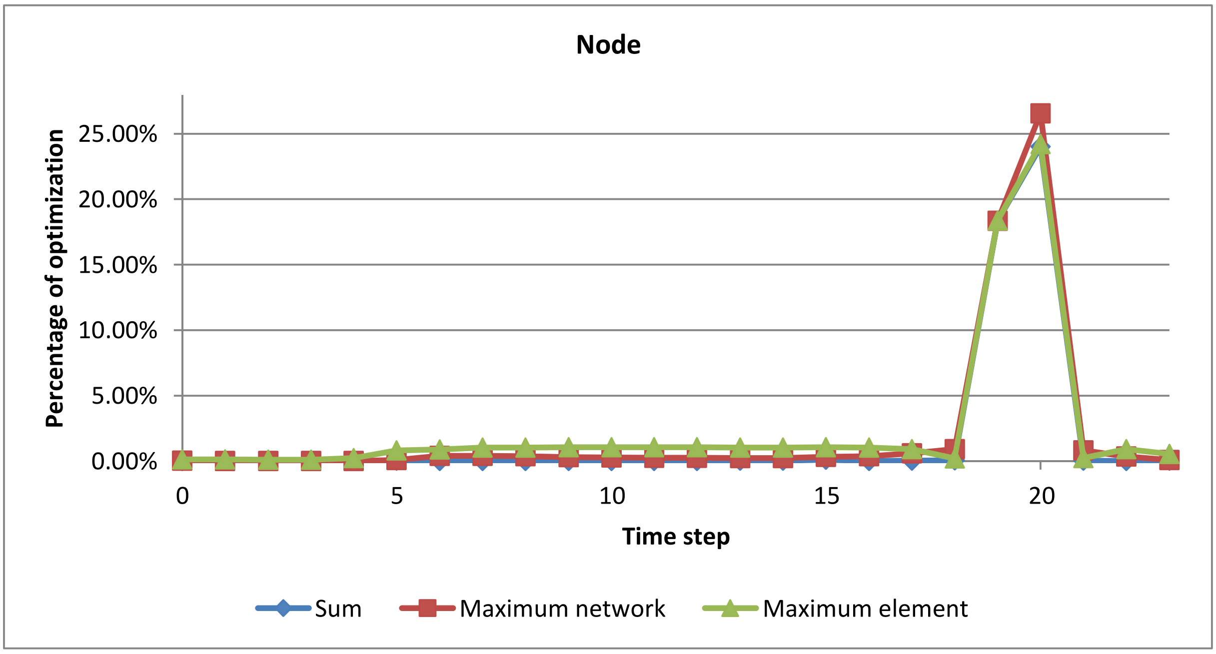
- Closed valves combination 4

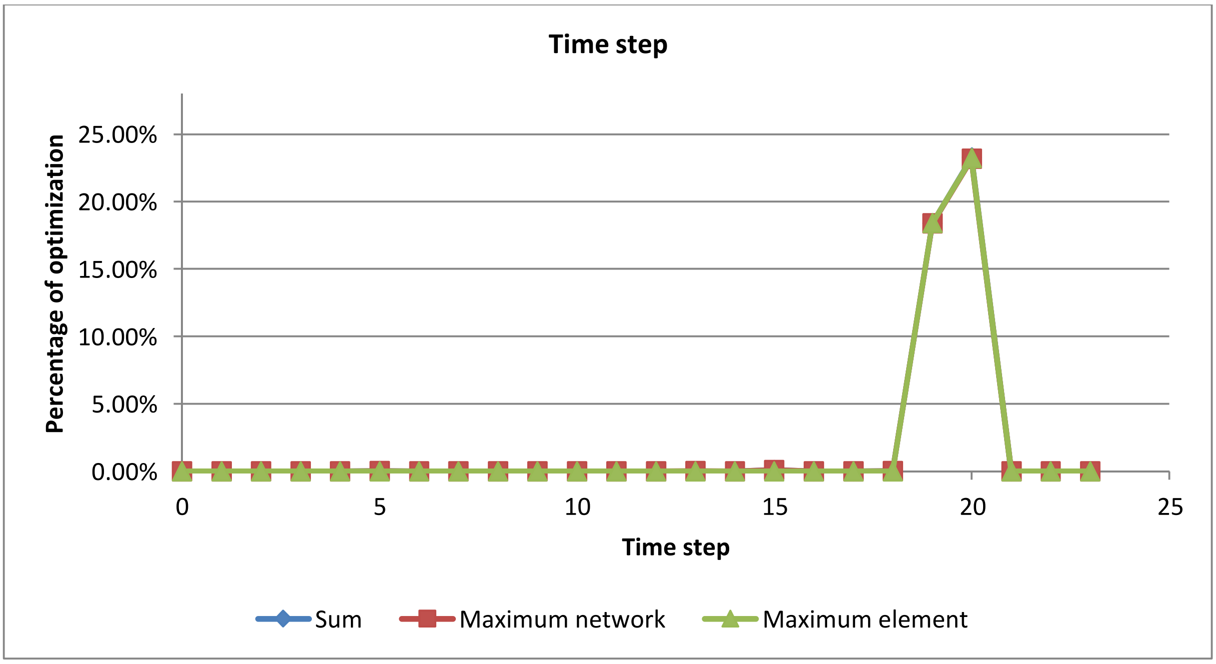
Figure 35. Combination of closed valves 4

8.2 FUNCTION COMPARISON

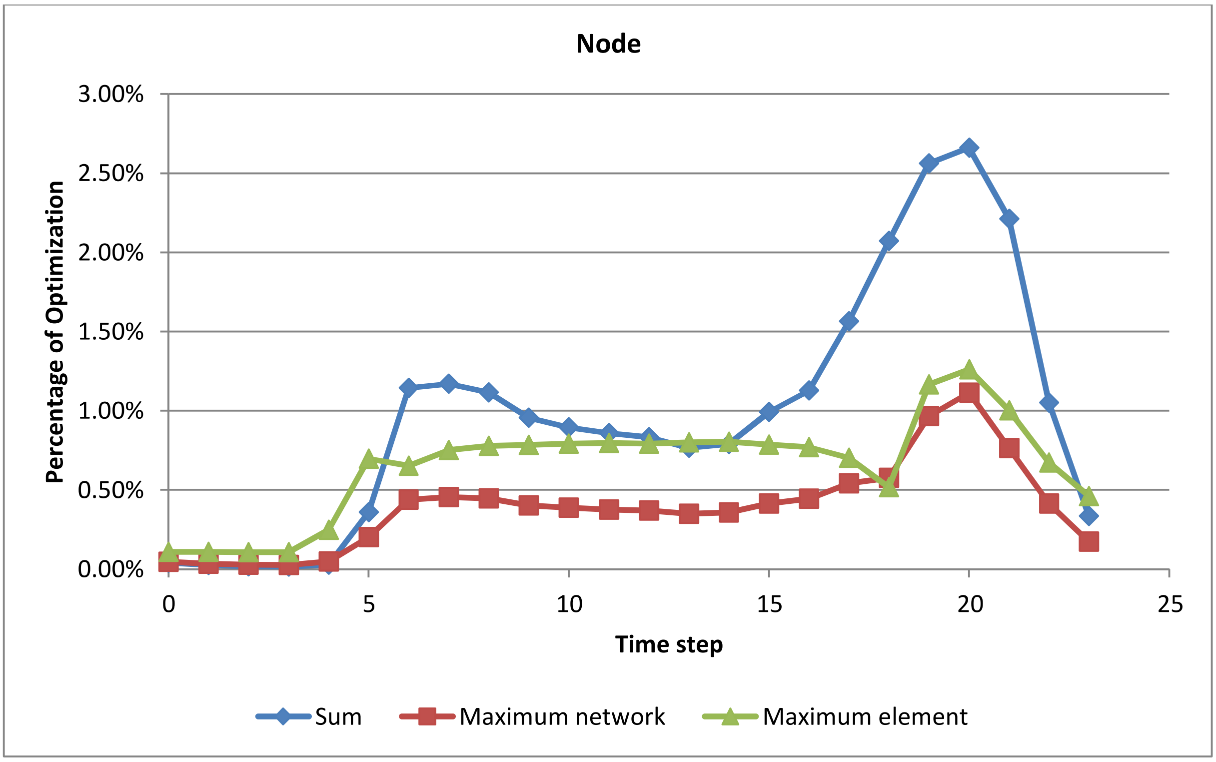
In the following graphs there is the comparison between the three different objective functions used in the analysis in terms of percentage of improving of the unsatisfied demand either per time steps or node.

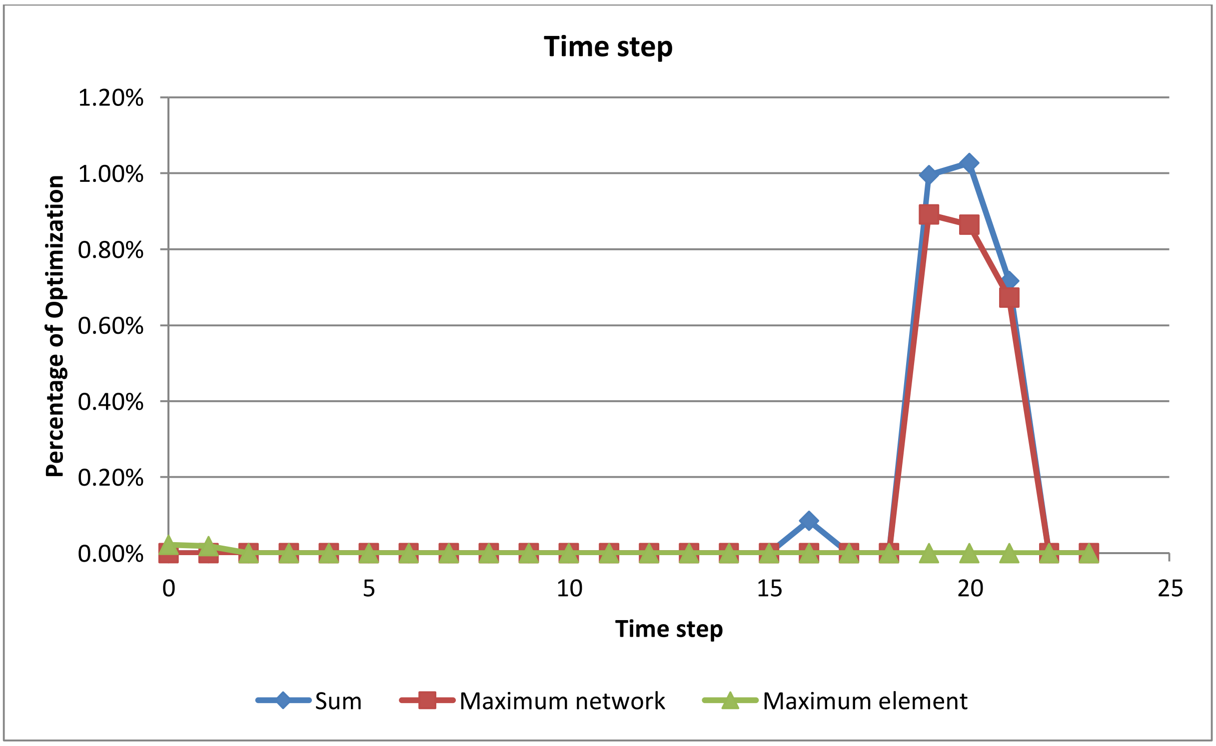
- Pipe 2



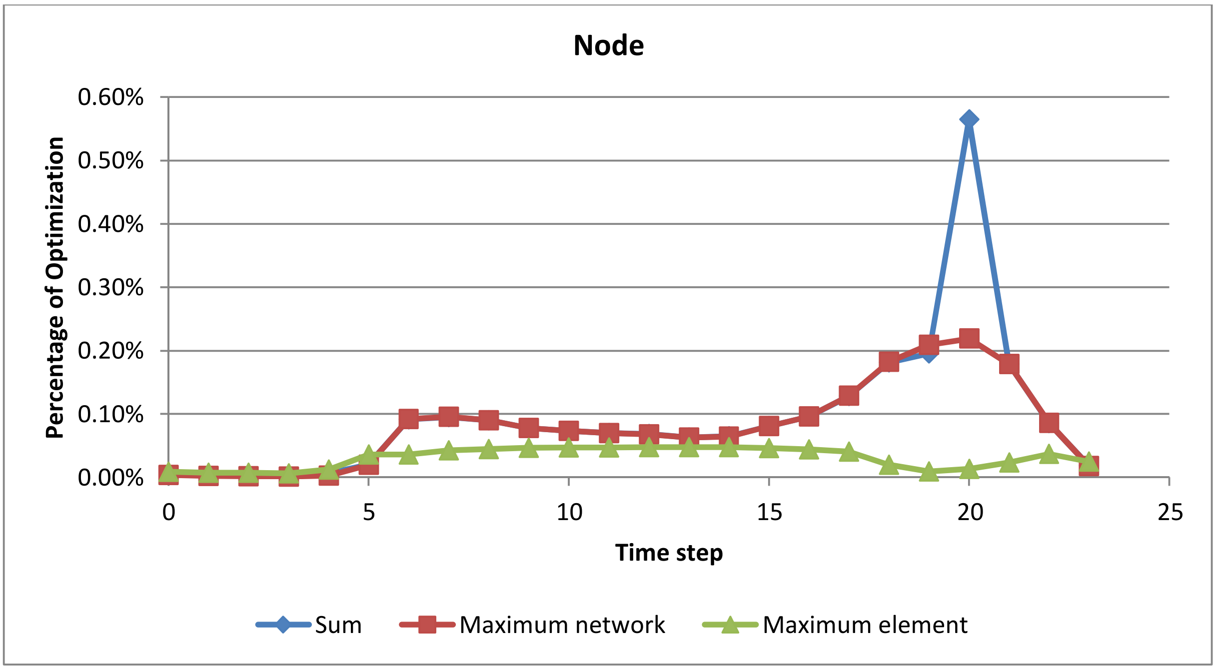


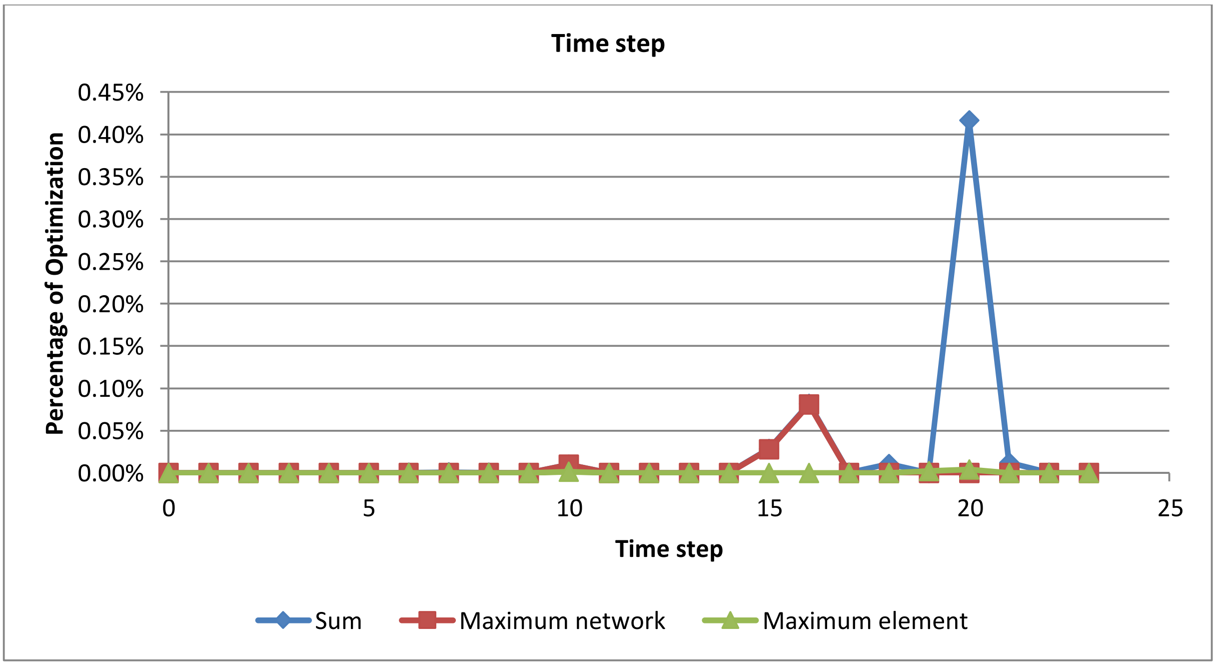
- Pipe 13


Node
Percentage of Optimization
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

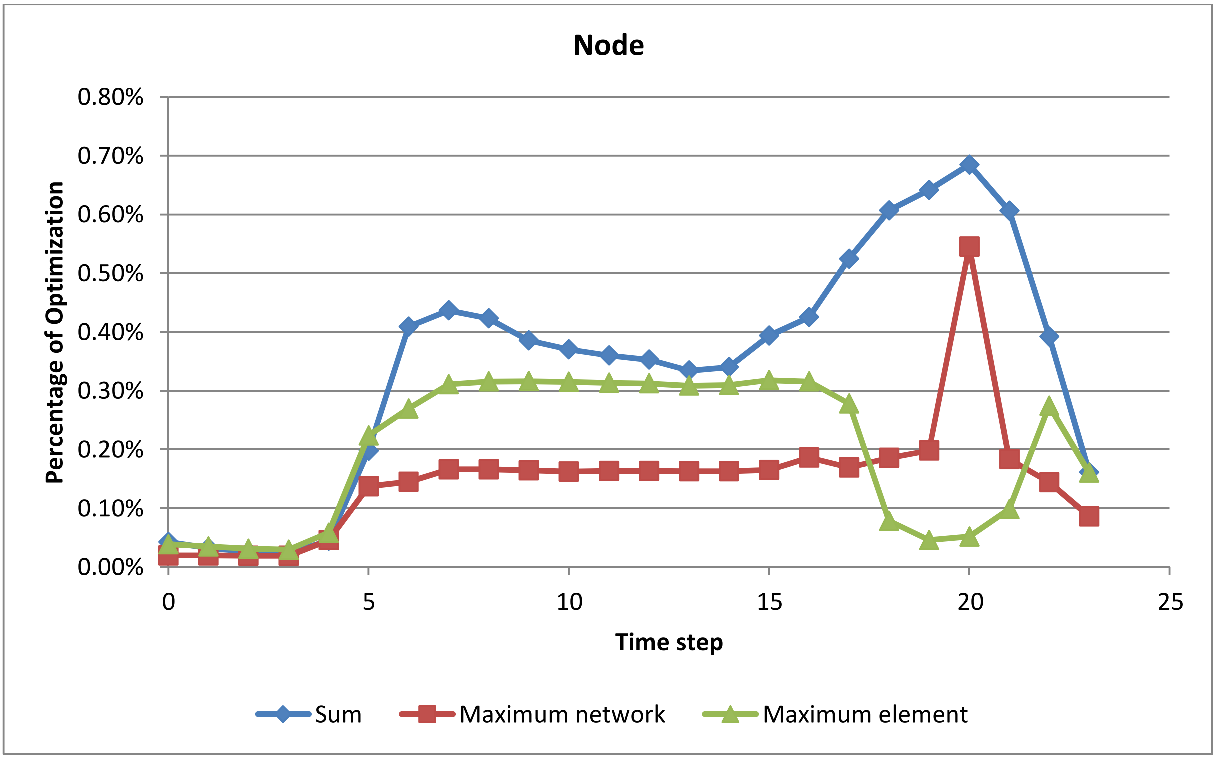

Time step
Percentage of Optimization
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

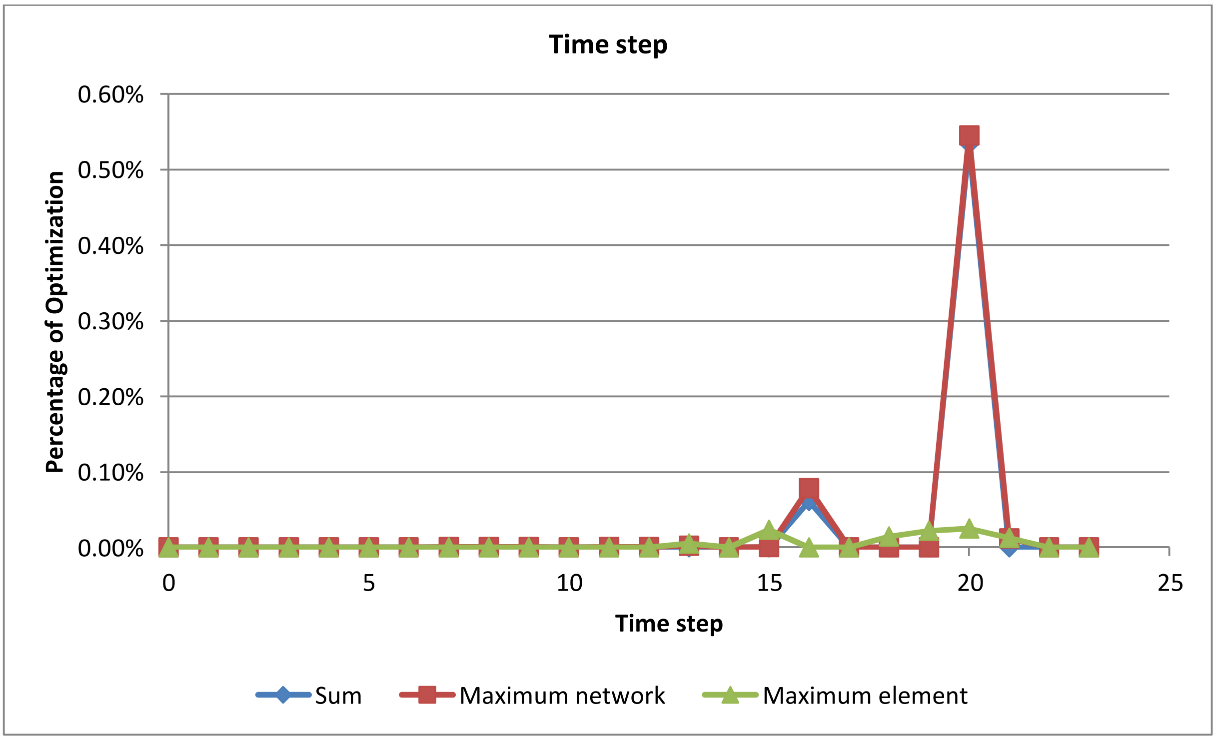
- Pipe 20


Node
Percentage of Optimization
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

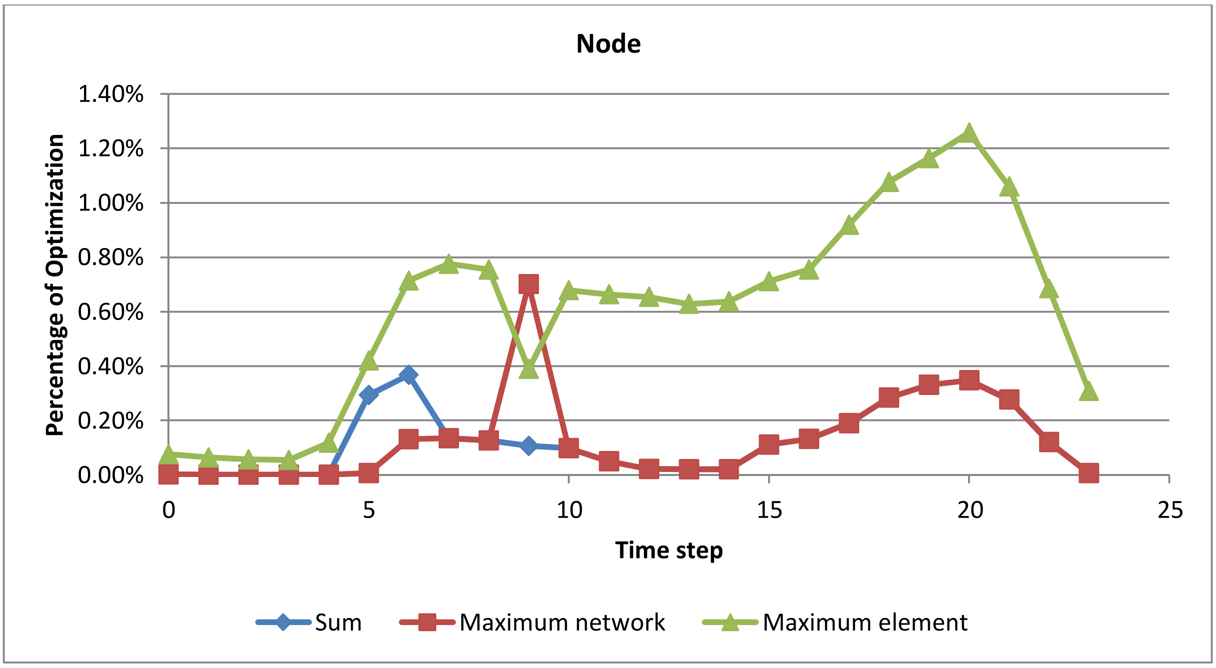

Time step
Percentage of Optimization
0.45%
0.40%
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

- Pipe 25


Node
0.80%
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
Percentage of Optimization
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element


Time step
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
Percentage of Optimization
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

- Pipe 21


Node
Percentage of Optimization
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1.20%
1.00%
0.80%
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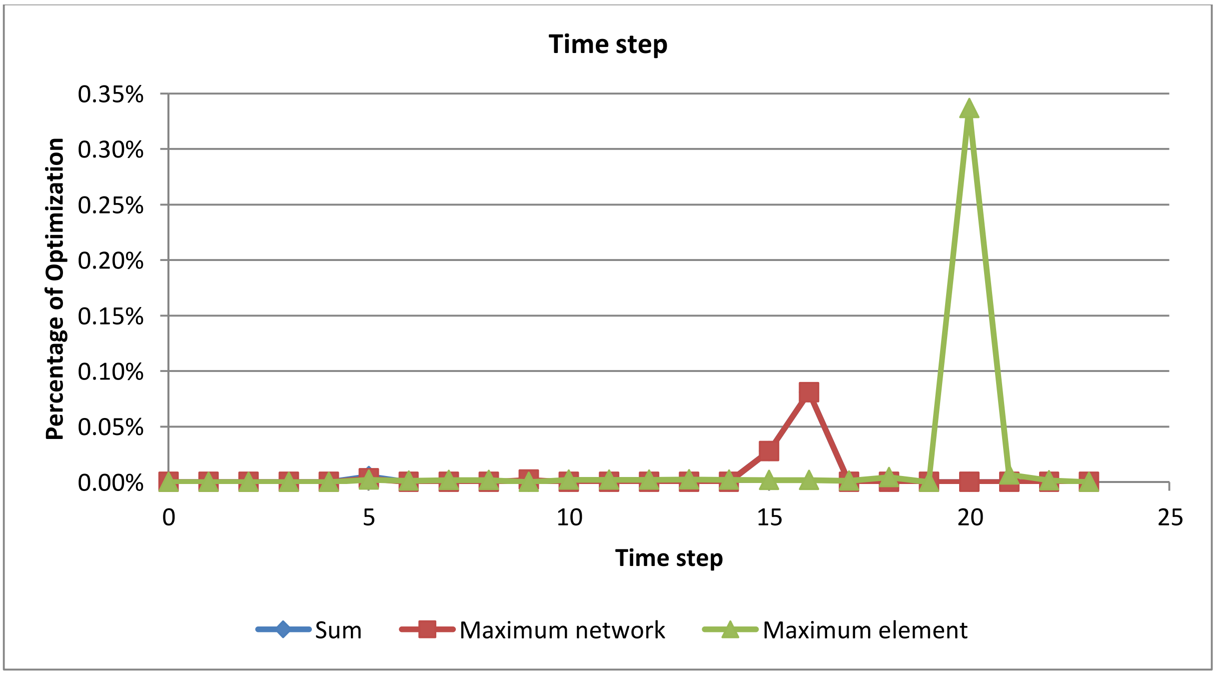
0.20%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element


Time step
Percentage of Optimization
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0.20%
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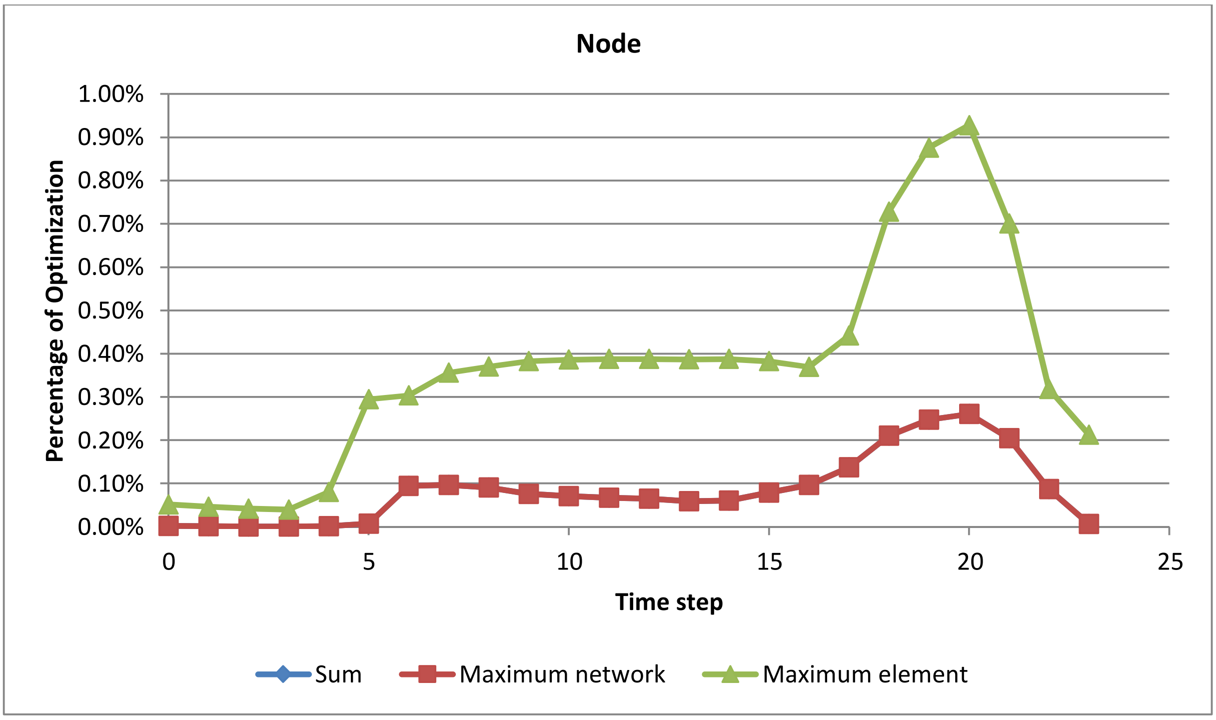
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

- Pipe 24


Node
Percentage of Optimization
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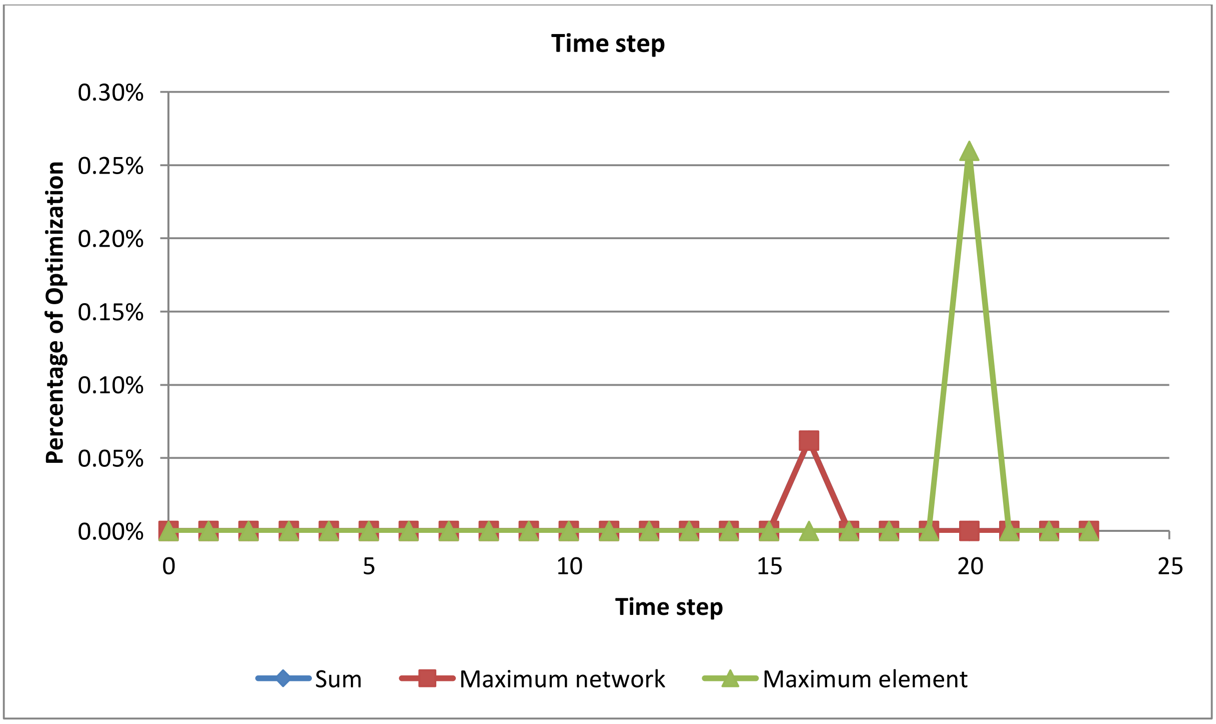
0.80%
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element


Time step
Percentage of Optimization
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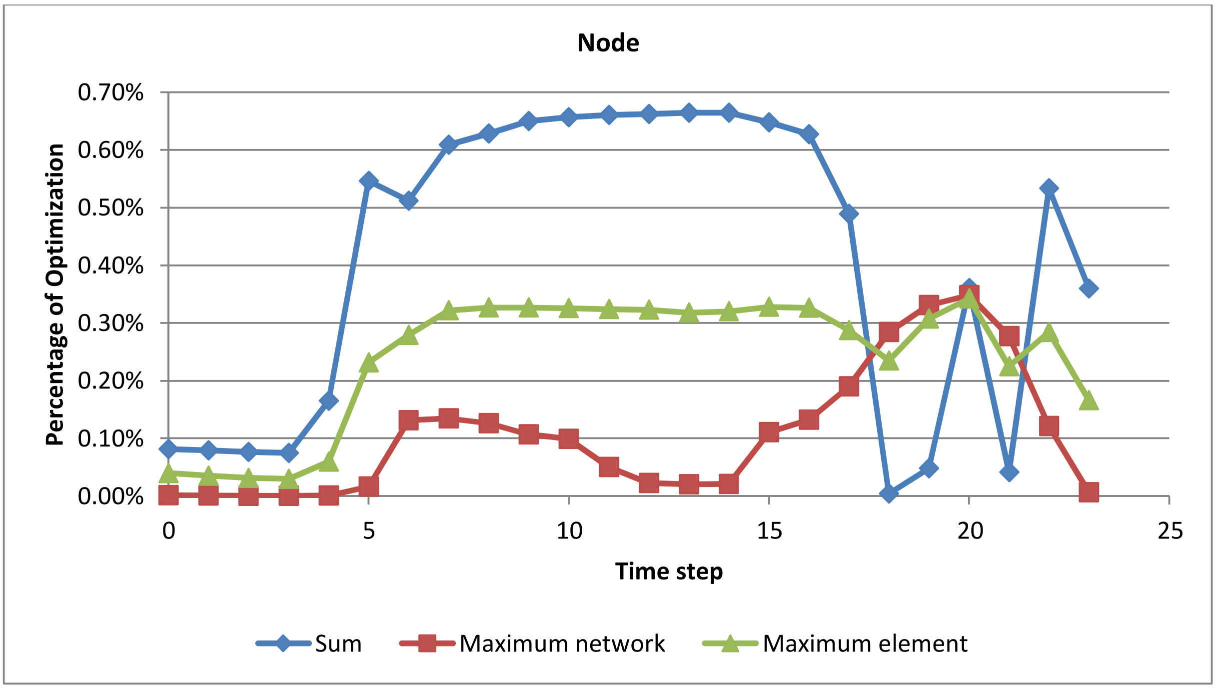
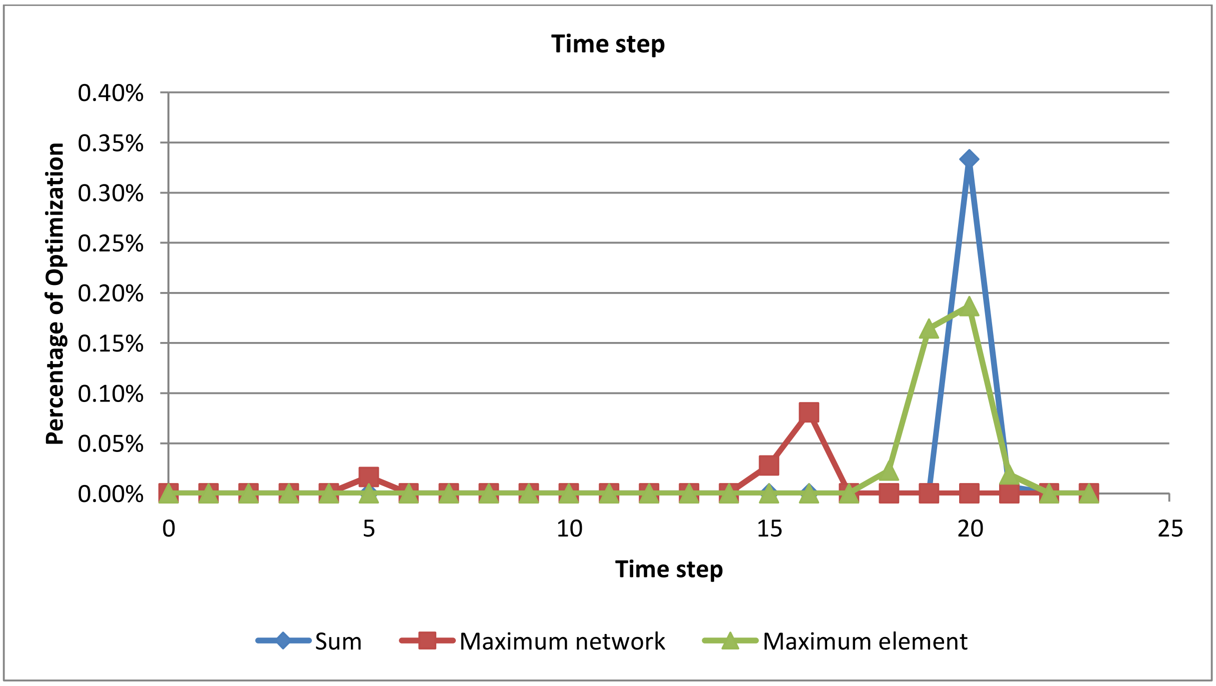
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

- Pipe 17


Node
Percentage of Optimization
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element


Time step
Percentage of Optimization
0.40%
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0
5
10
15
20
25
Time step
Sum
Maximum network
Maximum element

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