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Optimization of Water Distribution Networks and assessment of pipe deterioration by applying the Harmony Search algorithm

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ABSTRACT

The relevance of the optimal design of water distribution networks lies in its sustainable applicability. Thus, the design must be as efficient and affordable as possible, meaning that it achieves a minimum level of serviceability using an appropriate amount of resources. In this context, an ideal water network requires the use of minimum-size elements to reach the minimum head pressure required for each node of the system with the lowest energy consumption. For this purpose, a relatively new meta-heuristic algorithm, called Harmony Search, was used in this study to optimize the water distribution network of Cheongna International City (S. Korea), in terms of the pipe diameter. Furthermore, using the same algorithm under a different approach, an assessment of the deterioration of conduits over time was conducted by analyzing the optimal roughness coefficient for the original pipe material, which provides a useful tool for decision making. Other heuristic and meta-heuristic algorithms have been applied to this type of problem; however, Harmony Search provides a convenient implementation at a reasonable computational cost. In this study, Harmony Search is demonstrated to be a valuable tool for water distribution networks optimization as well as for pipe aging assessment.

RESUM

La rellevància del disseny òptim de les xarxes de distribució d'aigua rau en la seva capacitat d'aplicar-les de manera sostenible. Per tant, el seu disseny ha de ser el més eficient i econòmic possible, és a dir, proveint un nivell mínim de servei utilitzant una quantitat apropiada de recursos. En aquest context, una xarxa ideal requereix de l'ús d'elements de la menor mida possible que sigui capaç de proveir aigua amb la pressió mínima requerida a cada node de la xarxa amb el menor consum energètic. Amb aquesta finalitat, en aquest estudi es va fer ús d'un algorisme meta heurístic relativament nou, anomenat Harmony Search, per a optimitzar la xarxa de distribució d'aigua de la ciutat internacional de Cheongna (Corea del Sud), en termes de diàmetre de canonada. A més, utilitzant el mateix algorisme amb un enfocament diferent, es va realitzar una avaluació del deteriorament de les canonades al llarg del temps mitjançant l'anàlisi del coeficient de rugositat òptim per al material original de la canonada, i que proporciona una eina útil per a la presa de decisions. A aquest tipus de problemes d'optimització, en altres estudis, s'han aplicat altres algorismes heurístics i meta heurístics. Tanmateix, l'algorisme Harmony Search proporciona una implementació senzilla amb un cost computacional raonable. En aquest estudi es demostra que el Harmony Search és una eina potent per a l'optimització de xarxes de distribució d'aigua, així com per a l'avaluació del deteriorament de les canonades pel pas del temps.

RESUMEN

La relevancia del diseño óptimo de las redes de distribución de agua recae en su capacidad de aplicarlas de un modo sostenible. Por lo tanto, su diseño debe ser lo más eficiente y económico posible, es decir, proveyendo un nivel mínimo de servicio utilizando una cantidad apropiada de recursos. En este contexto, una red ideal requiere del uso de elementos del menor tamaño posible que sea capaz de abastecer agua con la presión mínima requerida en cada nodo de la red con el menor consumo energético. Con esta finalidad, en este estudio se hizo uso de un algoritmo meta heurístico relativamente nuevo, llamado Harmony Search, para optimizar la red de distribución de agua de la ciudad internacional de Cheongna (Corea del Sur), en términos de diámetro de tubería. Además, utilizando el mismo algoritmo con un enfoque diferente, se realizó una evaluación del deterioro de las tuberías a lo largo del tiempo mediante el análisis del coeficiente de rugosidad óptimo para el material original de tuberías, y que proporciona una herramienta útil para la toma de decisiones. Para este tipo de problemas de optimización, en otros estudios se han aplicado otros algoritmos heurísticos y meta heurísticos. Sin embargo, el algoritmo Harmony Search proporciona una implementación sencilla con un coste computacional razonable. En este estudio se demuestra que el Harmony Search es una potente herramienta para la optimización de redes de distribución de agua, así como para la evaluación del deterioro de las tuberías por el paso del tiempo.

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1.- Introduction

1.1.-Motivation and interest

One of the primary objective for the sustainable development of today's societies is to guarantee safe and stable access to drinking water for the entire population. Considering climate change and its consequences, the design of infrastructures, both current and future, must be as efficient and sustainable as possible. This means that they must be capable of meeting their intended service requirements with the lowest possible energy consumption, and at the lowest possible cost. Thus, the construction, operation, and maintenance cost must provide the desired level of serviceability while fitting into the budgets of the administration and meeting their sustainable objectives.

In this sense, the ideal design for water distribution networks is one in which the water inside the entire system flows by gravity because it is not necessary to provide external energy so that the water reaches all the supply points. This means avoiding the need to install pumping stations to increase the water head pressure, which implies significant energy and cost savings. In other words, the design of the infrastructure must be optimal in terms of construction, operation and maintenance.

1.2.-Objectives

The main objective of this study was to optimize the water distribution network of Cheongna International City, in the Republic of Korea. For this purpose, the Harmony Search (HS) algorithm [1] was implemented to determine the optimal pipe diameter considering the required limitations on the head pressure in the nodes and the flow velocity in the pipe network. The pipe diameter was chosen to be the main element for optimization because of its high impact on water flow followed by the roughness coefficient and conduit length [2]. In this manner, the aim of this optimization process was to reduce the pressure inside the water distribution network to avoid problems related to leakage and the quick deterioration of the elements due to high pressure.

The second part of this research was to find the critical conduits in the system by applying the same HS algorithm scheme using a different approach. this consists of using the Hazen-Williams C value of the roughness coefficient as the parameter to be optimized in the objective function, applied to the original water distribution network (WDN). Therefore, the outcomes of this approach provide the C value range that should be maintained in order to maintain the desired level of serviceability in the system. Consequently, conduits exhibiting higher values of C can be identified as the critical pipes that should be substituted in the first term as the WDN ages. Thus, as the Cheongna International City WDN is formed by ductile iron pipes, whose C value can be assumed to decrease by a factor of ten every 10 years [2], the objective of this part of the study was to provide a useful tool for decision making in the assessment of deteriorated pipes. Through this approach it is possible to create different scenarios to evaluate the consequences of either repairing or replacing the deteriorated pipes or not. In this manner, the administrations can define the maintenance strategies for their water distribution networks.

The implementation of the HS algorithm was carried out using the EPANET-MATLAB Toolkit [3], an open-source software tool that allows EPANET to interface with MATLAB. This tool allows the user to integrate the governing equations and functions of EPANET using different mathematical approaches for WDN optimization. Some of the different approaches used by other researchers include linear programming (LP) [4,5], simulated annealing (SA) [6,7], and genetic algorithms (GA) [7,8]. However, the HS algorithm was chosen for this study because of its relatively new meta-heuristic approach that encompasses convenient implementation and rapid convergence with reasonable computational cost [1,9–13].

The scope of this research is, then, to demonstrate the applicability of the Harmony Search algorithm along with the EPANET-MATLAB Toolkit for the optimization of the water distribution network of the study area, focusing on hydraulic aspects rather than on the computational characteristics of the algorithm. Thereafter, once it is achieved the optimization of the network, the subsequent minor objective is to provide a tool for the assessment of deteriorated conduits.

1.3.-Structure

The structure of this Master thesis is as follows:

- Chapter 2 describes the theoretical background needed to conduct this study, introducing the Harmony Search algorithm, the EPANET software, and the EPANET-MATLAB Toolkit.
- Chapter 3 introduces the study area presenting an overview of the Cheongna International city in South Korea and the relevance of the region.
- Chapter 4 describes the original WDN model, and the construction of the models for both pipe diameter optimization and pipe deterioration assessment approaches.
- Chapter 5 present the results and discussion of the optimal diameter set and the assessment of pipe deterioration.
- In Chapter 6 the conclusions drawn from this study are presented, along with the proposed future works.
- The Appendixes show the main pseudocodes used in this study for the implementation of the HS algorithm and its objective functions for both approaches.

2.- Theoretical background

The aim of this chapter is to introduce the theoretical background that has been followed in this study. As the main objective of this thesis is the optimization of the water distribution network of the study area, the implemented Harmony Search algorithm is first described in this section. Then, a general overview of the EPANET software is provided as it is the main tool used for defining the WDN model of the study area and interfacing the results of its optimization. Lastly, the EPANET-MATLAB Toolkit, which is the tool used to implement the HS algorithm in MATLAB using the EPANET functions, is introduced.

2.1.-Harmony Search algorithm

The Harmony Search (HS) is a relatively new meta-heuristic algorithm based on the improvisation process followed by musicians to find a pleasing harmony [1]. It possesses several advantages over the traditional optimization techniques: (1) it is a simple meta-heuristic algorithm that does not require initial setting for decision variables; (2) it uses stochastic random searches, so derivative information is not necessary; and (3) it has a few parameters for fine tuning [11].

For this reasons, HS has been demonstrated in several studies to be a useful optimization algorithm for various engineering applications, including water distributions networks, owing to its convenient implementation, rapid convergence, and reasonable computational cost. This can be conveniently found in the literature as applications to continuous and discrete optimization problems [12,14–19].

The concept of HS is based on the idea that during improvisation process, musicians try different combinations of familiar (memorized) pitches, which is analogous to the optimization process applied to most engineering problems. In this sense, music improvisation aims to find the best harmony (best state) which is determined by aesthetic estimation, while optimization algorithms strive for a best state (i.e., global optimum or maximum benefit or efficiency) which is determined by the evaluation of the objective function [12,20,21].

Thus, while aesthetic estimation is determined by the given sound generated by joined instruments, the objective function evaluation is given by the set of the values produced by component variables. Then, analogously, the harmonies for better aesthetic in music improvisation can be improved by practicing, in the same way as values for better objective function evaluation are improved by iteration process. Therefore, in HS algorithm, a feasible solution is called a harmony, and each decision variable corresponds to a note, which generates a value for finding the global optimum.

The aforementioned improvisation procedure is controlled by a set of parameters, which are the Harmony Memory Size (HMS), Harmony Memory Considering Rate (HMCR), Pitch

Adjustment Rate (PAR), Bandwidth (bw) and the Number of Improvisations (NI), i.e., the stopping criterion. The most relevant parameters are described as follows.

- HMCR: its value ranges [0,1] and defines the probability of using historical values stores in the Harmony Memory (HM) for selecting a note. Small values of HMCR results in random search (with a probability of 1-HMCR) and vice versa.

- PAR: its value ranges [0,1] and represents the chance that each improvised value from the HM has to be replaced by a value located at the vicinity of the selected value from HM. Consequently, large values of PAR increase the probability of pitch adjustment and vice versa.

- bw: the value of this parameter determines the step size of movement if the pitch adjustment is selected. Using large values of bw implies that the distance between the new value and the HM value increases. In point of fact, it is possible to tune the global and local search by means of the bw.

The implementation of the HS algorithm consists of the following steps [20]:

1. Initialize the problem and algorithm parameters:

   The optimization problem is defined as

$$\text{Minimize (or maximize)} \qquad \text{f(x)} \tag{1}$$

$$\text{Such that } \; LB_i \leq x_i \leq UB_i \tag{2}$$

   Where $f(x)$ is the objective function, x is a candidate solution consisting of N decision variables x_i. LB_i and UB_i are the lower and upper bounds for each decision variable, respectively.

2. Initialize the Harmony Memory (HM)

   The Harmony Memory (HM) is a memory location where the solution vectors are stored, and is similar to the genetic pool in a GA [20,22]. The initial HS is generated from a uniform distribution of ranges, filling a matrix with a quantity of randomly generated solution vectors equal to the HMS.

$$x_i^l = LB_i + Rand\text{x}(UB_i - LB_i), \qquad l = 1,2, \dots HMS \tag{3}$$

3. Improvise a new harmony

   The generation of a new harmony is called improvisation, this new harmony vector, $x' = (x'_1, x'_2, \ldots, x'_N)$, is generated based on three rules: memory consideration, pitch adjustment, and random selection.

4. Update the Harmony Memory

   If the new vector is better than the worst harmony vector in the HM in terms of the objective function value, and no identical harmony vector is already stored in the HM, the new harmony is included in the HM, and the existing worst harmony is excluded.

5. Check the Stopping Criterion

   The algorithm terminates when the maximum number of improvisations is reached. Otherwise, Steps 3 and 4 are repeated.

Figure 1 shows the flowchart of the HS algorithm [12]:

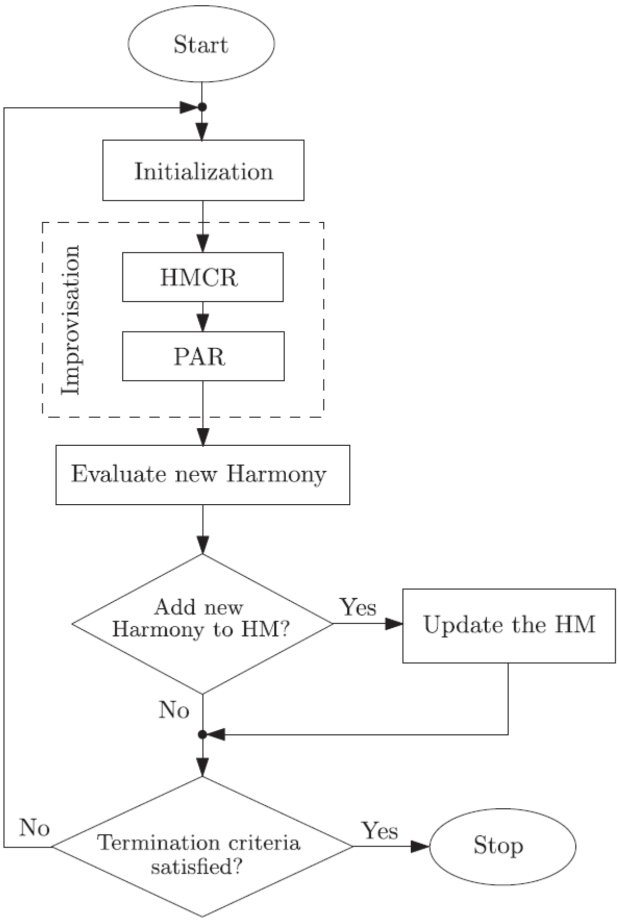

Figure 1.- Harmony Search algorithm flowchart [12,19].

2.2.-EPANET

EPANET is an open-source software that was developed by the US Environmental Protection Agency (EPA) in 1994 to model the hydraulics and water quality dynamics of water distribution systems. EPANET was designed as a research tool to better understand the dynamics of drinking water constituents, taking into account bulk flow and pipe wall reactions [23]. EPANET conducts simulations considering a geometric representation of a pipe network, along with a set of initial conditions (e.g., water levels in tanks) and rules on how the system is operated, and uses this information to compute flows, pressures, and water quality (e.g., disinfectant concentrations and water age) throughout the network for a certain period of time [23].

EPANET models pipes as links that convey water from one point in the network to another, and are assumed to be full at all times. The flow direction is from the higher hydraulic head (internal energy per weight of water) point to the lower head point. The principal hydraulic input parameters for the pipes are the start and end nodes, diameter, length, roughness coefficient (for determining head loss), and current status (open/closed). Then, the computed outputs for the pipes include the flow rate, velocity, head loss, and friction factor.

The hydraulic head lost by water flowing in a pipe due to friction with the pipe walls can be computed using one of the three different formulas given by Hazen-Williams, Darcy-Weisbach, and Chezy-Manning. The Hazen-Williams formula cannot be used for liquids other than water and was originally developed for turbulent flow only. The Darcy-Weisbach formula is the most theoretically correct, and applies over all flow regimes and to all liquids. The Chezy-Manning formula is more commonly used for open-channel flow [23].

Each formula uses the following equation to compute the head loss between the start and end nodes of the pipe:

$$h_L = Aq^B \tag{4}$$

Where $h_L =$ head loss (Length), $q =$ flow rate (Volume/Time), $A =$ resistance coefficient, and $B =$ the flow exponent. Table 1 lists expressions for the resistance coefficient and values for the flow exponent for each of the formulas. Each formula uses a different pipe roughness coefficient, which must be empirically determined [23].

Table 1.- Resistance coefficient and flow exponent for each head loss formula in EPANET

Formula	Resistance Coefficient (*A*)	Flow Exponent (*B*)
Hazen-Williams	$4.727C^{-1.852}d^{-4.871}L$	1.852
Darcy-Weisbach	$0.0252f(\epsilon, d, q)d^{-5}L$	2
Chezy-Manning	$4.66n^{2}d^{-5.33}L$	2

In the table 1, C = Hazen-Williams roughness coefficient, ϵ = Darcy-Weisbach roughness coefficient, f = friction factor, n = Manning roughness coefficient, d = pipe diameter, L = pipe length and q = flow rate.

From a software engineering point of view, EPANET is used within procedural programs through a series of direct calls to its library. This requires the user to be aware of all the different functions offered by EPANET (as well as the sequence of function calls) in order to successfully implement a simulation cycle, when programming [3].

2.3.-EPANET MATLAB-Toolkit

EPANET can be used by two different approaches: as a standalone executable software, or as a shared object library. As a standalone executable software, EPANET launches the application on Windows operating systems. As a shared object library, by its Dynamic Link Library (DLL) for Windows, EPANET can be called by means of a programming interface by external software based on different programming languages such as C/C++, MATLAB, Python and Visual Basic. This external software can make calls to specific EPANET functions which modify and evaluates parameters of the system, the time series and the simulation setting [3].

In this context, programming languages such as MATLAB are widely used by researchers to design and assess new methodologies and tools for analyzing water distribution networks. MATLAB is a high-level programming environment used for data processing and analysis, that allows the development of applications in different platforms, and has a large number of built-in sophisticated applications for optimization, control, signal processing and others. MATLAB is also able to connect to external software libraries, which allows researchers to use tools and simulators developed originally in a different language, such as C or C++ [3]. The methods for interfacing EPANET with MATLAB are as follows [3]:

i. Making direct calls to the EPANET library: via the built-in function of the programming tool. This requires using the MATLAB built-in methods for loading and calling library functions, i.e., using the *loadlibrary* and *calllib* functions.

ii. Using "wrappers": MATLAB methods which follow similar naming conventions as the EPANET functions, that handle the communication with the library internally. This method requires the user to design custom data structures, i.e., for each EPANET function a corresponding MATLAB function is required, and new algorithms need to be designed using those functions.

iii. Using an Object-Oriented approach: by defining a MATLAB Class, which provides a standardized way to handle the network structure, to call all functions as well as procedures using multiple functions, to simulate and in general to perform different types of analysis in the network, through the corresponding object.

The EPANET-MATLAB Toolkit is based on the last method. It defines a class, *epanet*, which is composed of the following elements: properties of the input network model, static properties, public methods (i.e., functions) that the user can directly use in MATLAB, and local (internal) functions the Toolkit uses to make direct calls to EPANET. An *epanet* object is a specific instance of the *epanet* class. In order to illustrate how an *epanet* object for a specific network is created is created in MATLAB, it is shown the following command that was used in this study:

```
d = epanet('incheon_3.inp'); % Load network and use the EPANET library
```

where "incheon_3.inp" is the file containing the WDN model of the study area. Thus, the element *d* is an object which can be defined mathematically as the comprised set of the network topology, structural parameters and functions. This *epanet* object can be shared between different MATLAB functions [3].

Once the object is defined, the Toolkit reads the input (.inp) file and populates more than 300 object parameters, including pipe diameters and node elevations. The Toolkit can update these parameters when there is a change in the network model [3]. In other words, when the model is loaded, it is possible to retrieve all the properties and parameters and modify them from the MATLAB script or the *Command Window*.

After the construction of the object, it is possible to call the Toolkit functions. The Toolkit provides an extensive set of methods which allow the user to retrieve data and to simulate hydraulics and quality dynamics using the EPANET libraries. To simulate the system dynamics, such as flows/pressures and water quality, the different implemented methods are: solve using the EPANET shared object library and get the desired results from memory (step-wise mode); solve using the EPANET shared object library and create a Binary output file, which is then read to retrieve all the results (batch mode); or solve using the EPANET executable and create a Binary output file, which is then read to retrieve all the results (batch mode) [24].

3.- Study area

This chapter is aimed to describe the study area, not only in terms of dimensions and population, but also to give a comprehensive overview of its territorial relevance. Hence, as the Republic of Korea is located in a high competitive economic and commercial region in East Asia, between China and Japan, it is remarkable to briefly review the development strategy carried out by the central government, in which the study area is framed.

In the early 2000s, the Korean Free Economic Zones (FEZ) were planned in order to attract foreign direct investments with the objective of making South Korea the economic hub of Northeast Asia [24]. The motivation of this planning process stands on the recovering from the financial crisis of the late 1990s, and also the fact that the rapid economic development of China was foreseen as a future trade menace in the region [25]. This way, FEZ were aimed to become a growth economic engine to make Korea a dominant commercial competitor.

By its definition, FEZ are especial economic areas designated in order to attract higher levels of foreign investment by: improving business and residential conditions for foreign investment companies, and by relaxing various regulations to ensure the engage in economic activities and offer attractive investment incentives as much as possible [24,26]. The forethought of the original plan was to develop three FEZ in term in the cities of Incheon, Busan-Jinhae, and Gwangyang.

Figure 2.- Location of Incheon, Republic of Korea. Source: IFEZ Authority.

The Incheon Free Economic Zone (IFEZ) was the first FEZ developed by the Korean government and is the frame of the study area of this thesis, the city of Cheongna, also known as Cheongna International City. In the following subsections, both IFEZ and Cheongna are introduced.

3.1-Incheon Free Economic Zone (IFEZ)

The Incheon Free Economic Zone (IFEZ), developed in the city of Incheon, Republic of Korea, is a Korean Free Economic Zone officially designated by the Korean government in August 2003 that consists of three regions: Songdo, Cheongna, and the island of Yeongjong, with a total area of 123.65 km^2, and an expected population of 545,803 people [26]. Incheon is located in the west coast of Korea and it serves as the gateway to Seoul and its high populated metropolitan area, with approximately 26 million persons (by 2020 [27]). Thus, IFEZ is the main access to the center of economic, logistic, industrial and land development in Korea, with the main of becoming the business hub for the economy of Northeast Asia.

Figure 3.- Development of the IFEZ: Cheongna, Songdo and Yeongjong. Source: IFEZ Athority.

IFEZ is located 8 km from downtown Incheon and 50 km from the center of Seoul, so this area and its adjacent Incheon port, as well as the Incheon International airport, are highly accessible with major metropolitan areas around 60-90 minutes away [26]. It makes this location to be especially relevant as the surface transportation between Korea, China and Japan is interrupted by geographical factors and by political border lines. In fact, the Korean west ports as Incheon and Pyongtaek are main transshipment points for combined sea and air transportation routes because they are along the shortest path to Incheon International airport from China across the Yellow sea [25]. And, despite the fact that the Incheon International airport, opened in 2001, is farther away from Seoul than the older Gimpo airport, its infrastructure is much more equipped to support the increasing air traffic and the complex logistic operations [25].

As mentioned before, the designation of Free Economic Zone sets IFEZ to attract foreign investment to stablish itself as a hub for future industries as biotechnology, telecommunications and information technology, artificial intelligence, and other cutting-edge technology, as well as a center for distribution, logistics and tourism [26]. This implies that, unlike other development projects in South Korea, which were led by the public administration, the development of IFEZ relies on private investment. However, the city budget covers the construction cost of infrastructures such as roads, public transportation and hydraulic infrastructures, including water distribution and sewage [28].

3.2.-Cheongna International City

The selected study area for this Thesis is the Cheongna International City, located on the northern zone of IFEZ, in the mainland adjacent to Yeongjong Island. It is an urban development project built on 17.80 km^2, aiming to become an international business town with a completion period comprised between the years 2003 and 2024 [26]. The conceptualization of this international business town is to create an area capable to both attract high levels of investment for technology industries and to provide high standards residential convenient facilities, including leisure and tourism activities, especially for foreign investors.

Furthermore, Cheongna has a strategic location due to its proximity to the Incheon international airport and the fact that has a convenient access to the major axes connections to Seoul. These includes large public transportation nodes, principal roads such as the Incheon international airport Expressway or the Gyeongin Expressway, and also the Ara Waterway, a navigable channel that connects the west coast with the Han river that crosses the center of Seoul.

Despite the current project for the city, Cheongna territory was originally built by reclamation of tidal flats carried out from 1979 to 1989 and was used as farmland in the 1990s and 2000s. In fact, the original reason for reclaiming this area was to use it as agricultural land [29]. Figure 4 shows the location of the study area.

Figure 4.- Satellite view of the location of Cheongna International city.

According to the master plan, the expected population was 90,000, but already surpassed 100,000 in April 2019, and is expected to increase to 120,000-130,000 in the future if only apartment houses, officetels (common Korean multi-purpose buildings with residential and commercial units), townhouses, and detached houses that are currently on sale are counted. According to the June 2021 resident registration figures, the population is approximately 112,000 [27].

In this context, as it is an area that is still currently being developed, it will be observed in the model construction section that the WDN contains several nodes with no water demand that are assumed to be points where nothing is built yet and, therefore, there is no current demand. Consequently, there are some pipes in which the flow velocity is null, most of the times linking these nodes. Thus, the necessary previous considerations are described in the aforementioned section.

4.- Model construction

This section presents the procedure for the model construction used in this study, both for optimizing the pipe diameter of the WDN and the assessment of deteriorated pipes based on the roughness coefficient. For this purpose, the HS algorithm was implemented in MATLAB along with the EPANET-MATLAB Toolkit using two different approaches. In the next subsections, it is described the original model of the Cheongna WDN, the construction of the model for the pipe diameter optimization, and lastly the procedure for the assessment of deteriorated conduits.

4.1.-Original model

EPANET models the physical objects that constitute a distribution system as well as their operational parameters. Networks consists of pipes, nodes (pipe junctions), pumps, valves, and storage tanks or reservoirs. The characteristics and description of these objects are stored in "Network" (.net) or "input" (.inp) files, which can also be modified by text editors or other programs such as Excel. In the case of the study area, the characteristics of the Cheongna pipe network were provided by the Incheon Metropolitan City Technical Report 2015 through an input (.inp) file.

Tables 2 and 3 list the main aspects and hydraulic characteristics of the original Cheongna WDN, respectively. Figure 5 shows the pipe size distribution of the WDN. Figure 6 shows the distribution of the hydraulic pressure in the nodes, both from the original model.

Table 2.- Main characteristics of the original Cheongna WDN model.

No. of Reservoirs	**No. of Junctions**	**No. of Pipes**	**Roughness Coefficient *C***	**Flow Units**	**Headloss Formula**
1	152	200	100	CMD[1]	Hazen-Williams

[1]Cubic Meters per Day

Table 3.- Hydraulic characteristics of the original Cheongna WDN model.

Min. Ø (mm)	**Max. Ø (mm)**	**Average Ø (mm)**	**Min. Hydraulic Head (m)**	**Max. Hydraulic Head (m)**	**Min. flow velocity (m/s)**	**Max. flow velocity (m/s)**	**Average flow velocity (m/s)**
80	900	244.15	32.83	65.51	0	2.35	0.35

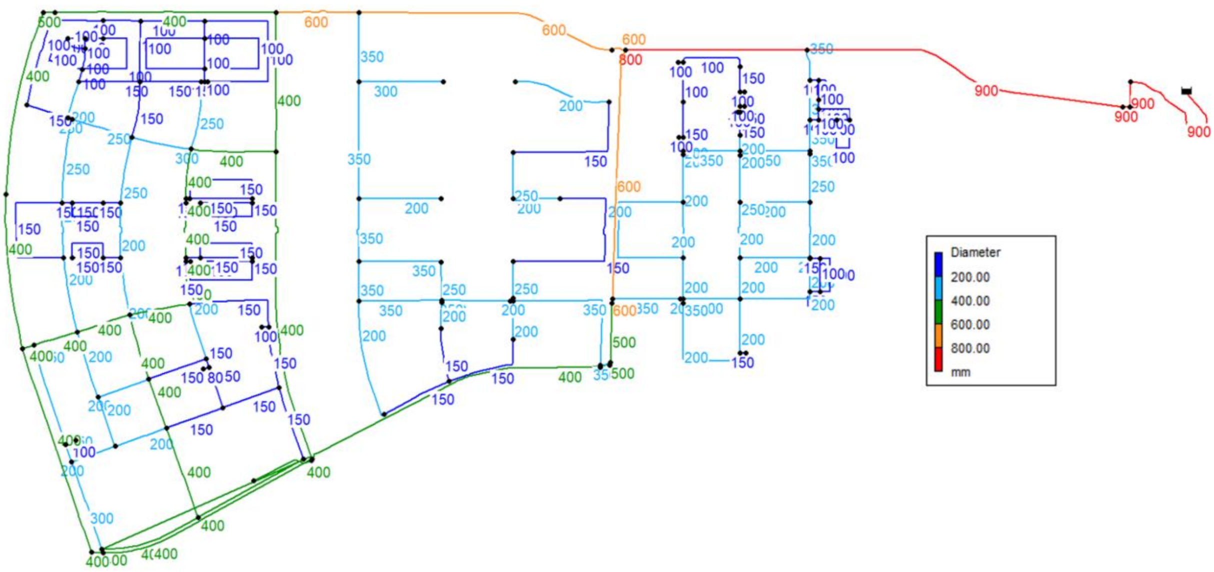

Figure 5.- EPANET original model of the Cheongna WDN indicating the current pipe diameters.

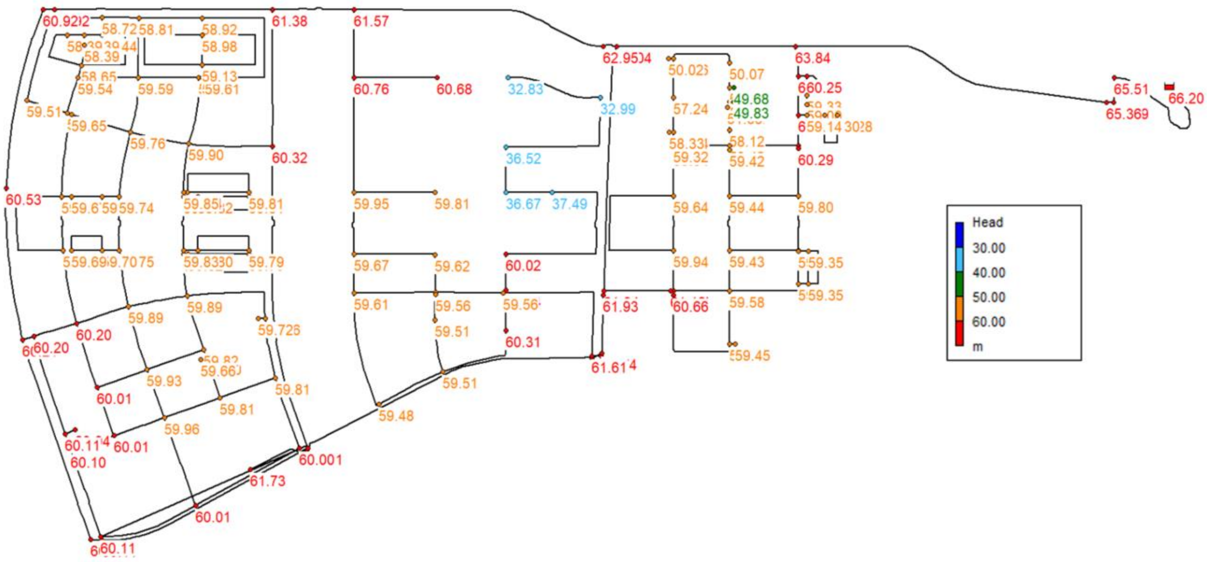

Figure 6.- EPANET original model of the Cheongna WDN indicating the current head pressures.

As it can be observed in figure 7, the original model of the Cheongna WDN contains few links in which the velocity of the water in the conduits is low (less than 0.05 m/s) and also, few junctions in which the water demand is null. As mentioned before, the study area corresponds to a developing project, so it is likely that most of these elements were included in the model for an expected expansion of the WDN. In this manner, those junctions in which the demand is currently null, they may either be future water supplying points or just future connection point to convey the water to other newly developed areas. Similarly, some of the existing conduits in the model connects these null demand junctions or present duplicities in areas that are already linked, which produces a consequent decrease of the water velocity in the vicinity area.

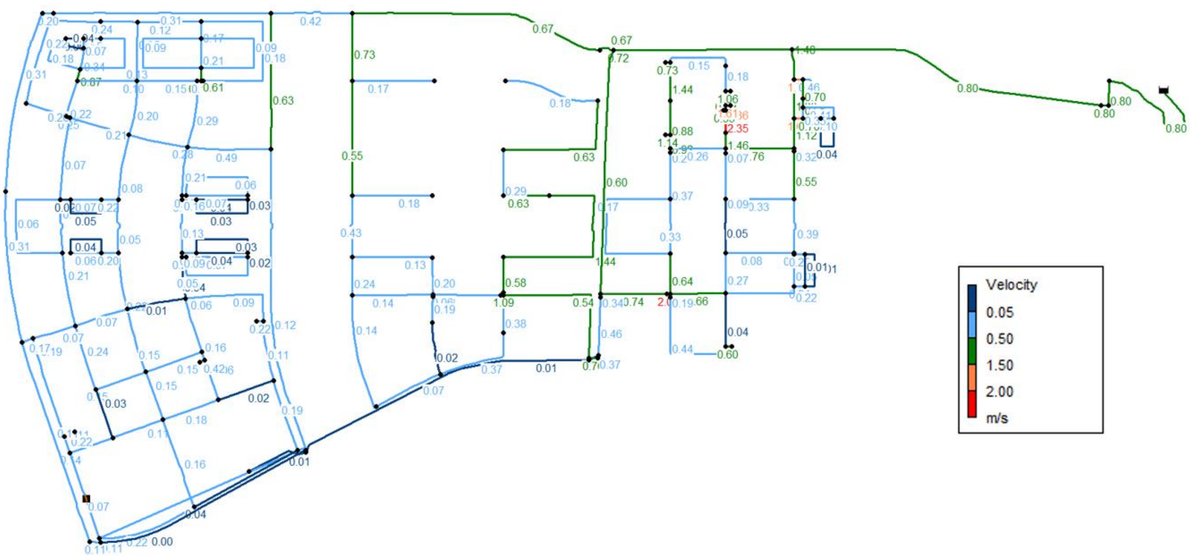

Figure 7.- EPANET original model of the Cheongna WDN indicating the current flow velocities.

Furthermore, as the study area is developed in a tidal flat reclamation land, that makes the location of Cheongna International city to be a highly flat terrain. As a consequence, and regardless of the fact the reservoir that feeds the WDN is located in an elevated hill near the city, there is no significant elevation gradients in the study area., which also reduces the water velocity flow in the system.

It is necessary to maintain a range of minimum and maximum velocities in the pipe network, because low water velocities may cause sedimentation of the present particles in the water. This produces consequent issues related to the reduction of the inner pipe diameter, the increase of the roughness coefficient, and other issues related to water quality. From the hydraulic point of view, these issues may also cause a reduction on the service level as the head pressure is decreased. On the contrary, high water velocities may cause erosion of the conduits and its consequent deterioration.

As the urban project is progressing, and the infrastructure is available, it is expected that those waiting points (i.e., the current null demand junctions) generate values of water demand. However, in the optimization process, the links with velocities equal or near to 0 m/s may cause some issues as a range of minimum and maximum velocities is established in the objective function. For this reason, it is necessary to modify the original model by deleting those conduits in which the velocity is null, as well as those junctions in which there is no current demand and are linked by these conduits. In the next subsection it is described the process for the model construction in the case of the optimization of the pipe diameter set.

4.2.-Pipe diameter optimization

Prior to initializing the algorithm, some considerations must to be taken into account. In terms of pipe diameter, the optimization of the water network implies finding the smallest diameter set that is capable of providing the expected service. This means that at every junction, a minimum head pressure has to be reached, but a maximum value should also be considered according to the local standard regulations.

In the case of the study area, the minimum and maximum values for the head pressures are 32.83 m and 65.51 m, respectively. However, in this study, a lower range of values (between 15 m and 40 m) was considered to achieve an optimal design in which the pressure in the system is reduced to avoid future leakage problems while also reaching a minimum suitable service value.

In addition to the considerations for the head pressure, a range of minimum and maximum water velocities in the pipes was also regulated for the WDN, as mentioned before. The reason for this regulation is to guarantee a stable level of water quality regardless of the demand pattern to avoid different problems related to chlorine decay. In this case, the velocity range was established to be between 0.2 and 3 m/s. Both head pressure and velocity limitation were used as the constraints –i.e., the penalties- in the objective function used in the HS algorithm.

As previously stated, the original model of the Cheongna WDN contains few conduits with low or null velocities. For this reason, some of these conduits have been deleted in order to avoid possible complications in the optimization process. Consequently, some of the junctions with no water demand that were linked to this conduits, have been also deleted. Figures 9, 8 and 10 show the modified network that has been used in this study and its characteristics. Tables 4 and 5 list the main aspects and hydraulic characteristics of this modified Cheongna WDN, respectively

Table 4.- Main characteristics of the modified Cheongna WDN model.

No. of Reservoirs	No. of Junctions	No. of Pipes	Roughness Coefficient *C*	Flow Units	Headloss Formula
1	143	153	100	CMD	Hazen-Williams

Table 5.- Hydraulic characteristics of the modified Cheongna WDN model.

Min. Ø (mm)	Max. Ø (mm)	Average Ø (mm)	Min. Hydraulic Head (m)	Max. Hydraulic Head (m)	Average Hydraulic Head (m)	Min. flow velocity (m/s)	Max. flow velocity (m/s)	Average flow velocity (m/s)
80	900	245.62	33.02	65.54	58.64	0.1	2.35	0.47

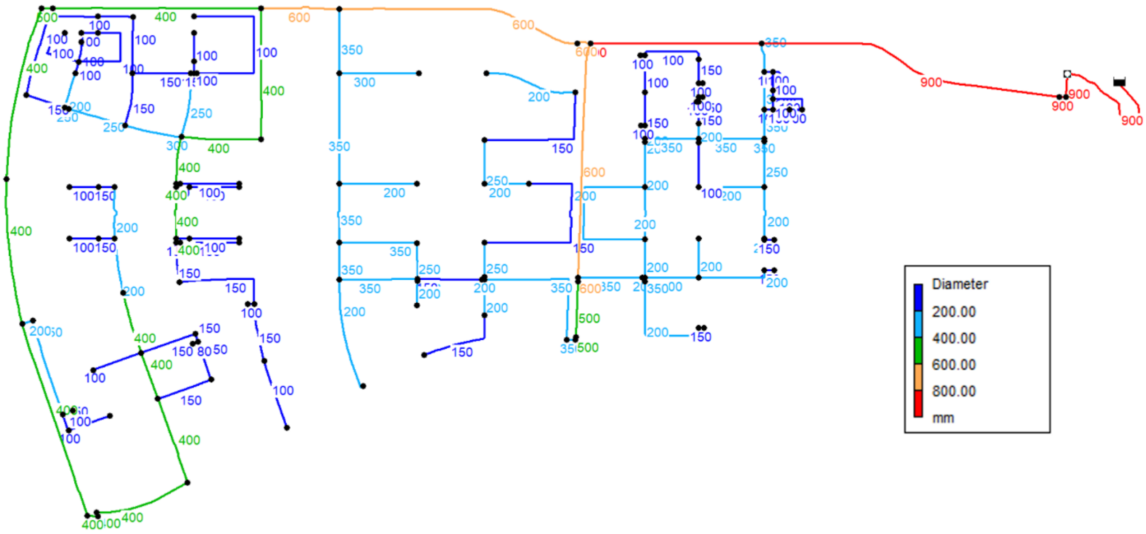

Figure 9.- EPANET modified model of the Cheongna WDN indicating the distribution of pipe diameters.

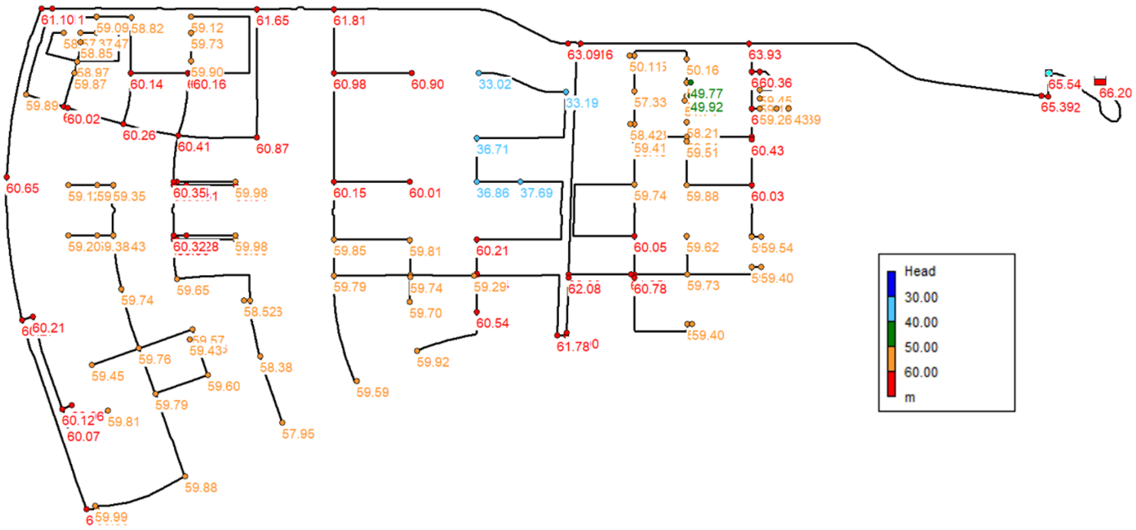

Figure 8.- EPANET modified model of the Cheongna WDN indicating the distribution of head pressures.

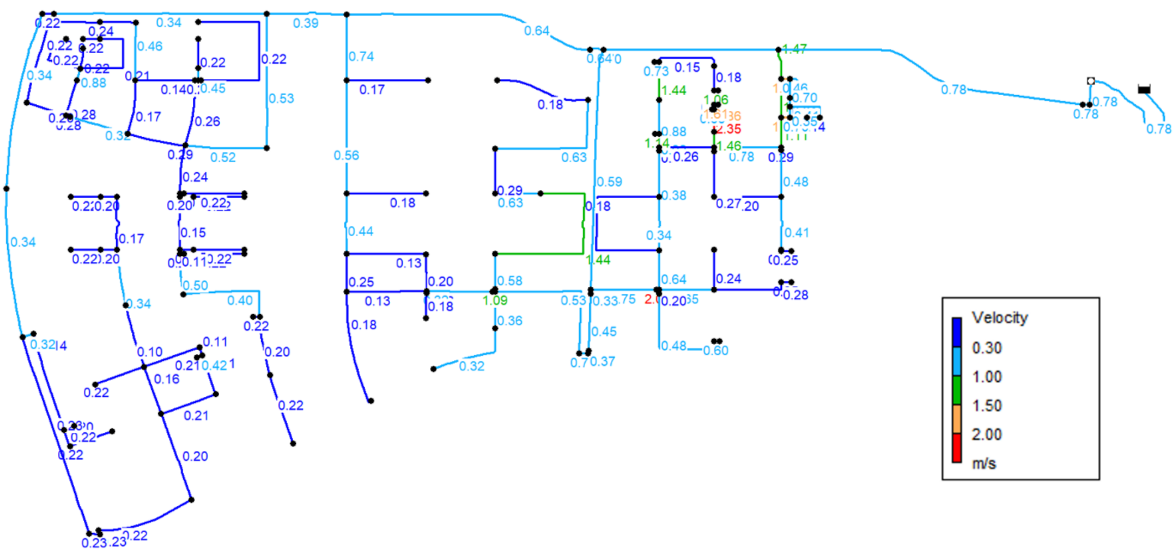

Figure 10.- EPANET modified model of the Cheongna WDN indicating the distribution of flow velocity.

4.3.-Assessment of pipe deterioration

To analyze the effect of pipe deterioration over time, the previous program was used, but a different approach was applied. In this case, the aim is to find the optimal C value that should be maintained across the entire system in order to conserve the original required level of serviceability. Thus, the HS algorithm can provide the distribution of the roughness coefficient for every conduit in the network, making it possible to identify those pipes that will affect the head pressure values in the nodes if they deteriorate. Therefore, the conduits exhibiting higher values of C can be assumed to be the most sensitive to pipe aging, and should be repaired or replaced in the first term.

As it can be observed in figure 11, there is a uniform distribution of the roughness coefficient along the WDN model with a value of C=100. In this case, the newly modified model conserves the original value of the roughness coefficient in the remaining conduits.

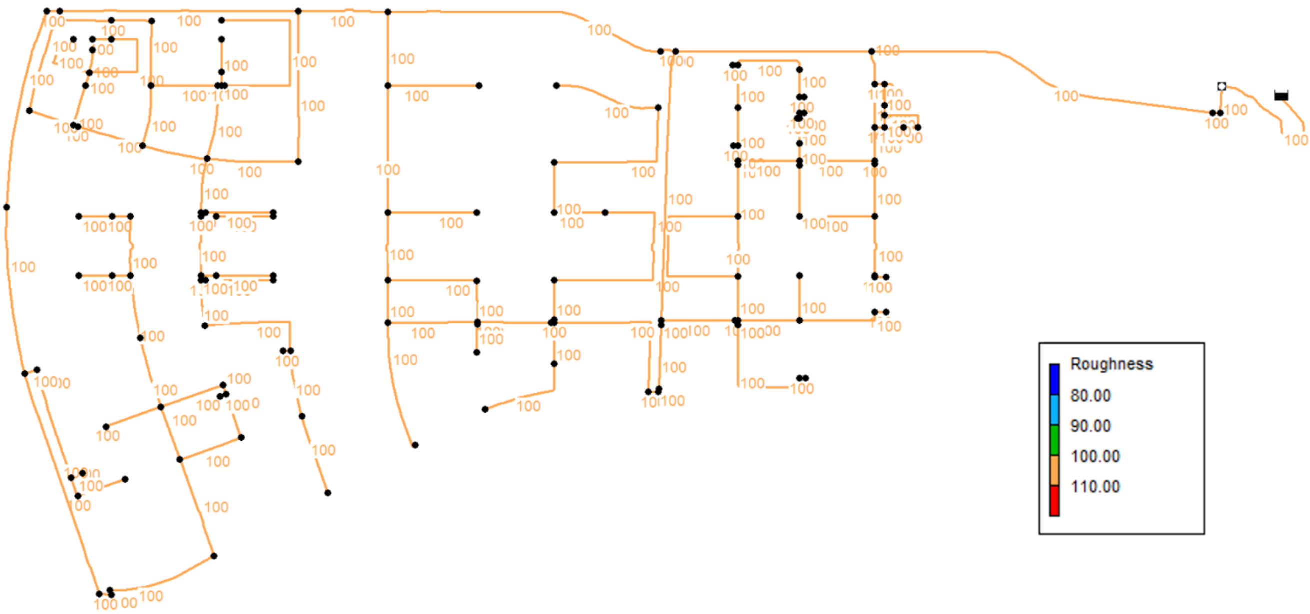

Figure 11.- EPANET modified model of the Cheongna WDN indicating the distribution of the roughness coefficient.

5.- Results and discussion

In this section, the results from the optimization process for the optimal pipe diameter set and the assessment of pipe deterioration derived from the identification of critical pipes based on the roughness coefficient C value, are presented and discussed. The pseudocode of the implementation of the HS algorithm for both processes is presented in the appendixes.

5.1.-Determination of optimal diameter set

The outcomes of the application of the HS algorithm provide a set of pipe diameters that is considered to be optimal based on the constraints imposed in the objective function. These constraints, as explained in the model construction section, guides the optimization process based on the limitations of head pressure on the nodes and the flow velocity in the pipes. For this reason, although a general reduction of the diameter is achieved in the network, in some particular pipes may be increased owing to hydraulic requirements. Table 6 shows the value of the parameters used for the HS algorithm as well as the objective function constraints.

Table 6.- Parameter values used in the implementation of the HS for pipe optimization.

NI	HMS	HMCR	PAR	Bw	H (m)	v (m/s)
50,000	30	0.95	0.3	0.01	15–40	0.2–3

In addition, before initializing the HS, it is necessary to set the upper and lower bounds between which the algorithm will find the solution for the optimization problem. In this case, both the upper and lower bounds for the pipe diameter were established as 80 mm and 900 mm, respectively. These values also correspond to the maximum and minimum pipe diameter that were initially set in the original model, so this range is maintained in case there is some hydraulic conditions that requires these minimum and maximum sizes.

However, if only the lower and upper bound are specified, the HS will blindly find continuous values within this range of sizes. Thus, a set of discrete commercial pipe diameters must be established to obtain real-world applicable solutions. Table 7 shows the set of commercial pipe diameters that are common in Korea for ductile iron, which was the material considered in this study.

Table 7.- Set of common commercial pipes in Korea used in the optimization of the Cheongna WDN.

Commercial pipe diameters (mm)														
80	100	125	150	200	250	300	350	400	450	500	600	700	800	900

Although some of the conduits may increase in diameter owing to hydraulic requirements, a reduction in the average size of the pipes is achieved, providing a general reduction in the head pressure in the system, which was the main objective.

Thus, a reduction of the maximum pipe diameter of the maximum pipe diameter from 900 mm to 800 mm is obtained along with a reduction of the average pipe diameter of approximately 20% (from 245.62 mm in the original model to 195.78 mm in the simulated one) using the HS algorithm.

In the case of the hydraulic head, owing to the restrictions imposed as the constraints of the objective function, both the lower and upper boundaries were reduced, as expected. The minimum hydraulic head is reduced from 33.02 m in the original model to 15.4 m in the HS model. The maximum value of the hydraulic head decreases from 65.54 m in the original model to 38.28 m in the simulation. This corresponds to a reduction of approximately 47% in the lower bound and 50% in the upper bound for the hydraulic head range in the system. In this manner, the outcomes achieved by means of the HS algorithm along with the setting of the objective function have led to an optimization of the Cheongna WDN in terms of a reduction in the pressure in the system along with a reduction in the pipe diameter of the conduit network. Therefore, both results imply a reduction in the probability of damage due to high pressure as well as a reduction in the construction costs of the system.

On the other hand, as the pipe diameter is generally reduced in the network, the water flow velocity consequently increases. In this case, the maximum flow velocity in the original model is 2.35 m/s, while in the HS model is 2.93 m/s, representing an increase of approximately 20%. Furthermore, the average flow velocity also increases from 0.47 m/s in the original model to 0.68 m/s in the simulated model, which represents an increase of approximately 30%. Despite the average increase in the flow velocity in the system, this parameter remains within the range of admissible values, as it does not exceed the 3 m/s upper bound. On the other hand, it is ensured a minimum water velocity above 0.1 m/s.

In addition, the obtained set of pipe diameters must follow a coherent distribution, i.e, the size of the conduits must gradually decrease as the supplying points are achieved. In other words, when a pipe reaches a node, the diameter of the next pipe must be less than or equal than the previous one. In this case, the implemented HS algorithm seeks for the optimal set of pipe diameters based on random combinations of the best values. As a consequence, if no other constraint is considered, the distribution of pipe sizes will not follow a coherent distribution. For this reason, the necessary constraint to achieve these condition is also applied to the objective function.

Figures 12 and 13, respectively, show the results of the optimization carried out by means of the HS in terms of pipe diameter and hydraulic head, and figure 14 shows the flow velocity distribution. Table 8 summarizes the main outcomes of this model. For clarification, in the analysis of the results the hydraulic head values of 66.2 m and higher than 60 m have been excluded, which correspond to the reservoir and to a non-supplying water point located near the reservoir, respectively.

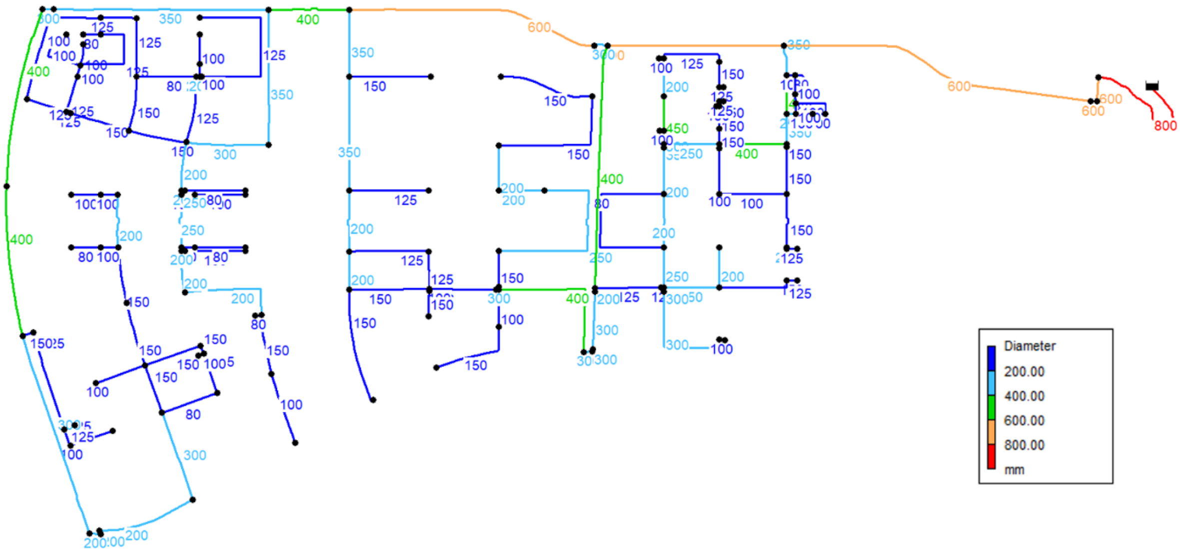

Figure 12.- Pipe diameter distribution of the Cheongna WDN as a result of the application of the HS.

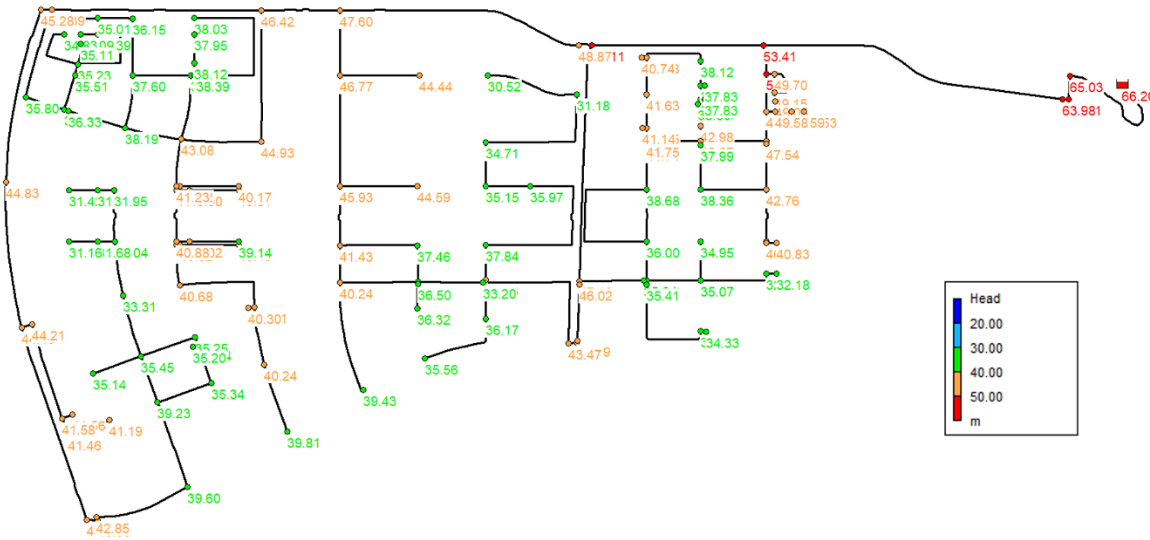

Figure 13.- Head pressure distribution of the Cheongna WDN as a result of the application of the HS.

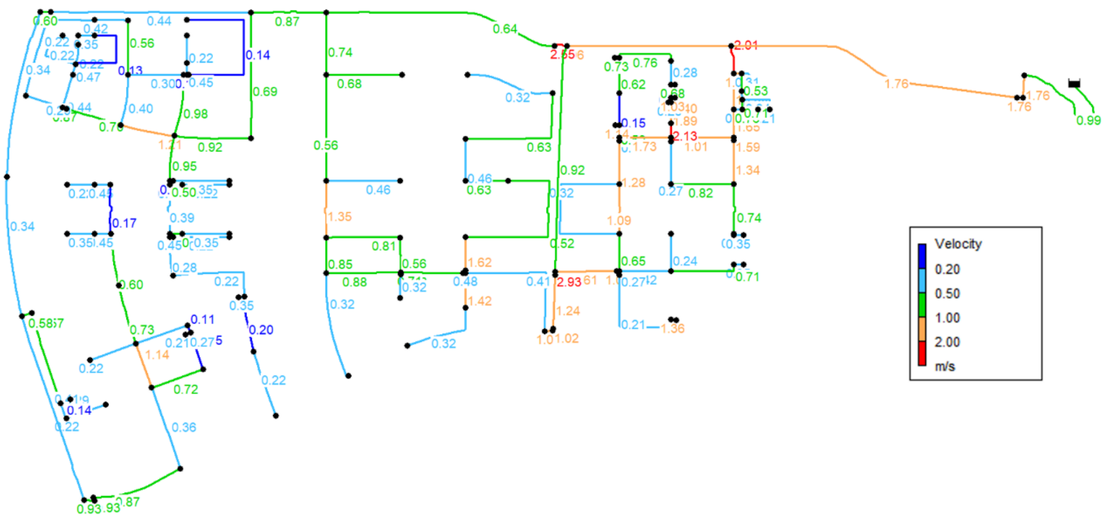

Figure 14.- Flow velocity distribution of the Cheongna WDN as a result of the application of the HS.

Table 8.- Outcomes from the HS algorithm for pipe diameter optimization of the Cheongna WDN.

Min. Ø (mm)	Max. Ø (mm)	Average Ø (mm)	Min. Hydraulic Head (m)	Max. Hydraulic Head (m)	Average Hydraulic Head (m)	Min. flow velocity (m/s)	Max. flow velocity (m/s)	Average flow velocity (m/s)
80	800	195.78	15.4	38.28	25.61	0.11	2.93	0.68

Despite the fact that, regardless of the constraints in the flow velocity implemented in the objective function, from the results of the optimization of the WDN few conduits with values lower than 0.2 m/s are observed. However, as in the original model of the Cheongna WDN the number of pipes with low or null velocities was considerably higher and the study area is located in a highly flat terrain, the results from the HS optimization are as expected. Anyhow, in case of requiring the minimum flow velocity to achieve values in the specified range, it is possible carry out simulations with higher number of iterations or refine the objective function and its constraints. Nevertheless, and as mention before, the main objective of this study is achieved by the reduction of the head pressure and the pipe diameter set, and also by ensuring a range of minimum and maximum range of water velocity.

5.2.-Assessment of pipe deterioration

The second part of this study is the application of the HS algorithm to find the critical pipes in terms of the roughness coefficient C. For this purpose, the HS was implemented in the same manner as for the optimal pipe diameter, but the C value was used as the objective function. In this case, by loading the modified Cheongna WDN model into the EPANET-MATLAB Toolkit, the optimal values of the roughness coefficient that must be maintained to provide the original level of serviceability were determined. In this manner, it is possible to identify the conduits that exhibit higher values of C, and are thus considered to be the ones that are most sensitive to pipe aging.

In this case, the range of values for the lower and upper bound in the HS was set between 70 and 100, stepped by 5, based on the assumption that ductile iron tends to increase its roughness coefficient by decreasing the Hazen-Williams value of C by 10 every ten years [2]. In this manner, a range of values for the head pressure and the water velocities was set in the objective function in order to achieve admissible results. Table 9 and 10 lists the different values of C as pipes age and the parameters of the HS used in this simulation, respectively.

Table 9.- Evolution of the Hazen-Williams C value for ductile iron deteriorated pipes.

Aging	Current	10 years	20 years	30 years
C value	100	90	80	70

Table 10.- Parameter values used in the implementation of the HS for the optimal C value distribution.

NI	HMS	HMCR	PAR	Bw	H (m)	v (m/s)
5,000	30	0.95	0.3	0.01	15–65	0.1–3

Figures 16, 15 and 17, and table 11 show the outcomes of this approach, in which the optimal distribution of the roughness coefficient for the entire network can be observed. Those conduits that maintain a value of C = 100 are considered as critical pipes and should be repaired or replaced in the first term as the WDN ages.

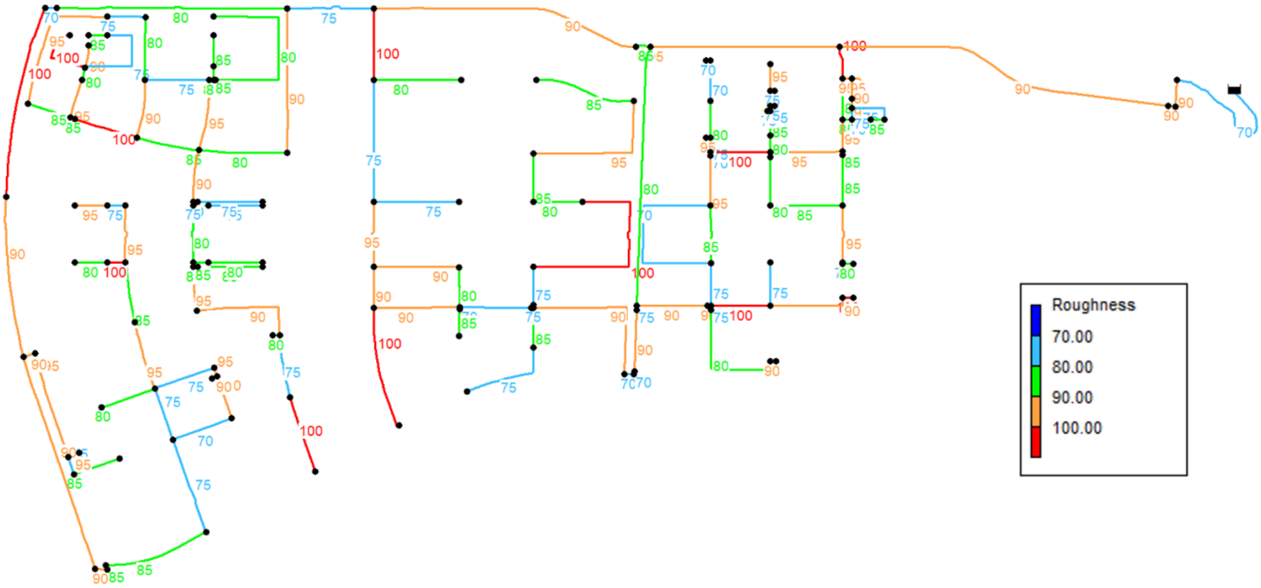

Figure 16.- Distribution of the optimal C value as a result of the application of the HS.

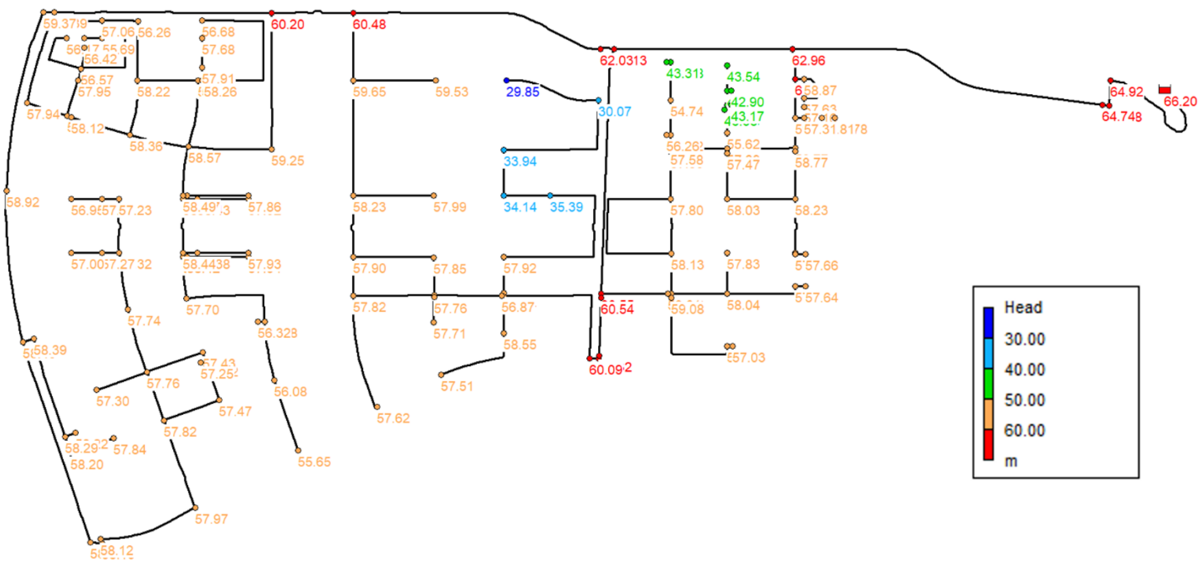

Figure 15.- Head pressure distribution of the Cheongna WDN as a result of the optimal C value obtained by the HS.

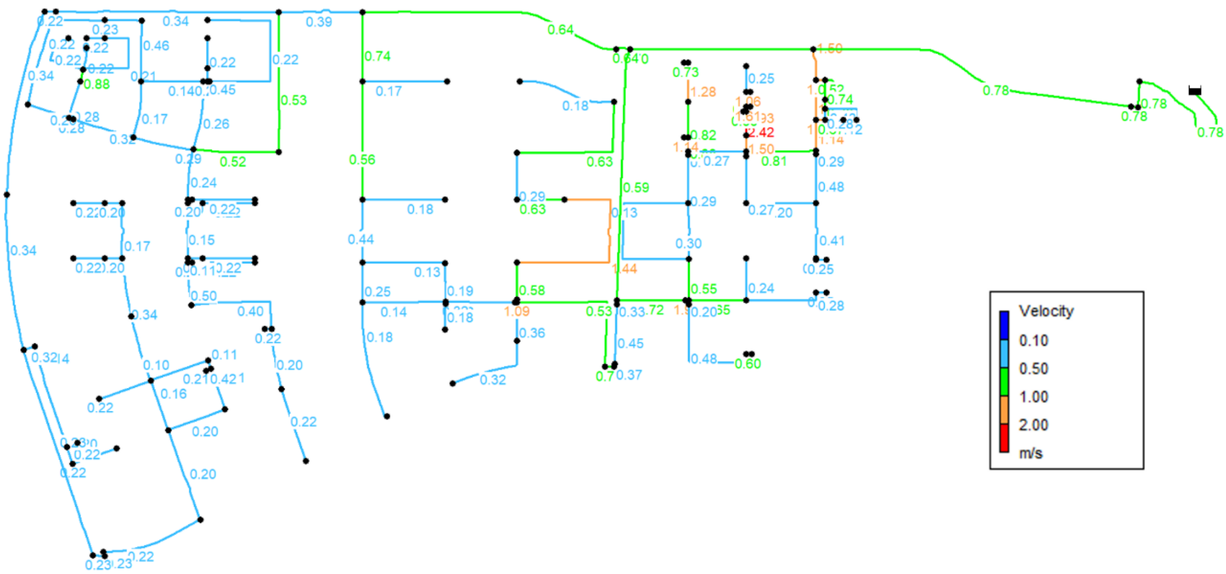

Figure 17.- Flow velocity distribution of the Cheongna WDN as a result of the optimal C value obtained by the HS.

Table 11.- Outcomes from the HS algorithm for the optimal C value distribution of the Cheongna WDN.

Min. C	Max. C	Average C	Min. Hydraulic Head (m)	Max. Hydraulic Head (m)	Average Hydraulic Head (m)	Min. flow velocity (m/s)	Max. flow velocity (m/s)	Average flow velocity (m/s)
70	100	84.51	29.85	64.92	56.42	0.1	2.42	0.47

As observed from the outcomes of the application of the HS algorithm using this approach, it is possible to identify the conduits that are most sensitive to aging, and thus, the critical pipes, while achieving the original required level of serviceability. Furthermore, as it was imposed a range of minimum and maximum water velocities, apart from obtaining the optimal distribution of the Hazen-Williams roughness coefficient, it is also assured a minimum water velocity which avoid future possible water quality issues in the system.

Thus, this approach can provide a useful tool for determining the repair or replacement of deteriorated pipes. From this results it is possible to generate different scenarios which evaluates the consequences of either applying different conservation techniques in the system or not. From this scenarios, decision-makers can decide the most suitable strategy for the maintenance of the water distribution network.

6.- Conclusions

The WDN optimization problem has been of interest to many researchers in the field of water engineering. However, many studies have focused on the optimal size of the elements of the water distribution system or its location. The main objective of this Master thesis was to conduct a simulation using the Harmony Search algorithm for obtaining the optimal pipe diameter for the Cheongna International city WDN, but also to attempt to provide a useful tool for future operation management and decision making in the second part. Using this method, the assessment of deteriorated conduits should assist in determining whether pipes in which the roughness coefficient is high should be replaced or repaired and to evaluate the consequences of each decision.

The application of the HS algorithm along with the EPANET-MATLAB Toolkit has allowed the optimization of the Cheongna International City WDN. In this sense, the average pipe diameter of the network achieved a reduction of approximately 20%, which implies a reduction of the costs through an optimal design of the network. From the outcomes of the HS algorithm a coherent set of pipe diameters was also obtained, in which the size of the conduits is less than or equal to the previous link, providing a realistic solution for the WDN. In addition, the average head pressure was reduced by approximately 60% across the entire system while still providing the desired level of serviceability, which was the main objective of this study. Thus, the optimization of this WDN also implies the reduction of the probability of damages due to high pressures as well as a significant reduction of the construction costs

In the second part of this study, the HS algorithm was demonstrated to be a useful tool for the identification of critical pipes that are most sensitive to aging. In this manner, the outcomes of the implementation of the HS provided a distribution of the roughness coefficient C for the entire pipe network that would maintain similar values of head pressure as in the original model. In this sense, a reduction of the C value in most of the conduits was achieved, but those that exhibited higher values were identified as pipes that are more likely to affect the level of serviceability due to pipe aging. Therefore, these critical conduits should be repaired or replaced in the first term.

In the future, additional work is proposed to refine the outcomes of the HS algorithm. In this study, the provided WDN model did not include water demand patterns, so each of the simulations were run as a single period analysis, i.e., with no variation along the time. In order to obtain more realistic results, it is possible to apply real demand patterns to the study area model and to evaluate the behavior of the WDN during a 24h period, with special attention to the peak and valley hours. In this simulations it is important to check the range of values for the minimum and maximum velocities, as well as the range of head pressure for the required level of serviceability of the network. Then, if the demand patterns are applied, the optimization of the WDN will show more realistic outcomes.

Another step in future works, in addition to the application of the demand patterns in the WDN model, could be the application of analysis for the water quality, and also the interaction with other hydraulic elements such as valves. In this manner, it is possible to achieve a complete simulation and optimization of the WDN by taking into account the hydraulic and water quality requirements of the network.

Finally, it could be also interesting to attempt to refine the parameters of the HS algorithm and the objective functions. In this manner, the objective of this process would be to obtain a possible reduction of the computational cost along with an improvement of the results.

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Appendix A – Main code for pipe diameter optimization

```
%% Variable Matrices for Harmony Search:

clc;
clear;
close all;

global VarMin;       % Lower bound of decision variables
global VarMax;       % Upper bound of decision variables
global VarSize;      % Dimension of decision vectors
global HMS;          % Capacity of the algorithm memory
global HMCR;         % Value of harmony memory consideration rate
global PAR;          % Value of pitch adjustment rate
global bw;           % Value of bandwidth distance
global VarCom;       % Set of commercial diameters



%% Project Definition for EPANET
% Load network and use the EPANET library
d = epanet('incheon_3_modif.inp');
% Retrieve the Link Diameter of each link in model"d"
diameter_x = d.getLinkDiameter;


%model_07: epanet pipe network model used to create the initial
harmony
model_07 = epanet('incheon_3_modif.inp');
diameter_07 = model_07.getLinkDiameter;

Nodes=d.getNodeCount;
Links=numel(diameter_x);
Resv=d.getNodeReservoirCount;
Junc=Nodes-Resv;


model_07.setLinkDiameter(diameter_07);
HTS07 = model_07.getComputedHydraulicTimeSeries;

Node_H_07 = HTS07.Head;      %Head pressure
Link_F_07 = HTS07.Flow;      %Flow velocity

model_07.plot;
```

```
%% Connectivity Link matrix generator
con = getConnectivityMatrix(d);

name = d.getNodeNameID;

NodeLinks = d.getNodesConnectingLinksID;

for k=1:2
    for i=1:size(NodeLinks,1)
        for j=1:length(name)
            if isequal(NodeLinks(i,k),name(j))
            NodeLinks2(i,k) = j;
            end
        end
    end
end

con2 = zeros(size(NodeLinks,1));

for i=1:size(NodeLinks,1)
       Ki=NodeLinks2(i,1)==NodeLinks2(:,2);
       con2(i,:)=Ki';
end


%% Problem Definition
% Definition of Cost function using function handle
CostFunction=@(diameter_x) fitness_Diametermin(diameter_x,d,con2);

nVar=Links;                       % Number of decision variables
VarSize=[1 nVar];                 % Decision variables matrix size

VarMin=80;                        % Decision Variables lower bound
VarMax=900;                       % Decision Variables upper bound

% Set of commercial pipe diameters in Korea
VarCom=[80 100 125 150 200 250 300 350 400 450 500 600 700 800 900];



%% Parameters of the Harmony Search Algorithm

MaxIt=50000;                   % Maximum number of iterations
HMS=30;                        % Harmony Memory Size

HMCR=0.95;                     % Harmony memory consideration rate
PAR=0.3;                       % Pitch adjustment rate
```

```
bw=0.01*(VarMax-VarMin);      % Band width distance


%% Initialization
% Empty harmony structure
base_harmony.Position=[];
base_harmony.Cost=[];

% Initialize harmony memory
HM=repmat(base_harmony,HMS,1);

% Create Initial Harmony memory
H_old=Node_H_07;         %Head pressure
F_old=Link_F_07;         %Flow velocity

for i=1:HMS
    HM(i).Position=unifrnd(VarMin,VarMax,VarSize);  % Create Harmony

    N=unifrnd(VarMin,VarMax,VarSize);

    % adapt to commercial diameters

    A = repmat(VarCom',[1 length(N)]);
    [minValue,closestIndex] = min(abs(A-N));
    closestValue = VarCom(closestIndex);
    HM(i).Position=closestValue;

    HM(i).Cost=CostFunction(HM(i).Position);          % Evaluate Harmony
        %      HM(i).Cost=CostFunction(HM(i).Position,P_old,F_old);
end

% Sort Harmony Memory
Costs=[HM.Cost];
[~, SO]=sort(Costs);
HM=HM(SO);

% Update Best solution ever found
BestSol=HM(1);

% Array to hold best costs values
BestCost=zeros(MaxIt,1);

% Array to hold mean costs values
MeanCost=zeros(MaxIt,1);
```

```
%% Harmony Search Main Loop
executetime_acc=0;
back_it=1;
it=1;
ini=0;
while BestCost(it)>=50 || ini==0
    if ini==0
        ini=1;
    else
        it=it+1;
        if it>MaxIt
            break
        end
    end
    tic;
    % Initialize Array for storing new Harmonies
    newHarmony=repmat(base_harmony,1,1);

    % Create new harmony:
    % New harmony positions Pre-Allocation: Create Randomly
    newHarmony.Position=Improvise(HM);

    % Evaluation
    newHarmony.Cost=CostFunction(newHarmony.Position);

    % Similarity Check
    newHarmony=SimiCheck(HM,newHarmony);

    % Update Harmony Memory
    HM=UpdateMemory(HM,newHarmony);
    % Update Best Solution ever found
    BestSol=HM(1);

    % Store the best cost
    BestCost(it)=BestSol.Cost;

    % Store Mean Cost
    MeanCost(it)=mean([HM.Cost]);

    % Show Iteration information
    disp(['Iteration ' num2str(it) ': Mean Cost= '
num2str(MeanCost(it)) '; Best Cost= ' num2str(BestCost(it)) '; Time =
' num2str(toc)]);

    % Band width:
    bw=bw*rand();
    if bw<0.00001
```

```
        bw=0.1*(VarMax-VarMin);
    end

    % Backup
    if mod(it,10)==0
        BestSol_back(back_it,:)=BestSol(1).Position(:);
        back_it=back_it+1;
    end


    executetime(it)=toc;
    executetime_acc=executetime(it)+executetime_acc;

end

%% Results visualization

figure;
semilogy(BestCost,'r','LineWidth',2);
hold on
semilogy(MeanCost,'b:','LineWidth',2);
hold off
xlabel('Iteration');
legend('Best Cost','Mean Cost');
grid on;


d.setLinkDiameter(BestSol.Position);
Sol=d.getComputedHydraulicTimeSeries;
Sol.Head
mean(BestSol.Position)
```

Appendix B - Objective function for optimal pipe diameter set

```
function y = fitness_Diametermin(x,epanet_model,con2)

epanet_model.setLinkDiameter(x);

HTS_HS = epanet_model.getComputedHydraulicTimeSeries;

%Solve hydraulics in library, HTS=Hydraulic Time Series
NodeHS_H = HTS_HS.Head;
LinkHS_F = HTS_HS.Flow;
LinkHS_V = HTS_HS.Velocity;
Diameter = epanet_model.getLinkDiameter;

N_Node = numel(NodeHS_H)-1;
N_Link = numel(LinkHS_F);
N_tot = N_Node+N_Link;

DN_Sum(1)=0;          %cost Nodes
DL_Sum(1)=0;          %cost Links

%Penalty on Head pressure
cont1=0;
for t=1:1:N_Node
    if NodeHS_H(t)<15 || NodeHS_H(t)>40
        DN_Sum(1)=1e4+DN_Sum(1);
        cont1=cont1+1;
    end
end

%Penalty on flow velocity in the pipes
cont2=0;
for t=1:1:N_Link
    DL_Sum(1)=Diameter(t)+DL_Sum(1);
    if LinkHS_V(t)<=0.2 || LinkHS_V(t)>3
        DL_Sum(1)=1e2+DL_Sum(1);
        cont2=cont2+1;
    end
end

%Penalty on higher diameters than previous pipes
cont3=0;
for t=1:1:N_Link
    Prev_Links=find(con2(t,:)); %previous links
    if length(Prev_Links)>=1
        for j=1:length(Prev_Links)
```

```
            if Diameter(t) > Diameter(Prev_Links(j))
                DL_Sum(1)=DL_Sum(1) + 1e;
                cont3=cont3+1;
            end
        end
    end
end

fprintf('%2.0f  %2.0f  %2.0f  %2.0f
\n',cont1,cont2,cont3,cont1+cont2+cont3)

y =(DN_Sum(1)/N_Node+DL_Sum(1)/N_Link);
```

Appendix C – Main code for C value optimization

```
%% Variable Matrices for Harmony Search:
clc;
clear;
close all;

global VarMin;       % Lower bounde of decision variables
global VarMax;       % Upper bound of decision variables
global VarSize;      % Dimension of decision vectors
global HMS;          % Capacity of the algorithm memory
global HMCR;         % Value of harmony memory concideration rate
global PAR;          % Value of pitch adjustment rate
global bw;           % Value of bandwidth distance
global VarC;         % Set of C values


%% Project Definition for EPANET
d = epanet('incheon_3_modif.inp');
%Retrieve the value of the roughness coeff for each link in model "d"
roughness_x = d.getLinkRoughnessCoeff;

%%model_07: epanet pipe network model used
model_07 = epanet('incheon_3_testXX.inp');
roughness_07 = model_07.getLinkRoughnessCoeff;

Nodes=d.getNodeCount;
Links=numel(roughness_x);
Resv=d.getNodeReservoirCount;
Junc=Nodes-Resv;

HTS07 = model_07.getComputedHydraulicTimeSeries;

Node_H_07 = HTS07.Head;      %Head pressure
Link_F_07 = HTS07.Flow;      %Flow velocity


%% Problem Definition
% Definition of Cost function using function handle
CostFunction=@(diameter_x) fitness_Ccriticalpipes(roughness_x,d);

nVar=Links;                    % Number of decision variables
VarSize=[1 nVar];              % Decision variables matrix size
VarMin=70;                     % Decision Variables lower bound
VarMax=100;                    % Decision Variables upper bound
VarC=[70 75 80 85 90 95 100];  % Set of C values
```

```
%% Parameters of the Harmony Search Algorithm

MaxIt=5000;                  % Maximum number of iterations
HMS=30;                      % Harmony Memory Size

HMCR=0.95;                   % Harmony memory consideration rate
PAR=0.5;                     % Pitch adjustment rate
bw=0.01*(VarMax-VarMin);     % Band width distance


%% Initialization
% Empty harmony structure
base_harmony.Position=[];
base_harmony.Cost=[];

% Initialize harmony memory
HM=repmat(base_harmony,HMS,1);

% Create Initial Harmony memory
H_old=Node_H_07;         %Head pressure
F_old=Link_F_07;         %Flow velocity

for i=1:HMS
    HM(i).Position=unifrnd(VarMin,VarMax,VarSize);  % Create Harmony

    N=unifrnd(VarMin,VarMax,VarSize);  % Create Harmony

    % adapt to set of C values
    A = repmat(VarCom',[1 length(N)]);
    [minValue,closestIndex] = min(abs(A-N));
    closestValue = VarCom(closestIndex);
    HM(i).Position=closestValue;

    HM(i).Cost=CostFunction(HM(i).Position);      % Evaluate Harmony
end

% Sort Harmony Memory
Costs=[HM.Cost];
[~, SO]=sort(Costs);
HM=HM(SO);

% Update Best solution ever found
BestSol=HM(1);

% Array to hold best costs values
BestCost=zeros(MaxIt,1);
```

```
% Array to hold mean costs values
MeanCost=zeros(MaxIt,1);

%% Harmony Search Main Loop
executetime_acc=0;
back_it=1;
it=1;
ini=0;
while BestCost(it)>=50 || ini==0
    if ini==0
        ini=1;
    else
        it=it+1;
        if it>MaxIt
            break
        end
    end
    tic;
    % Initialize Array for storing new Harmonies
    newHarmony=repmat(base_harmony,1,1);

    % Create new harmony:
    % New harmony positions Pre-Allocation: Create Randomly
    newHarmony.Position=Improvise(HM);

    % Evaluation
    newHarmony.Cost=CostFunction(newHarmony.Position);

    % Similarity Check
    newHarmony=SimiCheck(HM,newHarmony);

    % Update Harmony Memory
    HM=UpdateMemory(HM,newHarmony);

    % Update Best Solution ever found
    BestSol=HM(1);

    % Store the best cost
    BestCost(it)=BestSol.Cost;

    % Store Mean Cost
    MeanCost(it)=mean([HM.Cost]);

    % Show Iteration information
    disp(['Iteration ' num2str(it) ': Mean Cost= '
num2str(MeanCost(it)) '; Best Cost= ' num2str(BestCost(it)) '; Time =
' num2str(toc)]);
```

```
    % Band width:
    bw=bw*rand();
    if bw<0.00001
        bw=0.1*(VarMax-VarMin);
    end

    % Backup
    if mod(it,10)==0
        BestSol_back(back_it,:)=BestSol(1).Position(:);
        back_it=back_it+1;
    end

    executetime(it)=toc;
    executetime_acc=executetime(it)+executetime_acc;

end


%% Results visualization
figure;
semilogy(BestCost,'r','LineWidth',2);
hold on
semilogy(MeanCost,'b:','LineWidth',2);
hold off
xlabel('Iteration');
legend('Best Cost','Mean Cost');
grid on;

d.setLinkRoughnessCoeff(BestSol.Position);
Sol=d.getComputedHydraulicTimeSeries;
Sol.Head
mean(BestSol.Position)
```

Appendix D – Objective function for optimal C value

```
function y = fitness_Diametermin(x,epanet_model)

epanet_model.setLinkRoughnessCoeff(x);

%Solve hydraulics in library, HTS=Hydraulic Time Series
HTS_HS = epanet_model.getComputedHydraulicTimeSeries;

NodeHS_H = HTS_HS.Head;
LinkHS_F = HTS_HS.Flow;
LinkHS_V = HTS_HS.Velocity;
Diameter = epanet_model.getLinkDiameter;

N_Node = numel(NodeHS_H)-1;
N_Link = numel(LinkHS_F);
N_tot = N_Node+N_Link;

DN_Sum(1)=0;          %cost Nodes
DL_Sum(1)=0;          %cost Links


%Penalty on Head pressure
for t=1:1:N_Node
    if NodeHS_H(t)<15 || NodeHS_H(t)>60
        DN_Sum(1)=1e5+DN_Sum(1);
    end
end

%Penalty on Flow velocity
for t=1:1:N_Link
    DL_Sum(1)=Diameter(t)+DL_Sum(1);
    if LinkHS_V(t)<0.1 || LinkHS_V(t)>3
        DL_Sum(1)=1e5+DL_Sum(1);
    end
end

y =(DN_Sum(1)/N_Node+DL_Sum(1)/N_Link);
```

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