

**UNIVERSITY MASTER IN
INDUSTRIAL ENGINEERING**

MASTER'S THESIS

**<RESEARCH AND IMPLEMENTATION OF
NETWORK REDUCTION METHODS FOR DISTRICT
COOLING SYSTEMS>**

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Resumen

Los *District Energy Systems* son una de las formas más eficientes de suministrar calor y frío a un grupo de consumidores. Aun así, es necesario hacer funcionar estos sistemas de la manera más eficiente posible, sobre todo los sistemas *District Cooling* en los cuales por diferentes razones técnicas es esencial un funcionamiento óptimo para que sea rentable. Y con ese objetivo parte este proyecto, que se centra particularmente en las redes de distribución de frío de los sistemas *District Cooling*. Para conocer el funcionamiento de una red de distribución a fondo, dependiendo de su tamaño, es necesario tener en cuenta las inercias en la red, tanto térmicas como hidráulicas, y para ello un modelado dinámico es necesario, lo que conlleva que las variables a modelar sean demasiadas. Por lo tanto, se van a estudiar diferentes métodos de reducción de redes, con el objetivo de obtener redes equivalentes con menos variables, y se van a aplicar para el caso de la red de *District Cooling* del hospital de Basurto. Los procesos de reducción de redes se van a automatizar mediante *Matlab* y simular los resultados obtenidos con el simulador de redes del departamento de ingeniería térmica de Tekniker.

Palabras clave

District Energy Systems, District Cooling, Matlab.

Laburpena

District Energy Systems kontsumitzaile-talde bati beroa eta hotza emateko modurik eraginkorrenetako bat da. Hala ere, sistema horiek ahalik eta modurik eraginkorrean funtzionarazi behar dira, batez ere *District Cooling* sistemetan, non, arrazoi teknikoengatik, ezinbestekoa da funtzionamendu egokia errentagarria izateko. Eta helburu horrekin abiatzen da proiektu hau, bereziki *District Cooling* sistemen hotza banatzeko sareetan oinarritzen dena. Banaketa-sare baten funtzionamendua sakonki ezagutzeko, haren tamainaren arabera, beharrezkoa da sareko inertziak kontuan hartzea, bai termikoak, bai hidraulikoak, eta, horretarako, modelatze dinamikoa beharrezkoa da, eta horrek modelatu beharreko aldagaiak gehiegi izatea dakar. Beraz, sareak murrizteko hainbat metodo aztertuko dira, aldagai gutxiagoko sare baliokideak lortzeko, eta Basurtuko ospitaleko *District Cooling* sarearen kasuan aplikatuko dira. Sareak murrizteko prozesuak automatizatu egingo dira *Matlab* bidez, eta lortutako emaitzak simulatu egingo dira Teknikerreko ingeniaritza termikoko saileko sareen simulagailuarekin.

Gako hitzak

District Energy Systems, District Cooling, Matlab.

Abstract

District Energy Systems are one of the most efficient ways of supplying heat and cold to a group of consumers. However, it is necessary to operate these systems as efficiently as possible, especially *District Cooling* systems in which for various technical reasons optimum operation is essential for cost-effective operation. This is the aim of this project, which focuses particularly on the cooling distribution networks of *District Cooling* systems. In order to know the operation of a distribution network in depth, depending on its size, it is necessary to take into account the inertias in the network, both thermal and hydraulic, and for this a dynamic modelling is necessary, which means that the variables to be modelled are excessive. Therefore, different network reduction methods will be studied, with the aim of obtaining equivalent networks with fewer variables, and they will be applied to the case of the *District Cooling* network of Basurto hospital. The network reduction processes will be automated using *Matlab* and the results obtained will be simulated with the network simulator of Tekniker's thermal engineering department.

Keywords

District Energy Systems, District Cooling, Matlab.

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Acronyms

DH&C	District Heating and Cooling
DH	District Heating
DC	District Cooling
DE	District Energy
ES	Energy System
SES	Smart Energy Systems
DM	Danish Method
GM	German Method
AE	Absolute error
MAE	Mean absolute error
MSER	Mean squared error's root
MSNER	Mean squared normalized error's root
MSEVC	Mean squared error's variation coefficient

1. INTRODUCTION

This document contains the report of The Master's Thesis entitled: "*Research and implementation of network reduction methods for District Cooling Systems*". It is an industrial project carried out in the Mechanical Engineering department of the company Tekniker, more specifically in the area of Thermal Engineering.

The first part of the report presents the context of the project, its objectives and scope, as well as the benefits it can bring.

Subsequently, the state of the art is reviewed. The state of the art begins with a brief overview of DH&C systems. Then it focuses on DC systems, followed by a presentation of the Indigo project and the Basurto hospital DH&C installation. Then, two different methods of network reduction are presented, the Danish and German methods, and after that it ends with an example of both methods application in the Ishoej DH system.

Following the state of the art, the work development is going to be carried out. In this section, three reduction processes will be done starting from the original DC distribution network of Basurto hospital. The first process for the heat loss and temperature calculation of the DM, the second one for the pressure drop calculation of the DM and the third one for the calculation of the GM. The three reduction processes will be automated using Matlab, these functions will be valid to reduce any pure tree structure network entering the original network's data and will be applied to the case of the Basurto hospital network which we are working with.

The work development will continue by statically simulating different equivalent networks obtained with each of the reduction processes at different degrees of reduction. These simulations will be done using the static Matlab simulator designed by the thermal engineering department of Tekniker for the Indigo project. The appropriate changes will be made to the simulator in order to simulate each of the equivalent networks at different degrees of reduction, as it is designed only for using it with the original network.

Once the work development is done and the simulations are completed the results obtained and the errors done for the different reduction processes at different reduction degrees are going to be analysed.

In the final part of the work, a risk analysis during the execution of the project is carried out, the expenses and amortisations, and the work plan with the different stages and their duration throughout the project. In addition, conclusions are drawn from what has been studied and the results obtained, and future lines of action are presented.

2. CONTEXT

The Master's Thesis is carried out within the company Tekniker, a technology centre legally constituted as a private non-profit foundation. Tekniker is part of the *Basque Research and Technology Alliance* (BRTA) and it is the essential technological ally of an important group of leading companies in its sectors, with products and processes of high added value and high technology. Its mission is to boost the innovative capacity of its clients and increase their technological capital to improve their competitiveness in a sustainable way, through the generation and application of scientific-technological knowledge. Within the multiple departments of Tekniker, the project has been developed in the department of Mechanical Engineering, more specifically in the area of thermal engineering.

Tekniker took part in the Indigo Project [1]. The Indigo Project involves the development of highly efficient and intelligent DC systems based on the development of an innovative and optimized DC system Management Strategy, and the integration of predictive controllers at component level, some of them including self-learning algorithms for accuracy improvement. The innovative and optimized management strategy will be focused mainly on energy efficiency maximization but also on energy cost minimization.

All these improvements in the DC systems were applied to the DC network of Basurto hospital, improving both the efficiency of cooling production and distribution. Based on the fact that the Basurto network is small, all the simulations and controls were done by modelling the network statically.

In this case, as the network is not very large, the number of variables to be controlled is not very high and therefore good results were obtained with static modelling of the whole network. But in the case of wanting to optimise larger networks, in which thermal inertias play a decisive role, the networks must be modelled dynamically, which means that the number of variables increases considerably, and this can make modelling the entire network very complicated due to the excess of variables. This is where reduction methods are of interest, since, if equivalent networks to the original network are achieved, with fewer pipes and substations, and therefore, fewer variables, but which work in an equivalent way, dynamic modelling would be possible.

3. OBJECTIVES AND SCOPE

Considering the context in which this project is carried out, the objective of this work is to study and apply different methods for the reduction of distribution networks of DC systems.

Main objective

The main objective of this project is to apply different network reduction methods to model the distribution network of Basurto hospital's DC system.

Specific objectives

- Research of DE systems, with special emphasis on DC systems.
- Research and analysis of different distribution networks reduction methods.
- To prepare automated reduction processes with Matlab and apply them to the case of the Basurto hospital's distribution network.
- To model statically the equivalent networks obtained.
- To analyse the results obtained and the errors done in the simulations.

Scope

About the scope of the project, the reduction methods are only going to be applied to the distribution network of Basurto hospital's DC system and the equivalent networks obtained are only going to be simulated with the static Matlab simulator of the thermal engineering department of Tekniker.

4. PROYECT BENEFITS

By improving the efficiencies of DC systems in general and of its distribution networks in particular, which is the topic of this project, several technical, economic and environmental benefits are expected to be achieved.

4.2. Technical benefits

Applying reduction methods for both DH&C systems offer the possibility of modelling a network statically and dynamically in a simpler, faster and more efficient way. This is because the number of variables in the network is reduced. The benefits are more noticeable in the case of large networks such as the one presented in Section 5.6.3, as in these cases the number of variables is so large that dynamic modelling is not feasible.

Good network modelling and control improves the efficiency of the distribution network and of DH&C systems in general by making better use of the heat or cold generated, reducing thermal losses in the network and taking advantage of thermal inertias.

4.3. Economic benefits

The economic benefits of reduction methods by improving the modelling and control of distribution networks are quite clear, since improving the efficiency of the network means that the heat or cold produced must be less, and therefore the energy consumption of the heat and cold generators will be lower.

4.4. Environmental benefits

DH&C systems each self, without any improvement, have environmental benefits comparing with individual heating and cooling installations, because of their higher efficiency and lower energy consumption.

If we add to this the fact that by applying reduction methods and improving the control and modelling of the networks, the efficiencies and thermal utilisation improve, these consumptions will be even lower, reducing the emissions of pollutants generated in the production of heat and cold.

Also, the use of renewable energies to produce the heat and cold needed in DH&C systems will reduce the production of heat and cold with conventional engines, boilers and chillers, thus reducing the consumption of fossil fuels and the emission of greenhouse gases.

5. STATE OF THE ART

5.1. District Heating and Cooling

Today, heating and cooling account for more than 50% of total energy consumption in Europe. Considering that most of this energy consumption comes from non-renewable energy sources, the CO₂ emissions to the atmosphere are significant. Therefore, DE systems are an interesting alternative to mitigate this environmental impact. Compared to individual heating and cooling systems, DE systems have higher efficiency, are economically more attractive for areas with high consumption and reduce the consumption of fossil fuels [2].

DH is a DE system which provides both heating and domestic hot water. This system consists of: a centralized generation station, which generates hot water using different energy sources; a distribution network, which transports the generated hot water to each of the substations and returns the cooled water back to the generation station; and substations, which are heat exchangers that supply heat to each of the consumers [3].

DC systems are similar to DH systems. In this case, instead of hot water, chilled water is generated and used for both air conditioning and dehumidification. The chilled water is also transported through a network of pipes and supplied to consumers via substations. But as it is going to be presented, DH and DC systems have several differences with each other.

In relation to DH&C there is the option of installing a trigeneration plant, which as the name suggests providing three types of energy from a single process. These plants can operate both with internal combustion engines or turbines, which generate electricity, that is sold to the grid or used for self-consumption, and heat, which can be used for DH systems or by absorption chillers for DC systems, with provides the possibility of generating electricity, heat and cold at the same time.

5.2. District cooling

DC systems are becoming increasingly popular because of being a modern and efficient way of producing chilled water. These systems are an environment-friendly alternative to the traditional air conditioning systems being operated at individual buildings.

The centralized production of chilled water is driven by renewable energy sources, electrical chillers, absorption chillers or other sources as free cooling. The chilled water produced is supply to consumers through an insulated underground piping network as commented in the Section 5.1. Cold water enters the buildings and flows through a heat exchanger, called

substation, absorbing heat from the building space before recirculating back to the central plant through the return line, which is parallel to the supply one.

So that, a DC system, as DH ones, can be divided in three different parts: generation, distribution, and consumption. Each of the parts is presented in more detail on the Section 5.5 where the Basurto hospital's DC installation is described.

5.2.1. Past, present, and future.

The first major DC system was employed in Hartford, Connecticut, in 1962. Other systems were built in the 1960s and 1970s. DC experienced a renaissance during the 1990s, when many countries demanded the termination of the use of CFCs (Chlorofluorocarbons) due to ozone depletion. Cities as Stockholm, Hamburg, Paris, Tokyo, Chicago, Minneapolis, St. Paul, New Orleans, and Houston have DC systems in their downtown or commercial areas.

The greatest DC networks are in the United States, accounting for over 24 TWh per year. This amount still represents only 6% of the country's space cooling demand in residential and commercial buildings. Even so, North America represents 40% of the DC capacity over the world [4].

South America has not started the important implementation of facilities of DC, there are only 2 small networks of cold in the area, and only a new installation project is underway [4].

The Middle East is the most recent setting for the development of DC, and growth in the area is taking place at an unprecedented rate. From little use of DC networks eight years ago, this region has seen an implementation of more than 100 large networks which are already operating with a total power of cooling over 12 GW, and now DC systems accounts for 10% of the cooling market of the area [5]. There are numerous projects and experts predict a doubling of the installed capacity in the next 5 years [4].

Southeast Asia, followed by China, began to develop DC in the early 2000s, with a focus on big plants of cold production. Nowadays there are about 40 DC systems, with a cumulative capacity of 2.5 GW. Many new facilities or major upgrades will materialize in the coming years, mainly in China, Singapore, and Malaysia. The capacity of DC through chilled water in Korea alone more than tripled between 2009 and 2011, and as global space cooling demand continues to increase, DC solutions will have an important role in providing efficient, low-carbon cooling supply. It is also worth mentioning the case of Japan, which has been operating 154 DC systems since 2005 [5].

Even though it has been quite a few years since the first DC systems appeared, the European DC market for air conditioning can be characterized as a still un-developed field. The cooling demand is significantly lower than in other countries where the tradition using air conditioning is older like USA, Japan, and other Asian countries, as has been seen in the previous paragraphs.

Today’s cooling market in the European Union is estimated to be 285TWh per year and is predicted a significantly growth of cooling consumption in Europe (especially in the Mediterranean area) in particular, and all over the World in general, because of the rising of the living standards in future decades, reaching to 500TWh per year for 2030 in Europe as can be seen in the Figure 5.1 [4]. As can be appreciate the most part of the consumption takes place in service sector buildings (offices, shopping centres, hospitals...).

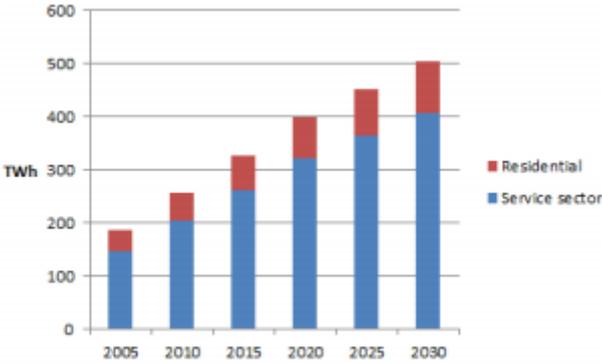


Figure 5.1: Europe’s cooling market development [4]

It is nowadays very common that electricity peak loads appear in city centres and commercial areas during summertime because of air conditioning consumption. If small scale and distributed conventional electric chillers are used to satisfy this demand, a significant rise in peak electricity demand will take place, and consequently, in greenhouse gas emissions and primary energy consumption will grow. In opposite to this situation if DC systems can offer a 5 to 10 times higher efficiency solutions [4].

In predictions done by the EU, it is hope that the 25% of the cooling market is going to be fulfil using DC, and if that happens 50GW of new conventional installations will be avoid. This is the reason why the EU Energy Efficiency Directive has recognised DC systems as one of the important pillars for achieving the energy efficiency target of reducing primary energy consumption by 20% [4].

5.2.2. Comparing Distinct Cooling with District Heating

Contrary to popular belief DC is not just pumping cold water at DH systems.

For a start, cold demands are much more difficult to predict than heat demands. Moreover, temperature differentials between the supply and the return water at DC are around 8°C, while in DH systems it is usually greater than 40°C. This causes an increase in the cost of pumping, the piping system, and the terminal equipment, so that low temperature difference makes DC distribution expensive, and networks can only be built in areas with high cooling demand densities, such as downtowns and commercial areas.

When trying to increase a DC system's differential temperature between the supply and the return physical limitations also appear. If DC systems work with water, supply temperature cannot be lower than 4°C because freezing can occur.

Also, in DC applications consumer's equipment usually works at temperatures not much higher than the supply temperature and that makes the return temperature lower than desired.

Consequently, in DC systems much more than in DH systems, an optimized operation of the system is essential to make the system cost efficient.

5.2.3. Sustainable energy technologies

Many sustainable energy technologies can be integrated into DC systems. This section will discuss the possibilities in terms of sustainable energy sources, trigeneration systems and thermal storage [5].

The main renewable energy sources used in DC systems are as follows:

- Using energy from de surface water. Many DC systems located in the coastline, near a river or a lake used its water as a cold source. This is known as *free cooling*. By eliminating or bypassing chillers, the energy consumption can be largely reduced.
- Using geothermal energy. Two different cases can be distinguished within the use of geothermal energy: on the one hand, the use of cold-water aquifers for *free cooling* as in the previous point, and on the other hand, the use of hot water aquifers using them with absorption chillers.

- Using solar energy. Here we can also differentiate between two cases: on the one hand, using the heat generated by solar thermal energy to produce cold using absorption chillers, and on the other hand, using the electricity generated by photovoltaic panels to generate cold using conventional chillers.

Using biomass energy. As in the second case of geothermal energy, the heat generated in biomass boilers can be used for cooling by means of absorption chillers.

- Using cold waste energy. Residual cold from industries can be used as a source of cold, such as the cold expelled during the gasification of liquefied natural gas.
- Using hot waste energy. Residual hot from industries can be used to produce cold using absorption chillers.

As briefly discussed in Section 5.1, the idea of generating electricity, heat and cooling simultaneously in a trigeneration plant is another way to integrate DC systems in a more sustainable way.

To reduce operating costs and minimize power demand during peak hours, DC systems can integrate cold storage systems into their network. The operation of such systems is quite simple: they will store cold during off-peak hours and use the stored cold at peak times. In this way, it is possible to store the cold generated by renewable energies and generate cold at off-peak times, reducing production at peak times and thereby reducing consumer bills. Generally, water at about 4°C is used to store cold, since it is quite cheap and has a high thermal capacity.

5.3. 4th generation District Heating and Cooling

In the design of a sustainable ES for the future, based on the highest possible percentage of renewable energies and utilization of both waste heat and biomass, DE systems are, due to their energy efficiency, supposed to be one of the pillars in that future plan.

One of the challenges of the future will be to integrate DE systems, together with the electricity and transport sectors, in what is known as SES. SES will focus on integrating the electricity, heating, cooling and transport sectors, so that the networks are coordinated to identify synergies between them and obtain an optimal solution for each of them individually as well as obtaining an optimal solution for the ES as a whole [6].

It is also true that DE systems will have to develop and evolve a lot for SES to become a reality, those DE systems developed are called 4th generation DH&C systems [6].

To fulfil their role in SES DE systems should be developed in the following areas [6]:

- In the case of DH systems, the capacity to supply heat at a lower temperature (low-temperature DH), and in the case of DC systems, the capacity to supply cold at a higher temperature (high-temperature DC).
- Minimize heat losses in DH networks and heat gains in DC networks. Improving the functioning of distribution networks is essential to meet this first two objectives.
- Ability to recycle heat and cold, and to integrate all kind of renewable energy sources.
- Develop predictive control systems for DE networks to minimize consumption and operating costs as much as possible and maximize energy efficiency. For all this, it is essential to integrate heat or cold storage systems in DE networks, as the ones presented in the Section 5.2.3.

5.4. Indigo project

Almost all the studies for the development of 4th generation DE systems have been carried out for DH systems, and this is the origin of the Indigo Project, which studies how to develop and implement all the advances discussed in the previous section in DC systems.

The Indigo project aims to overcome all the challenges that DC presents by pushing DC technology one step further. The main objective of Indigo proposal is the development of a more efficient, intelligent, and cheaper generation of DC systems by improving system planning, control, and management [7].

To achieve this main objective, two specific objectives have been established:

- To increase DC systems efficiency, contributing to a reduction over 45% of the primary energy consumption compared to current DC systems. To increase the efficiency the optimization has focused on some key points: an accurate cooling demand prediction, the incorporation of components efficiency analysis and the integration of cooling sources (free cooling, heat waste using absorption chillers, conventional chillers...)
- To validate the benefits of Indigo developments in a real DC installation, as it has been done in Basurto hospital's DC system, that will be used in this work to study the different network reduction methods.

The main approaches to achieve these objectives are the following:

- Development of an innovative and optimized global DC system management strategy focused on energy efficiency maximization and energy cost minimization. One of the main characteristics of this strategy is the predictive management, that allows to predict values for consumers' demand, meteorological conditions, and the price of energy to establish the DC system components appropriated set-points for an optimized operation.
- Development and implementation of Predictive Controllers at Component level. Many components to be controlled are characterized by high-order dynamic behaviour or a large time constant and time-delays. That Predictive Controllers are going to be used at consumer, distribution, storage, and generation levels.

Development and integration of self-learning algorithms for DC systems. Two self-learning capabilities have been identified as a key for the optimization of DC system Control and Management: demand prediction correction and correction of component efficiency calculations.

- Development of DC components' models and DC system designing tool. INDIGO will develop these models based on the thermo-fluid dynamic behaviour of all kind of components in a DC system (generation, distribution, storage, buildings) implemented in Modelica. These models are called Detailed Models, since they represent in detail the dynamic behaviour of each component, thus allowing a good understanding of the system physics. Besides, they will serve to perform in-depth study of the design conditions for the optimization on DC systems, and to carry out the tuning and check of developed Predictive Controllers.
- District cooling systems' stakeholder's (consumers, public administrations...) empowerment.

Once the Indigo project's main points have being presented and explained globally, we are going to focus on what affects to our work, that are the control techniques in the distribution level of the DC system.

The distribution system is responsible for delivering the chilled water produced by the cold generation sources to the customers. Before Indigo Project, the main control in existing DC systems was the differential pressure control, that focus on fulfilling the requirement of minimum differential pressure to service the most remote customer. Using that type of controllers, the distribution system is not able to attend demand changes properly. Distribution flow changes propagate quickly through the distribution systems. However more complicated dynamic changes appear when the supply temperature is modified, it takes some time for the supply temperature increase or decrease to reach the substations,

because of the finite flow velocity. Furthermore, the heat storage capacity of the pipes must be considered to get an accurate idea of how the distribution system works. To control all those variables in a proper way and get accurate results a predictive control system is going to be implemented with the Indigo project.

The innovative management strategy and component's predictive controllers developed under Indigo will be firstly validated in laboratory conditions (simulations) and finally in relevant environment. For the latter test site has been selected: Basurto hospital DC system.

5.5. Basurto hospital's cogeneration plant

Basurto hospital was erected during the first decade of the 20th century in the city of Bilbao (Spain) and currently comprises more than 15 buildings, most of them maintaining their original architectural special features. The hospital belongs to Osakidetza, the public health service of the Basque Country. Heating and cooling demand of the hospital is satisfied thanks to a DH&C installation connected to a trigeneration plan.



Figure 5.2: Basurto hospital [4]

The trigeneration plant consist of 2 natural gas internal combustion engines of 2MWe each, some natural gas backup boilers, 2 absorption chillers and 4 conventional chillers.

The gas engines generate electricity that is sold to the Electric Grid. This way the Hospital gets cheaper electricity prices than those ones that can be found in the market.

Heat from the CHP is employed for DH supply as well as for feeding absorption chillers for DC supply. Apart from the heat coming from gas engines there are some gas boilers and conventional chillers for DH and DC supply, respectively.

DH temperature level is 80°C in supply and 65/70 °C in return while DC temperature level is 7°C in supply and 10/12°C in return.

After this brief presentation, we will be focused on the DC system, which is the topic of the INDIGO project, and particularly in the distribution network that is in what this work is going to focus on.

5.5.1. The District Cooling installation

This section will briefly present the different parts of the DC installation of the Basurto hospital and will explain the operation and control of this installation without much detail.

5.5.1.1. Generation plant

The generation plant is located inside the hospital limits and includes chillers, storage, pumping and control. In the next Figure 5.3 and Figure 5.4 the main layout of the DC system can be seen, where the generation plant is marked with a dark blue arrow, the distribution system with dark blue lines and the connected buildings with white arrows.



Figure 5.3: Basurto hospital's DC network (Photograph) [7]

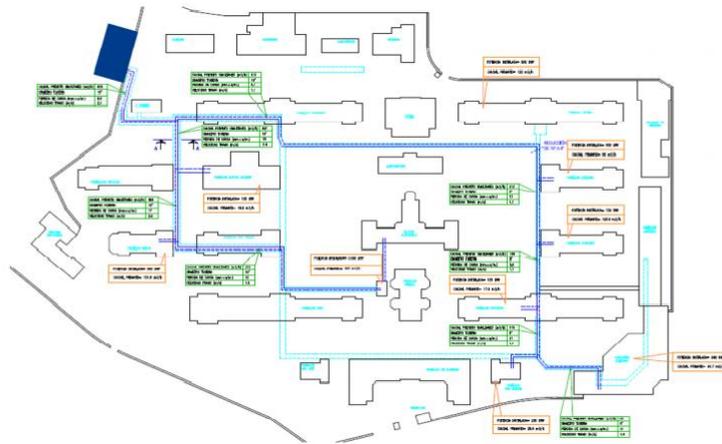


Figure 5.4: : Basurto hospital's DC network (Scheme) [4]

Figure 5.5 shows a simple diagram of the main elements inside the chilled water generation plant. As it can be seen all the chillers are installed in parallel and connected to supply and return manifolds. The two absorption chillers are connected to the gas engines that supply them the heat they need to produce cold water.

Outside the generation plant building there is a buffer tank for cold water that is connected between the return and supply manifolds as it can be seen in the Figure 5.5, and it is only employed to control the flow variations, it has not enough capacity to used it as storage tank.

The pumping station consist of four centrifugal pumps that connects the supply manifold (suction) with the distribution manifold (discharge). These pumps are connected to a frequency converter giving the possibility of controlling the speed of the pump (performance curves).

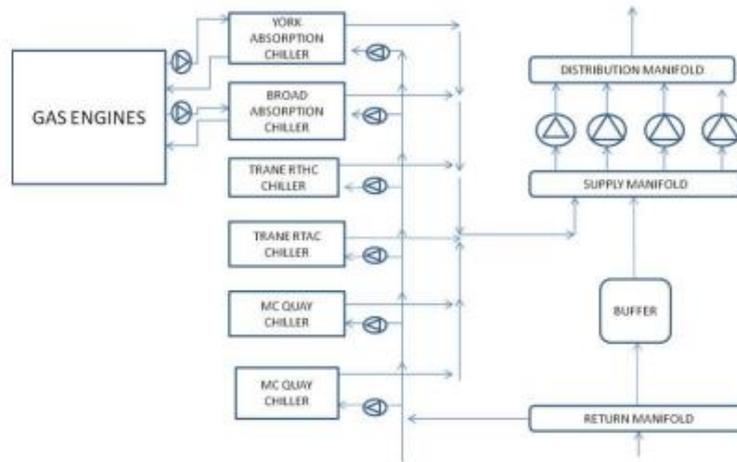


Figure 5.5: Generation plant [7]

The main characteristics of the chillers are presented in the following table:

CHILLER TYPE (MANUFACTURER)	COOLING CAPACITY	HEAT REJECTION
Single stage absorption chiller (YORK)	650 kW _t	Water cooled
Single stage absorption chiller (BROAD)	1 MW _t	Water cooled
Electrical chiller (TRANE)	1,5 MW _t	Water cooled
Electrical chiller (TRANE)	730 kW _t	Air cooled
2 x Electrical chiller (McQUAY)	974 kW _t	Air cooled

Table 5.1: Chiller types [7]

Regarding absorption chillers they use a heat source, in this case the heat generated by the combustion engines, to produce cold water. Commonly employed absorption chillers, like those installed in this DC, are based on a Lithium Bromide (LiBr)-Water working pair where the water acts as a refrigerant. Nominal ratings of the installed absorption chillers are:

MODEL	HOT WATER IN/OUT	CHILLED WATER IN/OUT	HEAT REJECTION WATER IN /OUT	COOLING CAPACITY	COP
BROAD BDH86X	39.7m ³ /h 102.5°C/72.5°C	172 m ³ /h 12°C/7°C	333 m ³ /h 35°C/29°C	1000 kW _t	0.75
YORK YIA-HW-3B2	26 m ³ /h 105°C/65°C	149 m ³ /h 12°C/7°C	222.6 m ³ /h 35°C/29°C	650 kW _t	0.69

Table 5.2: Absorption chillers' nominal ratings [7]

Regarding conventional chillers the four chillers work with R134a as refrigerant. In the next table rated conditions of the conventional chillers are shown:

MODEL	CHILLED WATER IN/OUT	CONDENSER INLET AIR TEMPERATURE	COOLING CAPACITY	COP or EER
McQUAY AWS-XE-280.2	12°C/7°C	35°C	974 kW	3.15
TRANE RTAC-200 (Low noise and High Eff. version)	12°C/7°C	35°C	730 kW	2.85
MODEL	CHILLED WATER IN/OUT	HEAT REJECTION WATER IN/OUT	COOLING CAPACITY	COP or EER
TRANE RTHC-E3	12°C/7°C	29°C/35°C	1360-1560 kW	5.6-7

Table 5.3: Conventional chillers rated conditions [7]

5.5.1.2. Distribution network

The chilled water produced in the generation plant is distributed to the consumers through the pumping station and the piping layout that can be seen in Figures 5.5 and Figure 5.7, respectively.

From the pumping station installed inside the generation plant, the pipes extend to the different buildings through the underground galleries available to interconnect buildings, as the one in Figure 5.6. The length of the piping is about 2 km.



Figure 5.6: Basurto hospital's underground galleries [7]

The DC network sends cold water to nine buildings where substations are installed. The total number of substations is eleven because in two of the buildings there are two substations, as can be seen in Figure 5.7, where each substation is represented by a dark blue arrow.

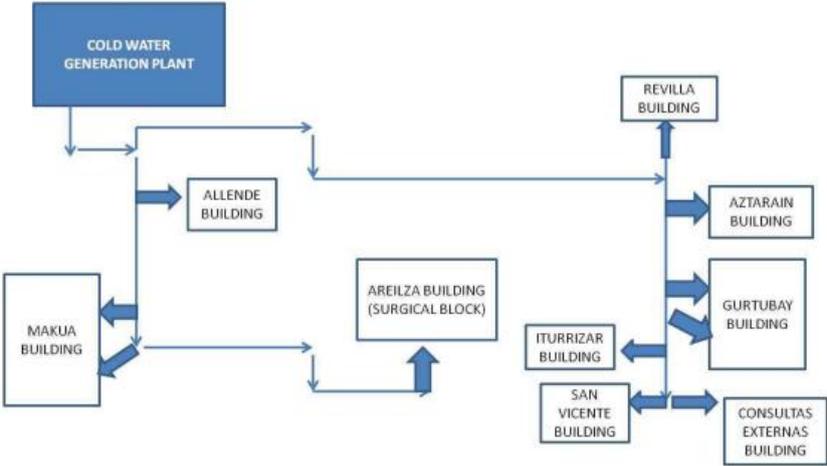


Figure 5.7: Layout of the distribution network of the DC [7]

All the pipes employed in the grid are made of black steel DIN 2448 and DIN 2440. The size of the pipes for distribution ranges from DN 14" (main supply and return pipes) to DN 6" (pipes connecting the last building in the longest branch).

The pipes are insulated with flexible elastomeric nitrile rubber foam with a thermal conductivity of 0.040 [W/m K] at 10°C. The thickness of the insulation for the piping follows IT 1.2.4.2.1 Spanish regulation. Taking this regulation into account and that the pipes are installed indoor (galleries), the thickness is 40mm for all the distribution piping.

5.5.1.3. Substations

The DC is connected to eleven different consumers and the main demand corresponds to air conditioning. The consumers are connected to the DC system by the substations. In the case of this DC system there are not conventional heat exchangers separating both sides, instead of that there are hydraulic separators. The separator is a kind of slim tank where two pipes from distribution side and two pipes from building side are connected.

The substation includes one (or more in parallel) regulating valve(s) and one static balancing valve in the distribution side. Three temperature sensors are available (supply and return in the building side, return in the distribution side). Apart from that an energy meter is installed

in the building side of the substation. Those meters calculate the energy (cold) consumed by the building.

A typical substation for this installation is represented in the next Figure 5.8:

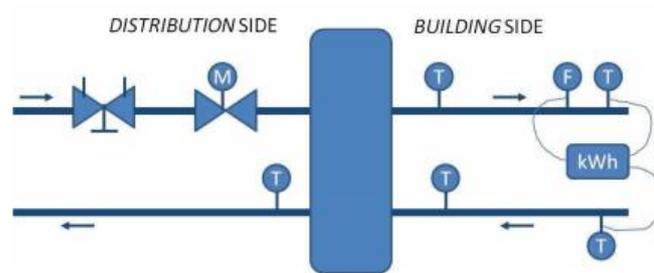


Figure 5.8: Simple diagram of a substation [7]

As it has been said the energy consumed by the buildings from the district is collected by energy meters. Next Table 5.4 shows the energy consumed by each building during the year 2011:

BUILDING	ENERGY [MWh/year] (2011)
Allende	145.206 (3%)
Areilza (Surgical Block)	1333.284 (28.5%)
Aztarain	237.981 (5%)
Consultas Externas	43.737 (0.9%)
Gurtubay	926.484 (20%)
Iturrizar	120.403 (2.6%)
Makua	957.757 (20.5%)
Revilla	829.881 (17.7%)
San Vicente	82.827 (1.8%)
Total	4677.560 (100%)

Table 5.4: Energy consumption [7]

5.5.1.4. Operation and control

Related to the generation system strategy, the trigeneration plant schedule is worked out according to the electricity price. The internal combustion engines are operated daily during high electricity prices, thus prioritizing electricity generation.

During this period heat from cogeneration is stored and used for hospital's hot demand and for cold generation. The difference with respect to the cooling demand is covered by a pre-established electrical chiller start sequence management. For the rest of the time (no electric energy generation) another electrical chillers start sequence and cold-water storage (buffer for internal chillers management) is automated.

5.6. Equivalent networks

An equivalent model of DH&C networks using a few consumers and a few pairs of pipes to represent a complete network is an attractive idea. The simplified model, referred to us as an equivalent network, is generated by gradually reducing the topological complexity of the original network. During this reduction, the relevant model parameters of the network are transformed in such a way that the dynamic behaviour of the equivalent network will resemble the original one.

Simulations and especially optimizations of the operation of DH systems with tens or hundreds of pipes and consumers will take a considerable time. For each time step the simulations take in account flow, temperature, heat loss and differential pressure loss in each branch of the network. To improve the situation various ways of simplifying the network can be used. The original network can be reduced to only one pipe and one consumer, but then it must be accepted that all details of the system are lost. So that, as in our case we want to control and optimize different parameters of our network, we are going to first analyse the different techniques to simplify networks, and afterwards try to apply them into our DC system.

This equivalent network models can be combined with critical point model [8]. If we apply critical point model along with the equivalent network model the first step is to determinate the critical points of the network, then according to the location of this critical points the network must be divided into sub-networks, and once that is done the sub-networks where critical points are located must be kept unchanged and the rest of sub-networks must be transformed into equivalent networks.

We are going to analyse two different methods of getting equivalent networks, the DM and the GM. Both methods are systematic ways of gradually reducing the complexity of a large DH&C systems and they are similar one to each other but as we are going to see they have some differences in the algorithm used. In the case of the DM, we will study an initial case in which only the heat loss in the network is considered, and an extended case in which both heat loss and pressure drop are considered.

In both methods, The German and The Danish, the followings are considered [9]:

- The mass flows into and out of the aggregated net remain constant.
- The total pipe volume remains constant.
- All time delays in the subnet remain constant.
- The temperatures at the subnet remain constant.
- The pressures at the subnet boundary remain constant. (In the cases where the pressure drop is calculated).
- The sum of consumers mass flows remains constant.
- The sum of consumers heat loads remains constant.
- The total heat loss in the subnet remains constant. (In the cases where the heat losses are calculated)

Most of the research have been done for DH systems, so the first step is going to be studying them, and then, if it is possible, we are going to try to apply the equivalent networks methods to our case of DC system.

5.6.1. The Danish method

5.6.1.1. The initial Danish method

In this section the initial case of the DM is explained, that gets an equivalent network starting from an original model of the DH network [10]. To apply the DM the DE network must have a pure tree structure, with no loops. Firstly, that tree structure is converted into a line one, with the substations in series, and then the line structure obtain is simplified grouping substations and pipelines. Unlike the extended case of the DM, in this case, an equivalent network is only calculated for the heat loss, and the way of calculating the pressure drop is done by identifying the critical consumer, and then only considering those parts of the original network that affect that consumer.

So that, the first step is to reduce the tree structure into a line structure:

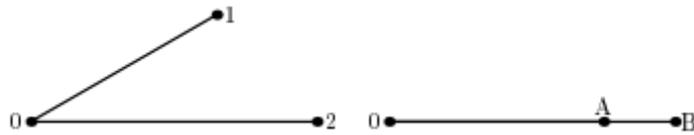


Figure 5.9: From tree structure to line structure [10]

The DH original network with pure tree structure can be considered as several two branch sub-networks, as shown in the left side of Figure 5.9, where two branches (1 and 2) originating from the same node 0 lead to the nodes 1 and 2. Each branch represents a supply and a return DH pipe, and we assume that the delay time in branch 1 is less than the delay time in branch 2.

We assume the same supply temperature and flow at node 0 in the two networks, then the following main conditions are fulfilled for the equivalent network:

- The return temperature in node 0 is the same for the two networks.
- The sum of the loads in nodes A and B is equal to the sum of the loads in nodes 1 and 2.

- The total heat loss from branches A and B is equal to that from branches 1 and 2.

- The total water volume in branches A and B is equal to that in branches 1 and 2.

The symbols used to reduce the original network are presented in the following tables:

Original variables	Symbols	Units
Mass Flow	m	kg/s
Velocity	v	m/s
Time delay	τ	s
Pipe length	L	m
Inner diameter	d	m
Outer diameter	D	m
Volume	V	m ³
Pipe inside area	A	m ²
Specific heat conductivity	h	W/(m * °C)
Heat conductivity	H	W/°C
Specific heat capacity	c	kJ/(kg * °C)
Heat capacity per meter	C	kJ/(m * °C)
Density	ρ	kg/m ³

Table 5.5: Original variables, subscripts and superscripts [8]

Definition	Condition
$\alpha = \frac{m_2}{m_1}$	$\alpha > 0$
$\beta = 1 + \alpha$	$\beta > 1$
$\theta = \frac{C^w}{C^w + C^p}$	$0 < \theta < 1$
$\psi = \frac{\theta_2}{\theta_1}$	$\psi > 0$
$\gamma = \alpha * \frac{V_1}{V_2}$	$0 < \gamma \leq 1/\psi$
$X = \frac{\rho^p * c^p}{\rho^w * c^w}$	$X > 0$

Table 5.6: Auxiliary variables

It is assumed the following:

- The time delay in branch 1 is less or equal to the time delay in branch 2.
- Mass flows in branches 1 and 2 are varying proportionally with time (α , β , γ and δ constant). Naturally, this assumption is never fulfilled in practice, meaning that the equivalent network found below will not give the same results as the original network.

We proceed in obtaining our equivalent network by demanding the following:

- Time delay in branch A must equal the delay in branch 1:

$$\tau_A = \tau_1 \quad [5.1]$$

- Time delay in branches A and B must equal delay in branch 2:

$$\tau_B = \tau_2 - \tau_1 \quad [5.2]$$

- Water volume must be conserved:

$$V_A + V_B = V_1 + V_2 \quad [5.3]$$

- Mass flow must be conserved:

$$m_A + m_B = m_1 + m_2 \quad [5.4]$$

- Heat load must be conserved:

$$P_A + P_B = P_1 + P_2 \quad [5.5]$$

- Heat loss from the pipes must be conserved:

$$Q_A + Q_B = V_1 + V_2 \quad [5.6]$$

Summarizing the results obtained:

$$m_A = m_1 \quad [5.7]$$

$$V_A = V_1 * (1 + \alpha * \psi) \quad [5.8]$$

$$A_A = \frac{\beta * (1 + \alpha * \psi) * A_1 * A_2}{A_2 + A_1 * \alpha^2 * \psi} \quad [5.9]$$

$$L_A = \frac{L_1 * (1 + \alpha^2 * \psi * A_1/A_2)}{\beta} \quad [5.10]$$

$$d_A = \sqrt{\frac{\beta * (1 + \alpha * \psi) * A_1 * A_2}{\pi * (A_2 + A_1 * \alpha^2 * \psi)}} \quad [5.11]$$

$$\theta_A = \frac{\theta_1 + \alpha * \theta_2}{1 + \alpha} \quad [5.12]$$

$$D_A = d_A * \sqrt{1 + \frac{1 - \theta_A}{X * \theta_A}} \quad [5.13]$$

$$m_B = m_2 \quad [5.14]$$

$$d_B = d_2 \quad [5.15]$$

$$D_B = D_2 \quad [5.16]$$

$$A_B = A_2 \quad [5.17]$$

$$L_B = L_2 * (1 - \gamma * \psi) \quad [5.18]$$

$$V_B = V_2 * (1 - \gamma * \psi) \quad [5.19]$$

$$\theta_B = \theta_2 \quad [5.20]$$

Now the dimensions (except for the insulation) for the equivalent network have been determined.

The supply side heat conductivities of the equivalent branches A and B are given by the following formulas:

- *If $(\theta_2 \geq \alpha)$ or $(H_2/H_1) \geq \alpha$*

$$H_A = (1 + \alpha) * H_1 \quad [5.21]$$

$$H_B = H_2 - \alpha * H_1 \quad [5.22]$$

- *If $(\theta_2 < \alpha)$ or $(H_2/H_1) < \alpha$*

$$H_A = H_1 + \gamma * \psi * H_2 \quad [5.23]$$

$$H_B = H_2 * (1 - \gamma * \psi) \quad [5.24]$$

When a DH network consisting of many branches is converted to an equivalent one, many nodes in the equivalent network will be positioned close to each other separated by relatively short pipes. Such nodes can be collapsed to further simplify the equivalent network as shown in Figure 5.10. The method can also be used to reduce the equivalent network to only a few or just one branch. This will of course reduce the quality of the resulting network model.

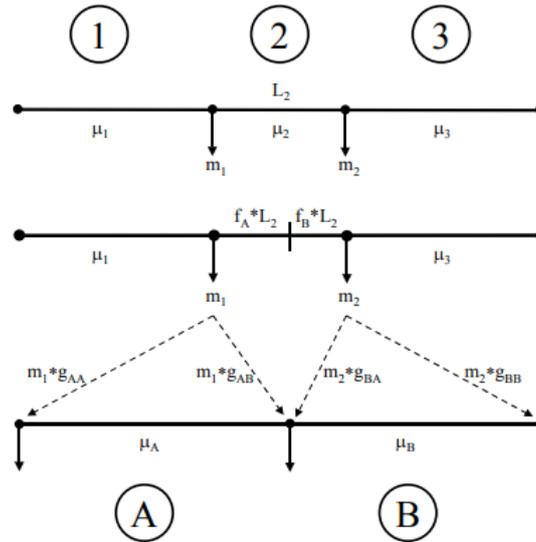


Figure 5.10: Collapsing nodes [10]

The algorithm for changing branches 1, 2 and 3 into branches A and B is as follows:

$$m_1 = \mu_1 - \mu_2 \quad [5.25]$$

$$m_2 = \mu_2 - \mu_3 \quad [5.26]$$

$$f_A = \frac{m_2}{m_1 + m_2} \quad [5.27]$$

$$f_B = \frac{m_1}{m_1 + m_2} = 1 - f_A \quad [5.28]$$

$$L_A = L_1 + f_A * L_2 \quad [5.29]$$

$$L_B = L_3 + f_B * L_2 \quad [5.30]$$

$$\theta_A = \left(1 + X * \frac{V_1^P + f_A * V_2^P}{V_1 + f_A * V_2} \right)^{-1} \quad [5.31]$$

$$\theta_B = \left(1 + X * \frac{V_3^P + f_B * V_2^P}{V_3 + f_B * V_2} \right)^{-1} \quad [5.32]$$

$$V_A = V_1 * \frac{\mu_A}{\mu_1} * \frac{\theta_A}{\theta_1} + V_2 * f_A * \frac{\mu_A}{\mu_2} * \frac{\theta_A}{\theta_2} \quad [5.33]$$

$$V_B = V_3 * \frac{\mu_B}{\mu_3} * \frac{\theta_B}{\theta_3} + V_2 * f_B * \frac{\mu_B}{\mu_2} * \frac{\theta_B}{\theta_2} \quad [5.34]$$

$$V_A^P = V_A * \frac{1 - \theta_A}{\theta_A * X} \quad [5.35]$$

$$V_B^P = V_B * \frac{1 - \theta_B}{\theta_B * X} \quad [5.36]$$

$$d_A = \sqrt{\frac{V_A}{\pi * L_A}} \quad [5.37]$$

$$d_B = \sqrt{\frac{V_B}{\pi * L_B}} \quad [5.38]$$

$$D_A = \sqrt{\frac{V_A + V_A^P}{\pi * L_A}} \quad [5.39]$$

$$D_B = \sqrt{\frac{V_B + V_B^P}{\pi * L_B}} \quad [5.40]$$

$$h_A = \frac{h_1 * L_1 + f_A * h_2 * L_2}{L_A} \quad [5.41]$$

$$h_B = \frac{h_3 * L_3 + f_B * h_2 * L_2}{L_B} \quad [5.42]$$

$$\tau_1 = \frac{\rho^W * V_1}{\mu_1 * \theta_1} \quad [5.43]$$

$$\tau_2 = \frac{\rho^W * V_2}{\mu_2 * \theta_2} \quad [5.44]$$

$$g_{AA} = \frac{f_A * \tau_2}{\tau_1 + f_A * \tau_2} \quad [5.45]$$

$$g_{AB} = \frac{\tau_1}{\tau_1 + f_A * \tau_2} \quad [5.46]$$

$$g_{BA} = \frac{\tau_3}{\tau_3 + f_B * \tau_2} \quad [5.47]$$

$$g_{BB} = \frac{f_B * \tau_2}{\tau_3 + f_B * \tau_2} \quad [5.48]$$

5.6.1.2. The extended Danish method

The extended DM was developed from the initial method [10].

In this case, unlike the previous one, two equivalent networks are calculated:

- The first one to calculate the heat loss in the network, in the same way as the one calculated in the initial DM, presented in the section 5.7.1.1.
- The second one to calculate the pressure drop in the network, which will be presented below.

The procedure to obtain the this second equivalent network is quite similar to the one used before, first getting a line structure from a tree structure and then simplifying that line structure, but in this case, we focus on the pressure loss instead of the delay.

For applying this system some assumptions must be considered:

- Pressure drop in branch 1 is less than pressure drop in branch 2.
- The load at the right end of branch A is equivalent to the load at the right end of branch 1.
- The load at the right end of branch B is equivalent to the load at the right end of branch 2.

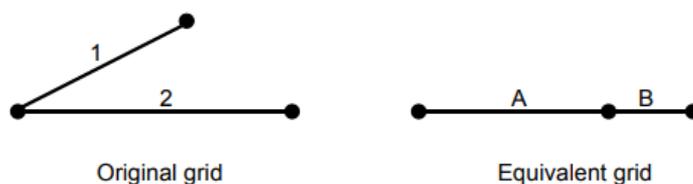


Figure 5.11: From tree structure to line structure [9]

In the algorithms shown below the symbol Π represents pressure drop. The connection between pressure loss and surface roughness is handled by Darcy-Weisbach's equation.

φ is the ratio between velocity of a temperature front and water velocity:

$$\theta_1 = \frac{1}{1 + X \left(\left(\frac{D_1}{d_1} \right)^2 - 1 \right)} \quad [5.49]$$

$$\theta_2 = \frac{1}{1 + X \left(\left(\frac{D_2}{d_2} \right)^2 - 1 \right)} \quad [5.50]$$

Velocity of a temperature front v :

$$v_1 = \frac{4 * \theta_1 * m_1}{\rho^W * \pi * (d_1)^2} \quad [5.51]$$

$$v_2 = \frac{4 * \theta_2 * m_2}{\rho^W * \pi * (d_2)^2} \quad [5.52]$$

First, we look at branch B:

$$m_B = m_2 \quad [5.53]$$

$$\Pi_B = \Pi_2 - \Pi_1 \quad [5.54]$$

We choose to let branch B been equal to branch 2 (except for the length):

$$d_B = d_2 \quad [5.55]$$

$$D_B = D_2 \quad [5.56]$$

Then length is the branch B is calculated as follows:

$$L_B = L_2 * (1 - \Pi_1/\Pi_2) \quad [5.57]$$

Next, consider branch A:

$$m_A = m_1 \quad [5.58]$$

$$\Pi_A = \Pi_1 \quad [5.59]$$

It is chosen to let φ_A equal φ_1 :

$$\theta_A = \theta_1 \quad [5.60]$$

Volume is calculated:

$$V_A = V_1 + V_2 * \Pi_1/\Pi_2 \quad [5.61]$$

It is assumed that the velocity of a temperature front in branch A is a weighted average of the values for branches 1 and 2:

$$v_A = \frac{(v_1 + \alpha * v_2)}{\beta} \quad [5.62]$$

Then:

$$L_A = \frac{\rho^W * v_A * V_A}{\beta * m_1 * \theta_A} \quad [5.63]$$

$$d_A = 2 * \sqrt{\frac{\beta * m_1 * V_A}{\pi * \rho^W * v_A}} \quad [5.64]$$

$$D_A = d_A * \sqrt{1 + \frac{1 - \theta_A}{X * \theta_A}} \quad [5.65]$$

A rather simple model is used for heat loss since we are focussing on pressure loss:

$$h_A = h_B = \frac{h_1 * L_1 + h_2 * L_2}{L_A + L_B} \quad [5.66]$$

Once we have a complete line structure, we can start removing pipes. The algorithm used to calculate how to remove pipes in series used for the temperature and heat loss case must be used here again, and the differential pressure loss is given by:

$$\Pi_A = \Pi_1 + f_A * \Pi_2 \quad [5.67]$$

$$\Pi_B = \Pi_3 + f_B * \Pi_2 \quad [5.68]$$

5.6.2. The German method

The GM, as mentioned above, is another method to reduce the original network and obtain an equivalent network, which works in a very similar way to the DM. The most significant advantage of this method comparing with the Danish one is that it can be applied to any kind of structure, contrary to the DM which can only be applied to pure tree structures.

Even so, in this work, we will only analyse the part of the GM that concerns us, which are the methods to reduce substations in parallel and in series, but it was necessary to make clear that the greatest advantage of the GM with respect to the Danish one was its versatility and usefulness [12].

Another advantage of the GM is that it provides a single equivalent network for the calculation of both heat losses and pressure drops [9].

For the calculation of equivalent networks starting from tree-structured networks, two types of steps are used as in the previous methods:

- From tree structure to line structure. For this step, the same algorithms used in the initial Danes method are used [12], that algorithms are explained in section 5.7.1.1.

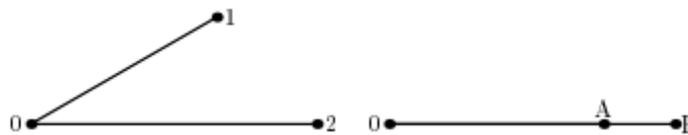


Figure 5.12: From tree structure to line structure

- Removing substations in series. In this case, unlike the two previous cases of the Danes method, a single pipeline and two equivalent substations are obtained.

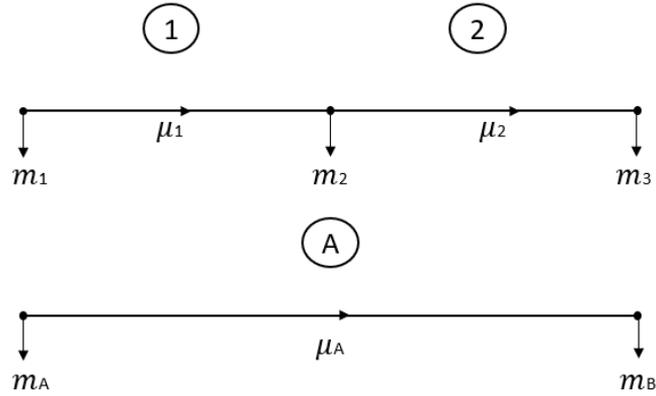


Figure 5.13: Removing substations in series

The algorithm for changing branches 1 and 2 into branch A is as follows:

$$\mu_A = \frac{V_1 + V_2}{\frac{V_1}{\mu_1} + \frac{V_2}{\mu_2}} \quad [5.69]$$

$$m_A = (m_1 + m_2 + m_3) - \mu_A \quad [5.70]$$

$$m_B = \mu_A \quad [5.71]$$

$$V_A = V_1 + V_2 \quad [5.72]$$

$$L_A = L_1 + L_2 \quad [5.73]$$

$$d_A = \sqrt{\frac{d_1^2 * L_1 + d_2^2 * L_2}{L_A}} \quad [5.74]$$

$$\tau_A = \tau_1 + \tau_2 \quad [5.75]$$

5.6.3. Example: The Ishoej DH system

An example will be presented in which the two previous methods, the DM and the GM, have been applied to reduce the Ishoej DH system, and compare the results obtained with different degrees of aggregation [7].

The distribution network of the Ishoej DH system is the one presented in the Figure 5.14. It has approximately 8.3km of length, all consumers are connected through 23 substations and has 44 main branches.

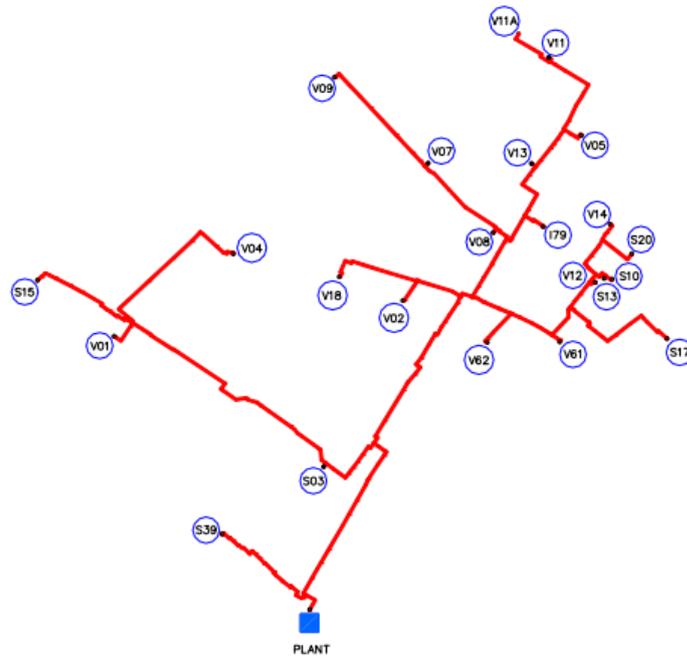


Figure 5.14: Ishoej DH system's distribution network

Both the DM and the GM have been applied for different degrees of aggregation. Table 5.7 shows the different degrees of aggregation using the DM, presenting the number of branches, substations and a brief description of what is reduced in each step.

Model	Number of branches	Number of loads	Description
Original network	44	23	The physical system.
D_44	44	23	All branches in line.
D_23	23	23	All branches with no loads in-between are collapsed.
D_20	20	20	Short branches are removed.
D_15	15	15	Short branches are removed.
D_10	10	10	Short branches are removed.
D_5	5	5	Short branches are removed.
D_4	4	4	Short branches are removed.
D_3	3	3	Short branches are removed.
D_2	2	2	Short branches are removed.
D_1	1	2	Short branches are removed. There is also a load at generation plant.

Table 5.7: Aggregation steps, DM

Table 5.8 shows the same as in the previous table, but with reference to the aggregation process using the GM.

Model	Number of branches	Number of loads	Description
Original network	44	23	The physical system.
G_20	20	18	Reduction of the physical system. The tree-structure is maintained.
G_10	10	9	Further reduction. The tree-structure is maintained.
G_6	6	5	Further reduction. All branches in line.
G_2	2	2	Further reduction. All branches in line.

Table 5.8: Aggregation steps, GM

There will be analysed the results obtained from the simulations applying the DM for three reduction degrees of all those presented in Table 5.7: D_23, D_5 and D_2. For each reduction degree heat production, return temperature at the plant and flow at the plant are going to be analysed and the errors done comparing with the original network are going to be presented.

Starting with the heat production, it can be seen in Figure 5.15 how for the equivalent network D_23 the error generated compared to the original network is almost zero. In Figure 5.16 it can be seen how for the equivalent network D_5 it increases, although it is still quite small and acceptable, and for the last case in Figure 5.17 for the equivalent network D_2 the error becomes significantly larger than in the two previous cases.

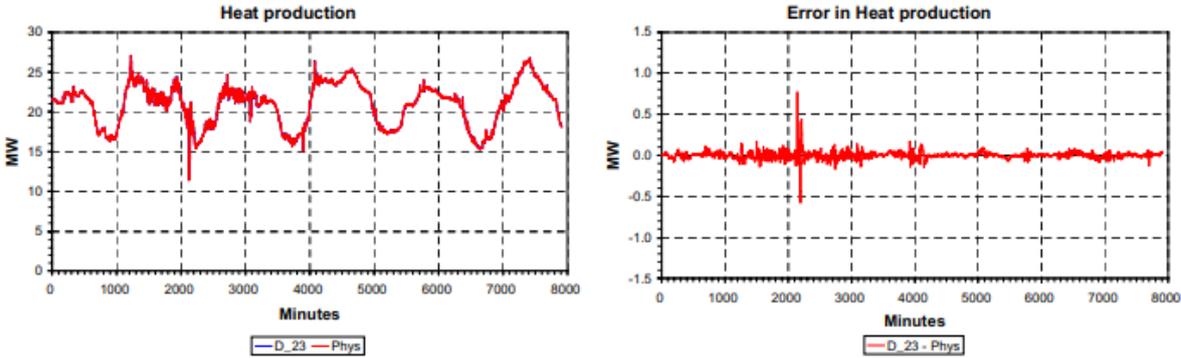


Figure 5.15: Heat production and error done for D_23

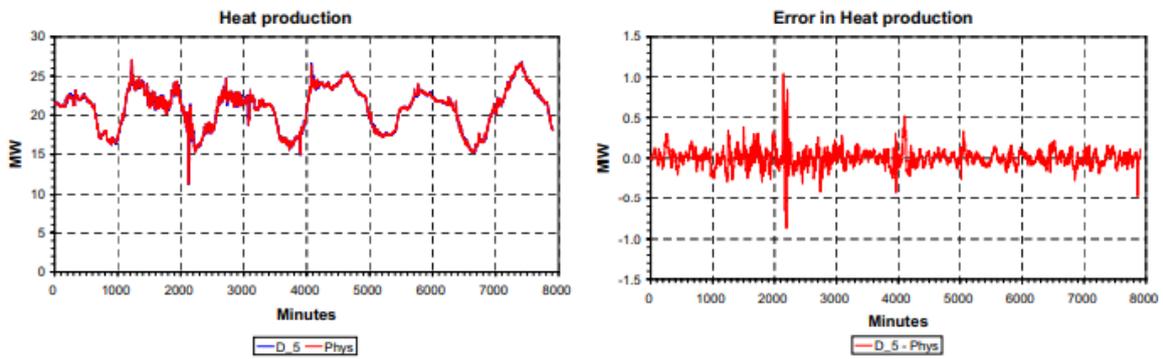


Figure 5.16: Heat production and error done for D_5

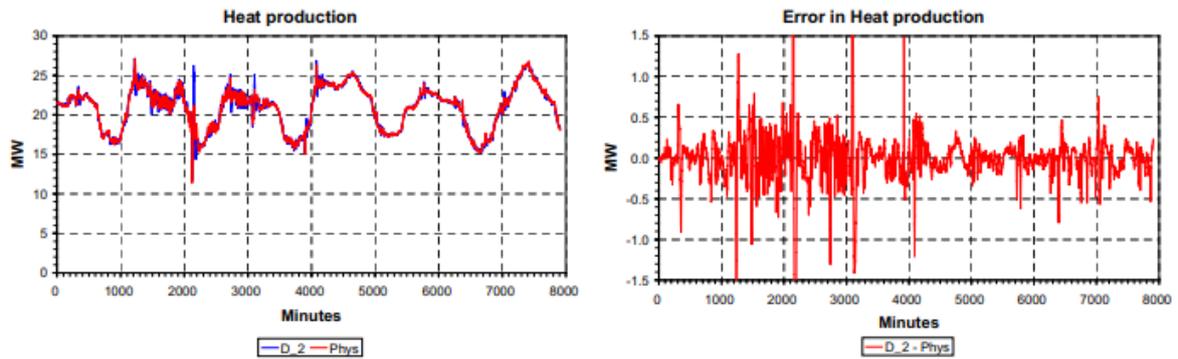


Figure 5.17: Heat production and error done for D_2

For the return temperature to the plant, Figure 5.18 shows that the error done with the equivalent network D_23 is almost non-existent, Figure 5.19 shows that for the equivalent network D_5 the error increases but always is below 1°C difference, and Figure 5.20 shows

for the equivalent network D_2 that the variation is higher with peaks of up to almost 2°C difference, although in most of the time it is less than 1°C.

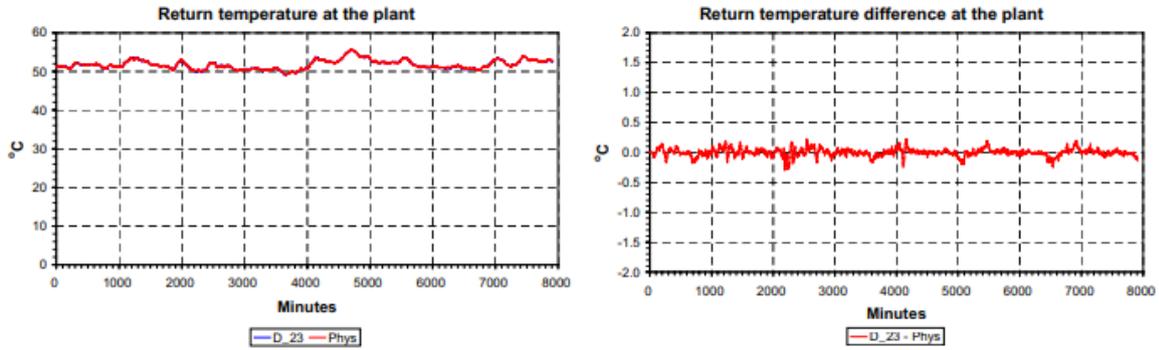


Figure 5.18: Return temperature and error done for D_23

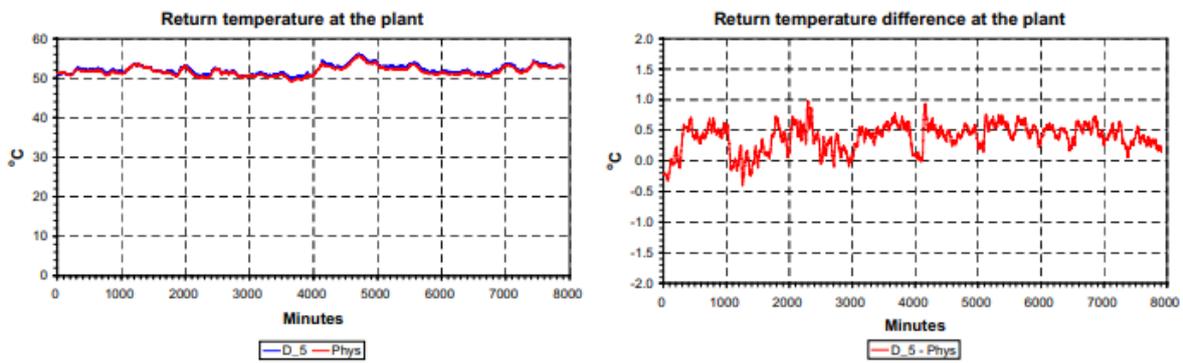


Figure 5.19: Return temperature and error done for D_5

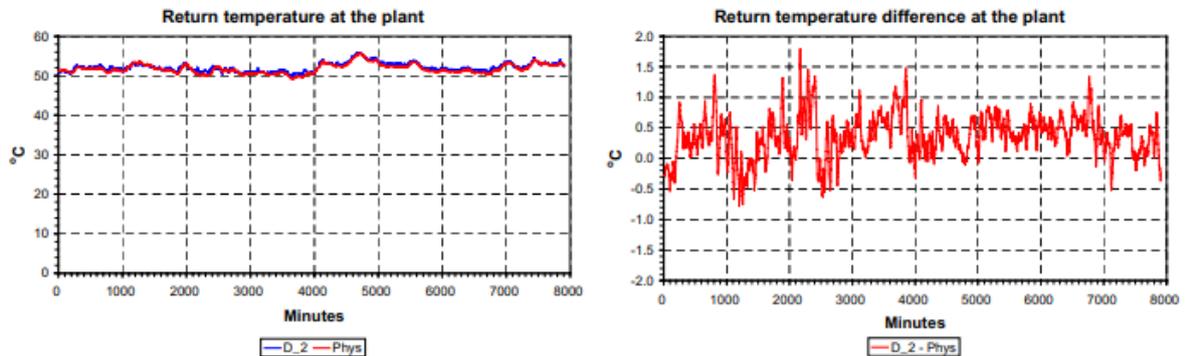


Figure 5.20: Return temperature and error done for D_23

For the mass flow supplied by the generation plant, Figure 5.21 shows that in the case of the equivalent network D_23 the error generated is quite small, the difference always is less

than 1kg/s, except at a specific moment where there is a peak of 3kg/s of difference. In the case of the equivalent network D_5 in Figure 5.22 it can be seen how the difference is higher, always around 1kg/s and with a peak of 5kg/s at the same time as the previous peak in case D_23. In Figure 5.23 it can be seen how for the case of the equivalent network D_2 the difference in mass flow supplied is much higher than in the two previous cases, being at many times above 1kg/s difference and having a few peaks of up to 5kg/s.

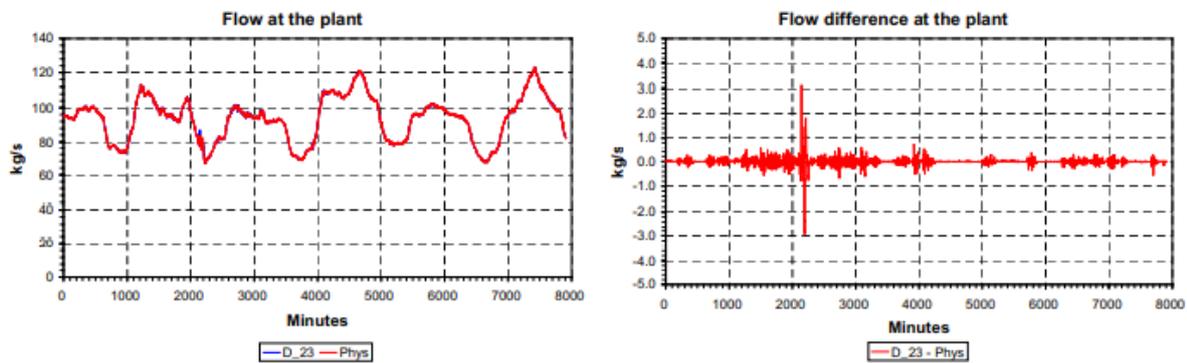


Figure 5.21: Flow at the plant and error done for D_23

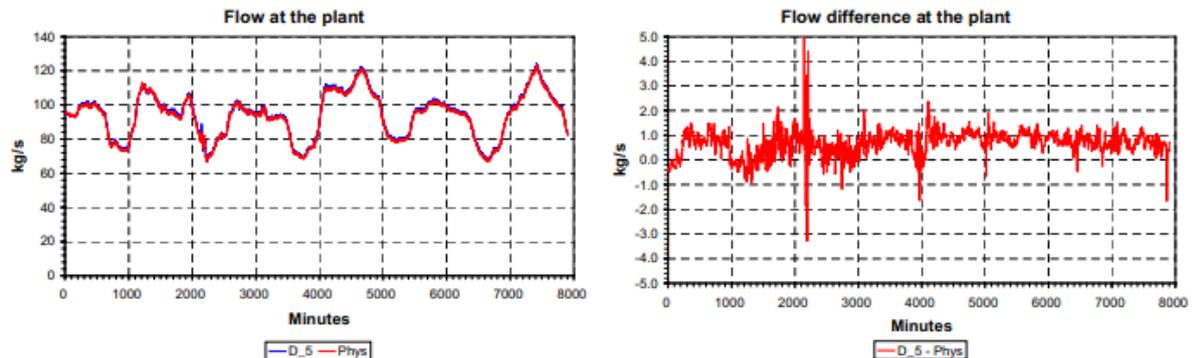


Figure 5.22: Flow at the plant and error done for D_5

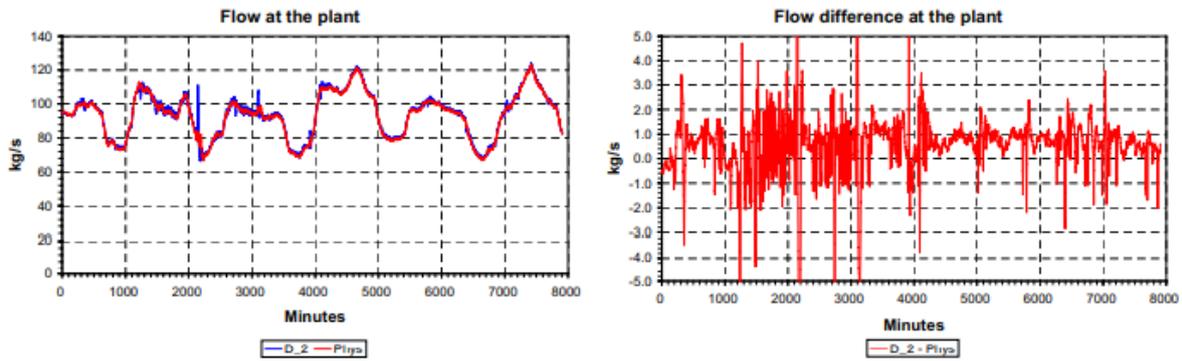


Figure 5.23: Flow at the plant and error done for D_2

For the results obtained with the different equivalent networks of the GM, there are far fewer results than for the DM, the only result presented in the study is the heat production and the error generated in the case of the equivalent network G_6.

Figure 5.24 shows how the error generated in the heat production comparing the original network with the equivalent network G_6 is quite constant and less than 0.5 MW always except at a peak of more than 2 MW.

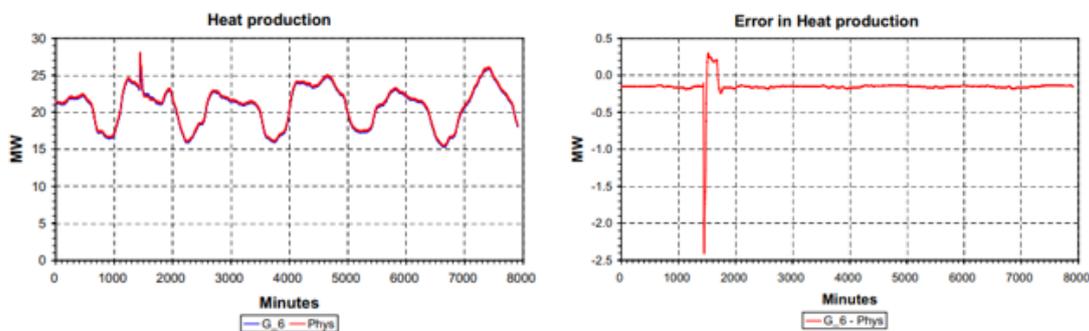


Figure 5.24: Heat production and error done for G_6

The study concludes that both methods work correctly for small reduction levels, and that by applying the DM it is possible to reduce from the original 44 branches to 3 branches with acceptable errors, and that by applying the GM it is possible to reduce up to 10 branches [8].

6. WORK DEVELOPMENT

6.1. Procedure to obtain equivalent networks

Three reduction processes will be carried out starting from the original network. First, the extended DM will be applied, with which two reduction processes will be performed: one for the calculation of the heat losses and the other for the calculation of the pressure drop. Then the GM will be applied to obtain a third reduction process, which will be used to calculate heat losses.

The procedure followed to obtain each of the equivalent networks starting from the original network will be explained step by step.

6.1.1. 1st reduction process

The first reduction process is the one used for the calculation of heat losses in the extended DM, which will be applied on the original network of Figure 5.1.

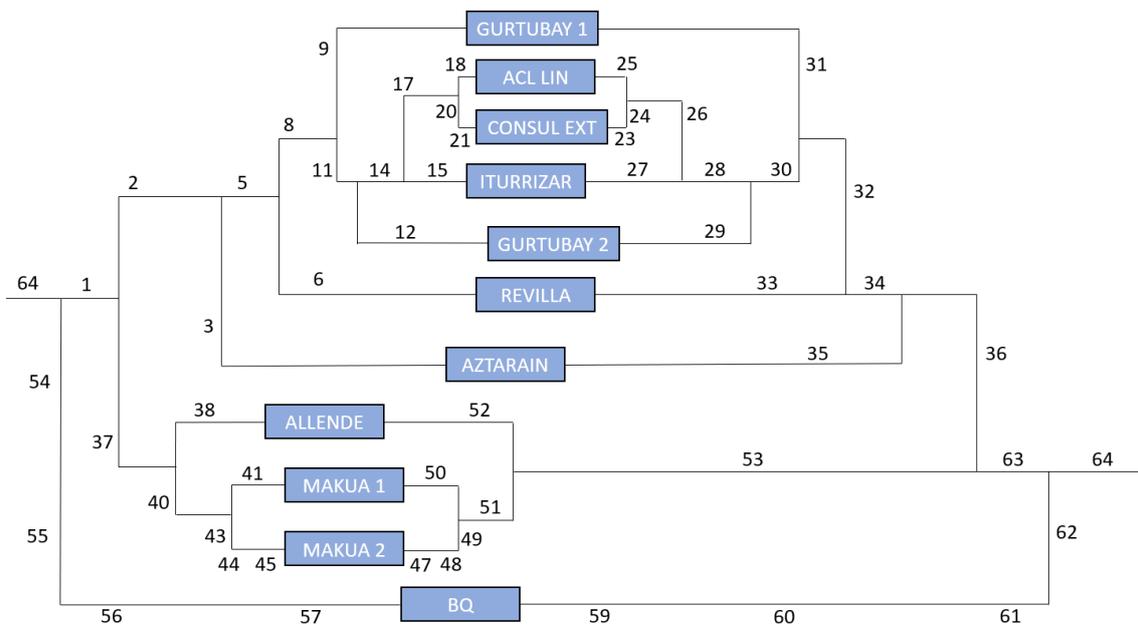


Figure 6.1: Original distribution network

In the reduction of the network three different type of steps are going to be applied:

- The first type of step is used to reduce pipes in series with an equivalent pipe.

The first assumption done is that the total length of the pipes in series remains constant. So that the length of the equivalent pipe (L_{eq}) is equal to the sum of the lengths of the pipes in series:

$$L_{eq} = \sum_{i=1}^n L_i \quad [5.1]$$

In the cases where all the diameters of the pipes in series that are joined are the same, the diameter of the equivalent pipe will be the same:

$$D_{eq} = D_i \quad [5.2]$$

In the case that all diameters are not equal, the calculation for the pipes to be both hydraulically and thermally equivalent is more complex.

To obtain a hydraulically equivalent pipe, it is assumed that the primary losses of the equivalent pipe are equal to the sum of the losses in the pipes in series:

$$h_{f_{eq}} = \sum_{i=1}^n h_{f_i} \quad [5.3]$$

To obtain the equivalent pipe diameter, the following formula is used which relates the primary losses to the pipe diameter:

$$h_f = \frac{8 * f * L * Q^2}{\pi^2 * g * D^5} \quad [5.4]$$

Where f is the friction factor, L and D are the length and diameter of the pipe respectively, Q is the flow rate through the pipe and g is the gravity constant.

The friction factor for turbulent regime is:

$$f = 0.11 * \left(\frac{\varepsilon}{D} + \frac{68}{Re} \right)^{0.25} \quad [5.5]$$

Where ε is the absolute roughness of the pipe and Re the Reynolds number.

The Reynolds number for turbulent regime is:

$$Re = \frac{4 * Q}{\pi * D * \nu} \quad [5.6]$$

Substituting Equations 5.5 and 5.6 into Equation 5.4 we obtain the diameter of the equivalent pipe.

Once a hydraulically equivalent pipe is obtained, it must also be made thermally equivalent, for which it will be assumed that the thermal coefficient U of the equivalent pipe will be the sum of the thermal coefficients of the pipes in series:

$$U_{eq} = \sum_{i=1}^n U_i \quad [5.7]$$

The coefficient U has been estimated by considering the losses by conduction and convection in all the parts:

$$U = \frac{1}{R_{cv,in} + R_{cd,pip} + R_{cd,ins} + R_{cv,out}} \quad [5.8]$$

- $R_{cv,in}$ is the **thermal resistance for the inner surface fluid convection**, that is estimated:

$$R_{cv,in} = \frac{1}{\pi * h_{v,w} * D * L} \quad [5.9]$$

Where $h_{v,w}$ is the forced convection coefficient for the water inside the piped, and it is calculated as:

$$h_{v,w} = K_{th,w} * 0.023 * Re^{\frac{4}{5}} * Pr^{0.4} \quad [5.10]$$

Where $K_{th,w}$ is the **thermal conductivity of the water**, Re is calculated as in Equation 5.6 and Pr is the Prandtl number that for the water can be calculated as:

$$Pr = \frac{\nu_w * c_{p,w}}{K_{th,w}} \quad [5.11]$$

Where ν and c_p are respectively the kinematic viscosity and the heat capacity of the water.

- $R_{cd,pip}$, the **thermal resistance due to conduction through the pipe**, is obtain from:

$$R_{cd,pip} = \log\left(\frac{D_{out,pip}}{D}\right) * \frac{1}{2 * \pi * K_{th,pip} * L} \quad [5.12]$$

Where $D_{out,pip}$ is the outer diameter of the pipe and $K_{th,pip}$ is the thermal conductivity of the pipe.

- $R_{cd,ins}$, **the the thermal resistance due to conduction through the insulation**, is obtain from:

$$R_{cd,ins} = \log\left(\frac{D_{out,pip} + 2 * e_{ins}}{D_{out,pip}}\right) * \frac{1}{2 * \pi * K_{th,ins} * L} \quad [5.13]$$

- $R_{cv,out}$ is the **natural convection resistance**, it is calculated as:

$$R_{cv,out} = \frac{1}{\pi * h_{v,a} * (D_{out,pip} + 2 * e_{ins}) * L} \quad [5.14]$$

Where $h_{v,a}$ is the natural convection coefficient for the outer surface of the pipe, and is calculated as:

$$h_{v,a} = \left(\frac{K_{th,a}}{D}\right) * \left(0.6 + 0.387 * \frac{Ra^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 \quad [5.15]$$

Where $K_{th,a}$ is the thermal conductivity for the air and Ra is the Raleigh number, that is obtain as:

$$Ra = g * D^3 * \alpha * \left(\frac{T_{amb} - T_{ext}}{\nu * k}\right) \quad [5.16]$$

The coefficients $R_{cv,in}$, $R_{cd,ins}$ and $R_{cv,out}$ are calculated with the new values of diameter and length of the equivalent pipe. Knowing the coefficient U and the other three coefficients, the coefficient $R_{cd,pip}$ is calculated using Equation 5.8.

The simulator presented in Section 5.3, which is going to be used to simulate both the original network and the different equivalent networks, the value of the thermal conductivity of the pipes ($K_{th,pip}$) must be given, which in all cases in the original network is the same, the thermal conductivity of the steel. However, in order to obtain thermally equivalent pipes, this coefficient will be recalculated by means of equation 5.12. Therefore, it will be assumed that the equivalent pipes are not made of steel but of a fictitious material.

- The second type of step is the first step explained in the extended DM, the one that obtains two substations in series from two substations in parallel.
- The third type of step is the second step explained in the extended DM, the one that reduces the network once all the substations are in series.

All the reductions are done for the supply part of the network, but as the return side is equal to the supply all the simplifications of the equivalent network can be applied to the return.

- Step 1:

In this first step we have obtained three equivalent pipes 65, 66 and 67 reducing three different groups of pipes in series 54/55/56/57, 43/44/45 and 20/21 as shown in the figure below.

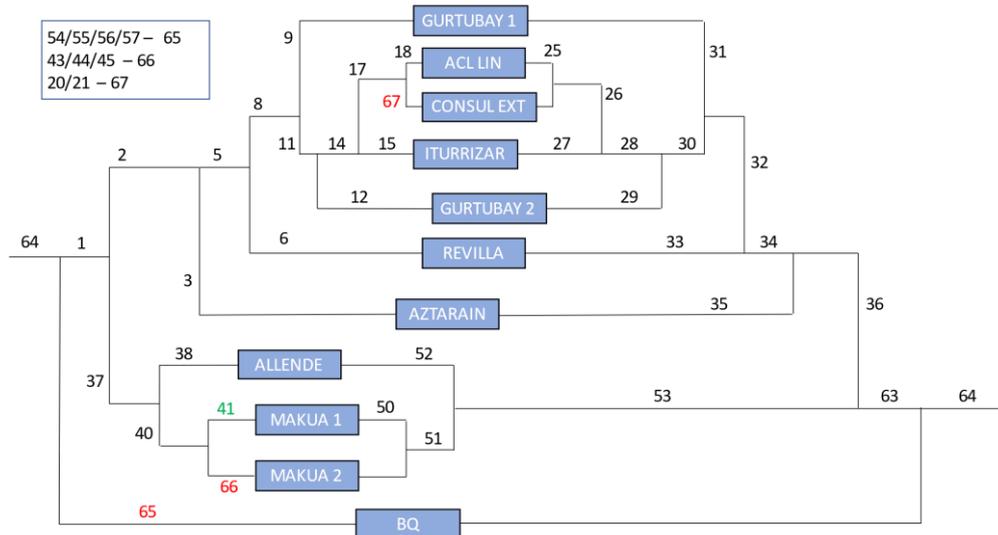


Figure 6.2: Equivalent heat loss network (DM) – Step 1

- Step 2:

In the second step Makua 1 and Makua 2 are transformed from parallel to series substations as shown in the figure below, and the pipes 41 and 66 are transformed into the equivalent 68 and 69 pipes.

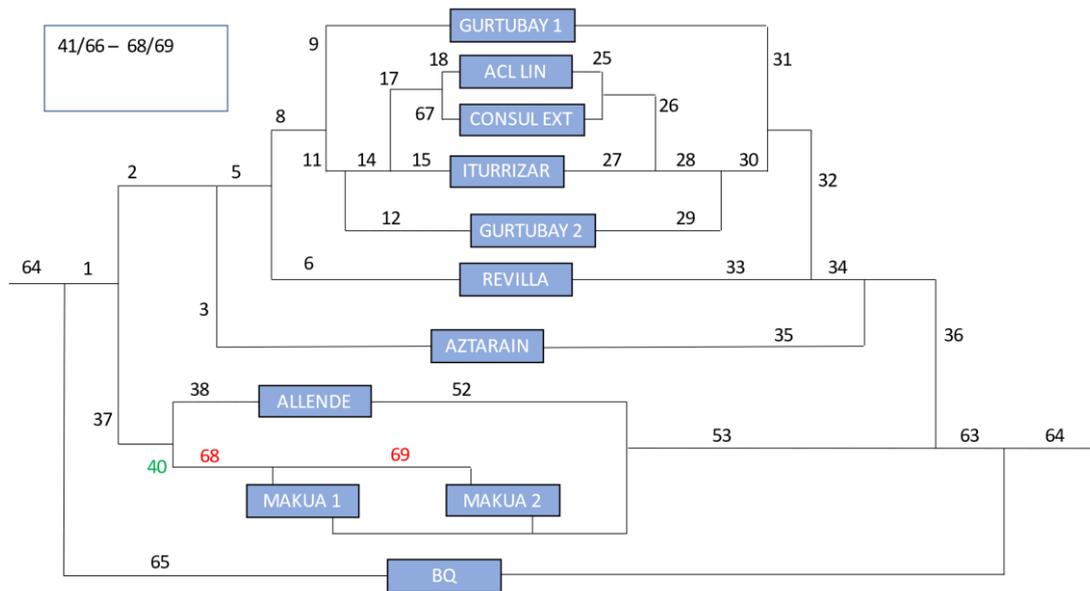


Figure 6.3: Equivalent heat loss network (DM) – Step 2

- Step 3:

Once Makua 1 and Makua 2 are in series, the equivalent pipe 70 is calculated from the pipes in series 40 and 68 as shown in the figure below.

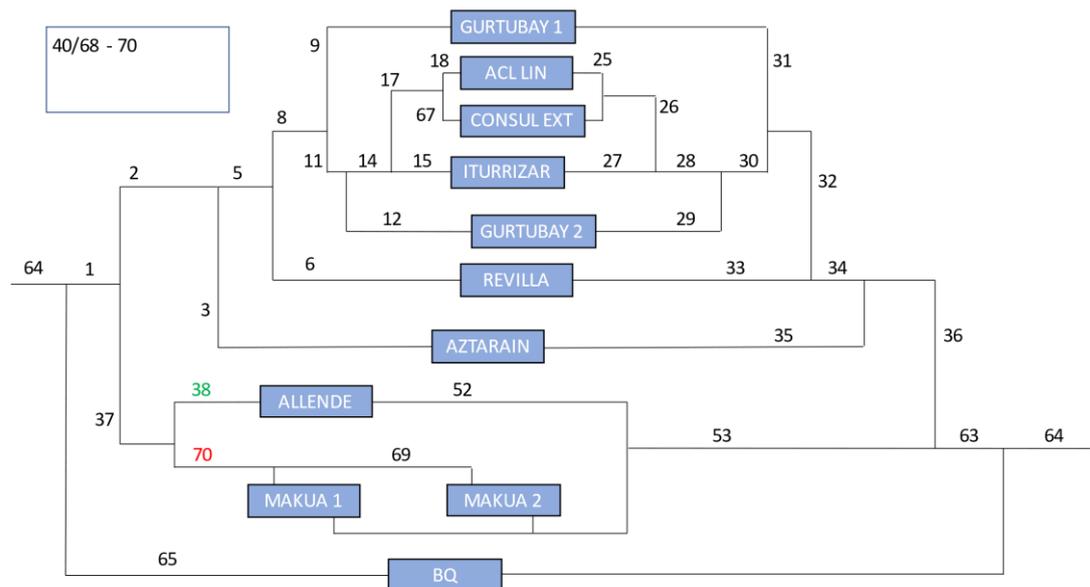


Figure 6.4: Equivalent heat loss network (DM) – Step 3

- Step 4:

The next step is to put Allende substation in series with Makua 1 and 2 substations as shown in the figure below, and the pipes 38 and 70 are transformed into the equivalent 71 and 72 pipes.

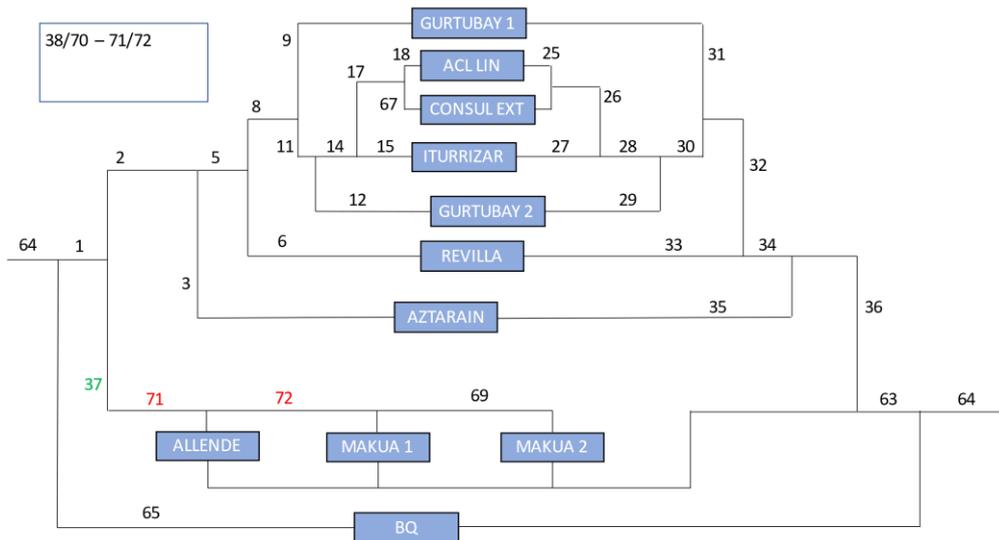


Figure 6.5: Equivalent heat loss network (DM) – Step 4

- Step 5:

Once those three substations are in series, the equivalent pipe 73 is calculated as shown in the figure below from the pipes in series 37 and 71 that were in series.

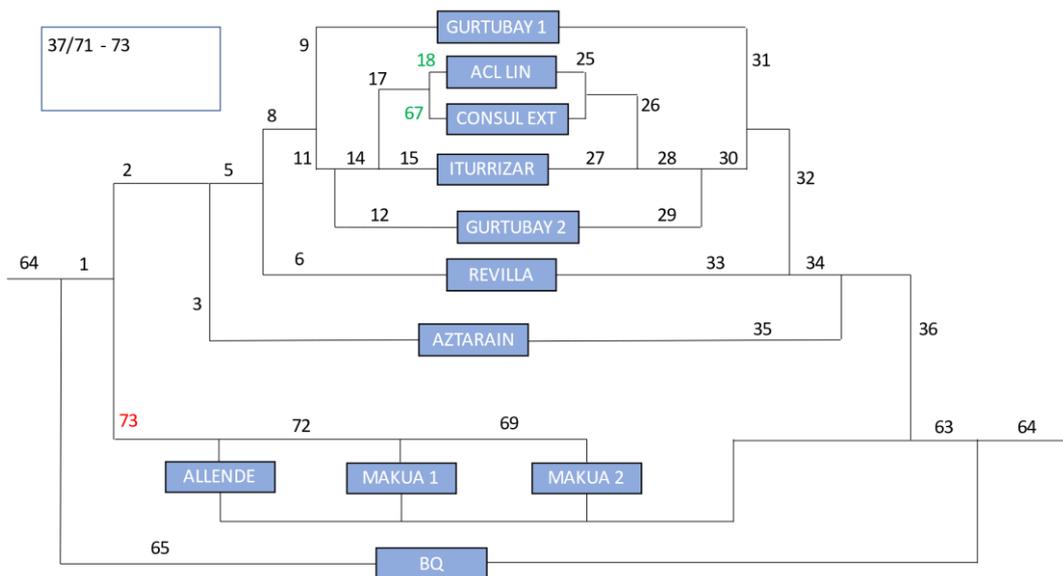


Figure 6.6: Equivalent heat loss network (DM) – Step 5

- Step 6:

In this step Acl. Lin. and Consul. Ext. substations are transformed from parallel to series substations as shown in the figure below, and the pipes 18 and 67 are transformed into the equivalent 74 and 75 pipes.

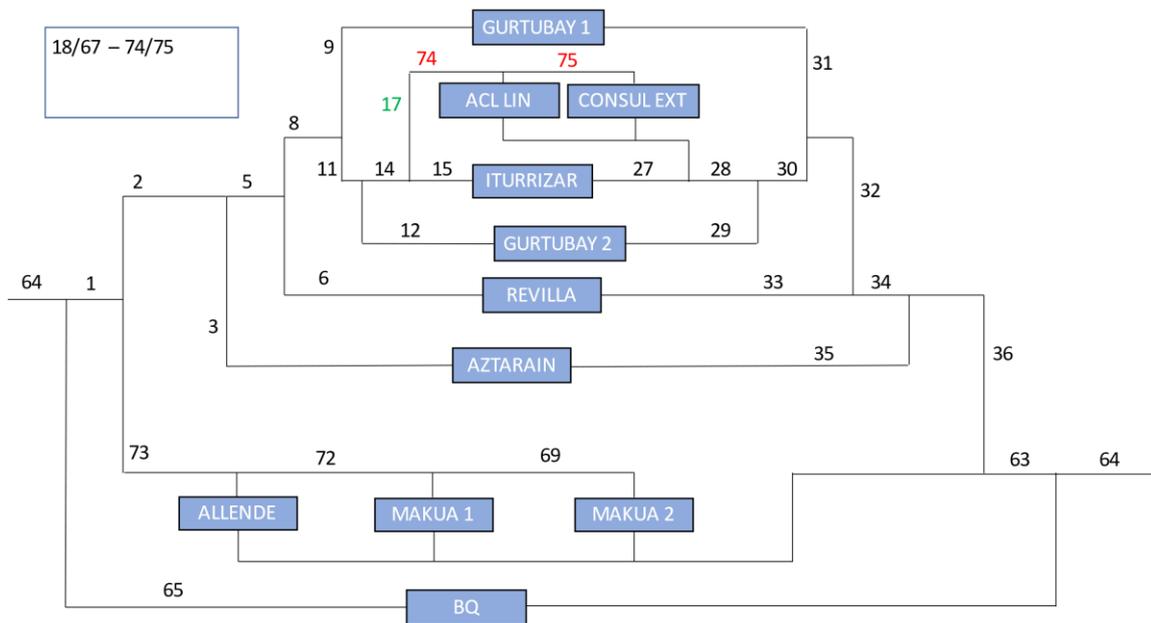


Figure 6.7: Equivalent heat loss network (DM) – Step 6

- Step 7:

Once Acl. Lin. and Consul. Ext. substations are in series, the equivalent pipe 76 is calculated from the serial pipes 17 and 74 as shown in the figure below.

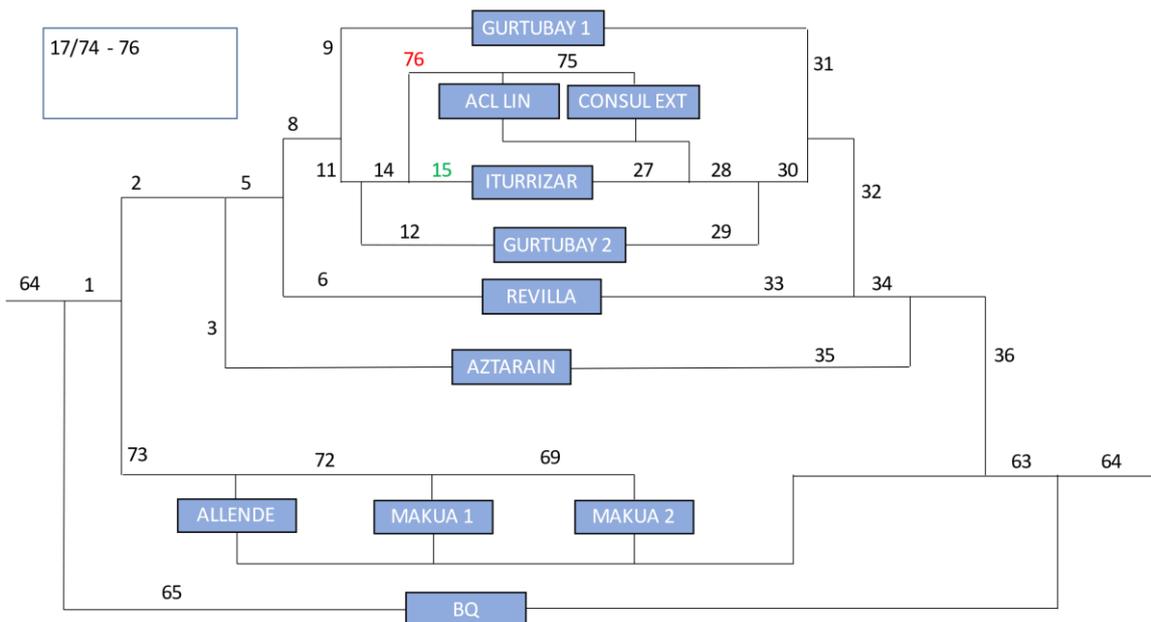


Figure 6.8: Equivalent heat loss network (DM) – Step 7

- Step 8:

The next step is to put Iturrizar substation in series with Acl. Lin. and Consul. Ext. substations as shown in the figure below, and the pipes 15 and 76 are transformed into the equivalent 77 and 78 pipes.

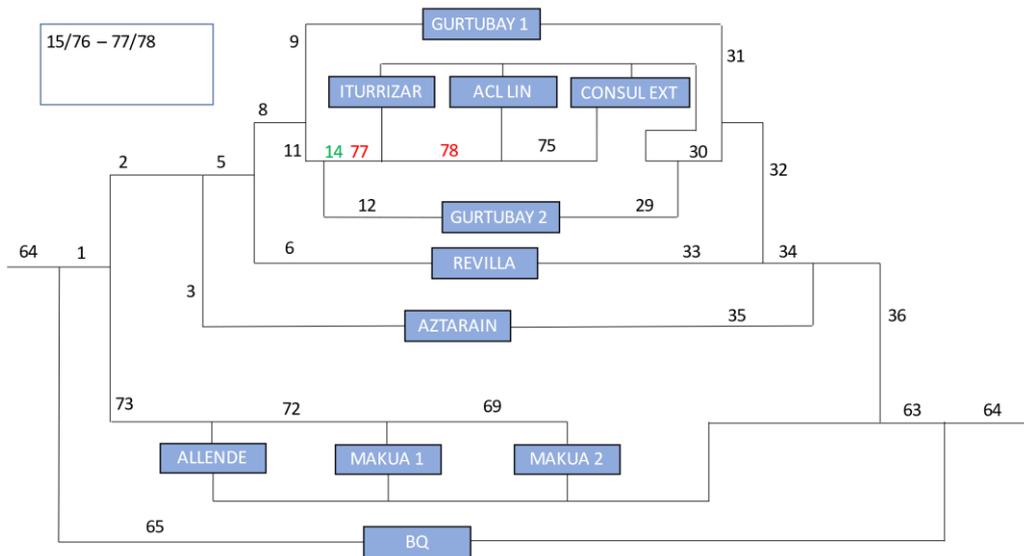


Figure 6.9: Equivalent heat loss network (DM) – Step 8

- Step 9:

Once those three substations are in series, the equivalent pipe 79 is calculated from the pipes 14 and 77 as shown in the figure below.

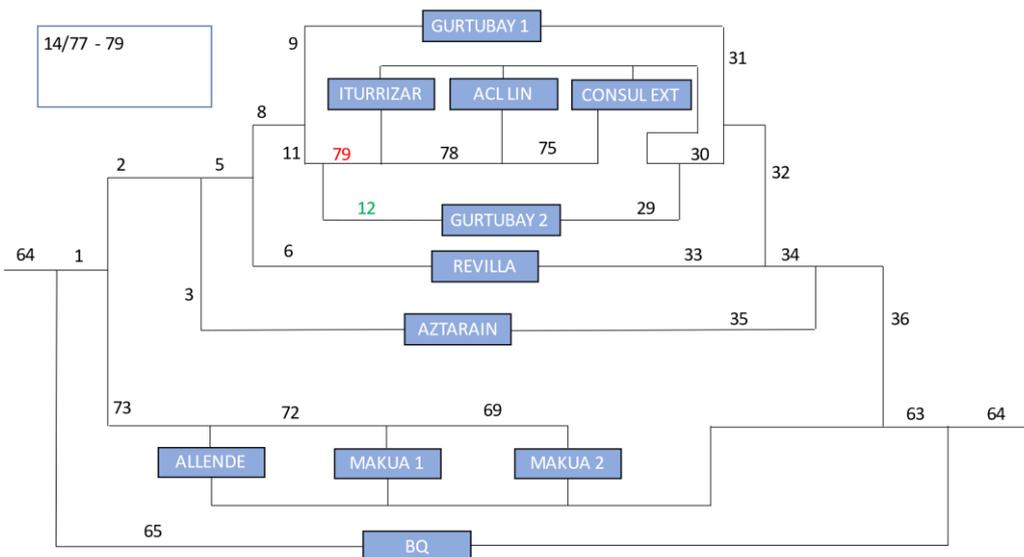


Figure 6.10: Equivalent heat loss network (DM) – Step 9

- Step 10:

The next step is to put Gurtubay 2 substation in series with the other three substations as shown in the figure below, and the pipes 12 and 79 are transformed into the equivalent 80 and 81 pipes.

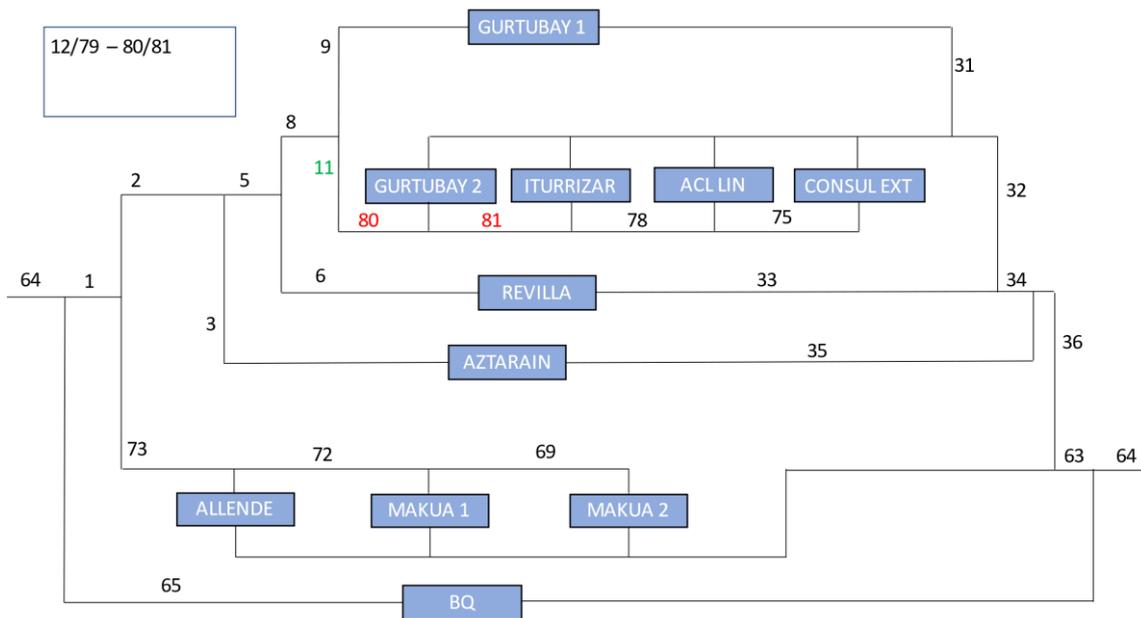


Figure 6.11: Equivalent heat loss network (DM) – Step 10

- Step 11:

Once those four substations are in series, the equivalent pipe 82 is calculated from the pipes 11 and 80 as shown in the figure below.

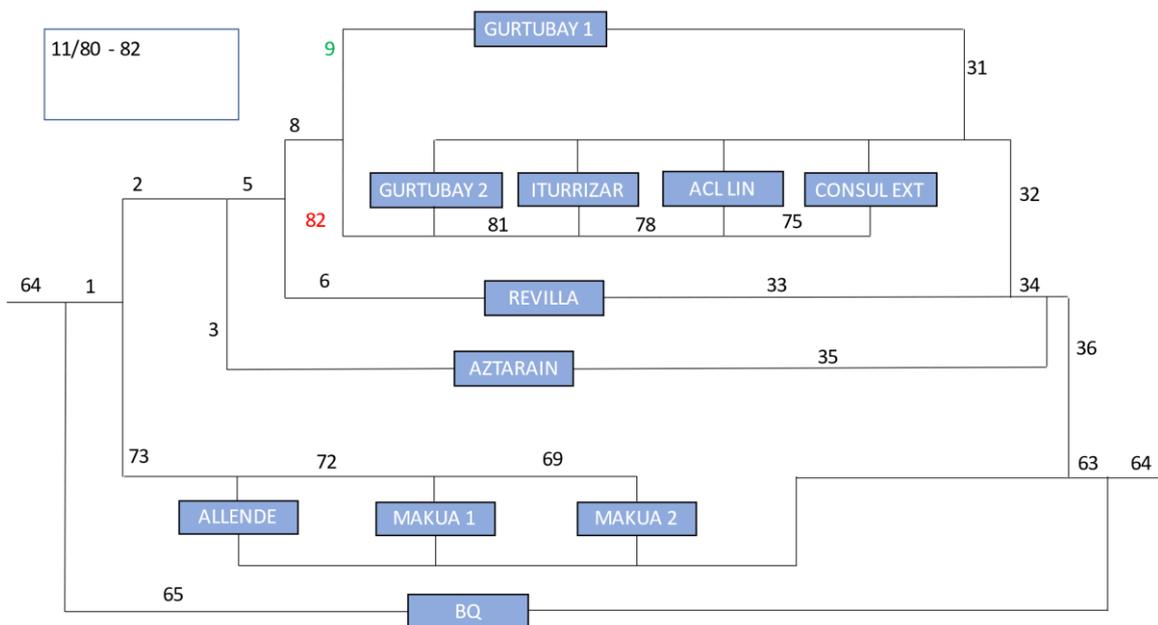


Figure 6.12: Equivalent heat loss network (DM) – Step 11

- Step 12:

The next step is to put Gurtubay 1 substation in series with the other four substations as shown in the figure below, and the pipes 9 and 82 are transformed into the equivalent 83 and 84 pipes.

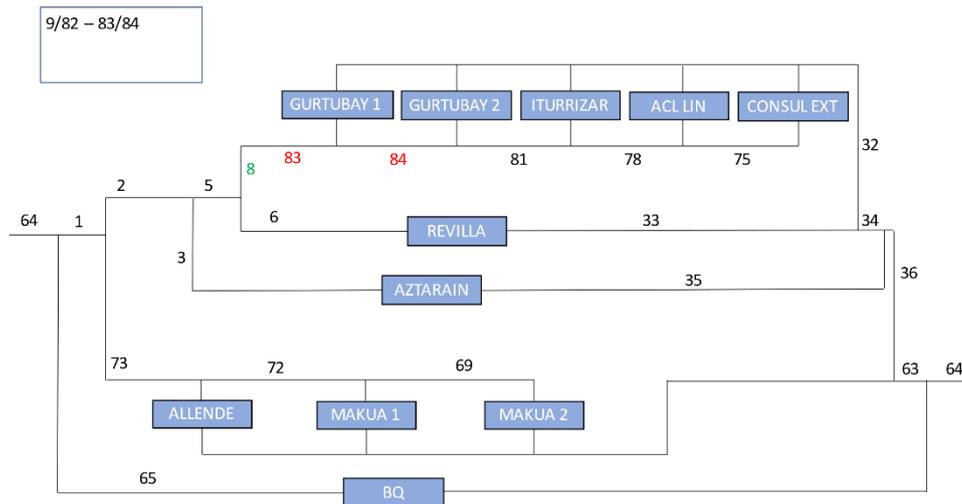


Figure 6.13: Equivalent heat loss network (DM) – Step 12

- Step 13:

Once those five substations are in series, the equivalent pipe 85 is calculated from the pipes in series 8 and 83 as shown in the figure below.

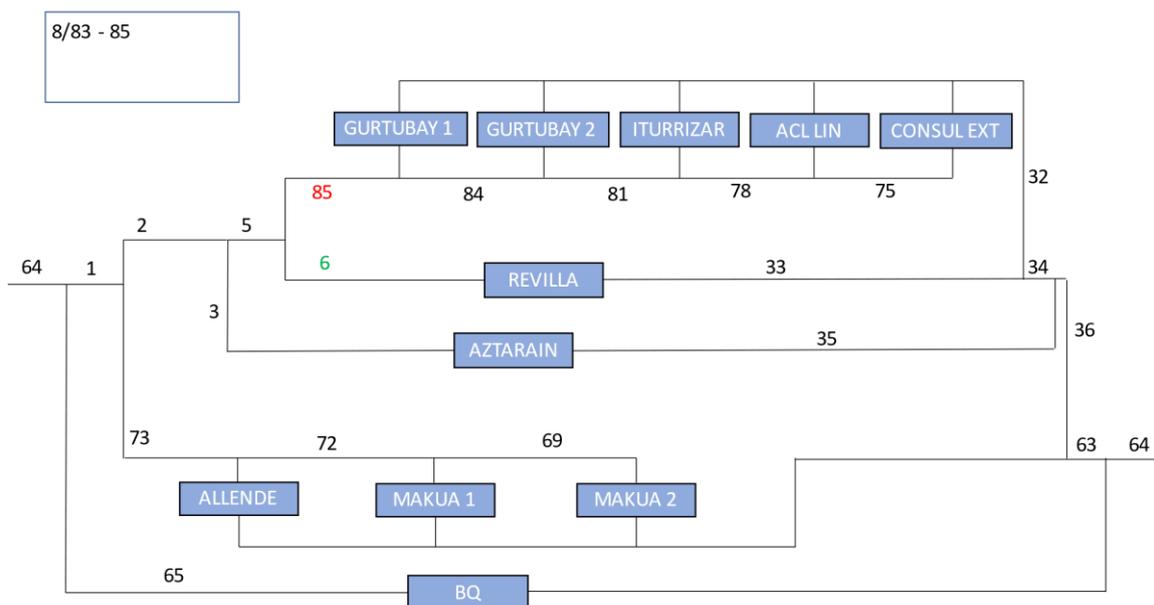


Figure 6.14: Equivalent heat loss network (DM) – Step 13

- Step 14:

The next step is to put Revilla substation in series with the other five substations as shown in the figure below, and the pipes 6 and 85 are transformed into the equivalent 86 and 87 pipes.

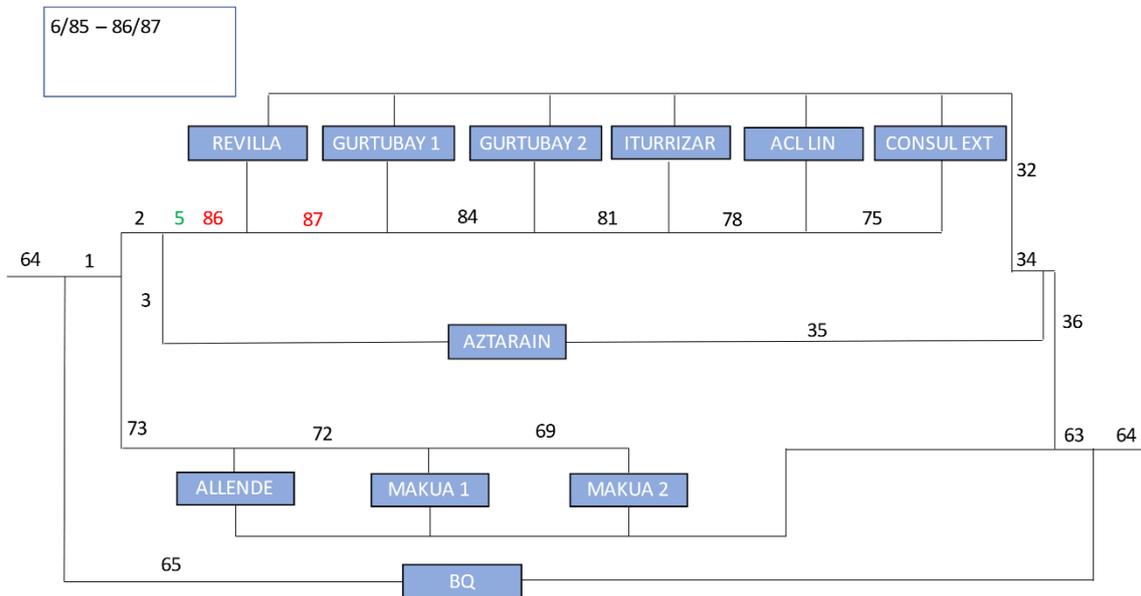


Figure 6.15: Equivalent heat loss network (DM) – Step 14

- Step 15:

Once those six substations are in series, the equivalent pipe 88 is calculated from the pipes in series 5 and 86 as shown in the figure below.

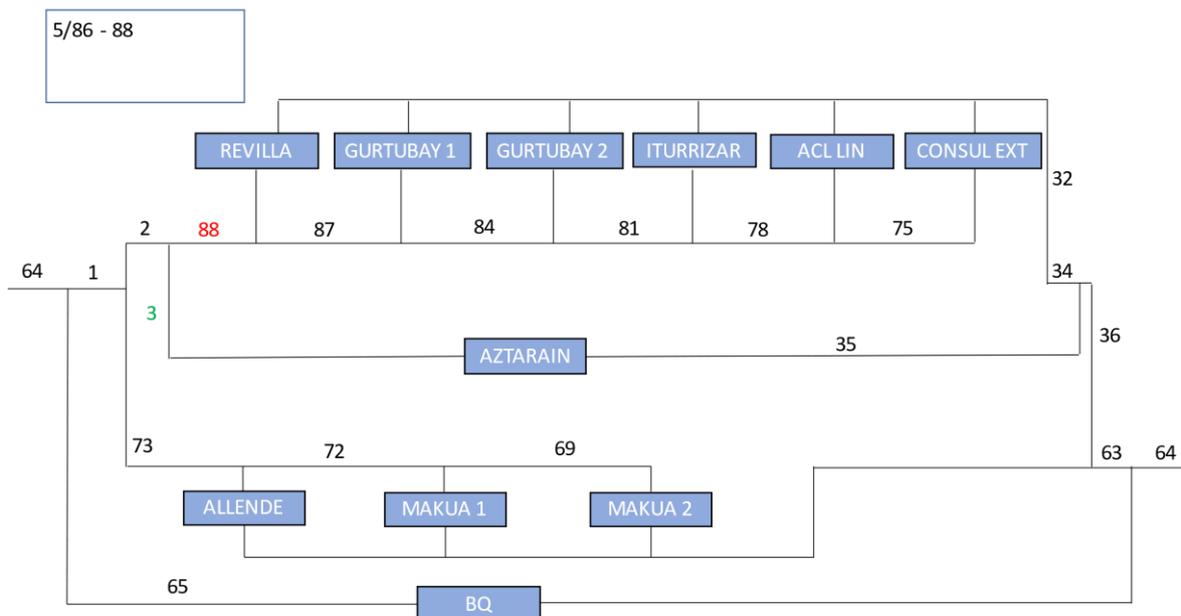


Figure 6.16: Equivalent heat loss network (DM) – Step 15

- Step 16:

The next step is to put Aztarain substation in series with the other six substations as shown in the figure below, and the pipes 3 and 88 are transformed into the equivalent 89 and 90 pipes. Due to the algorithm used for this calculation, the Aztarain substation will be placed at the end, therefore all the mass flows of the pipes 87, 84, 81, 78 and 75 will have variations.

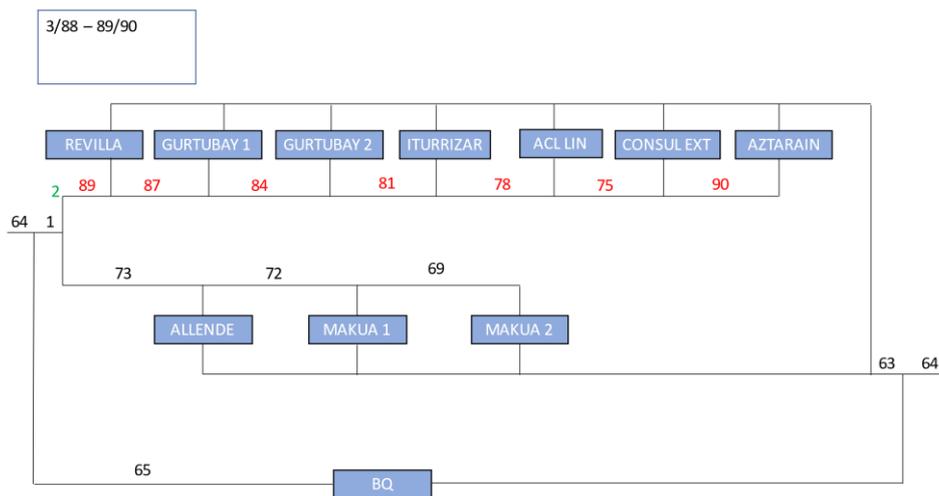


Figure 6.17: Equivalent heat loss network (DM) – Step 16

- Step 17:

Once those seven substations are in series, the equivalent pipe 91 is calculated from the pipes 2 and 89 as shown in the figure below.

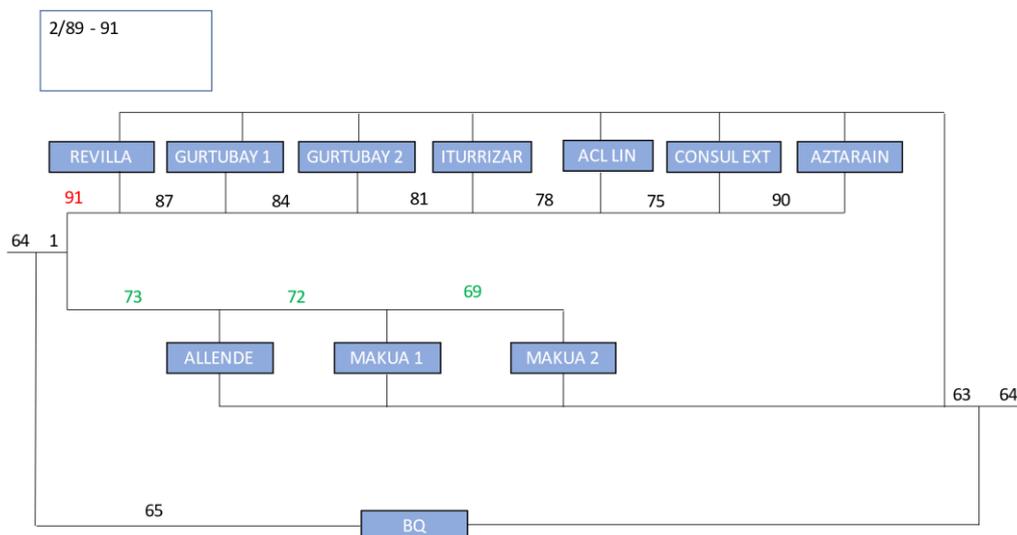


Figure 6.18: Equivalent heat loss network (DM) – Step 17

As can be seen in the figure above the network has now three branches, one with only a substation, another one with three substations in series, and a third one with seven substations in series. The next steps are going to simplify those two branches with substations in series obtaining one less pipe in each step.

- Step 18:

In this step the pipes 69, 72 and 73 are reduced to pipes 92 and 93 and the equivalent substations a, b and c are obtained from Allende, Makua 1 and 2 substations.

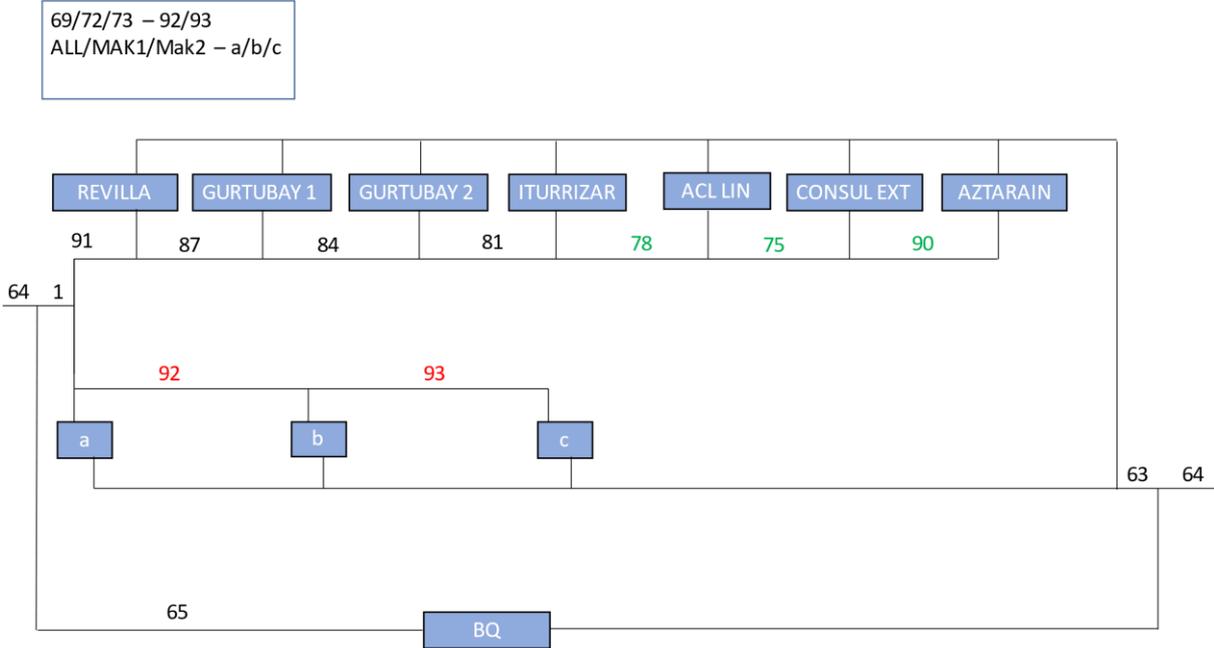


Figure 6.19: Equivalent heat loss network (DM) – Step 18

- Step 19:

In this step the pipes 78,75 and 90 are reduced to pipes 94 and 95, and the equivalent substations d, e and f are obtained from Iturrizar, Acl. Lin. and Consul. Ext. substations. The substations Gurtubay 2 and d are joined into a unique substation.

78/75/90 – 94/95
ACL/CON/AZT – d/e/f

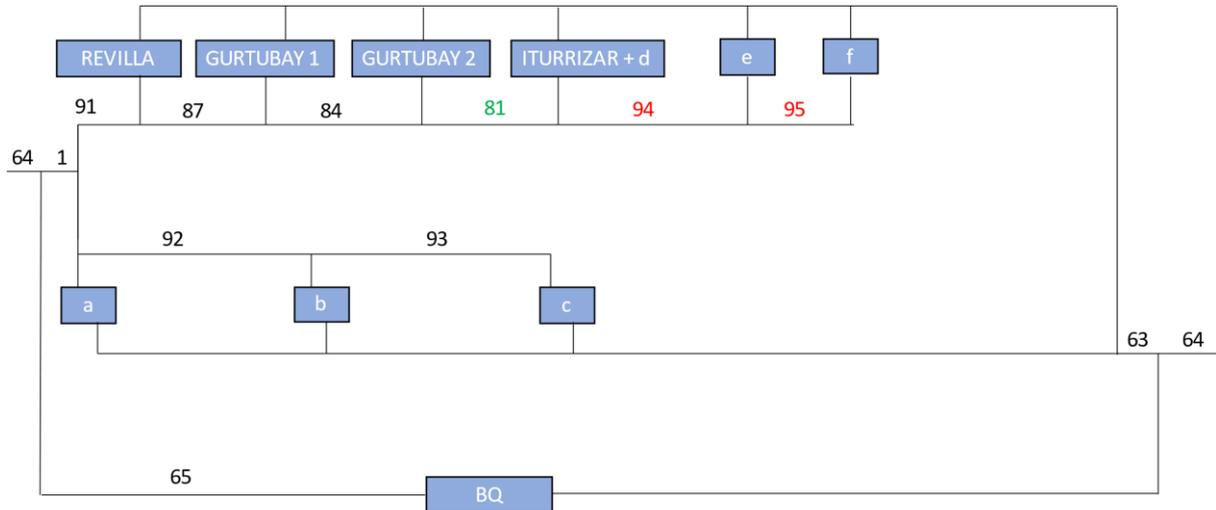


Figure 6.20: Equivalent heat loss network (DM) – Step 19

- Step 20:

In this step the pipes 81, 94 and 95 are reduced to pipes 96 and 97, and the equivalent substations g, h and i are obtained from Gurtubay 2 + d, e and f substations. The substations Gurtubay 1 and g are joined into a unique substation.

81/94/95 – 96/97
ITU+d/e/f – g/h/i

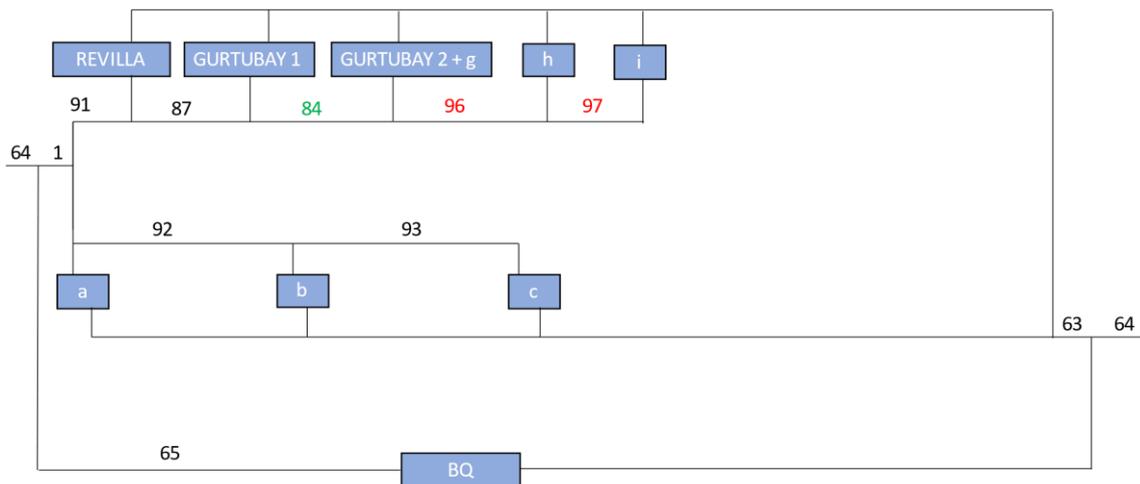


Figure 6.21: Equivalent heat loss network – Step 20

- Step 21:

In this step the pipes 84, 96 and 97 are reduced to pipes 98 and 99, and the equivalent substations j, k and l are obtained from Gurtubay 1 + g, h and i substations. The substations Revilla and j are joined into a unique substation.

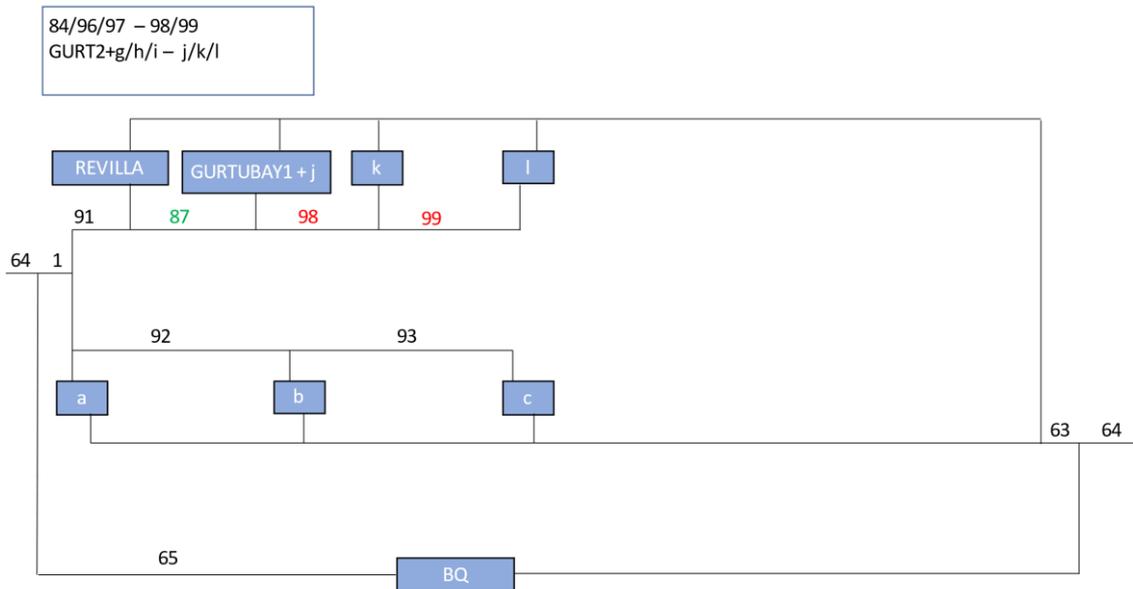


Figure 6.22: Equivalent heat loss network (DM) – Step 21

- Step 22:

In this step the pipes 87, 98 and 99 are reduced to pipes 100 and 101, and the equivalent substations m, n and o are obtained from Revilla + j, k and l substations. The substations Aztarain and m are joined into a unique substation.

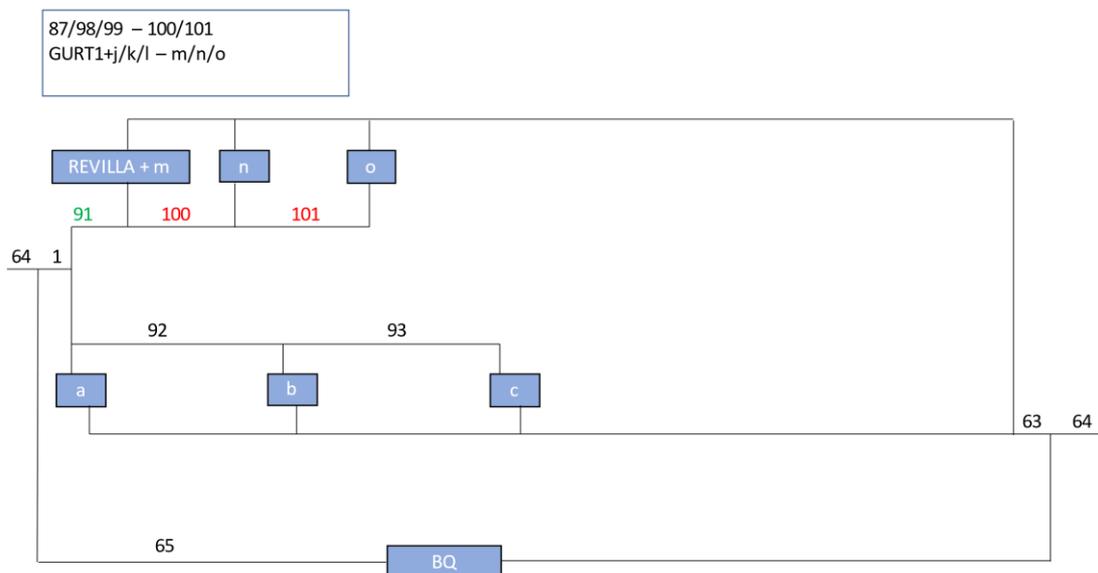


Figure 6.23: Equivalent heat loss network – Step 22

- Step 23:

In this last step the pipes 91,100 and 101 are reduced to pipes 102 and 103, and the equivalent substations p, q and r are obtained from Aztarain + m, n and o substations.

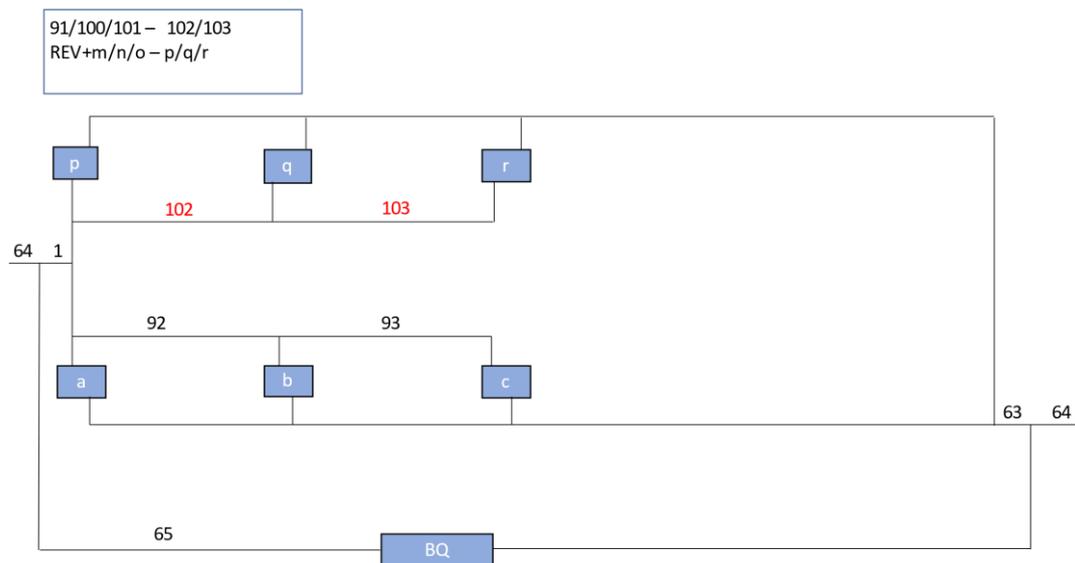


Figure 6.24: Equivalent heat loss network (DM) – Step 23

6.1.2. 2nd reduction process

The reduction process is also done by applying the extended DM, but in this case for the calculation of the pressure drop in the network. It starts from the same original network, and the three types of steps used are the same, but the algorithm used to calculate the equivalent pipes characteristics are going to be different because in this case we are focusing on the pressure drop in the network. Therefore, the equivalent network that will be obtained will be the same, three main branches with substations in series, but the characteristics of the equivalent pipes and the substations location are going to be different.

- Step 1:

In this first step we have obtained three equivalent pipes 65, 66 and 67 reducing three different groups of pipes in series 54/55/56/57, 43/44/45 and 20/21 as shown in the figure below.

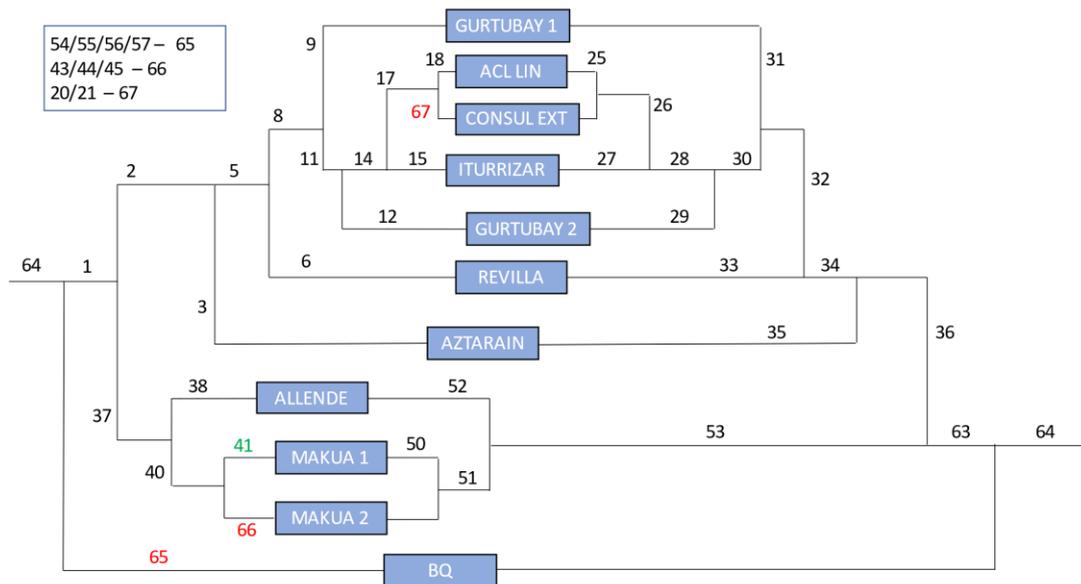


Figure 6.25: Equivalent pressure drop network (DM) – Step 1

- Step 2:

In the second step Makua 1 and Makua 2 are transformed from parallel to series substations as shown in the figure below, and the pipes 41 and 66 are transformed into the equivalent 104 and 105 pipes.

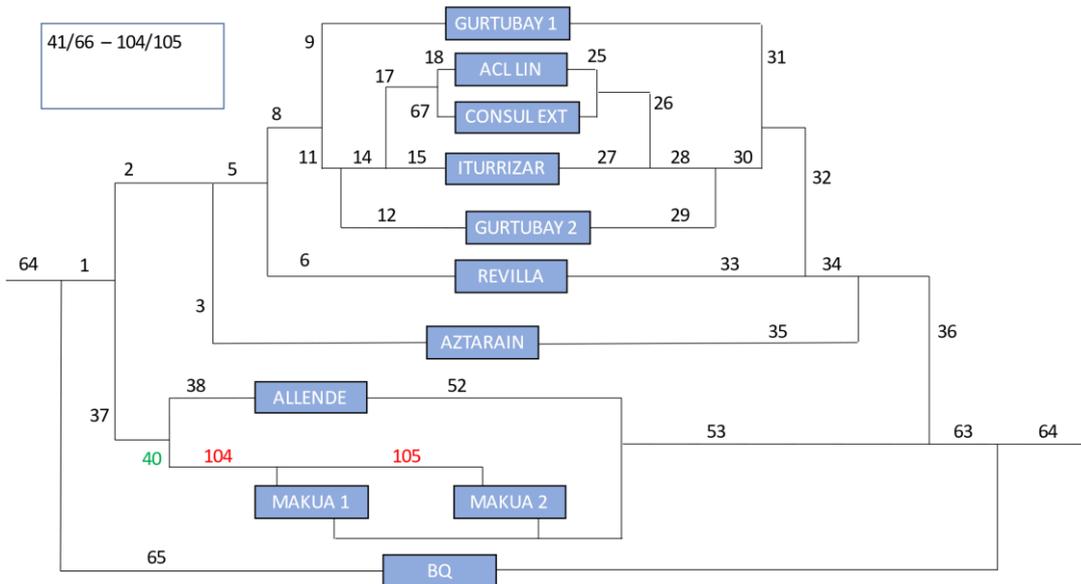


Figure 6.26: Equivalent pressure drop network (DM) – Step 2

- Step 3:

Once Makua 1 and Makua 2 are in series, the equivalent pipe 106 is calculated from the pipes 40 and 104 as shown in the figure below.

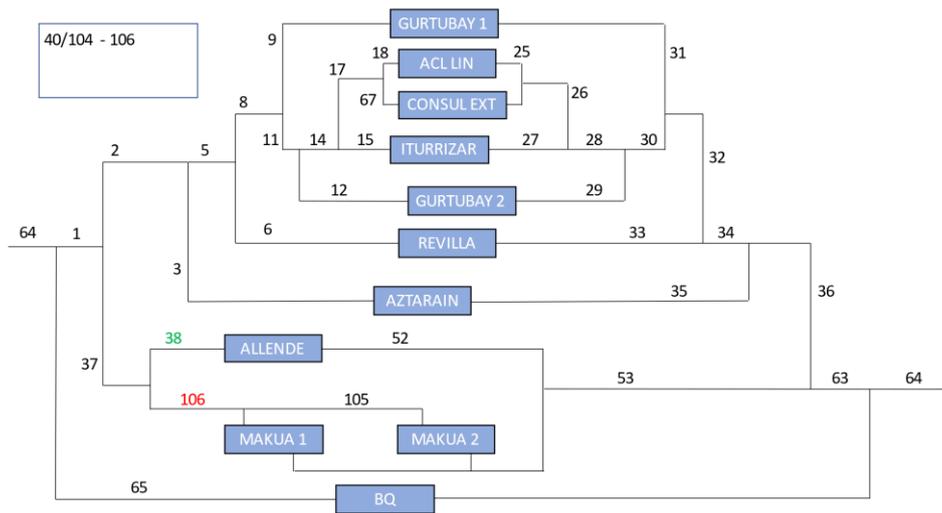


Figure 6.27: Equivalent pressure drop network (DM) – Step 3

- Step 4:

The next step is to put Allende substation in series with Makua 1 and 2 substations as shown in the figure below, and the pipes 38 and 106 are transformed into the equivalent 107 and 108 pipes. Unlike the first case when the equivalent network for heat loss was calculated in this case the Allende substation is located after Makua 1 and 2 substations because of the algorithm used, so that the mass flow in the pipe 105 is recalculated.

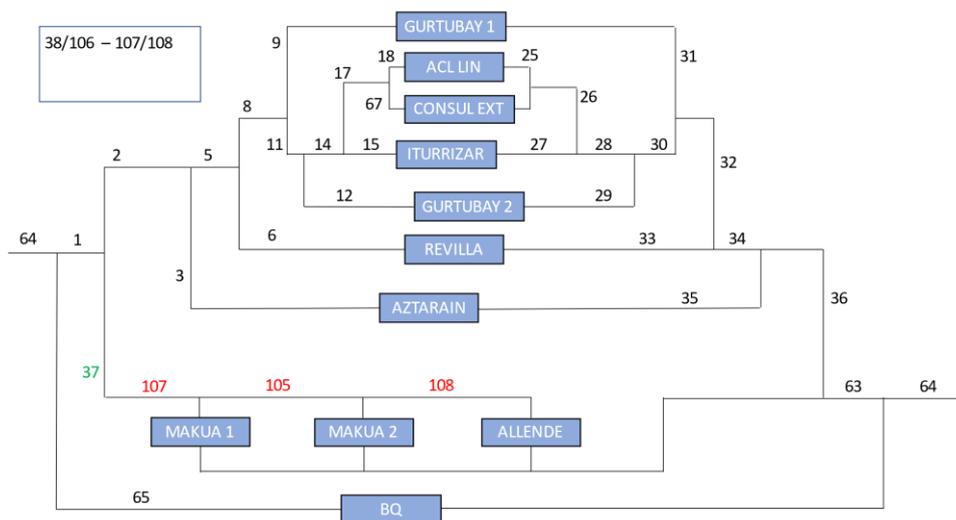


Figure 6.28: Equivalent pressure drop network (DM) – Step 4

- Step 5:

Once those three substations are in series, the equivalent pipe 109 is calculated as shown in the figure below from the pipes 37 and 107 that were in series.

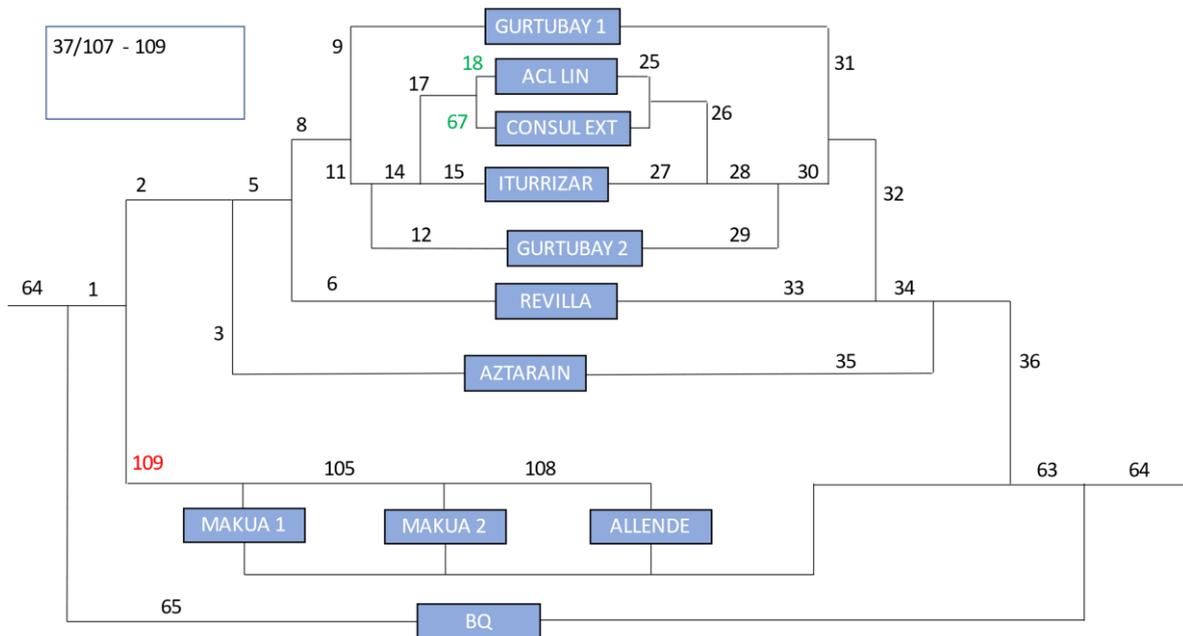


Figure 6.29: Equivalent pressure drop network (DM) – Step 5

- Step 6:

In this step Acl. Lin. and Consul. Ext. substations are transformed from parallel to series substations as shown in the figure below, and the pipes 18 and 67 are transformed into the equivalent 110 and 111 pipes.

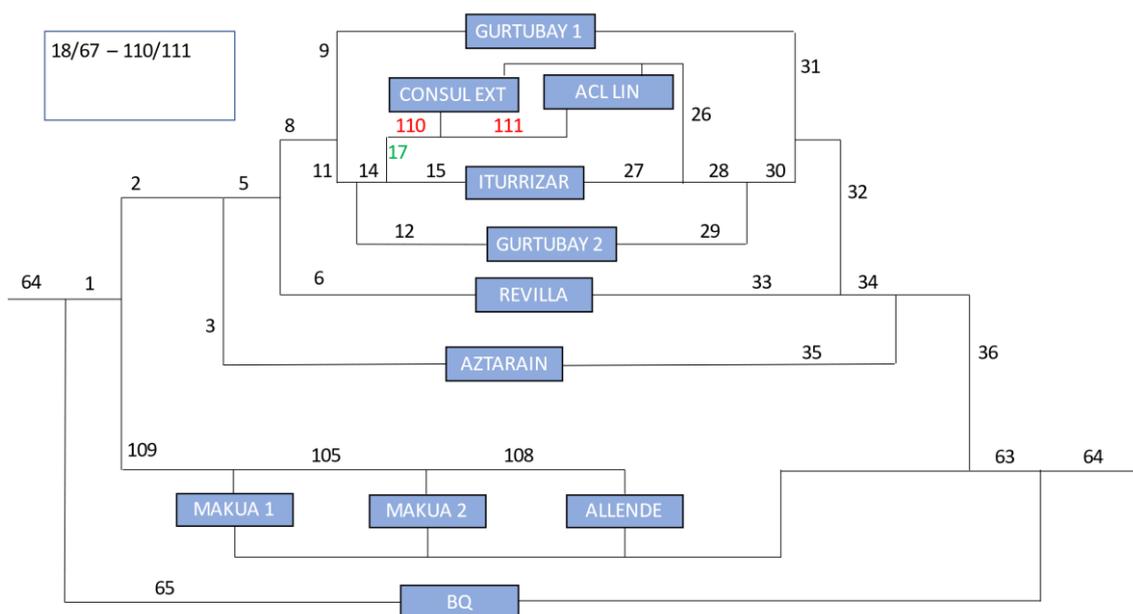


Figure 6.30: Equivalent pressure drop network (DM) – Step 6

- Step 7:

Once Acl. Lin. and Consul. Ext. are in series, the equivalent pipe 112 is calculated from the pipes 17 and 110 as shown in the figure below.

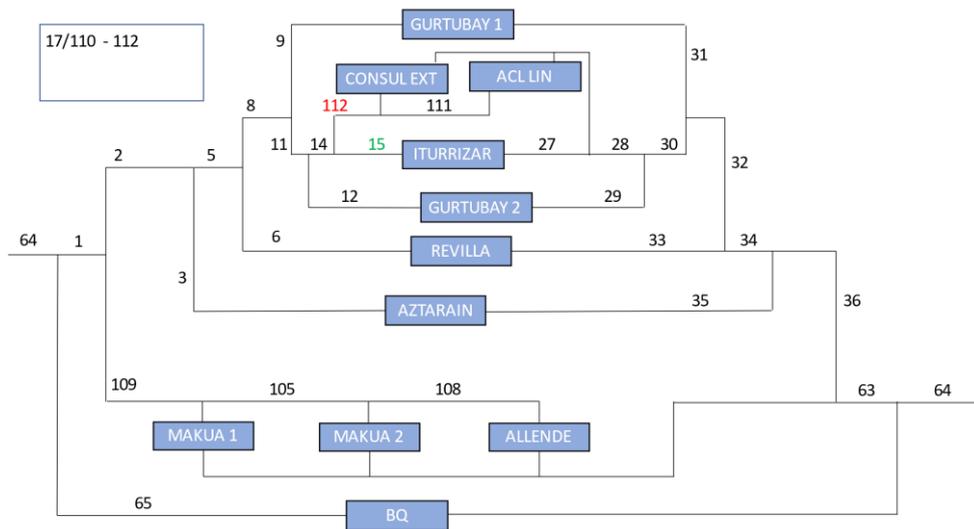


Figure 6.31: Equivalent pressure drop network (DM) – Step 7

- Step 8:

The next step is to put Iturrizar substation in series with Acl. Lin. and Consul. Ext. substations as shown in the figure below, and the pipes 15 and 112 are transformed into the equivalent 113 and 114 pipes.

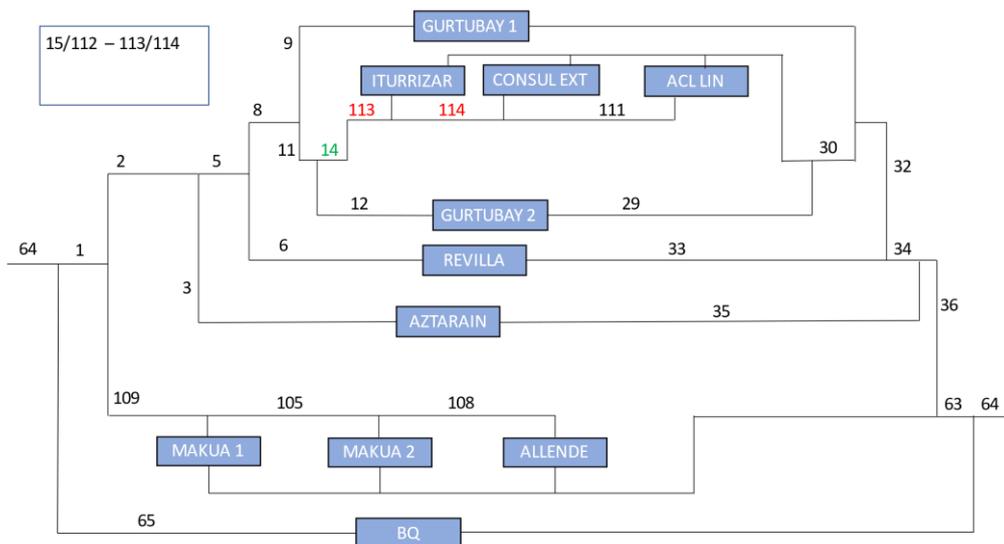


Figure 6.32: Equivalent pressure drop network (DM) – Step 8

- Step 9:

Once those three substations are in series, the equivalent pipe 115 is calculated from the pipes 14 and 113 as shown in the figure below.

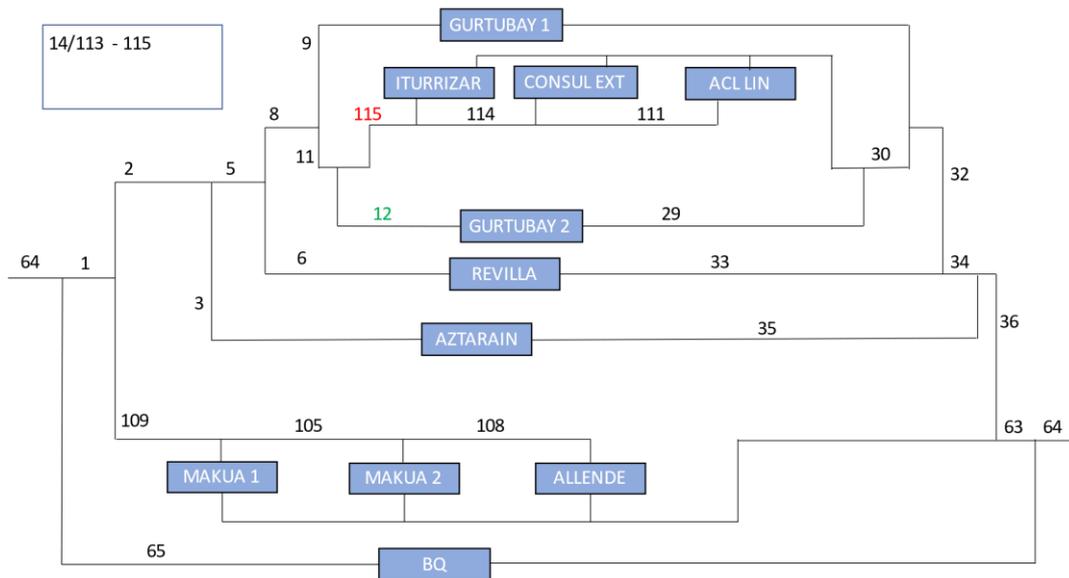


Figure 6.33: Equivalent pressure drop network (DM) – Step 9

- Step 10:

The next step is to put Gurtubay 2 substation in series with the other three substations as shown in the figure below, and the pipes 12 and 115 are transformed into the equivalent 116 and 117 pipes. Because of the algorithm used Gurtubay 2 substations places at the end of the serial substations row, so that the mass flow of the pipes 111 and 114 have to be recalculated.

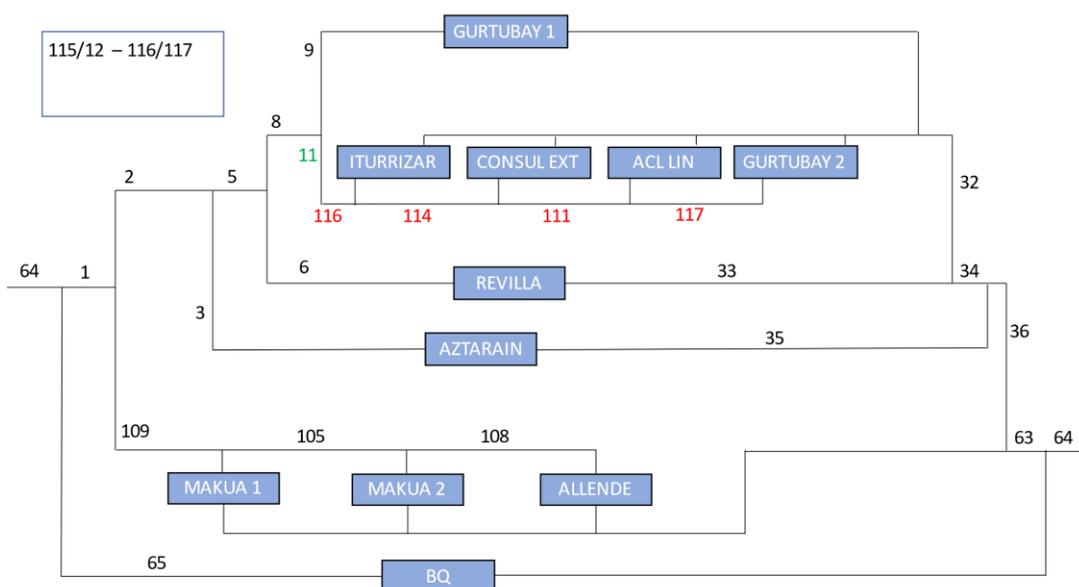


Figure 6.34: Equivalent pressure drop network (DM) – Step 10

- Step 11:

Once those four substations are in series, the equivalent pipe 118 is calculated from the pipes 11 and 116 as shown in the figure below.

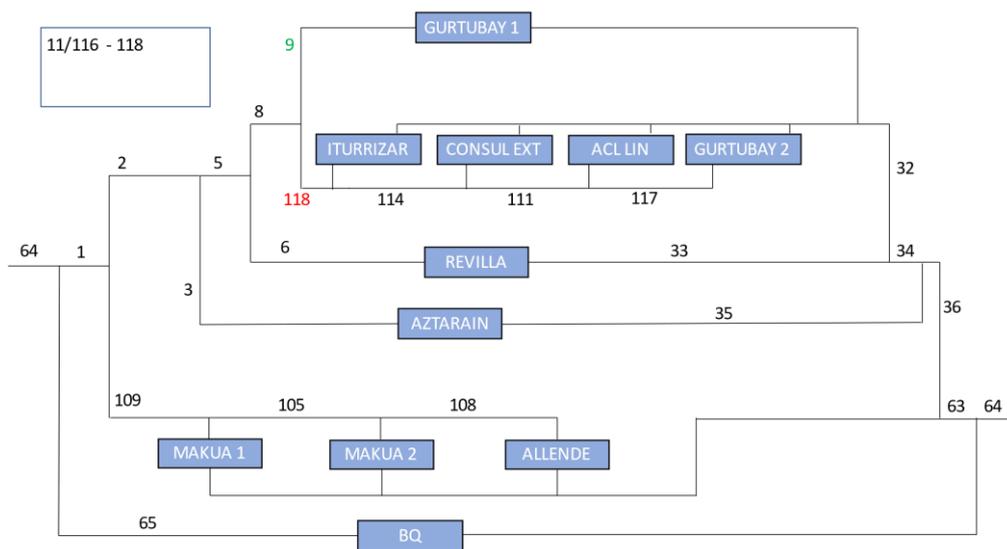


Figure 6.35: Equivalent pressure drop network (DM) – Step 11

- Step 12:

The next step is to put Gurtubay 1 substation in series with the other four substations as shown in the figure below, and the pipes 9 and 118 are transformed into the equivalent 119 and 120 pipes.

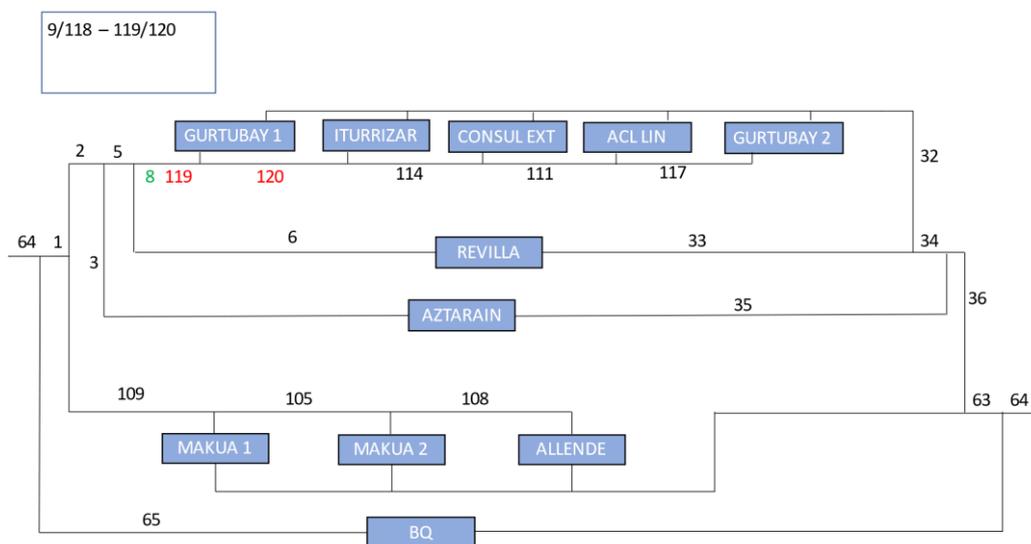


Figure 6.36: Equivalent pressure drop network (DM) – Step 12

- Step 13:

Once those five substations are in series, the equivalent pipe 121 is calculated from the pipes 8 and 119 as shown in the figure below.

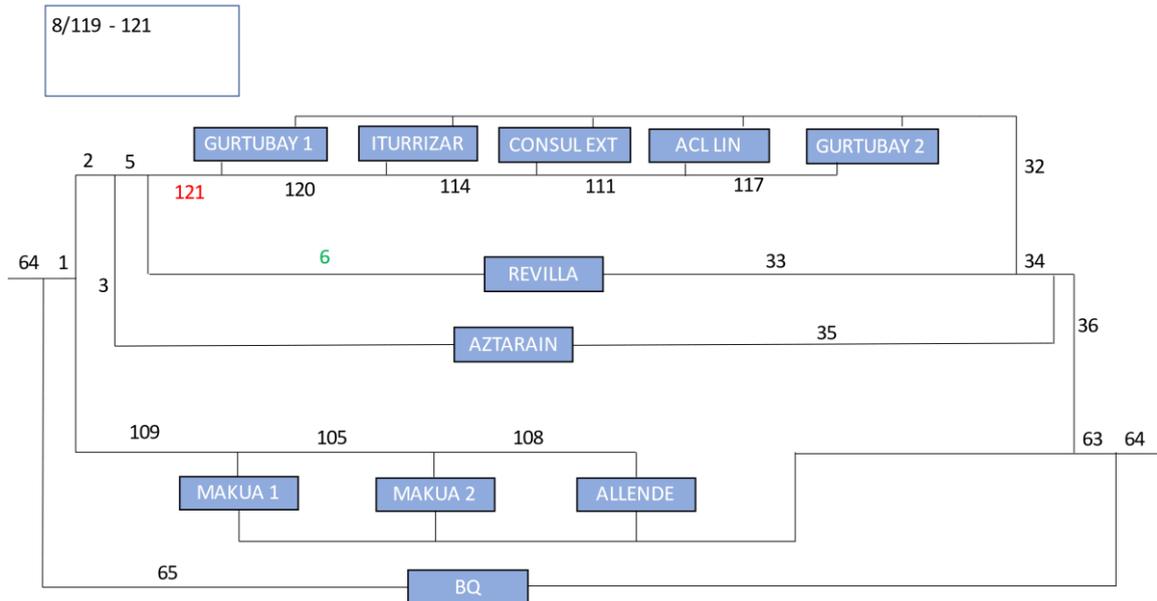


Figure 6.37: Equivalent pressure drop network (DM) – Step 13

- Step 14:

The next step is to put Revilla substation in series with the other five substations as shown in the figure below, and the pipes 6 and 121 are transformed into the equivalent 122 and 123 pipes.

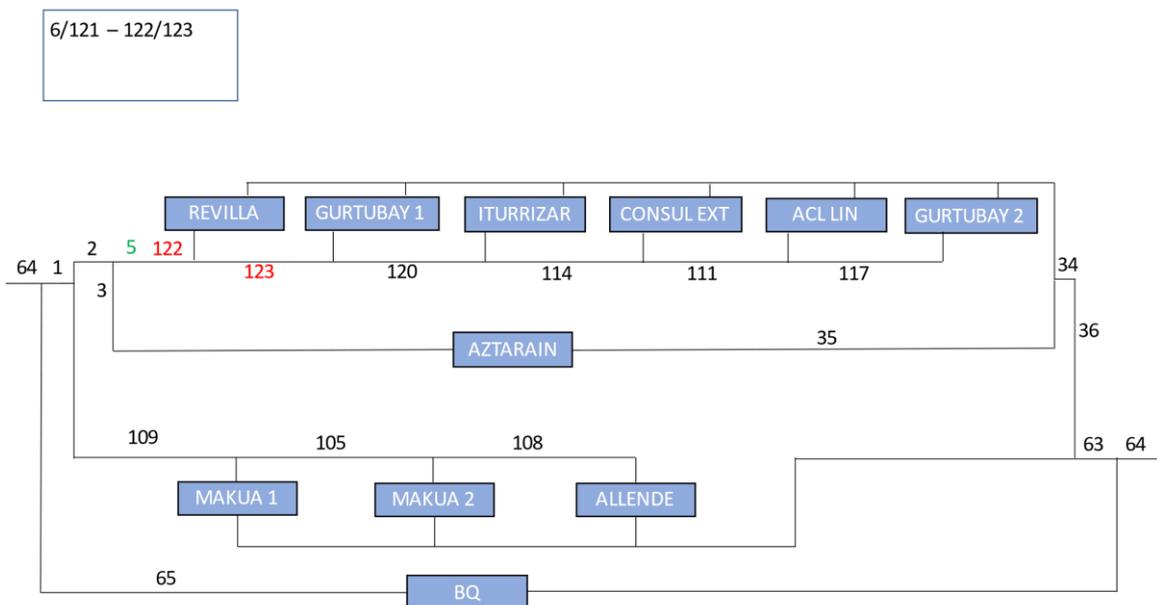


Figure 6.38: Equivalent pressure drop network (DM) – Step 14

- Step 15:

Once those six substations are in series, the equivalent pipe 124 is calculated from the pipes 5 and 122 as shown in the figure below.

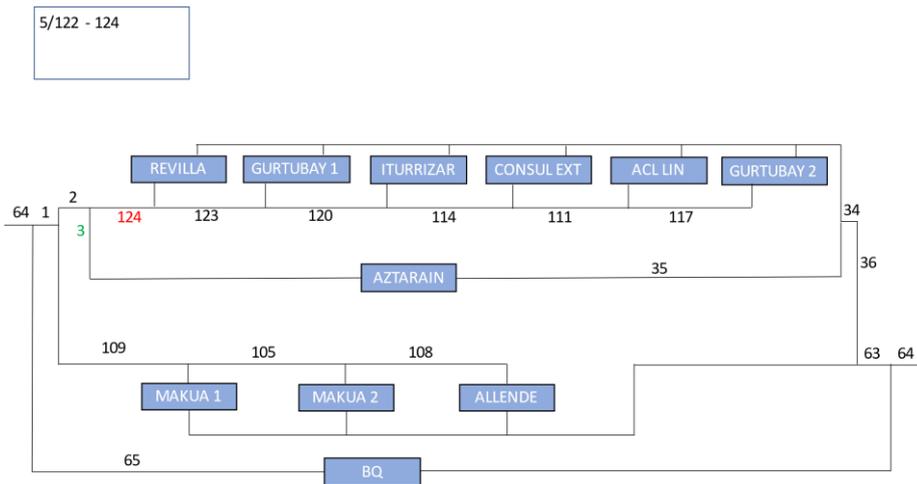


Figure 6.39: Equivalent pressure drop network (DM) – Step 15

- Step 16:

The next step is to put Aztarain substation in series with the other six substations as shown in the figure below. and the pipes 3 and 124 are transformed into the equivalent 125 and 126 pipes. In this case, because of the algorithm used, Aztarain is located at the end of the serial substations row, and the mass flows of pipes 123, 120, 114, 111 and 117 must be recalculated.

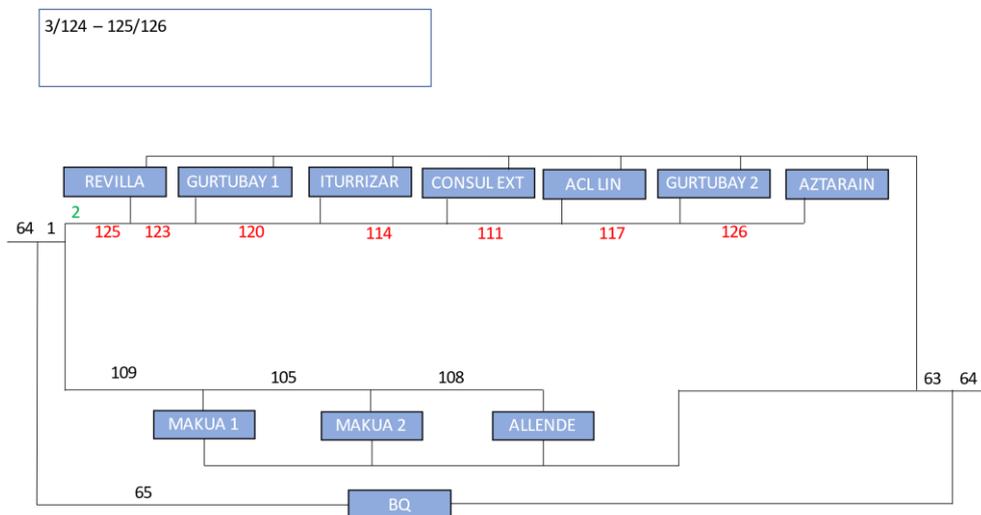


Figure 6.40: Equivalent pressure drop network (DM) – Step 16

- Step 17:

Once those seven substations are in series, the equivalent pipe 127 is calculated from the pipes 2 and 125 as shown in the figure below.

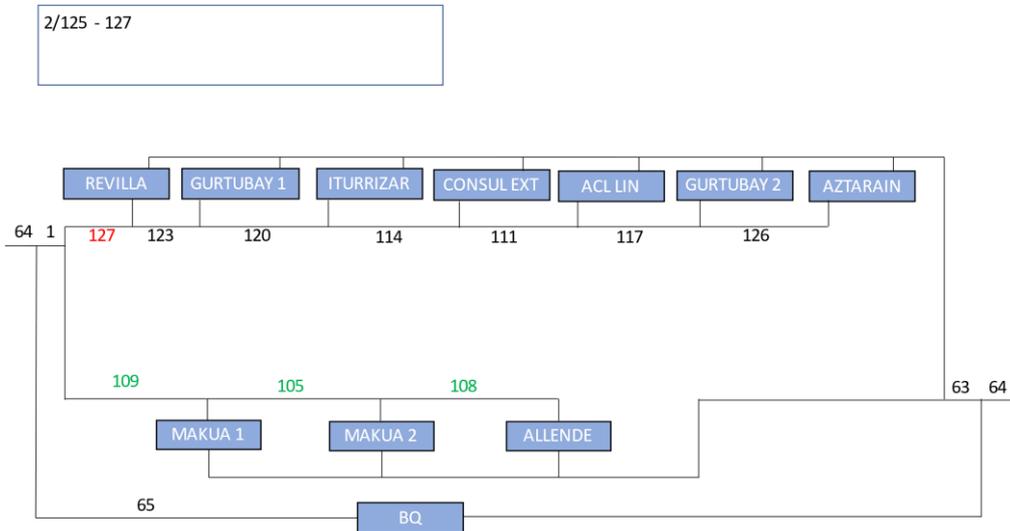


Figure 6.41: Equivalent pressure drop network (DM) – Step 17

As in the first case, the figure above shows a network with three branches, one with only a substation, another one with three substations in series, and a third one with seven substations in series. The next steps are going to simplify those two branches with substations in series obtaining one less pipe in each step.

- Step 18:

In this step the pipes 109, 105 and 108 are reduced to pipes 128 and 129, and the equivalent substations A, B and C are obtained from Makua 1, Makua 2 and Allende substations.

109/105/108 – 128/129
MAK1/MAK2/ALL – A/B/C

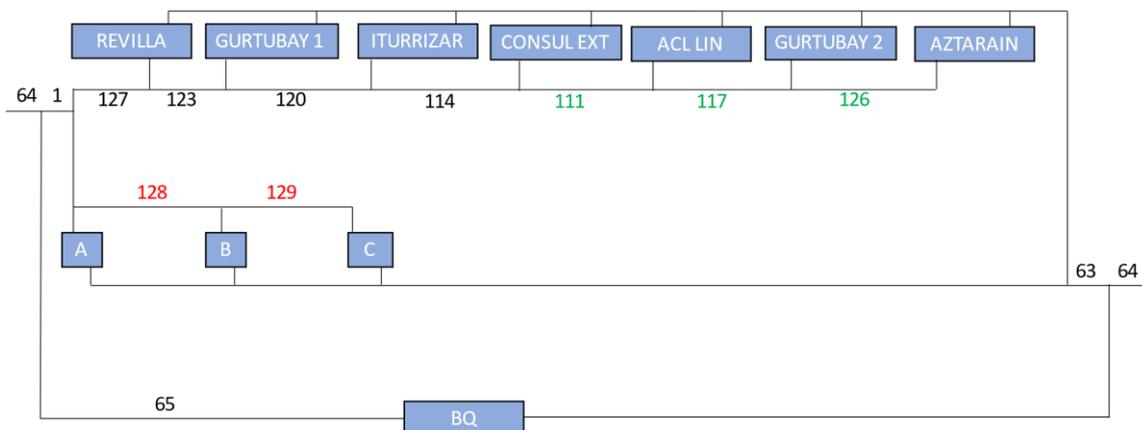


Figure 6.42: Equivalent pressure drop network (DM) – Step 18

- Step 19:

In this step the pipes 111, 117 and 126 are reduced to pipes 130 and 131, and the equivalent substations D, E and F are obtained from Acl. Lin., Gurtubay 2 and Aztarain substations. The substations Cons. Ext. and D are joined into a unique substation.

111/117/126 – 130/131
ACL/GURT2/AZT – D/E/F

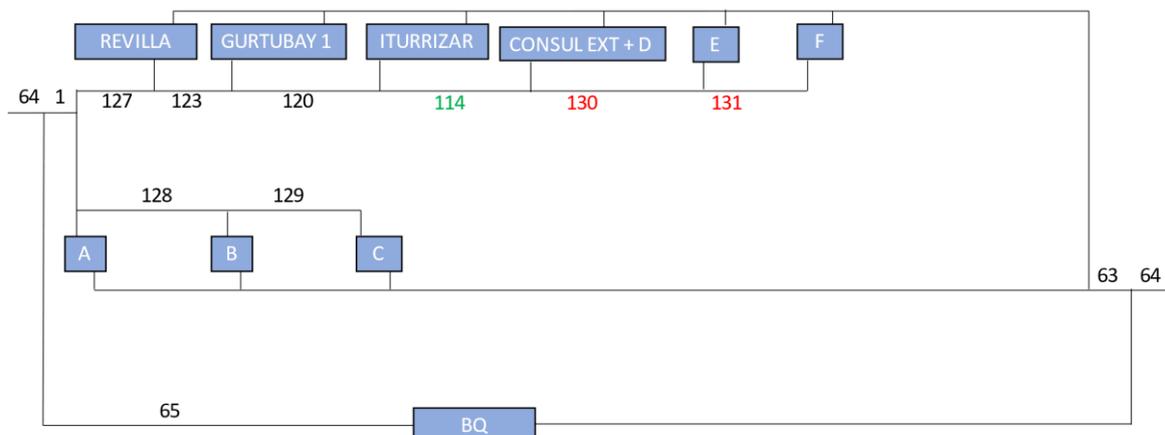


Figure 6.43: Equivalent pressure drop network (DM) – Step 19

- Step 20:

In this step the pipes 114, 130 and 131 are reduced to pipes 132 and 133, and the equivalent substations G, H and I are obtained from Cons. Ext. + D, E, and F substations. The substations Gurtubay 2 and G are joined into a unique substation.

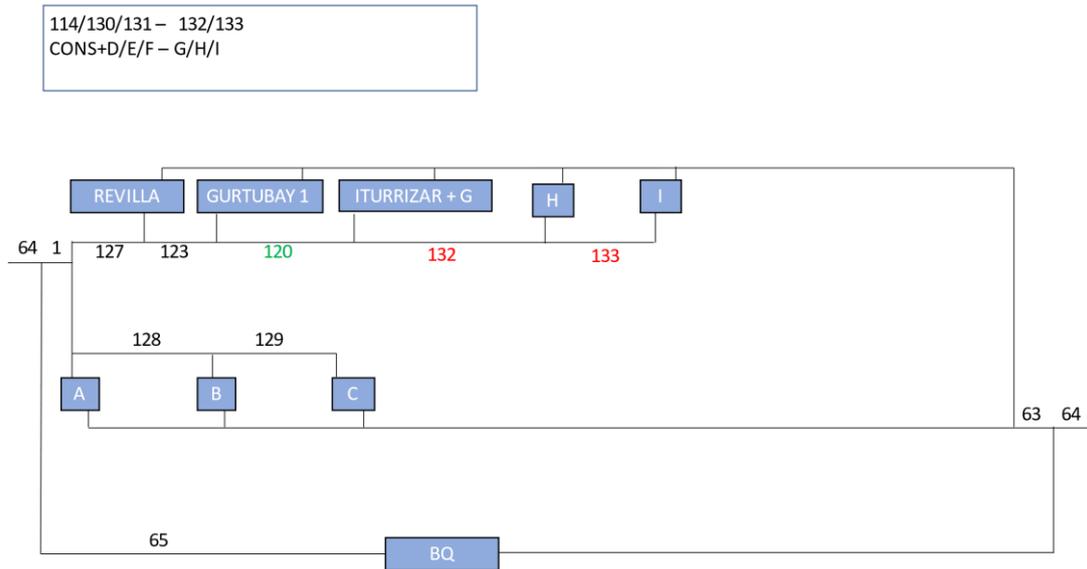


Figure 6.44: Equivalent pressure drop network (DM) – Step 20

- Step 21:

In this step the pipes 120, 132 and 133 are reduced to pipes 134 and 135, and the equivalent substations J, K and L are obtained from Iturrizar + G, H, and I substations. The substations Gurtubay 1 and J are joined into a unique substation.

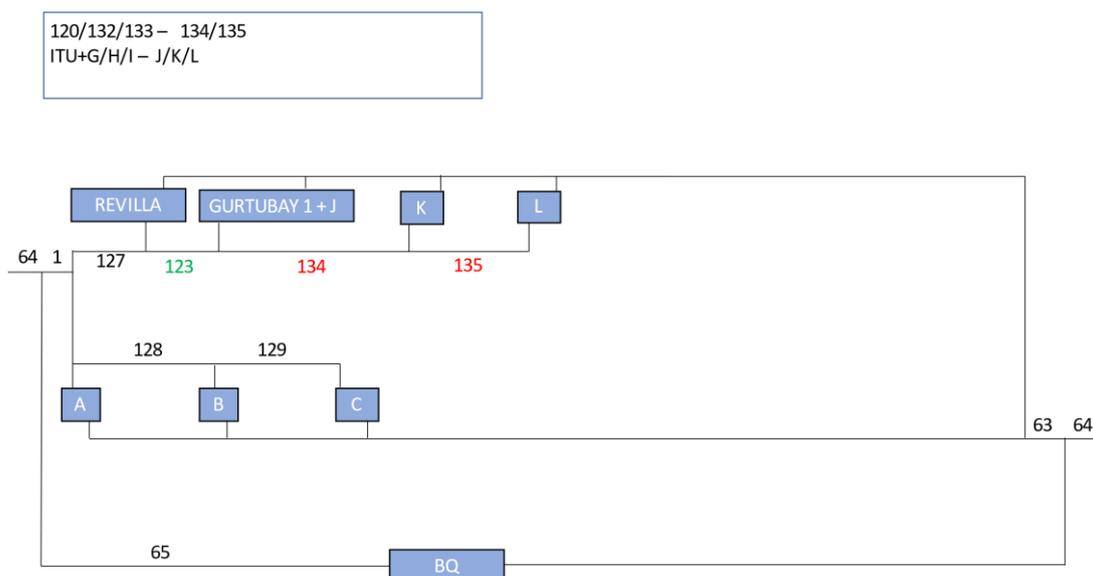


Figure 6.45: Equivalent pressure drop network (DM) – Step 21

- Step 22:

In this step the pipes 123, 134 and 135 are reduced to pipes 136 and 137, and the equivalent substations M, N and O are obtained from Gurtubay 1 + J, K, and L substations. The substations Revilla and M are joined into a unique substation.

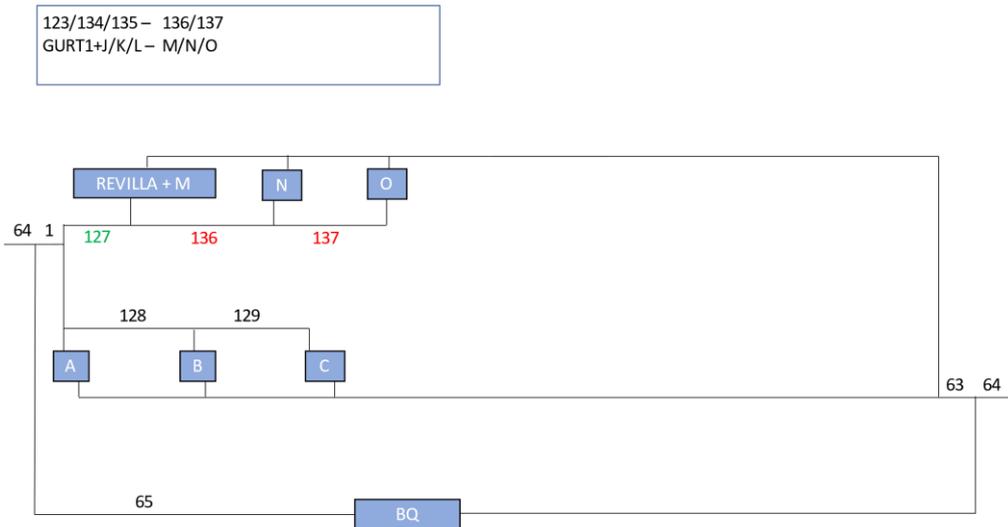


Figure 6.46: Equivalent pressure drop network (DM) – Step 22

- Step 23:

In this step the pipes 127, 136 and 137 are reduced to pipes 138 and 139, and the equivalent substations P, Q and R are obtained from Revilla + M, N, and O substations.

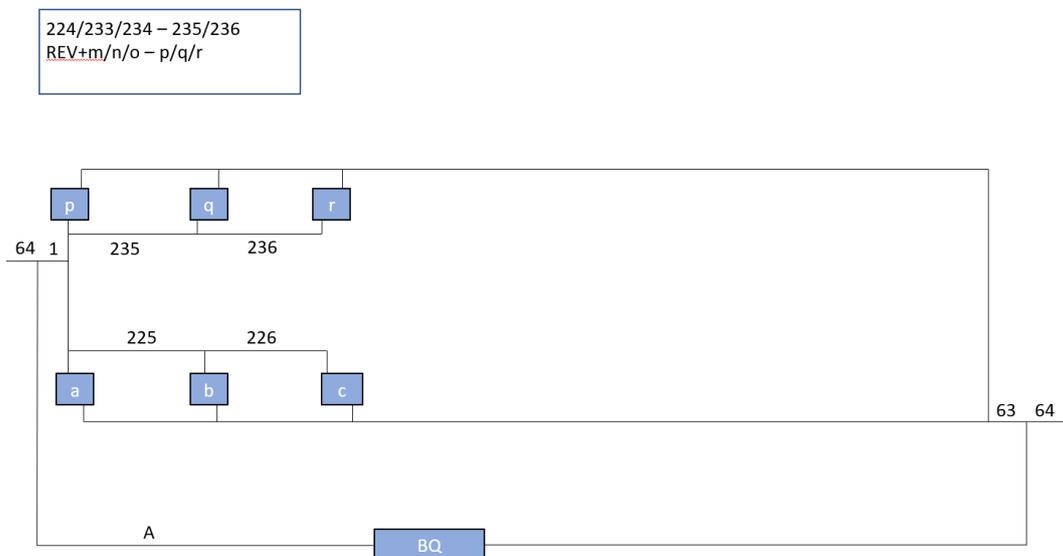


Figure 6.47: Equivalent pressure drop network (DM) – Step 23

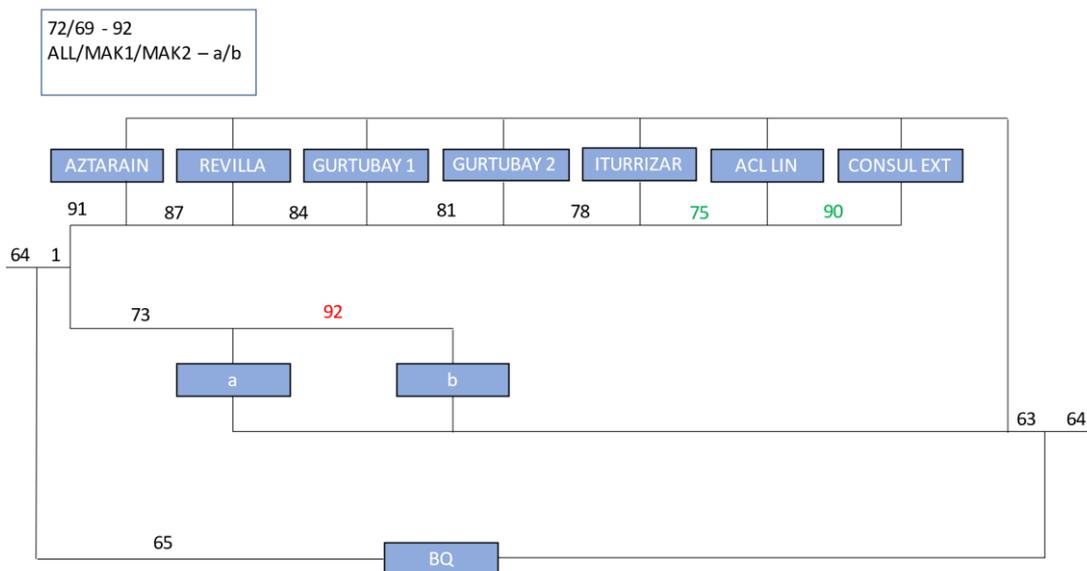


Figure 6.49:Equivalent network (GM) – Step 18

- Step 19:

In this step the pipes 75 and 90 are reduced to pipe 93, and the equivalent substations c and d are obtained from Iturrizar, Acl. Lin. and Consul. Ext. substations.

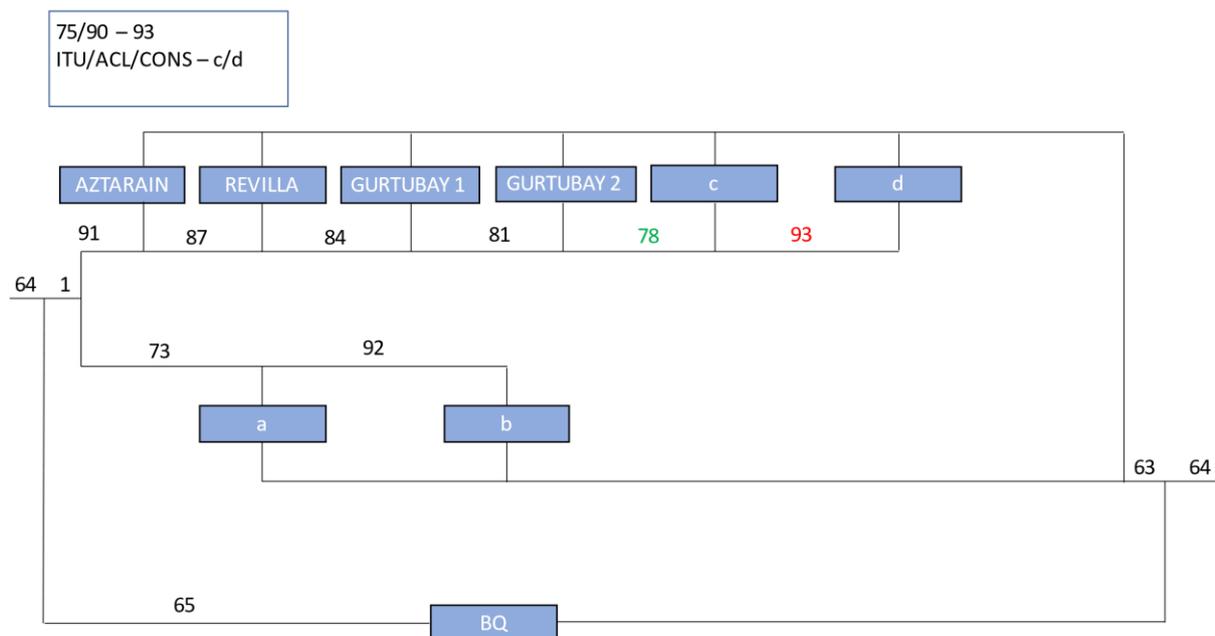


Figure 6.50:Equivalent network (GM) – Step 19

- Step 20:

In this step the pipes 78 and 93 are reduced to pipe 94, and the equivalent substations e and f are obtained from Gurtubay 2, c and d substations.

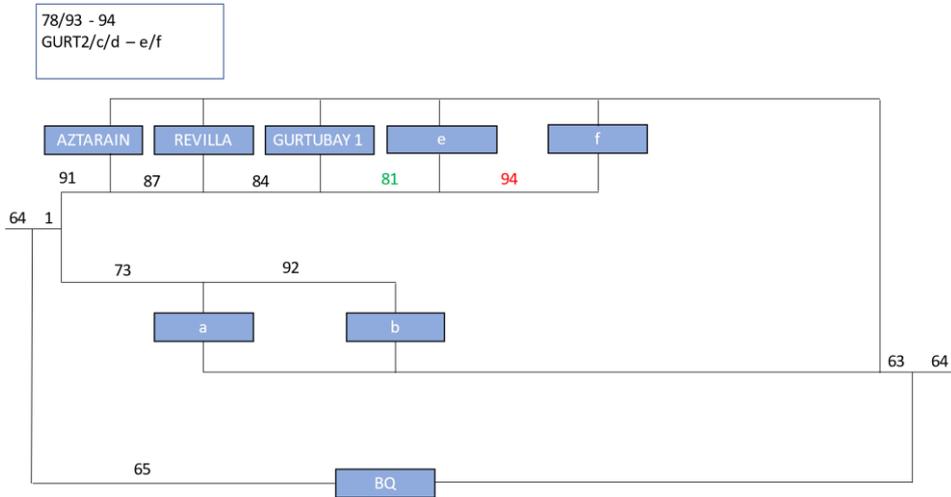


Figure 6.51:Equivalent network (GM) – Step 20

- Step 21:

In this step the pipes 81 and 94 are reduced to pipe 95, and the equivalent substations g and h are obtained from Gurtubay 1, e and f substations.

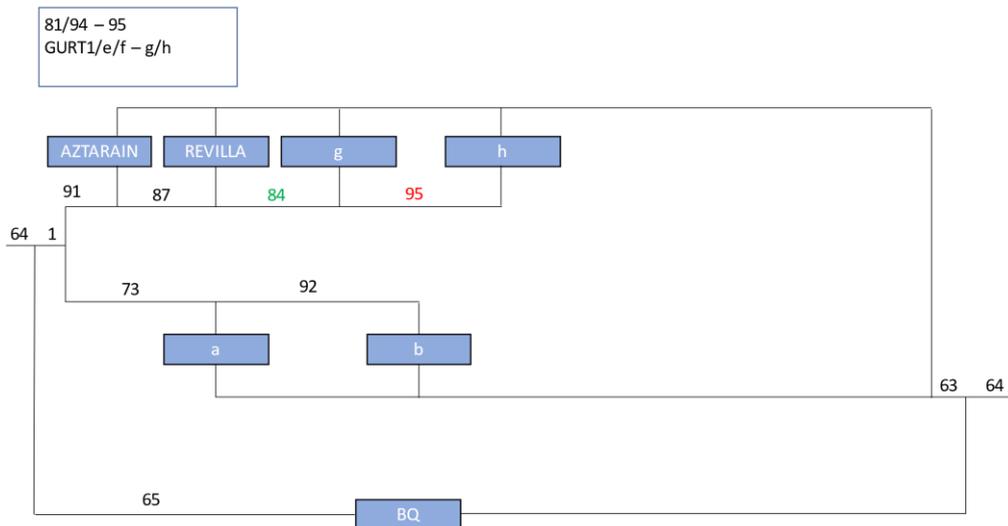


Figure 6.52:Equivalent network (GM) – Step 21

- Step 22:

In this step the pipes 84 and 95 are reduced to pipe 96, and the equivalent substations i and j are obtained from Revilla, g and h substations.

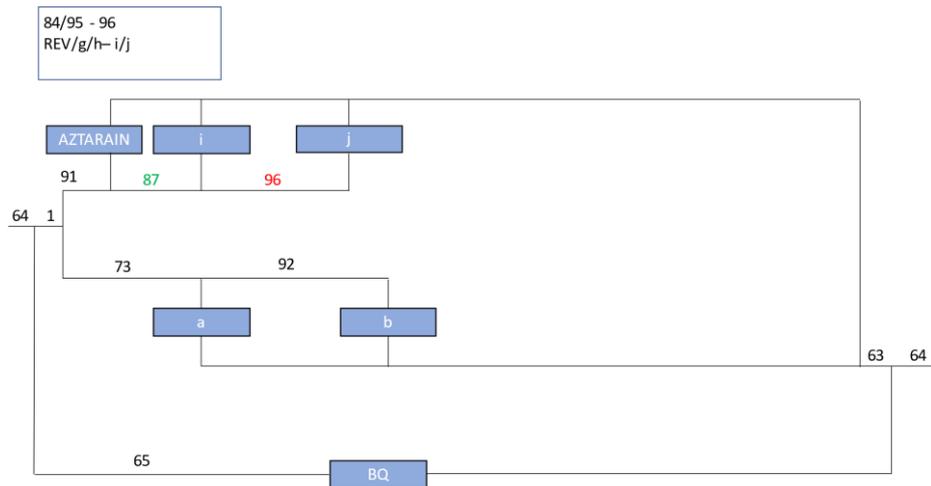


Figure 6.53:Equivalent network (GM) – Step 22

- Step 23:

In this step the pipes 87 and 96 are reduced to pipe 97, and the equivalent substations k and l are obtained from Aztarain, i and j substations.

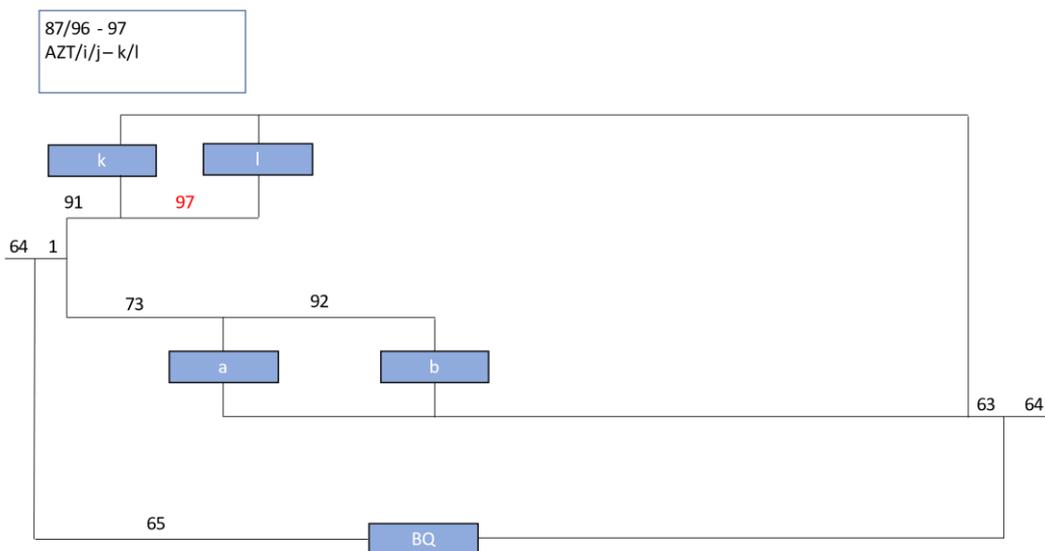


Figure 6.54:Equivalent network (GM) – Step 23

6.2. Automated network reduction processes

To obtain the equivalent networks presented in Section 5.1 three automated reduction processes have been implemented in Matlab. The first two processes are used for the calculation of the equivalent networks of the DM, one for the calculation of temperatures and heat losses equivalent networks and a second one for the pressure drop equivalent networks. The third process is used for the calculation of the equivalent networks of the GM.

The three processes have a very similar structure, the main differences are the algorithms used in the calculation of the characteristics of each of the equivalent pipes, and as explained in Section 5.7, the GM differs from the DM when reducing substations in series, so there are also differences in the automated reduction process.

The three automated processes have been used for the reduction of the Basurto hospital's network but could be used for any network with pure tree structure.

As the main steps followed in the three processes are the same, the process done for the temperature and heat loss equivalent network calculation of the DM is going to be used to explain how the processes have been done. The main functions of that reduction process are in the Appendix 1.

The first step is to read the data on the characteristics of the pipes and how those pipes are connected to generate the network. Then the pipes that belong to the supply part are identified, because the reduction will be carried out using that part because the return and the supply are parallel, and the results obtained in the supply will be extrapolated for the return.

Once the necessary network data has been identified the reduction begins. The first thing the programme does is to identify all the pipes that are in series with each other and do not have any other type of connection with other pipes or substations. This is done using the function '*Serial_pipes_location*' which returns a set of vectors with the groups of pipes that meet this requirement. Then an equivalent pipe is calculated for each group of pipes using the function '*Pipes_Series2*', the characteristics of the equivalent pipes are stored and the new configuration of the network is calculated.

The equivalent configuration and characteristics of the pipes at that instant are stored in '*Conf_1*' and '*Pipes_1*' respectively, and by means of the function '*Transform_for_Opti*' they are modified to be used for the simulation in the functions of the static model of the network that was prepared to simulate the Basurto hospital network in the Indigo project.

The network configuration and pipe characteristics obtained in '*Transform_for_Opti*' are stored in '*ConfOpt_1*' and '*PipesOpt_1*' respectively.

Once the serial pipes have been reduced to a single equivalent pipe, the substations that are in parallel are transformed into series substations.

The function '*Parallel_subs_location*' searches for all substation pairs that meet the requirement of being in parallel with each other, the function '*Parallel_equivalent_temp2*' calculates the two serial equivalent pipes, that equivalent pipes are saved using the function '*Sum_Pipes_Table2*', the equivalents to those pipes in the return part are calculated using '*Return_pipes*' and the structure is modified using the function '*Structure_modification_Parallelsubs*'.

In the case where there is already more than one substation in series and another one is added, if the algorithms of the function '*Parallel_equivalent_temp2*' determine that the new substation to be joined must go at the end of the row of serial substations, the rest of the previously calculated substations are recalculated using the function '*Recalc_pipes*'.

This process is repeated until the main branches of the network have all their substations in series one after the other, at this point the conditions '*COND1*' and '*COND2*' would be equal to zero and the '*While*' loop would be ended.

As before, the '*Transform_for_Opti*' function is used to save the '*ConfOpt_2*' configuration and '*PipesOpt_2*' pipeline characteristics at that instant to be used in the static model.

Once the main branches of the network have all their substations in series, substations are reduced in the branches where there are more than three substations in series. In the case of the GM, in this step each branch of the network would be left with two substations in series instead of three, because as already explained in Section 5.7.2 the GM obtains an equivalent pipe of two in series.

The '*Series_subs_location*' function searches for all the substations in series with each other and returns a set of vectors with the numbers of the incoming pipes to these substations. By means of the function '*Structure_Modification_Seriessubs*' each of the obtained vectors is reduced to have only three equivalent substations per main branch.

As before, the '*Transform_for_Opti*' function is used to save the '*ConfOpt_3*' configuration and '*PipesOpt_3*' pipeline characteristics of the final reduced equivalent network to be used in the static model.

Ten different structures will be simulated in the static model: the original structure, and three structures for each of the reduction processes carried out, which as presented in this

section will be the three equivalent structures obtained by joining all the pipes in series, the three structures obtained by modifying the substations from parallel to series and the three structures at the end of each of the reduction processes.

6.3. Static model simulator

The equivalent networks obtained at different reduction degrees by the automated reduction processes presented in Section 5.2 will be statically simulated using the Matlab simulator created by the thermal engineering department of Tekniker to simulate the original network of Basurto hospital for the Indigo project. This simulator was already verified and validated during the project, and starting from the original simulator, the necessary changes will be made to simulate the different equivalent networks obtained.

The simulator is provided with all the necessary data on the characteristics of the pipes, the network configuration and the characteristics of the substations, among others. Once all the necessary data have been entered, both the flow and the water temperature at the distribution inlet are introduced, and with all this, the simulator solves both the hydraulic and the thermal problem for the whole network.

To solve the hydraulic problem, both primary and secondary hydraulic losses in each pipe of the network are considered. The primary losses are modelled with the following equation:

$$h_{f,p} = \frac{8 * f * L * Q^2}{\pi^2 * g * D^5} \quad [5.17]$$

Where f is the friction factor, D and L are the length and diameter of the pipe respectively, Q is the flow rate through the pipe and g is the gravity constant. The friction factor for turbulent regime is calculated as:

$$f = 0.11 * \left(\frac{\varepsilon}{D} + \frac{68}{Re} \right)^{0.25} \quad [5.18]$$

Where ε is the absolute roughness of the pipe and Re is the Reynolds number, that for turbulent regime is calculated as:

$$Re = \frac{4 * Q}{\pi * D * \nu} \quad [5.19]$$

The secondary losses have been modelled by the equation:

$$h_{f,s} = K_{sec} * Q^2 \quad [5.20]$$

Where K_{sec} is the secondary pressure losses coefficient in each pipe.

For the secondary losses' calculation control valves, balancing valves and other auxiliary elements as butterfly valves or bends have been considered.

The total hydraulic losses in each pipe are calculated with the total loss coefficient K :

$$h_{L,i} = K * Q^2 = (K_{pri} + K_{sec}) * Q^2 \quad [5.21]$$

Where K_{pri} is the primary losses coefficient in each pipe that can be assume from equation 5.17 that is:

$$K_{pri} = \frac{8 * f * L}{\pi^2 * g * D^5} \quad [5.22]$$

The pressure restrictions are modelled by assuming that the pressure at each pipe port concurring in the same node must be the same, which implies that the pressure drop along two or more parallel pipes must be the equal.

For the temperatures calculation the model is based in the following thermal principles:

- The energy balances at each node must be satisfied.
 - **Supply part:** as the flow is divided is divided in all the nodes of the supply part, the temperatures of the flows at the pipes exiting the nodes must be the same as the temperature of the pipe entering the node.

$$T_{out,1} = T_{in,2} = T_{in,3} \quad [5.23]$$

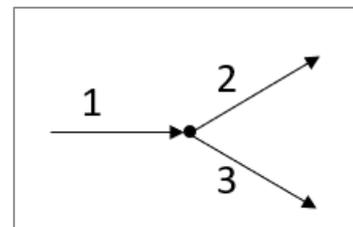


Figure 6.55: Temperature balance in the supply part

- **Return part:** as the entering flow is mixed in this case, an energy balance must be established.

$$Q_6 * T_{in,6} = Q_4 * T_{out,4} + Q_5 T_{out,5} \quad [5.24]$$

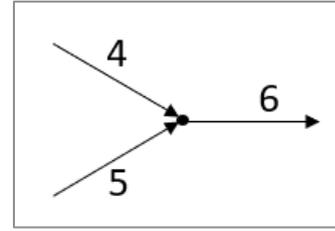


Figure 6.56: Temperature balance in the return part

- The inlet and outlet temperatures in each pipe are related as follows:
 - In pipes without heat exchangers:

$$\rho * c_p * Q * (T_{out} - T_{in}) = U * (T_{amb} - T_{out}) + h_{L,kw} \quad [5.25]$$

Where T_{in} and T_{out} are the inlet and outlet temperatures of the pipe, T_{amb} is the ambient temperature, U the total thermal coefficient of the pipe that is calculated with the equations presented at the beginning of the Section 5.1.1, Q is the flow rate through the pipe, ρ is the water density, c_p is the water specific heat and $h_{L,kw}$ are the friction losses that produce an increase of temperature that are calculated as following:

$$h_{L,kw} = h_L * g * \rho * Q \quad [5.26]$$

- In the substations the energy transfer must be satisfied.

$$P_c = \rho * c_p * Q * (T_{in} - T_{out}) = \rho * c_p * Q_c * (T_{sc} - T_{retc}) \quad [5.27]$$

Where Q_c is the demanded flow rate in the building, T_{sc} is the supply temperature to the building and T_{retc} the return temperature to the substation from the building.

7. RESULTS ANALYSIS

In this section the results obtained are going to be analysed by simulating the different equivalent networks obtained by applying both the DM and the GM. On the one hand, thermal results are going to be analysed. And on the other hand, hydraulic results are going to be analysed. For each of the reduction methods, the equivalent networks obtained at three different reduction degrees are going to be analysed and compared with the results obtained with the simulations done with the original network, which network characteristics and simulation variables are presented in Table 7.1 below.

Original Network	
	Nº
Pipes	64
Nodes	54
Substations	11
Thermal variables	194
Hydraulic variables	118
Total variables	312

Table 7.1: Original network

The three reduction degrees are the following:

- 1st reduction degree:** First, the equivalent network obtained by reducing the pipes in series by a single equivalent pipe is going to be analysed. The equivalent network obtained for this reduction degree is going to be the same in the three reduction processes performed. This network will be studied twice: a first simulation process to analyse both hydraulically and thermally the network, and a second simulation in which the flow rates of each of the substations of the network will be fixed with the flow rates obtained in the simulations of the original network, and with that flow rates the rest of the network flow rates will be calculated, and only the thermal part will be simulated.

From the original network with 64 pipes, 54 nodes and 11 substations an equivalent network is obtained with the characteristics of the network and the simulation variables presented in Table 7.2 by only reducing pipes in series.

1 st reduction degree		
	Nº	Reduction %
Pipes	52	18,75%
Nodes	42	22,22%
Substations	11	0,00%
Thermal variables	170	12,37%
Hydraulic variables	94	20,34%
Total variables	264	15,38%

Table 7.2: 1st reduction degree

- **2nd reduction degree:** The 2nd degree of reduction that is going to be analysed is the one in which all the substations in each of the main branches are in series. Two different equivalent networks are going to be obtained: the equivalent structure for the calculation of heat losses in both the DM and GM, that is going to be the same structure applying both methods, and the equivalent structure for the calculation of pressure drops applying the DM. Both structures will have the same number of pipes, nodes and substations, but the characteristics of the pipes and the order in which the substations are located will be different.

As can be seen in Table 7.3, the original network has been reduced to an equivalent network with 36 pipes, 26 nodes, and the same number of substations as at the beginning, 11. The simulation variables have been also reduced quite a bit. From this point on in the reduction process the number of substations in series starts to be reduced by equivalent substations.

2 nd reduction degree		
	Nº	Reduction %
Pipes	36	43,75%
Nodes	26	51,85%
Substations	11	0,00%
Thermal variables	138	28,87%
Hydraulic variables	62	47,46%
Total variables	200	35,90%

Table 7.3: 2nd reduction degree

- **3rd reduction degree:** Finally, a 3rd reduction degree is going to be analysed with the results obtained by reducing the original network to the maximum in each reduction process, respecting always the main three branches of the network. In this case, three equivalent networks will be obtained, in the thermal case the DM and the GM differ in the procedure of simplifying substations in series, so that the equivalent networks obtained are going to be different, and a third equivalent network will be obtained for the pressure drop applying the DM. A higher reduction percentage will be obtained

with the GM because of the procedure followed.

The two equivalent networks obtain applying the DM, one for the heat losses and the other one for the pressure drop calculation, are going to have the same structure, but, as in the 2nd reduction degree, the characteristics of the pipes and the location of the substations are going to be different. The original network is going to be reduced to an equivalent network with 24 pipes, 18 nodes and 7 substations as shown in Table 7.4, and the simulation variables have been reduced notably.

3rd reduction degree DM		
	Nº	Reduction %
Pipes	24	62,50%
Nodes	18	66,67%
Substations	7	36,36%
Thermal variables	55	71,65%
Hydraulic variables	42	64,41%
Total variables	97	68,91%

Table 7.4: 3rd reduction degree DM

In the case of the equivalent network obtain applying the GM, the structure is going to be different, as the way of reducing substations in series is not the same as the one used in the DM, the reduction degree obtain is going to be higher and the simulation variables less as shown in Table 7.5.

3rd reduction degree GM		
	Nº	Reduction %
Pipes	18	71,88%
Nodes	14	74,07%
Substations	5	54,55%
Thermal variables	41	78,87%
Hydraulic variables	32	72,88%
Total variables	73	76,60%

Table 7.5: 3rd reduction degree GM

All the simulations are going to be done statically using the simulator presented in Section 6.3. The results obtained with the methods applied and for different reduction degrees are going to be compared with the results obtained by simulating the original network shown in Figure 7.1 and with the characteristics of the Table 7.1 above.

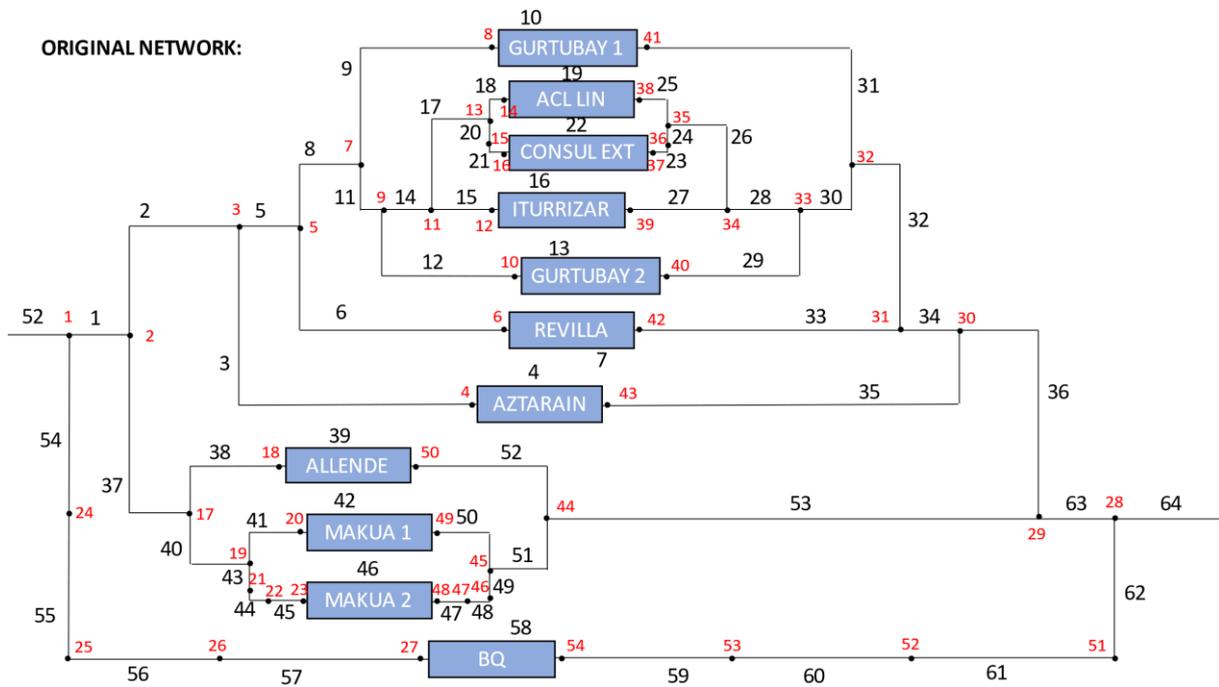


Figure 7.1: Original network

Twenty simulations will be carried out for each of the different equivalent structures. Each of these simulations will be for a different inlet flow rate to the distribution network. It must be considered that the equivalent networks are calculated for the nominal inlet flow rate, therefore, in principle, the errors should increase as the inlet flow rates move away from the nominal flow rate. Table 7.6 presents the inlet flow for each simulation.

Nº simulation	Q inlet [m ³ /s]
1	0,38
2	0,37
3	0,36
4	0,355 (Q _{nom})
5	0,35
6	0,34
7	0,33
8	0,32
9	0,31
10	0,3
11	0,29
12	0,28
13	0,27
14	0,26
15	0,25
16	0,24
17	0,23
18	0,22
19	0,21
20	0,2

Table 7.6: Simulations inlet flow

Apart from the inlet flow rate to the network, the inlet temperature will be also fixed, and in each substation the thermal power transfer and the flow rate on the consumer side will be also fixed. Both values will vary according to the input flow rate to the network, because it is logical that if the input flow rate to the network is smaller, it is because the power demanded in each of the substations is lower.

For the analysis of the results different errors will be calculated, on the one hand, for each substation, and on the other hand, for the return of the whole network. The errors to be calculated are the following:

- Absolute error:

$$AE = |\hat{y}_i - y_i| \quad [7.1]$$

- Mean absolute error:

$$MAE = \frac{\sum_{i=1}^n |\hat{y}_i - y_i|}{n} \quad [7.2]$$

- Mean squared error's root:

$$MSEER = \sqrt{\frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{n}} \quad [7.3]$$

- Mean squared normalized error's root:

$$MSNER = \frac{MSEER}{y_{Max} - y_{Min}} \quad [7.4]$$

- Mean squared error's variation coefficient:

$$MSEVC = \frac{MSEER}{y_{mean}} \quad [7.5]$$

Where \hat{y}_i are going to be the values of the different variables obtained simulating the original network, y_i the values of the different variables obtain for the equivalent networks analysed, and y_{max} , y_{min} and y_{mean} respectively are going to be the maximum, minimum and mean values of the different variables obtained simulating the original network.

In the case of the substations' analysis, errors are going to be calculated on the one hand for each simulation, and on the other hand for each substation, Table 7.7 shows the number that corresponds to each substation. In the cases where the substations are modified by equivalent substations, the equivalent substation to which each number corresponds will be specified. The variables that are going to be analysed in each substation are the following: inlet and outlet temperatures in the distribution side and the outlet temperature in the consumer's side. For the return temperature the errors are going to be calculated for each simulation.

SUBSTATIONS	
Number	Name
1	AZTARAIN
2	REVILLA
3	GURTUBAY 1
4	GURTUBAY 2
5	ITURRIZAR
6	ACL. LIN.
7	CONSUL. EXT.
8	ALLENDE
9	MAKUA 1
10	MAKUA 2
11	BQ.

Table 7.7: Substations

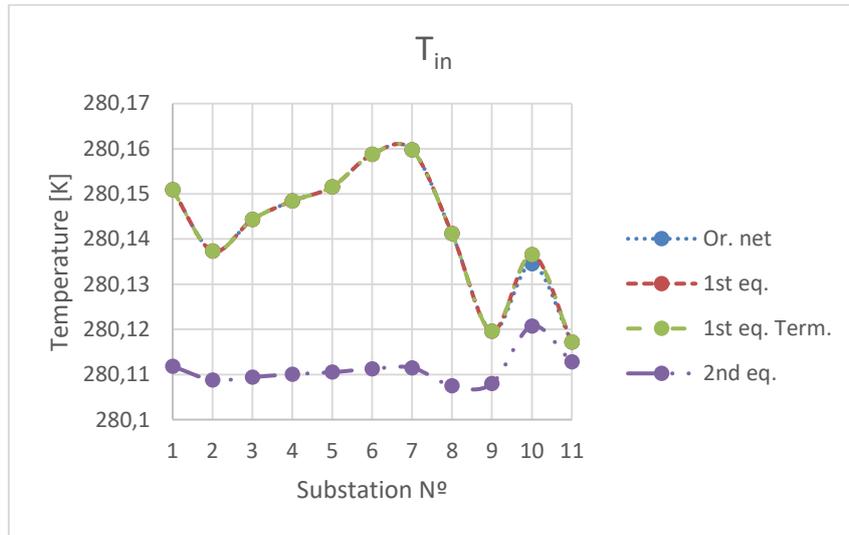
7.1. Thermal results

In this section, we will compare the main thermal results obtained for the variables analysed for the different degrees of reduction. Also, for some variables errors done will be presented.

Firstly, the inlet and outlet temperature in the distribution side and the outlet temperature in the consumption side of each of the substations will be analysed for the cases in which the number of substations remains the same as for the original network: for the two simulations carried out with the equivalent network of the 1st degree of reduction and the simulation carried out for the equivalent thermal network of both DM and GM of the 2nd degree of reduction. In the cases of 3rd degree of reduction, as the original number of substations is reduced by a smaller number with equivalent substations, the results obtained are not comparable for these variables. Because of that, and as the substation number 11 remains constant from 1st degree of reduction on, this particular substation is going to be analysed in order to compare the results obtained for all degrees of reduction.

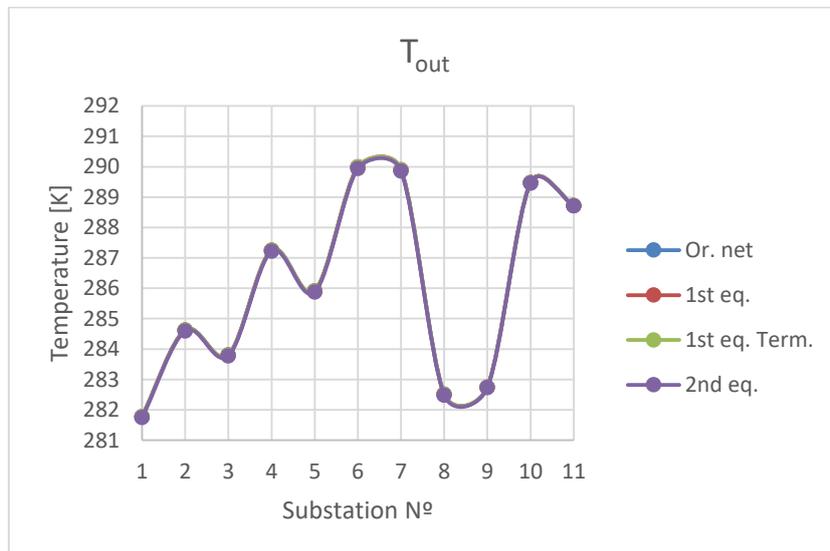
For the analysis of the inlet temperature in the distribution side to each of the substations the Graph 7.1 is presented, in the case of the two simulations carried out with the 1st degree of reduction, a minimum error can be seen in the 10th substation comparing with the results obtained when simulating the original network. Later on, when the calculated results are studied more deeply and errors done are analysed, the quality of the results obtained will be more precise, but at the beginning it can be seen that they are really good. In the case of the

2nd degree of reduction we can see how the error produced is greater but in all cases it is below 0.05 degrees Kelvin, which is more than acceptable.



Graph 7.1: Inlet temperature distribution side

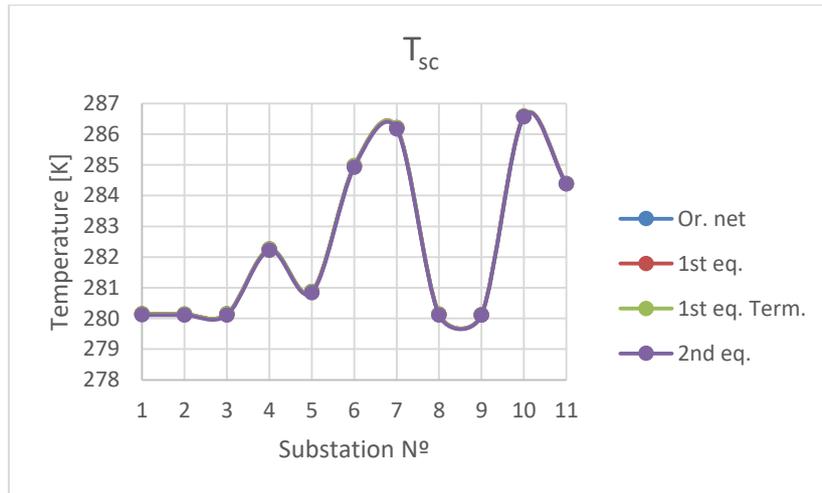
For the outlet temperature of the substations on the distribution side, as the temperature axis of Graph 7.2 varies by 12 degrees and the errors generated are quite small and they are hardly noticeable in this graph. Further analysis will show this better but doing an initial analysis it can be said that the results obtained for the three simulations are of good quality.



Graph 7.2: Outlet temperature distribution side

In the case of the analysis of the outlet temperature on the consumption side, it can be seen in the Graph 7.3 that for the 1st degree of reduction the results obtained are very good, there is apparently no error with the results obtained when simulating the original network,

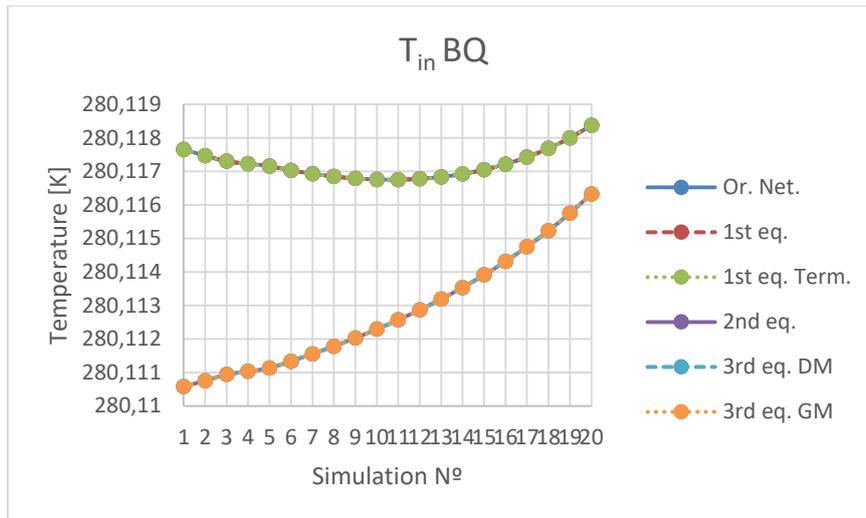
and for the case of the equivalent network of the 2nd degree the errors produced are very small, around one tenth in the worst case. As in the previous case, the temperature variation in this graph is also too large to be able to analyse in depth the quality of the results obtained but is a good way to observe that the quality of the results is really good.



Graph 7.3: Outlet temperature in the consumption side

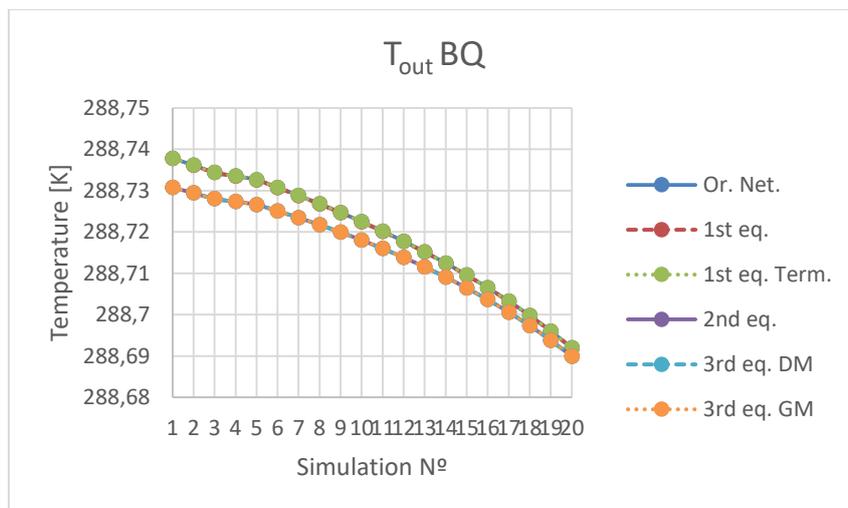
As is said before, results obtained for the last substation are going to be analysed particularly because as this substation has no changes since 1st degree of reduction, it is possible to compare results at all degrees of reduction.

Graph 7.4 shows the inlet temperature to the last substation (BQ). For the two simulations with the equivalent network of 1st degree of reduction the results obtained are almost the same as the ones obtained with the original network. For the other three cases, the 2nd degree of reduction equivalent network and the two equivalent networks of 3rd degree of reduction the results obtained are very similar between them, and the higher difference with the original network is lower than 0.008K, what is negligible.



Graph 7.4: T_{in} last substation

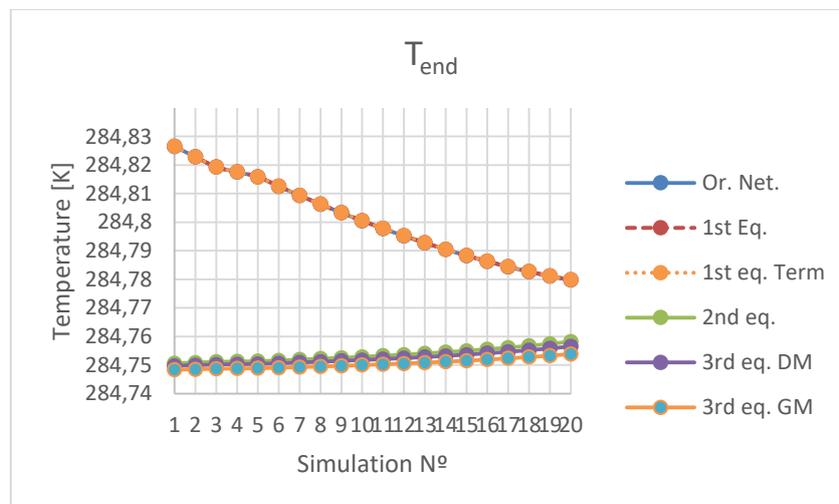
Graph 7.5 shows the outlet temperature from the last substation for all the degrees of reduction studied. The conclusions drawn for the inlet temperature can be extrapolated to the outlet temperature, all the results obtained are of very high quality.



Graph 7.5: T_{out} last substation

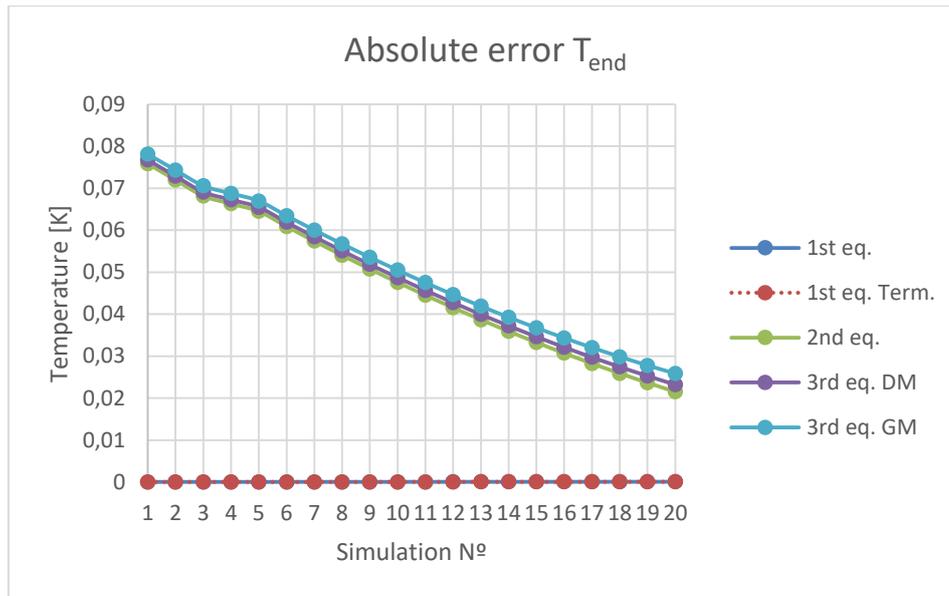
Regarding to the network return temperature, it can be seen in Graph 7.6 that for the two simulations with the equivalent network of the 1st degree of reduction, the results are almost identical to those obtained with the original network, and as the simulations progress, the return temperature decreases, which is logical, because as the flow rate decreases, on the one hand the thermal power required in the substations will be lower and therefore the heat exchange will also be lower, and on the other hand the thermal losses in the network will also be lower.

For the case of the 2nd degree of reduction and the two cases of the 3rd degree of reduction, the results obtained are very similar in the three cases, the error decreases as the simulations progress, which is surprising as the equivalent networks are supposed to be calculated for the nominal flow rate, and as the simulations progress the inlet flow rate decreases and we move away from that nominal flow rate. In these three cases the return temperature remains much more constant than in the first three cases and increases minimally as the simulations progress.



Graph 7.6: Return temperature

Graph 7.7 shows the AE carried out for each of the simulations studied, in which everything previously mentioned can be ratified, with the 1st degree of reduction the results are almost identical, the error made is imperceptible, and with the 2nd reduction degree simulation and 3rd reduction degree simulations the error is quite small and varies from a maximum of 0.08K to a minimum of 0.02K.



Graph 7.7: Return temperatures' absolute errors

With the remaining errors calculated for each case presented in Table 7.8, the above-mentioned is further confirmed.

	<u>T_{end}</u>			
	MAE	MSER	MSNER	MSEVC
1st reduction degree	6,11356E-05	6,2197E-05	0,00132987	2,18388E-07
1st reduction degree (Ter)	6,06006E-05	6,1713E-05	0,00131952	2,16689E-07
2nd reduction degree	0,047077848	0,04997213	1,06847953	0,000175464
3rd reduction degree DM	0,048281095	0,05103149	1,09113019	0,000179183
3rd reduction degree GM	0,050158579	0,05269844	1,12677217	0,000185036

Table 7.8: Return temperatures' errors

In order to have more relevant data we will calculate the energy transferred to the network in each of the simulations. To do this we will assume that the conditions remain constant for every 15 minutes.

Firstly, the thermal power transferred in the network will be calculated, which will be the sum of the power transferred in each of the substations plus the thermal losses in the network. As the thermal power transferred to each of the substations is one of the data we set, the errors produced in each of the simulations will depend on the thermal losses occurring along the distribution network.

The calculation of the transferred power is done with the following equation:

$$P_{transf} = q_{in} * \rho_w * c_{P_w} * (T_{in} - T_{out}) \quad [7.6]$$

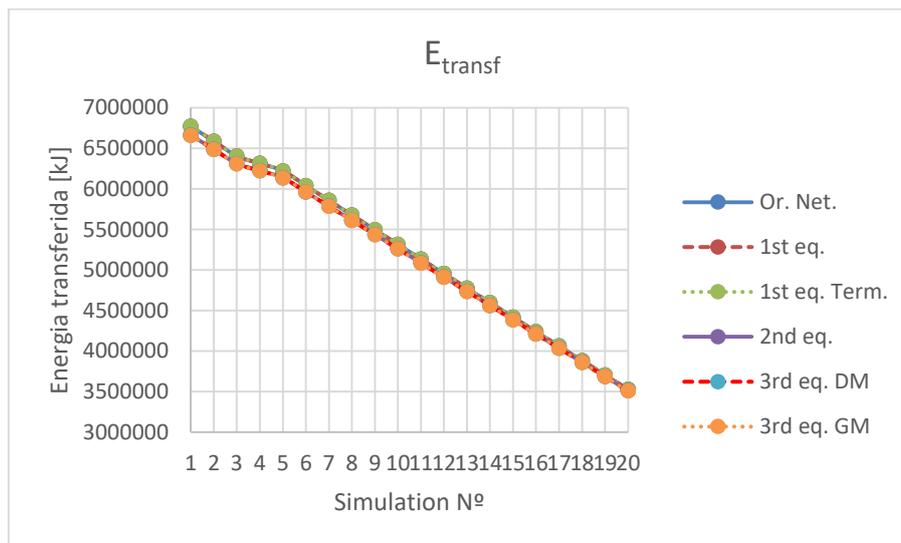
Where q_{in} is the inlet flowrate to the network, ρ_w the water density, c_{pw} the water specific heat, and T_{in} and T_{out} the inlet and outlet temperatures to and from the network, respectively.

As mentioned before, constant conditions every 15 minutes will be considered, therefore the energy will be calculated with the equation below:

$$E_{transf} = \int_{t=1}^{t=ts} P_{transf} * dt \quad [7.7]$$

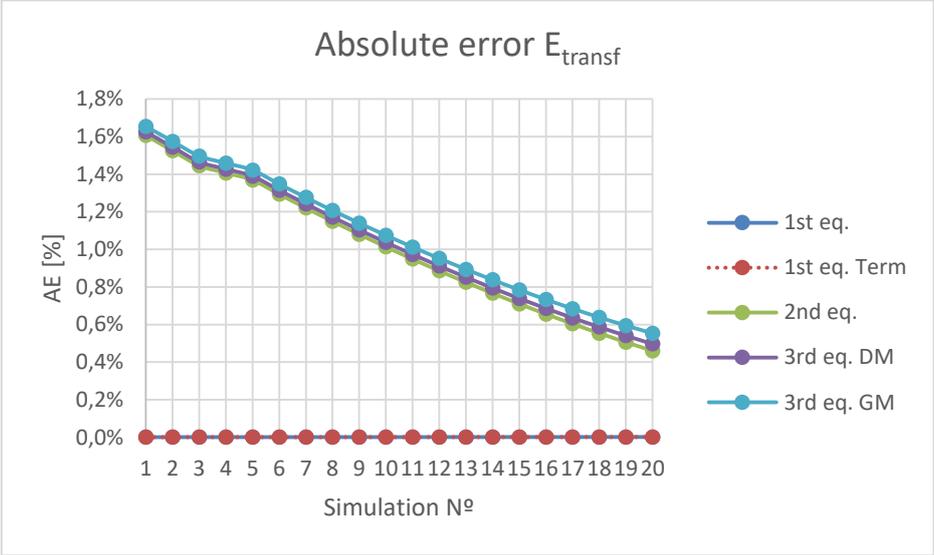
Where t_s is 15 minutes and P_{transf} is supposed the mean value for those 15 minutes.

The Graph 7.8 shows the results obtained for the energy transferred for each simulation in the different reduction degrees, the total energy transferred decreases notably in all cases, and this is because the power transferred in each of the substations decreases as the simulations progress. The results obtained for the two groups of simulations carried out with the equivalent network of 1st degree of reduction are almost identical to those obtained with the original network. For the other three simulations carried out, with the equivalent network of 2nd degree of reduction and with the two equivalent networks of 3rd degree of reduction, the results obtained are worse, but they are still quite notable and as the simulations progress the difference with the results obtained with the original network decreases.



Graph 7.8: Energy transferred

The conclusions drawn with Graph 7.8 of the energy transferred are reaffirmed with Graph 7.9 in which the absolute error realised in the energy transferred for each of the reduction levels is presented. It can be seen how the error for the 1st reduction degree is almost zero, and how for the other three cases the error produced is greater, but still acceptable in all three cases, less than 1,7% in the worst of the cases.



Graph 7.9: Energy transferred, absolute error

Table 7.9 presents the rest of the calculated errors around the transferred energy where all the conclusions drawn above can be clearly seen.

	E_{transf}			
	MAE	MSER	MSNER	MSEVC
1sr reduction degree	64,65292063	64,6547836	1,9941E-05	1,24355E-05
1st reduction degree (Ter)	64,65292063	64,6547836	1,9941E-05	1,24355E-05
2nd reduction degree	55567,83837	62474,5814	0,01926835	0,012016169
3rd reduction degree DM	56849,78788	63617,8257	0,01962095	0,012236057
3rd reduction degree GM	58849,69595	65410,8307	0,02017394	0,012580918

Table 7.9: Energy transferred, other errors

In order to have a more detailed analysis of the thermal energy transferred in the network, the thermal losses in each of the pipes will be calculated, and thus the total losses will be calculated by adding them all. For the calculation of the thermal losses in the network, the following Equation 6.9 will be used:

$$q_{loss} = U * (T_{amb} - \frac{T_{out} - T_{in}}{2}) \quad [7.8]$$

Where U is the thermal coefficient in each pipe that is calculated as shown in Section 6.1.1, T_{amb} is the environmental temperature with a value of 293.15K, and T_{in} and T_{out} are the inlet and outlet temperatures to each pipe, respectively.

The total losses in the network will be calculated by adding all the individual losses in each pipe of the network as shown in Equation 6.10:

$$P_{loss} = \sum_{i=1}^n q_{loss_i} \quad [7.9]$$

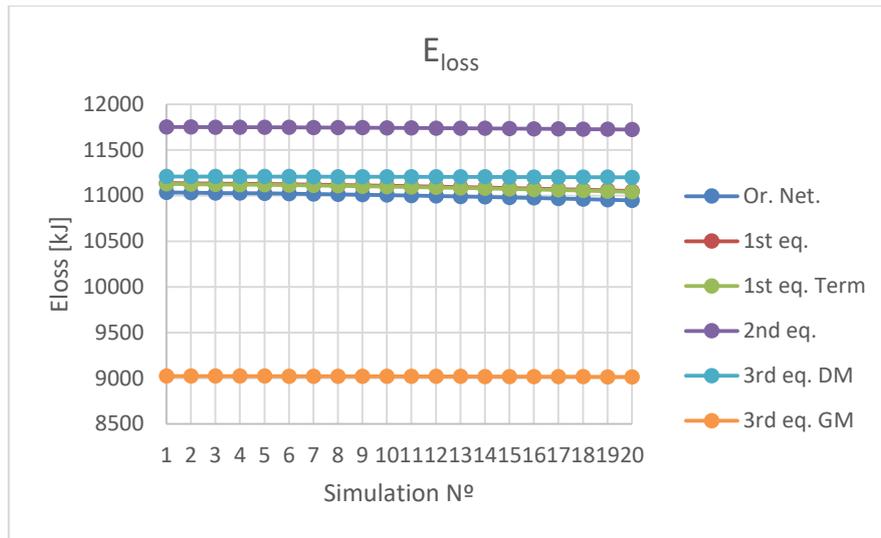
Where $q_{loss,i}$ are the losses in each pipe and n is the number of pipes in each network.

As in the case of the power transfer, constant conditions every 15 minutes will be considered to get the results in energy terms, therefore the energy loss will be calculated with the equation below:

$$E_{loss} = \int_{t=1}^{t=t_s} P_{loss} * dt \quad [7.10]$$

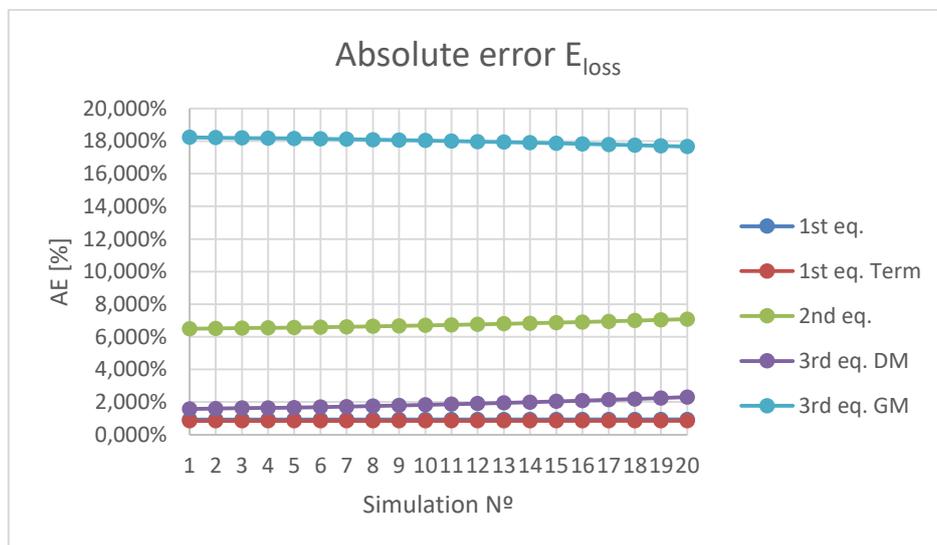
Where t_s is 15 minutes and P_{loss} is supposed the mean value for those 15 minutes.

Graph 7.10 shows the thermal energy loss in the different networks. As can be seen in all the equivalent cases the losses are bigger than in the original one except the case of the 3rd degree equivalent network of the GM, that is significantly lower. For the two simulations with the 1st reduction degree equivalent network can be seen that the results obtained are near the ones obtained with the original one, and that are better for the case in which the network has been only simulated thermally. So far, in all the variables analysed, the error increased as the reduction progressed, but as can be seen in this case, the error generated for the 2nd degree of reduction is greater than that generated for the 3rd degree of DM reduction.



Graph 7.10: Thermal energy loss in the network

Graph 7.11 shows the absolute errors made for each of the five equivalent cases studied. As can be seen for the two cases in which the 1st degree reduction equivalent network has been simulated errors are around 1%. As has been said before error increase notably for the 2nd degree of reduction to around 7%, and then for the 3rd degree of reduction of the DM surprisingly decreases to 2% and in the case of the GM it has a huge increase up to 18%.

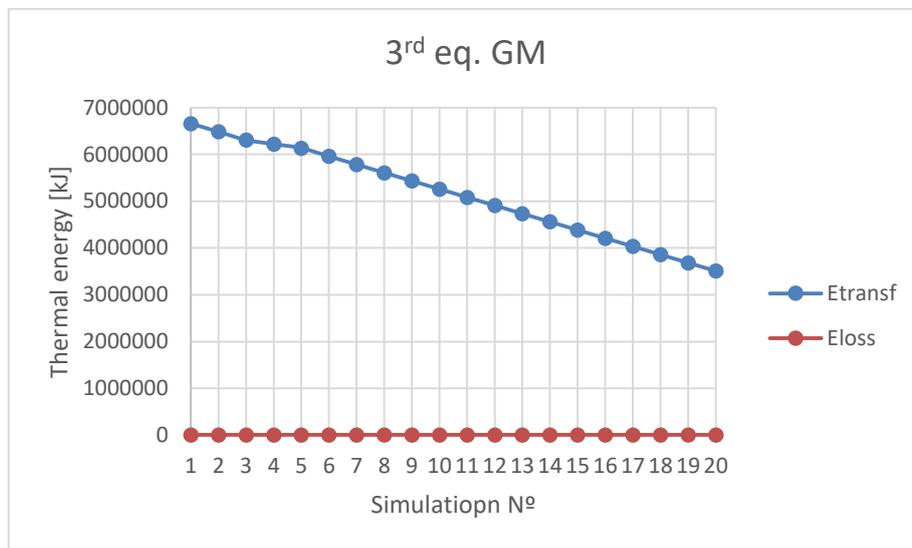


Graph 7.11: Absolute error of E_{loss}

The increase in the absolute error of the thermal energy loss in the network for the 3rd degree of reduction GM equivalent network is high as seen in the Graph 7.11, and as is said before the total energy transferred to the network is the thermal energy transferred in the substations plus the thermal energy losses:

$$E_{transf} = E_{subs} + E_{loss} \quad [7.11]$$

So, to appreciate in a better way the influence of that error done in the total thermal losses for the 3rd degree GM equivalent network, Graph 7.12 shows together the thermal energy transferred to the network and the thermal losses, and as clearly can be seen the influence of the losses is minimum. Therefore, although the error made in the losses is important, its influence on the network results is negligible.



Graph 7.12: E_{transf} and E_{loss} for the 3rd eq. GM

7.1.1. 1st reduction degree thermal errors

The equivalent network obtained for this 1st reduction degree, the one presented in Figure 7.4, as is said before, is going to be the same for the three reduction processes, because the step of reducing groups of pipes in series is the same for all the cases. These simplifications are made using the procedure presented in Section 5.1.1.

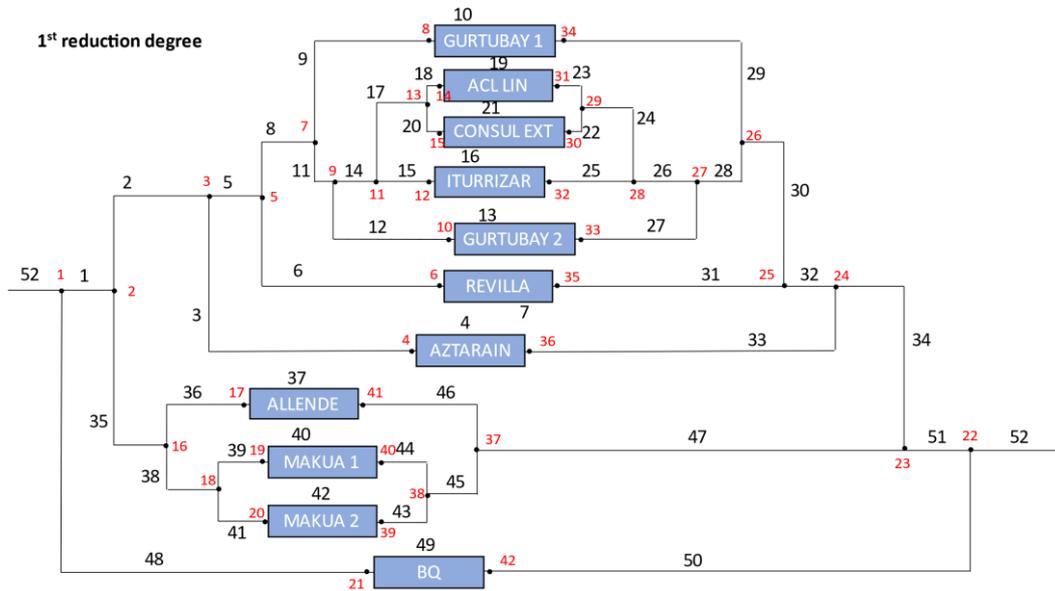
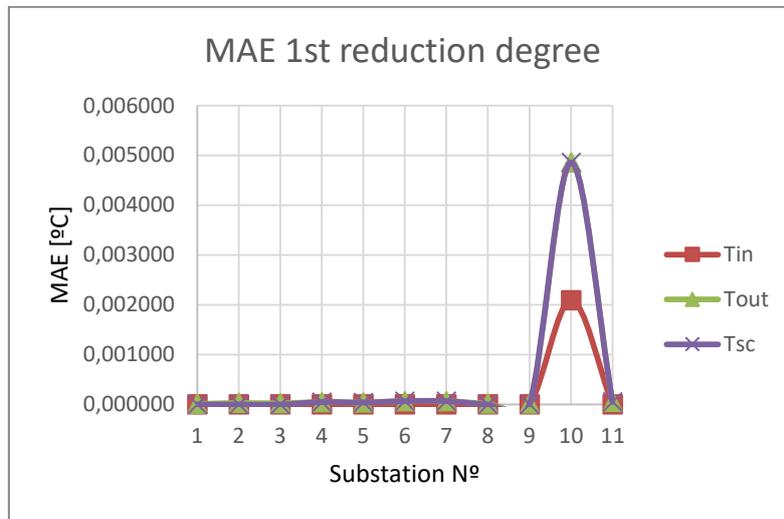


Figure 7.2: 1st reduction degree equivalent network

As mentioned at the beginning of Section 7, the equivalent network has been simulated in two different ways, a first time in which the network has been simulated both hydraulically and thermally with the simulator of Section 5.3, and a second simulation process in which the network has been simulated only thermally, assuming that the flow rates in each of the substations are the same as those obtained in the hydraulic part of the simulation of the original network, and the rest of flow rates are calculated starting from the flow rates of the substations. This has been done to see which part of the errors produced are due to the hydraulic simulation and which are due to the thermal simulation.

The thermal results analysed for each of the substations (inlet and outlet temperatures on the distribution side and outlet temperature on the consumption side) are almost identical for both cases (the case in which both hydraulically and thermally are simulated and the case in which only thermally is simulated), therefore only those of the case in which both hydraulically and thermally are simulated will be analysed that are a little bit higher. The rest of the errors done can be found in Appendix 2.

The MAE done for each of the three temperatures analysed are presented in Graph 7.17. The MAE done for the inlet temperature in the distribution side, for the outlet temperatures in the distribution side and the outlet temperature in the consumers side are negligible except on the 10th substation, in which they are not negligible but have only small variations from the third decimal place onwards, thus very small errors are made.



Graph 7.13: Tin, Tout and Tsc MAE for 1st reduction degree equivalent network

The rest of the errors calculated for each variable in this 1st reduction degree do not show any more different conclusion, they are in Appendix 2.

7.1.2. 2nd reduction degree thermal errors

In this 2nd degree of reduction only one equivalent network will be obtained: an equivalent network for the thermal calculation of both the DM and the GM, because the algorithm used in both cases for transforming substations in parallel into substations in series is the same.

The equivalent network analysed in this case is the one shown in Figure 7.5. As can be seen in each main branch all the substations are in series.

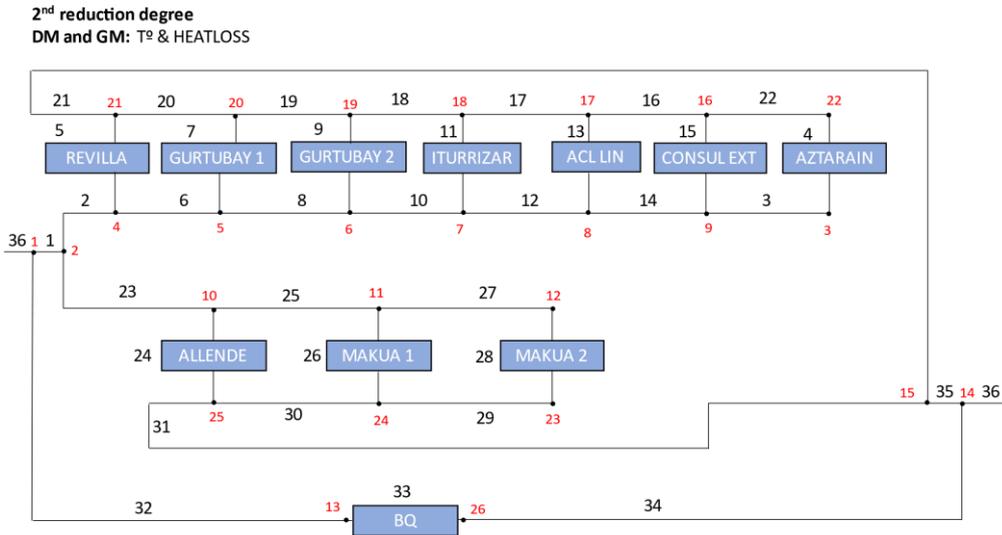
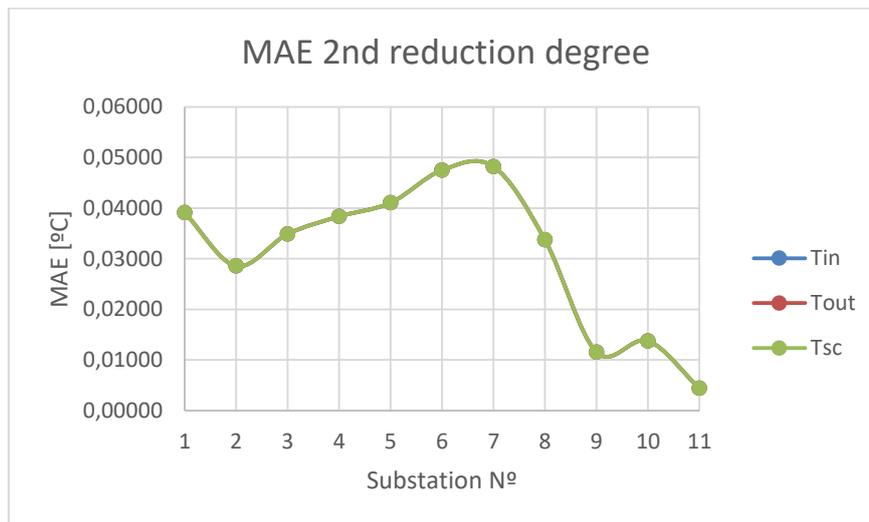


Figure 7.3: 2nd reduction degree's equivalent network for DM and GM heat losses calculation

As previously mentioned, this equivalent network has been analysed only thermally, the flow rates for each of the substations have been imposed with the values obtained by simulating the original network.

As can be seen in Graph 7.13, the errors in this 2nd reduction degree are more notable than in the 1st one, with variations in the mean temperatures in the substations of up to 0.05°C. Although the error produced has increased, it is still very small and acceptable in all cases.



Graph 7.14: MAE 2nd reduction degree Tin, Tout and Tsc

So that, it can be concluded that the results obtained for this degree of reduction are very good and interesting.

The rest of the results obtained for this degree of reduction can be found in Appendix 3.

7.1.3. 3rd reduction degree thermal errors

Three different equivalent networks will be obtained in this degree of reduction. Each of them will be the equivalent network with the highest degree of reduction of each of the reduction methods studied in this project.

From these three cases two have been used to simulate the thermal part. The temperatures on the consumption side have not been considered, since reducing the number of substations will make the results obtained not comparable. For the distribution of thermal power in each of the equivalent substations, the total power for each main branch has been calculated and with the percentage of the nominal flow rate through each of the equivalent substations that power has been divided.

Figure 7.7 shows the equivalent network for the 3rd reduction degree of the temperature and heat loss reduction process of the DM.

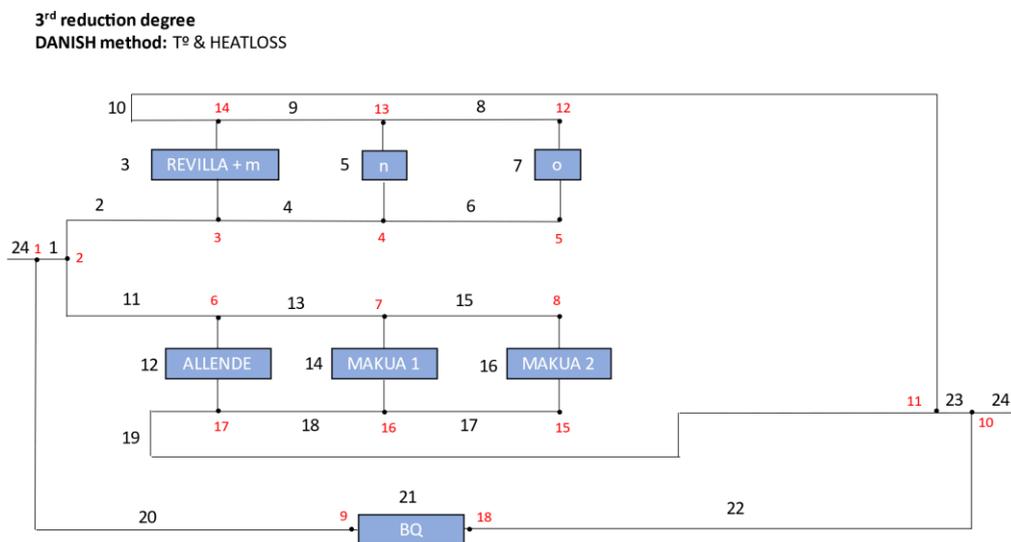
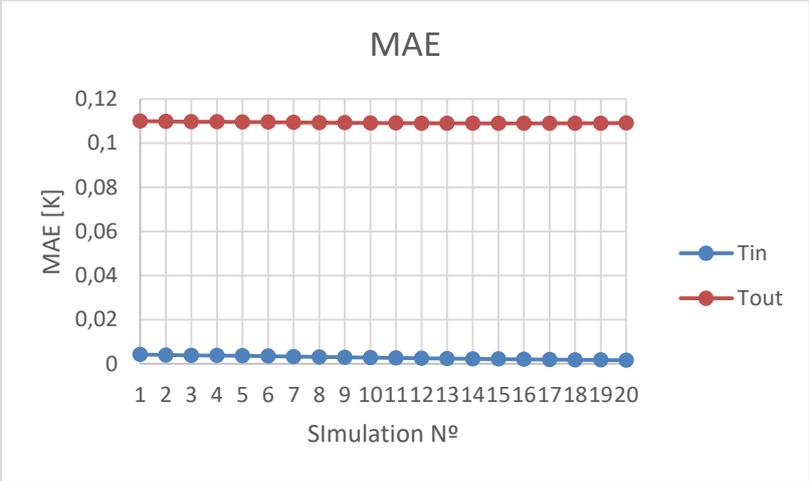


Figure 7.4: 3rd reduction degree DM thermal losses

As can be seen in Graph 7.14 that the MAE of the average inlet and outlet temperature at the equivalent substations is quite small in both cases, although it can be seen that the error

is higher in the case of the outlet temperature. The MAE at the outlet temperature of the equivalent substations is quite similar in all of them, around 0.11K.



Graph 7.15: MAE 3rd reduction degree DM Tin and Tout

Figure 7.8 shows the equivalent network for the 3rd reduction degree of the temperature and heat loss reduction process of the GM.

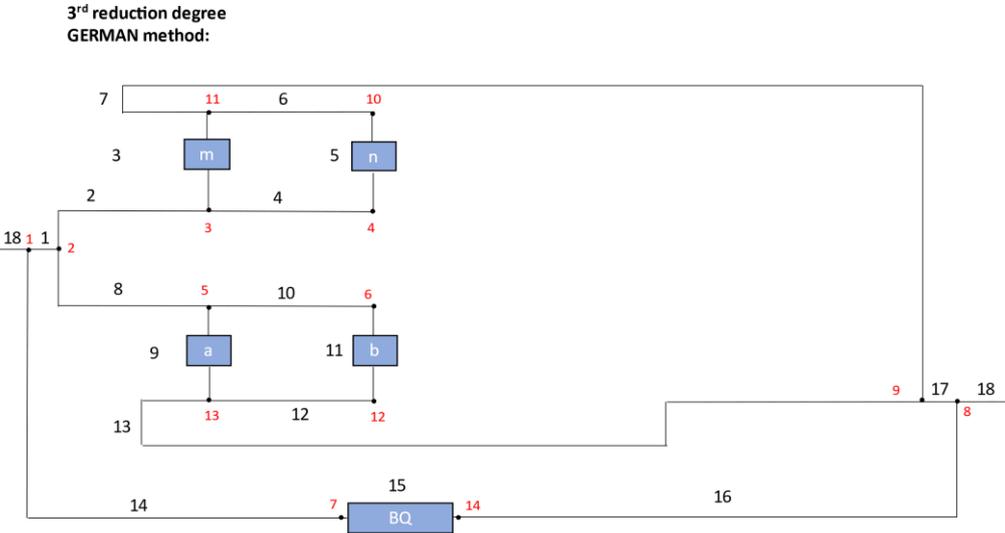
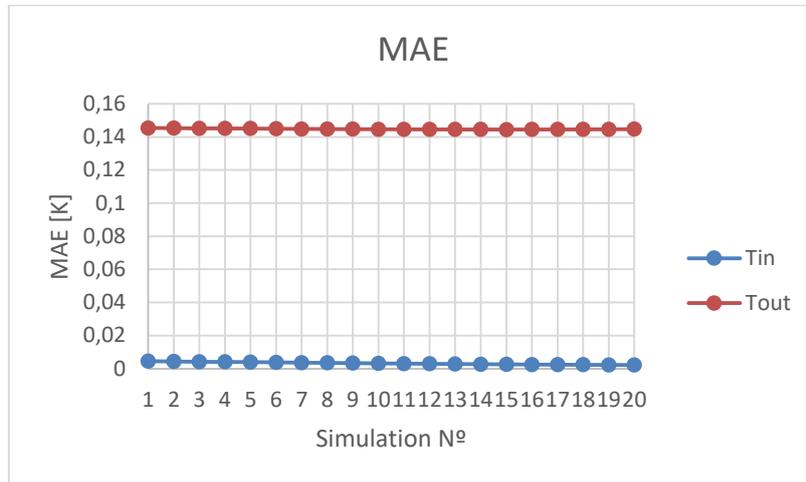


Figure 7.5: 3rd reduction degree GM

As can be seen in Graph 7.15 the MAE of the average inlet and outlet temperature at the equivalent substations is quite small in both cases, very similar to the results presented in Section 6.4.1, and as in that case, it can be seen that the error is higher in the case of the

outlet temperature. The MAE at the output temperature of the equivalent substations is quite similar in all of them, a little bit higher than 0.14K.



Graph 7.16: MAE 3rd reduction degree GM Tin and Tout

7.2. Hydraulic results

For the hydraulic analysis only, the DM has been applied. For the 1st degree of reduction, the equivalent network is the same for the three reduction processes, the one shown in Figure 7.2, and for the 2nd and 3rd reduction degrees the DM pressure drop procedure has been followed, and the equivalent networks that have been simulated are the ones presented in Figure 7.6 and Figure 7.7.

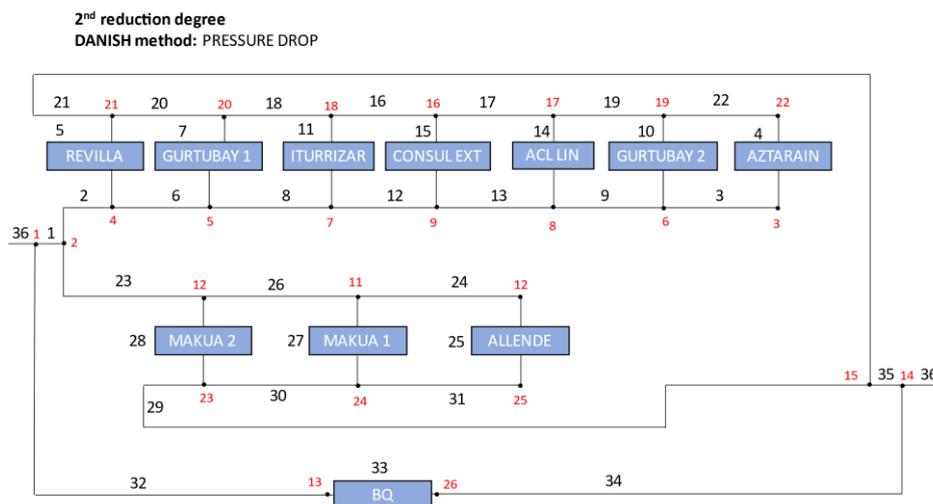


Figure 7.6: 2nd reduction degree DM pressure drop

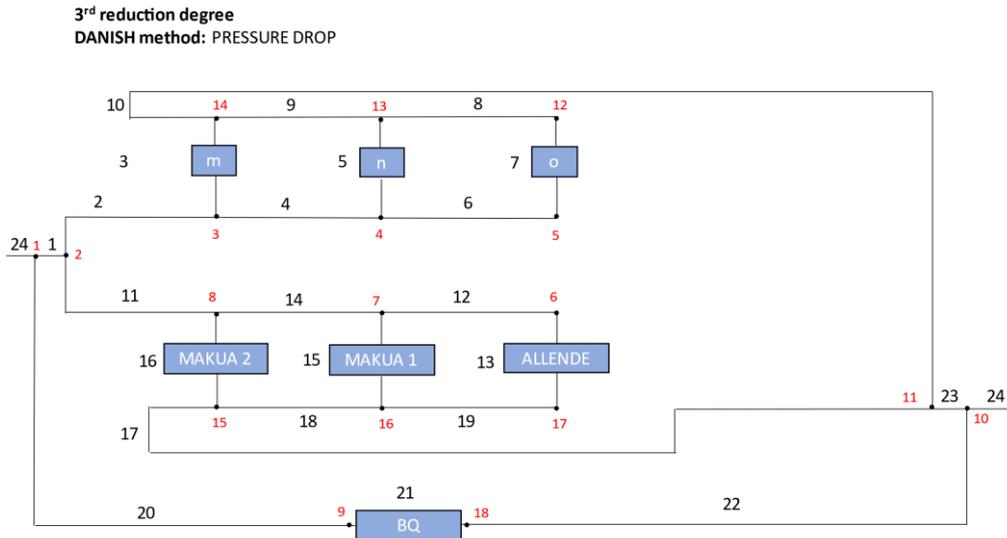
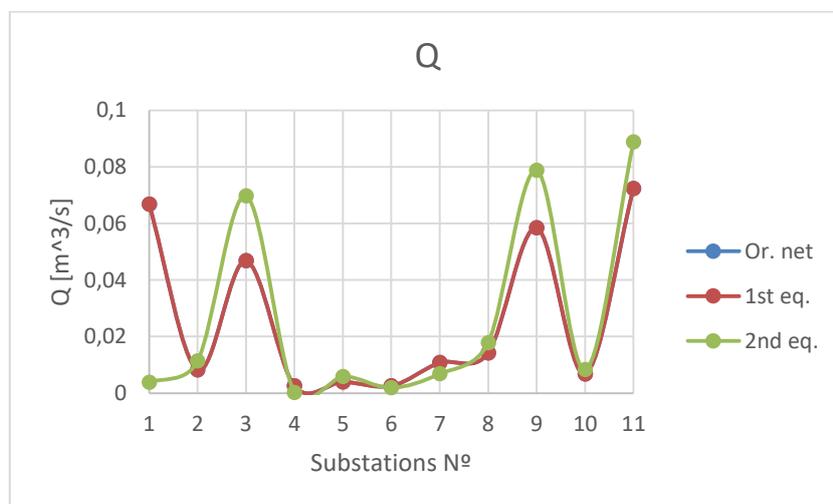


Figure 7.7: 3rd reduction degree DM pressure drop

For the hydraulic analysis, the flowrate in each substation is going to be analysed firstly. As with the temperature analysis, for the cases in which the number of equivalent substations is less than the original one the results obtained are not relevant, so that, to analyse all the degrees of reduction flowrate through each of the main three branches is going to be analysed.

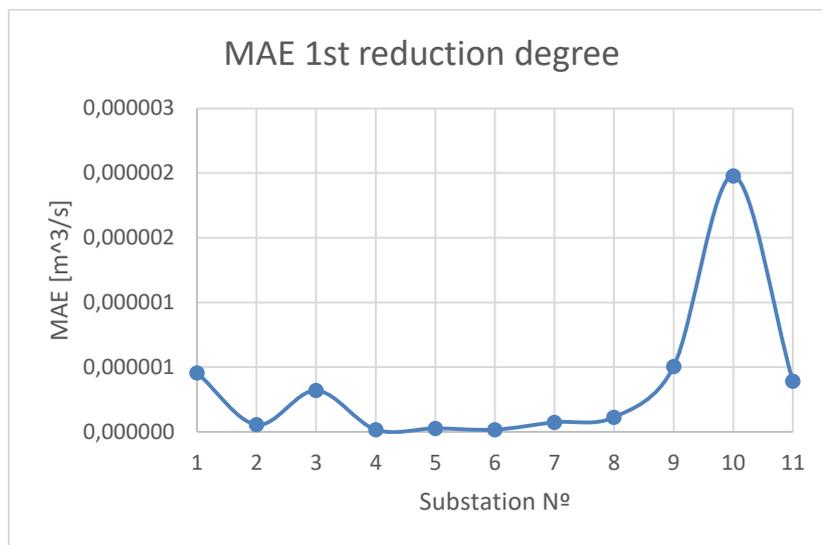
As can be seen in Graph 7.16, which shows the average flow rates in each of the substations for the cases of the simulation of the original network, the hydraulic simulation of the equivalent network of 1st reduction degree and the 2nd. The values obtained for the original network and for the 1st reduction degree are very similar and are not even visible. In the case of the 2nd degree of reduction the differences are noticeable in some substations, being quite large in the 1st substation.



Graph 7.17: Mean flow rate for each substation

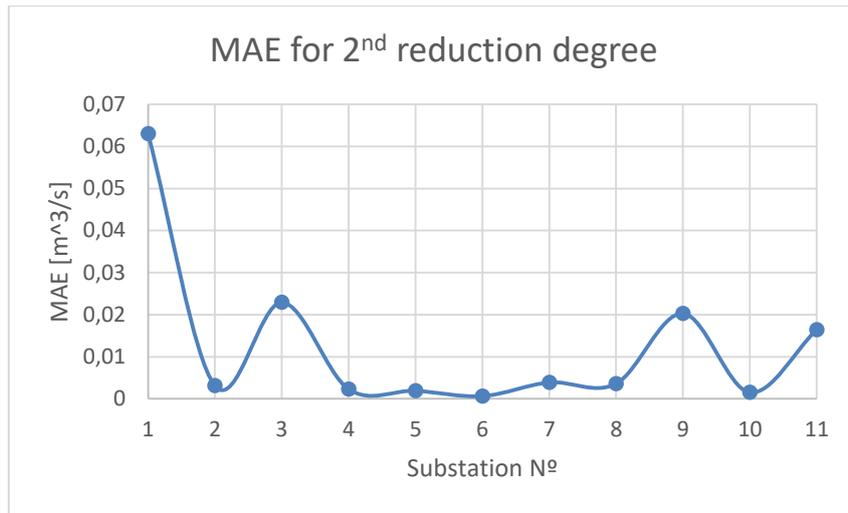
As the errors differ quite a lot in the two reduction degrees studied, to appreciate the errors in the flow rate, two graphs are presented here below, one for each reduction degree.

Graph 7.17 represents the MAE in each of the substations for the 1st reduction degree, and as can be seen in all cases is less than $2 \cdot 10^{-6}$. The maximum error is done in the 10th substation, which is the only one in which the reduction of pipes in series for pipes with different diameters has been applied. In the other two cases, in the inlet pipes to substation 7 and substation 11, all the pipes reduced in series have the same diameter, and as can be seen in the error made is negligible.



Graph 7.18: Flow rate's MAE for 1st reduction degree equivalent network

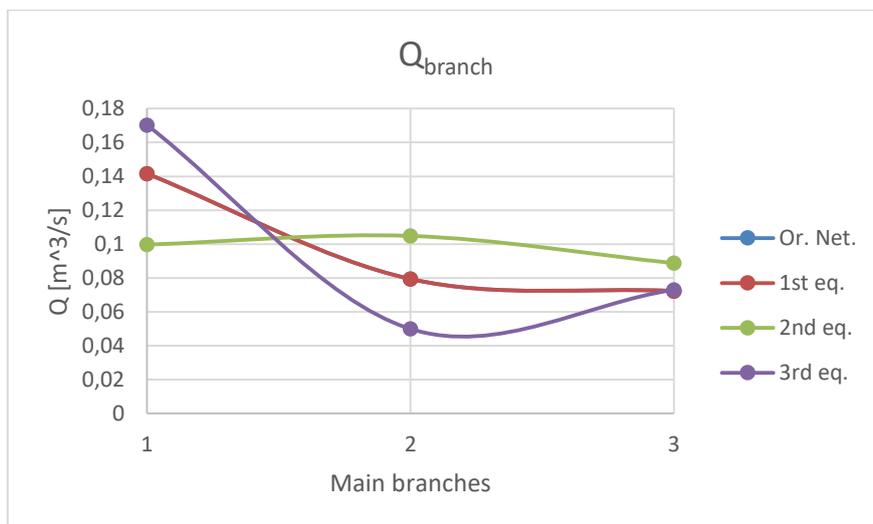
For the 2nd degree of reduction, it can be seen in Graph 7.18 how the realised errors increase quite a lot, as already mentioned above, being bigger for the 1st substation.



Graph 7.19: Flow rate's MAE for 2nd reduction degree equivalent network

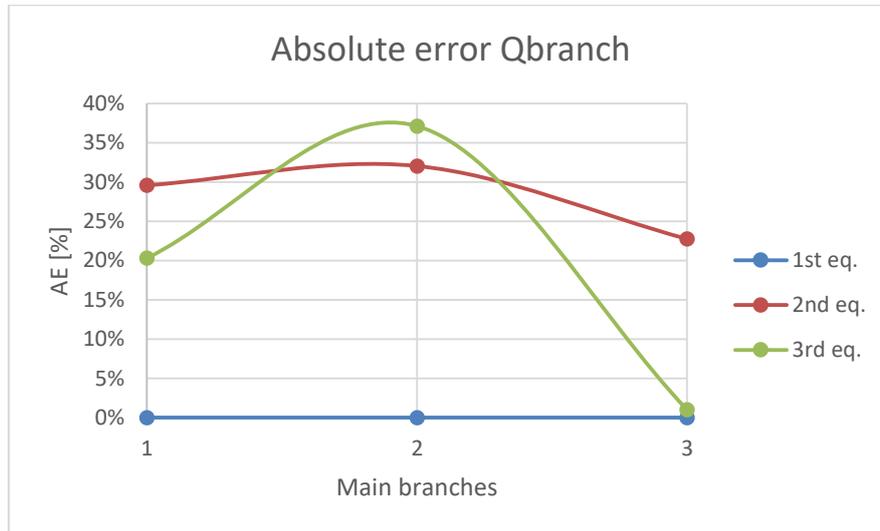
In order to be able to analyse the results obtained in terms of flow rate for the third degree of reduction and compare it with the rest of the cases, as the number of substations has not been conserved, it has been decided to plot the flow rate for each of the three main branches of the network, which, as explained in Sections 6.1 and 6.2, are respected at all times in the reduction process.

As in Graph 7.16 the difference between the results obtain with the original network and the 1st reduction degree are almost the same. The results for the other two cases, are quite bad, except the result obtain for the 3rd branch in the 3rd reduction degree.



Graph 7.20: Flow rate in each main branch

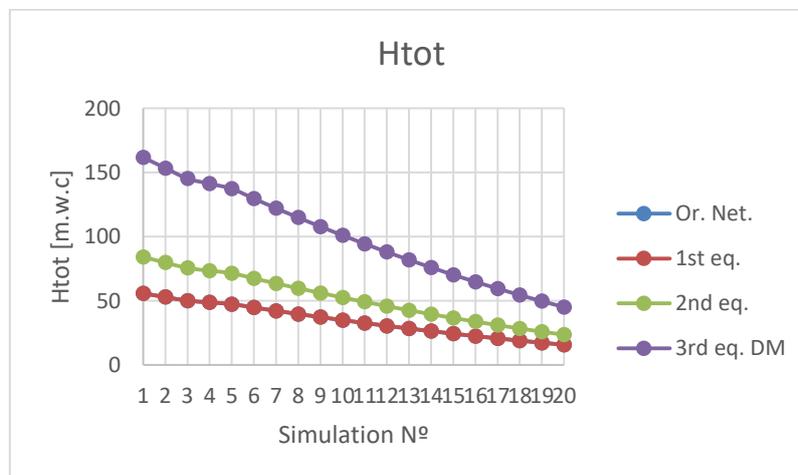
Graph 7.20 confirms the conclusion get in the graph above, errors for the 1st reduction degree are negligible, and for the 2nd and 3rd reduction degrees are quite large, with the exception of the 3rd branch in the 3rd reduction degree.



Graph 7.21: Flow rate's AE in each main branch

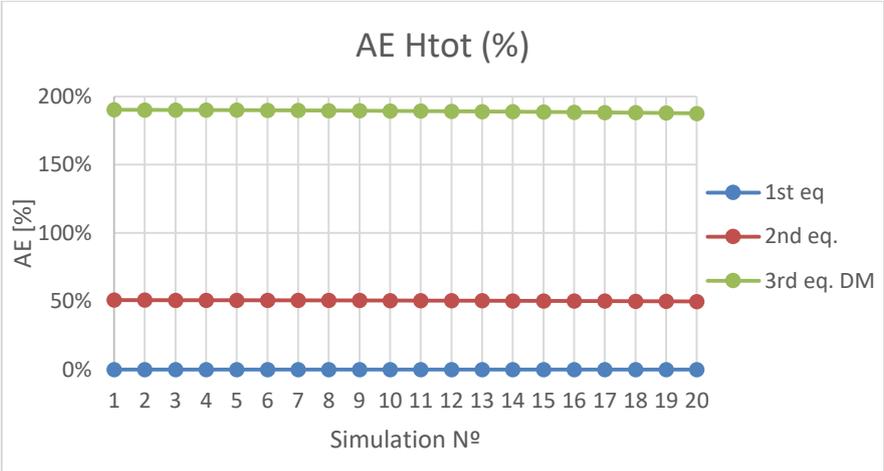
Once the flowrate has been studied, the total pressure drop in the network is going to be analysed.

As can be seen in Graph 7.18, the pressure drop is very similar for the original network and the 1st degree of reduction equivalent network, and the error generated is not noticeable. For the other two reduction degrees, the 2nd and the 3rd one, the errors made are huge, especially in the 3rd one.



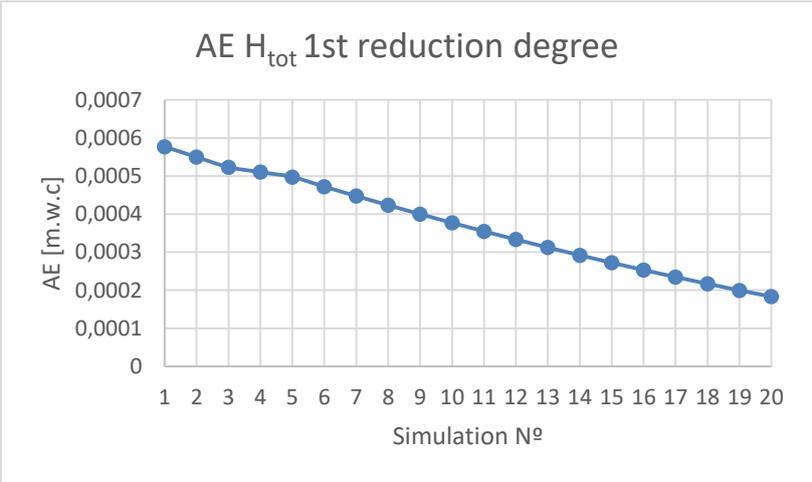
Graph 7.22: Total pressure drop in the network

What has been mentioned in the previous paragraph is verified by Graph 7.19. that shows that the errors made for the 1st reduction degree are not noticeable, the ones made for the 2nd reduction degree are around 50%, and the ones made for the 3rd reduction degree are huge, around 190%.



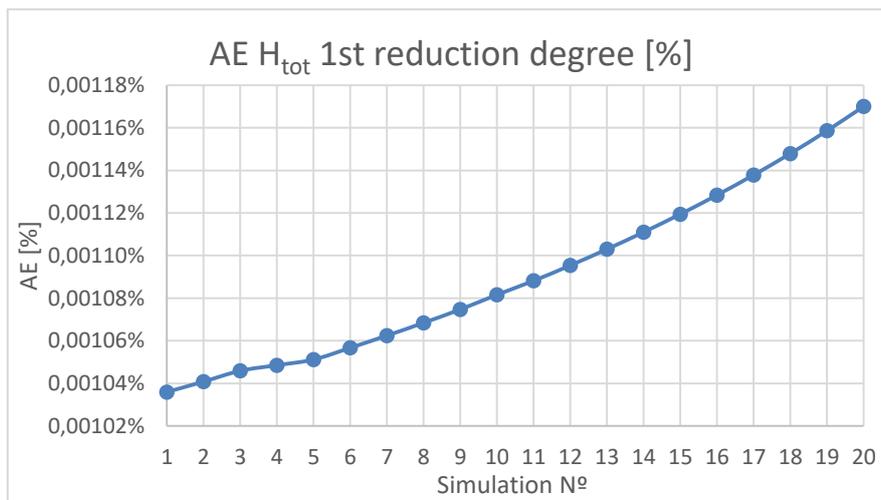
Graph 7.23: Absolute error of Htot

As the error are so small for the 1st reduction degree in order to analyse them in a better way, Graph 7.20 shows the AE in m.w.c only for the 1st reduction degree equivalent network. It can be seen how the AE for each of the simulations decreases as the simulations progress. As shown in Table 6.1, the inlet flow rate to the network decreases as the simulations proceed, and therefore the total pressure drop in the network also decreases.



Graph 7.24: AE of Htot in m.w.c for 1st reduction degree

As both H_{tot} and AE in m.w.c decrease, the results obtained for AE can be more representative if they are analysed in % instead of in m.w.c. Therefore, Graph 7.21 shows the results obtained for AE in %, and as can be seen, the error increases as the flow rate decreases, unlike Graph 7.20. The AE continues to be small in all cases, but the equivalent network is calculated to work with nominal flow rates and as we move away from these nominal flow rates the error will increase, as we thought it would.



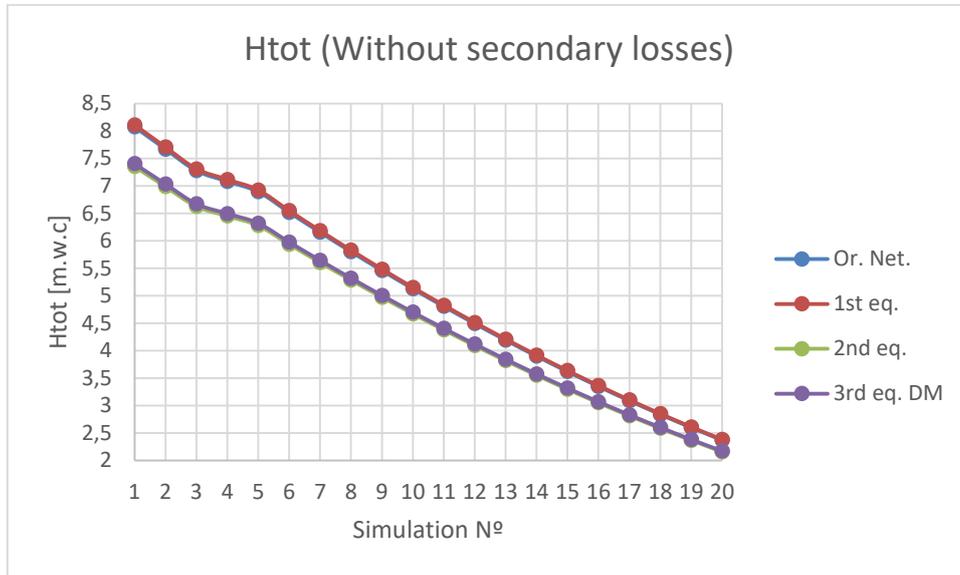
Graph 7.25: AE of H_{tot} in % for 1st reduction degree

As has been seen, the results for the first degree of reduction are excellent, and for the second and third degrees of reduction they are bad and very bad, respectively. These bad results are due to the fact that the reduction processes do not take into account the secondary head losses and the simulator used does, which means that when calculating the equivalent network, the pipes that were in parallel are in series and when the secondary losses of each of the pipes are added, the pressure drop increases enormously.

Therefore, the simulator will be modified so that it does not consider the secondary losses in the network and only takes into account the primary losses, in order to see the real error generated by the reduction methods at different % degrees, even if the pressure loss is not the real one in the network.

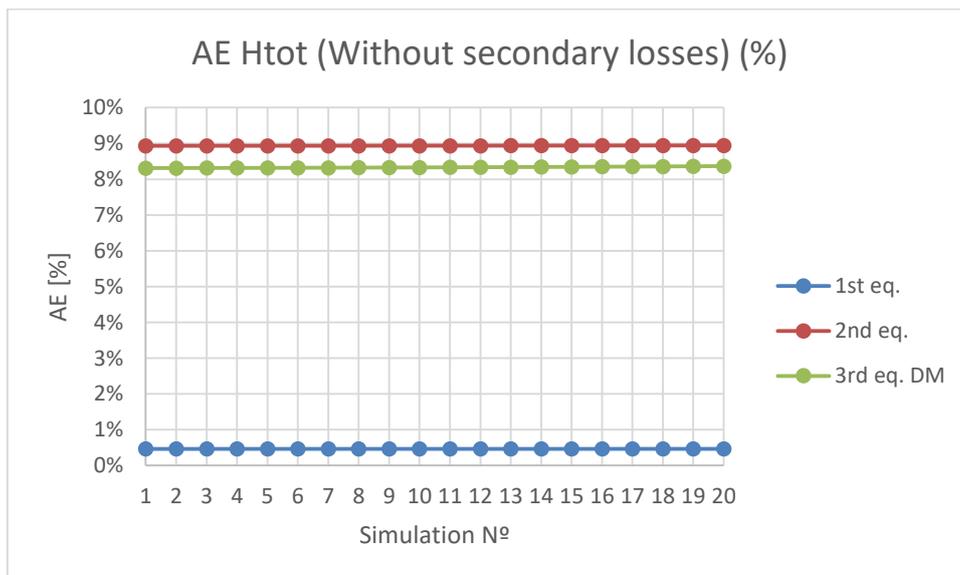
Graph 7.22 shows the total pressure drop for the original network and the three different equivalent networks without considering the secondary losses. As can be seen the pressure drops have decreased a lot compared to the results in Graph 7.18, which indicates that most of the pressure drop in the network is due to secondary losses. As already seen in the case where secondary losses were considered, the results obtained for the first degree of reduction are very good. For the other two cases, the 2nd and the 3rd degrees of reduction,

the results improve a lot, what means that the reduction method does not work as bad as can be thought with the previous results.



Graph 7.26: Total pressure drop in the network without secondary losses

As Graph 7.23 shows the AEs have decrease a lot compared to the previous ones. In the case of the 1st reduction degree, they continue being really good, around 0.5% in all simulations, and for the other two reduction degrees the errors decrease a lot but the results continue being bad, for the case of the 2nd reduction degree are a little bit higher than 8% and for the 3rd reduction degree are around 9%.



Graph 7.27: AE Htot without secondary losses

8. RISK ANALYSIS

This section analyses the possible risks that may affect the development of the project and details the solutions to try to avoid, or at least mitigate, the effect of such risks. The objectives of the analysis and subsequent risk management are to increase the probability and impact of positive events and decrease the adverse events. In addition, the probability of occurrence and impact of each risk has been evaluated and prioritized according to the risk matrix.

Risks can be internal, i.e., they depend on the project team members, or external, i.e., they originate outside the project team. For the identification of these risks, we use documentation of other previous projects, commercial databases or previous experiences of the project members.

Risks are divided into three main groups: office risks, computer risks and other risks.

First, there are the risks related to the office environment. These include excessive or inappropriate use of data display screens, furniture and other work equipment that can cause visual problems, cuts from office tools or electrical contacts, among others. Due to long workloads in the same office environment, inadequate working postures can also cause muscular pain, injuries and stress problems. Finally, office accidents such as collisions with stationary objects or fires are also included in this group.

Another important group of risks would be those related to computational elements. Within this group are modelling problems (either due to lack of knowledge or software convergence errors), loss of data, low accuracy of the results obtained and errors and availability of the necessary licenses to run the programs.

Finally, a group includes those risks that have not been included in the previous groups. This group includes risks related to commuting to the work environment (itinerary accidents), psychosocial problems such as harassment, social support or the work demands and the plant's power outage.

In summary, this is the list of risks that need to be addressed in the implementation of this project:

- A. Excessive or inappropriate use of data display screens, furniture and other work equipment
- B. Inadequate working postures

- C. Office accidents
- D. Modelling problems
- E. Loss of data
- F. Low accuracy of the data and the results obtained
- G. Errors and availability of the necessary licenses
- H. Itinerary accidents
- I. Psychosocial problems
- J. Power outage

The second step after identifying the different risks is to evaluate the probability of occurrence and impact of each risk. This can be seen in the following probability-impact matrix.

		IMPACT		
		Low (0,1)	Medium (0,5)	High (0,9)
PROBABILITY	Low (0,2)	J (0,02)	C, E (0,1)	H (0,18)
	Medium (0,5)	G (0,05)	A (0,25)	I, F (0,45)
	High (0,8)	D (0,08)	(0,4)	B (0,72)

Table 8.1: Probability-impact matrix

Those risks in red are the ones that need high attention and a better risk response plan. On the other hand, risks in orange are of moderate importance while those in green do not need immediate response.

Once the risks have been identified and quantified, risk management and response have been established. Four positions can be adopted in the face of these risks: avoid, accept, reduce or transfer them.

The measures to be adopted according to the degree of importance are as follows:

● **High importance:**

- ***Protocol for harassment situations***
- ***Flexible schedule***

Reduces the probability that the project will be affected by delays.

- ***In-depth bibliographic review***

It decreases the probability that data or results are accepted as reliable when they are not.

● **Medium importance**

- ***Compliance with road traffic regulations***
- ***Data display screens instructions***

Correct posture in front of a computer, hand positioning when typing and physical and mental exercises to be performed to avoid discomfort and fatigue.

● **Low importance**

- ***Be aware of the company's emergency plan***
- ***Data protection on a regular basis and in different locations***

Lastly, it is important to monitor the risks, verifying that the agreed measures are complied with and to look for new risks that could jeopardize the correct development of the project.

9. WORK PLANNING

The following section shows the planning followed to carry out the project, delimiting the project phases and developing a Gantt diagram.

9.1. Project phases

In this section we are going to present the different phases that have been followed during the realisation of the project.

P1: Bibliographic review

Research of the projects carried out to date and the state of the art.

Duration: 2 weeks

P2: Study of reduction methods

Both Danish and German network reduction methods have been studied in this phase.

Duration: 2 weeks

P3: Application of reduction methods

Both methods studied have been applied for the distribution networks of the Basurto hospital's DC system.

Duration: 6 weeks

Subphases:

- Phase 3.1: Manual reduction process with excel

The algorithms for each of the steps of the reduction methods are entered manually, are applied in order and the data obtained in each of the steps is stored in a table.

- Phase 3.2: Matlab tutorial

The tutorial 'Matlab Fundamentals' is done to remember how Matlab works and to be able to transfer what was done in the previous phase to Matlab.

- Phase 3.3: Manual reduction process with Matlab

The algorithms for each of the steps of the different reduction methods are designed in different functions and following the order in which the network is going to be reduced, they are inserted in a main function to perform the reduction of the entire network and save the data of each of the steps performed.

- Phase 3.4: Automated reduction process with Matlab

A process with Matlab is prepared to reduce any network with pure tree structure, in which introducing the initial configuration of the network and the data of the pipes and substations automatically reduces the entire network.

P4: Static modelling

The modelling has been done using Matlab, with the simulator created by Tekniker's thermal engineering department.

Duration: 4 weeks

Subphases:

- Phase 4.1: Simulator's modifications

Modifications have been done to the simulator to use it with the different equivalent networks.

- Phase 4.2: Running different simulations

Simulations have been done with the equivalent network at different reduction degrees and with different conditions.

P5: Results analysis

With the simulations carried out, an exhaustive analysis is made of both the results obtained and the errors made.

Duration: 4 weeks

Subphases:

- Phase 5.1: Thermal results and errors

The results get and the errors done for the thermal analysis are studied in this phase.

- Phase 5.2: Hydraulic results and errors

The results get and the errors done for the hydraulic analysis are studied in this phase.

P6: Project writing

Drafting of the deliverable project report as well as the presentation of the project.

Duration: 16 weeks

9.2. Gantt diagram

Table 9.1 shows the different tasks performed for the achievement of the project, and Figure 9.1 shows the Gantt diagram.

EDT	Nombre de tarea	Duración	Comienzo	Fin	Predecesoras
1	Bibliographic review	11 días	lun 01/03/21	lun 15/03/21	
2	Study of reduction methods	11 días	mar 16/03/21	mié 31/03/21	1
3	Application of reduction methods	29 días	mar 06/04/21	vie 14/05/21	2
3.1	Manual reduction process with excel	12 días	mar 06/04/21	mié 21/04/21	
3.2	Matlab tutorial	5 días	jue 22/04/21	mié 28/04/21	4
3.3	Manual reduction process with Matlab	5 días	jue 29/04/21	mié 05/05/21	5
3.4	Automated reduction process with Matlab	7 días	jue 06/05/21	vie 14/05/21	6
4	Static modelling	22 días	lun 17/05/21	mar 15/06/21	3
4.1	Simulator's modifications	9 días	lun 17/05/21	jue 27/05/21	
4.2	Running different simulations	13 días	vie 28/05/21	mar 15/06/21	9
5	Results analysis	21 días	mié 16/06/21	mié 14/07/21	10
5.1	Thermal results and errors	10 días	mié 16/06/21	mar 29/06/21	
5.2	Hydraulic results and errors	11 días	mié 30/06/21	mié 14/07/21	12
6	Project writing	87 días	lun 22/03/21	vie 23/07/21	

Table 9.1: Project tasks list

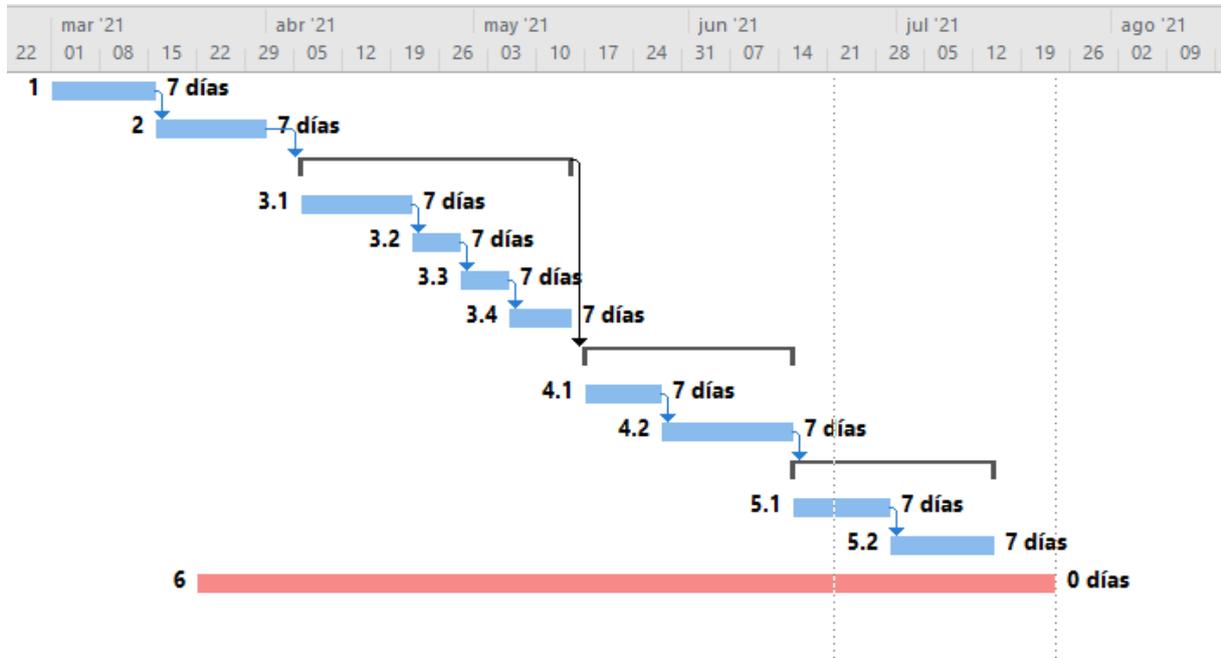


Figure 9.1: Gantt diagram

10. EXPENSES AND AMORTIZATIONS

In this section we present the expenses incurred during the completion of this master's thesis entitled 'Research and implementation of network reduction methods for District Cooling Systems'. The expenses download is broken down into internal hours, amortizations and expenses. Indirect expenses are taken as 5% of the subtotal 1, which is formed by internal hours, amortizations and expenses, and financial expenses as 4% of the subtotal 2, which is formed by subtotal 1 plus indirect expenses.

INTERNAL HOURS				
REF	CONCEPT	HOURS	UNIT COST	TOTAL COST
1.1	Junior Engineer	300	20€/h	6000 €
1.2	Engineer	10	60€/h	600 €
1.3	Project director	8	80€/h	640 €
INTERNAL HOURS SUBTOTAL				7240 €

Table 10.1: Internal hours

AMORTIZATIONS						
REF	CONCEPT	COST	SERVICE LIFE	HOURS	UNIT COST	TOTAL COST
2.1	Computer	1000 €	10 years	290	0,05€/h	14,5 €
2.2	Matlab license	800 €	1 years	150	0,4€/h	60 €
2.3	Dymola license	900 €	1 years	40	0,45€/h	18 €
2.4	Microsoft Office license	1000 €	1 years	100	0,5€/h	50 €
AMORTIZATIONS SUBTOTAL						142,5€

Table 10.2: Amortizations

EXPENSES				
REF	CONCEPT	HOURS	UNIT COST	TOTAL COST
3.1	Office material	-	-	15 €
EXPENSES SUBTOTAL				15 €

Table 10.3: Expenses

CONCEPT	TOTAL COST
Internal hours	7240 €
Amortizations	142,5 €
Expenses	15 €
Subtotal 1	7397,5 €
Indirect expenses (5%)	369,875 €
Subtotal 2	7767,375 €
Financial expenses (4%)	310,695 €
TOTAL	8078,07 €

Table 10.4: Total cost

The total cost of the project has been eight thousand and seventy-eight euros and seven cents.

11. CONCLUSIONS

In this work, different network reduction methods have been studied and applied to model and simulate the distribution network of the DC system of Basurto hospital.

Once the main and secondary objectives of the project have been achieved and having analysed the results obtained by simulating the network with the different reduction methods studied and at different degrees of reduction the relevant conclusions will be drawn.

The conclusions will be divided into three main blocks: a first block in which we will draw conclusions about DH&C systems in general; a second block in which we will analyse the usefulness of the automated network reduction process carried out using Matlab; and a third and last block in which we will analyse the results obtained and errors generated with the different simulations at different degrees of reduction carried out with the static simulator of Matlab.

DH&C systems:

It can be clearly concluded that DH&C systems are one of the most efficient and future-proof ways of supplying domestic hot water, heating and air conditioning to a group of customers. Their efficiency is already 5 to 10 times higher than using conventional individual boilers or chillers, and with all the improvements that are being made in the distribution of heat and cold, the implementation of renewable energies in the generation and storage systems of heat and cold, the possible improvement is still very noticeable and its great future is undoubtedly assured.

Automated network reduction process:

Focusing on what has been done in this project, the first main task was to create an automated network reduction process using Matlab. This process can be applied to any distribution network with a pure tree structure, in which the main branches, if any, are respected. Three different reduction processes have been carried out, one for each of the reduction methods applied, but only the algorithms used to calculate the equivalent pipes and substations vary, the main reduction function follows the same principles in all three cases.

The usefulness of these automated reduction processes is high, as they will be implemented in the control system generated by Tekniker for the Basurto hospital network. As mentioned before, the reduction processes are made for a fixed input flow, but as the simulation of the reduction process created with Matlab is so fast, what we are going to try to implement is to calculate the equivalent network for the input flow at that moment and as soon as the flow varies more than a certain percentage to recalculate the equivalent network with the aim of

controlling the network as efficiently as possible and with as few variables as possible. The degree of reduction to be used is yet to be determined, but it is likely to be the second degree of reduction, as all existing substations will be respected.

As previously mentioned, the distribution network of the Basurto hospital is small, and the thermal influence of the inertias is small and negligible, therefore the dynamic modelling of the network was not necessary and therefore when simulating it statically the number of variables is small and the need to apply reduction methods is not so important, but as a test bench for future application to a larger DC and DH networks it is very interesting to use these reduction methods and implementing them in the control system of a real DC distribution network is a necessity in order to understand better the quality of these reduction methods.

Simulations:

The third block we are going to focus on is that of all the simulations carried out with the different reduction methods and at different reduction degrees. This block will be divided into two parts: a first part in which we will draw conclusions from the results and errors of the thermal part, and a second part in which we will draw conclusions from the hydraulic simulations.

The conclusions regarding the thermal simulations in general are very positive, as can be seen in Section 7.1, which analyses the results and the thermal errors made in the simulations for the different degrees of reduction. In order to draw more concrete conclusions, we will focus on each of the degrees of reduction:

- **1st reduction degree:**

All thermal results obtained for this degree of reduction are extremely good, almost identical to the results obtained when simulating the original network. This was to be expected, as the level of reduction is very small, only the groups of pipes in series have been simplified by an equivalent pipe.

Therefore, as there is such a small difference with the original network, the number of variables is quite similar and when it comes to using it to control the network, it is not very interesting.

- **2nd reduction degree:**

For the 2nd reduction degree in which all the substations are conserved but they are in series one after each other, respecting the three main branches of the network,

results are also very good. All the temperatures studied in the substations vary less than 0.05K and the error made in the return temperature is less than 0.08K in all cases. As for the other thermal variables studied, thermal energy transferred to the network and total thermal losses in the network, the results obtained are quite good, with absolute errors of less than 1.7% in the thermal energy transferred to the network and with errors of around 7% in the total thermal losses in the network. So that, it can be concluded that the 2nd degree of reduction equivalent network is thermally equivalent to the original one.

Apart from that, in contrast to the 1st degree of reduction, in this case the variables do decrease considerably, and as all the substations are maintained, the data that can be obtained by simulating the network at this degree of reduction is quite complete, so it may be the most interesting degree of reduction when it comes to implementing it in the distribution network control system of Basurto hospital.

- 3rd reduction degree:

For the third degree of reduction, the equivalent networks are different when applying the DM and GM. With the GM the level of reduction obtained is higher than with the DM, and it is also seen that the errors generated are also somewhat higher, but quite good in both cases in terms of the temperatures studied in the substations and the return temperature of the network. As the number of substations have decreased for this reduction degree, the temperatures in the last substation have been studied only, as this branch does not vary since the 1st degree of reduction. The results obtained for this substation and for the return temperature are almost like the ones obtained for the 2nd degree of reduction. The results obtained for the thermal energy transferred to the network are also really similar to the ones obtained in the 2nd degree of reduction. The difference came when the total thermal losses in the network are analysed, that in the case of the DM the absolute error done is around 2%, decreases comparing with the ones obtained with the 2nd degree equivalent network, and for the GM increases a lot, up to 18%. But as is said in the Section 7.1 the influence of the thermal losses in the network compared with the total energy transferred is very small, and the errors done are almost negligible.

Taking the results analysis into account and that the number of substations has decreased, in the case of wanting to analyse each of the substations exhaustively, this degree of reduction is not very interesting, but for the purpose of studying general network data it can be very useful as the number of variables to be analysed is much smaller than in the original network and the results obtained are quite good. If we had to choose one of the two methods, all the results of the variables obtained are very similar except for the thermal losses in the network, for which the DM is much better. Therefore, when it comes to choosing one of the two methods, although the degree of reduction is lower, DM would be chosen. Because, even though for this small network the thermal losses have little influence, if these methods are to be applied to larger networks, the influence may be greater.

Therefore, it can be concluded that the results obtained for the thermal part are more than satisfactory in almost all cases and depending on what we want to control and analyse in the network, we will be interested in either the 2nd or the 3rd degree of reduction, since in the 1st degree, although the results are excellent, the degree of reduction is minimal. Therefore, if you want to control and monitor each of the substations, the 2nd degree of reduction would be more interesting, and to analyse only the general data of the network, the 3rd degree of reduction of the DM would be the best option.

In contrast to the thermal part, in the hydraulic simulations the results obtained are quite poor, as has been analysed in Section 7.2. Only the DM has been studied in the hydraulic calculation, and the reduction processes do not consider the secondary losses, something that the simulator does take into account, therefore, when going from substations in parallel to substations in series, the secondary losses of the pipes in series are added, greatly increasing the total load losses and thus the pressure drop in the network. But well, when simulating without considering the secondary losses, the errors generated from the 2nd degree of reduction onwards remain significant.

The conclusions took for the pressure drop are applicable to the flow through the network. The results obtained are very good for the 1st degree of reduction, but from the 2nd onwards the errors increase considerably.

Therefore, the reduction process would have to be improved in order to use it. The results for the 1st degree of reduction are excellent, but as we have said in the case of the conclusions of the thermal part, the degree of reduction is very small and therefore the number of variables to be controlled is very similar to the ones of the original network. For the 2nd and 3rd reduction degrees, the results obtain are not acceptable, apart from the reduction process algorithms do not consider the secondary losses, that as has been seen are the bigger part of the total losses, when only considering the primary losses, the results are neither good.

But well, the hydraulic changes in the network, the flow rate changes, expand through the network about a thousand times faster than thermal changes, so having an equivalent network to control and monitor pressure drop and flow rates is not as critical as in the thermal case, as the hydraulic inertias of the network are minimal.

12. FUTURE RESEARCH

For the possible future studies, the potential improvements in DH&C installations are very wide. But focusing on the subject of this work, network reduction methods applied to DC systems, future studies are several.

On the one hand, the next step would undoubtedly be to model and study the distribution network of the Basurto hospital dynamically applying the reduction methods studied and for different degrees of reduction. Although it is a small network and the thermal inertias have little influence on the network, which was studied by the thermal engineering department of Tekniker in the Indigo project, in order to give more reliability to the results obtained statically it would be very interesting to model the network dynamically. Apart from that, as far as the Basurto hospital network is concerned, the reduction methods analysed are calculated for a particular flow, trying to integrate the automatic network reduction process created using Matlab for this project into the Basurto network control system and with that to calculate equivalent networks for the input flow at any given moment and uses them to control the network could be of interest.

On the other hand, as already mentioned, the Basurto network is small, so applying the reduction methods to a network with a considerable size, and to see how the automated reduction process created by applying it to another network works as well as modelling both statically and dynamically the original network and the equivalent networks at different reduction degrees and analysing the results obtained would be very useful to see how a network behaves in which the thermal inertias have more influence and if the reduction methods are valid for these cases.

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Appendixes

Appendix 1: Matlab reduction processes formulation

```
%% NETWORK PARAMETERS
% Read parameters of the system from the csv files
[Water_prop,Air_prop,Oper_param,Conf_charac,Pipe,Substations,Control_curves] = Read_parameters_network;
% Model definition: configuration and characteristics
[Model,Water,Air,Conf,Oper,Pipes,Substations,Valves] = Model_descrip(Water_prop,Air_prop,Oper_param,Conf_charac,Pipe,Substations,Control_curves);

%% Netwqork pipes' parameters

Pipes=Read_Parameters_Pipes(Pipes);

% The substations have L=0, but to simulate them a length is needed
for i=1:length(Pipes.L)
    if Pipes.L(i)==0
        Pipes.L(i)=0.5;
    end
end

Prop=Water_Steel_Prop; %Water and steel properties
Subs=[];
Subs2=[];
```

Figure 0.1: Network parameters

```
%% REDUCTION PROCESS
%% LOCATE PIPES IN SERIES AND CALCULATE THE EQUIVALENT PIPE
% Each of the groups of pipes in series are transformed into an equivalent
% pipe.
[Conf, Nser] = Serial_pipes_location(Conf);
Conf.delete_pipes=ones(1,Conf.np);
Conf.delete_nodes=ones(1,Conf.nn);

for i=1:length(Nser)
    [PipeAux,Num]=Pipes_Series2(Pipes,Prop,Nser{i});
    Pipes=Sum_Pipes_Table2(Pipes,PipeAux,Num);
    Conf = Structure_Modification_Serialpipes (Conf,Nser{i});
end

% The equivalent structure in which all pipes in series with each other are
% substitute by equivalent pipes is modified and saved to use it in the
% simulator
Pipes_1=Transform_Pipesdata(Pipes,Conf);
Conf_1=Conf;
[PipesOpt_1,ConfOpt_1]= Transform_for_Opti (Pipes_1,Conf_1);
save('PipesOpt_1.mat','PipesOpt_1');
save('ConfOpt_1.mat','ConfOpt_1');
```

Figure 0.2: Serial pipes calculation

```

%% LOCATE SUBSTATIONS IN PARALLEL AND CALCULATE THE EQUIVALENTS IN SERIES
Npar=Parallel_subs_location(Conf);
COND1=1;
COND2=1;

% The loop is repeated until all the substations in each main branch of the
% network are in series with each other
while COND1==1 || COND2==1
  for i=1:length(Npar)
    [PipeAux1,PipeAux2,Npar1,Num1,Num2]=Parallel_Equivalent_Temp2(Pipes,Prop,Npar{i});
    Pipes=Sum_Pipes_Table2(Pipes,PipeAux1,Num1);
    Pipes=Sum_Pipes_Table2(Pipes,PipeAux2,Num2);
    Pipes=Return_pipes(Pipes,Conf,Num1,PipeAux1);
    Pipes=Return_pipes(Pipes,Conf,Num2,PipeAux2);
    [Conf,Nser2,NserR,Naux,NauxR]= Structure_Modification_Parallelsubs(Conf,Npar1,Npar{i});
    if length(Naux)>1 && (Npar{i}~=Npar1)
      Pipes= Recalc_Pipes (Pipes,Naux,NauxR,Prop);
    end
    [PipeAux,Num]=Pipes_Series2(Pipes,Prop,Nser2);
    Pipes=Sum_Pipes_Table2(Pipes,PipeAux,Num);
    [PipeAux,Num]=Pipes_Series2(Pipes,Prop,NserR);
    Pipes=Sum_Pipes_Table2(Pipes,PipeAux,Num);
    Conf = Structure_Modification_Serialpipes (Conf,Nser2);
    Conf = Structure_Modification_Serialpipes (Conf,NserR);
  end
end
  
```

Figure 0.3: Parallel substations calculation (I)

```

Npar=Parallel_subs_location(Conf);

if length(Npar)==1
    N=Npar{1};
    COND1=Are_there_substations(N(1),Conf);
    COND2=Are_there_substations(N(2),Conf);
else
    Npar1=Npar{1};
    COND11=Are_there_substations(Npar1(1),Conf);
    COND21=Are_there_substations(Npar1(2),Conf);
    Npar2=Npar{2};
    COND12=Are_there_substations(Npar2(1),Conf);
    COND22=Are_there_substations(Npar2(2),Conf);
    if COND11==0 & COND21==0 & COND12==0 & COND22==0
        COND1=0;
        COND2=0;
    end
    if (COND11==0 & COND21==0) & (COND12==1 || COND22==1)
        Npar=Npar2;
    end
    if (COND11==1 || COND21==1) & (COND12==0 & COND22==0)
        Npar=Npar1;
    end
end
if length(Npar)<1;
    COND1=0;
    COND2=0;
end

end

Pipes_2= Transform_Pipesdata(Pipes,Conf);
Conf_2=Conf;
[PipesOpt_2,ConfOpt_2]= Transform_for_Opti (Pipes_2,Conf_2);
save('PipesOpt_2.mat','PipesOpt_2');
save('ConfOpt_2.mat','ConfOpt_2');

```

Figure 0.4: Parallel substations calculation (II)

```

%% LOCATE SUBSTATIONS IN SERIES AND CALCULATE THE EQUIVALENT

Nser=Series_subs_location(Conf);

for i=1:length(Nser)
    [Conf,Pipes]= Structure_Modification_Seriessubs(Conf,Nser{i},Pipes,Prop);
end
Conf.delete_pipes=Conf.delete_pipes';

for i=1:Conf.np
    if Conf.delete_pipes(i)==1
        if Conf.bhx(i)==1 || Conf.p_supply(i)==1
            Conf.end_pipes(i)=1;
        end
    end
end
Conf.end_nodes=Conf.delete_nodes.*Conf.n_supply;

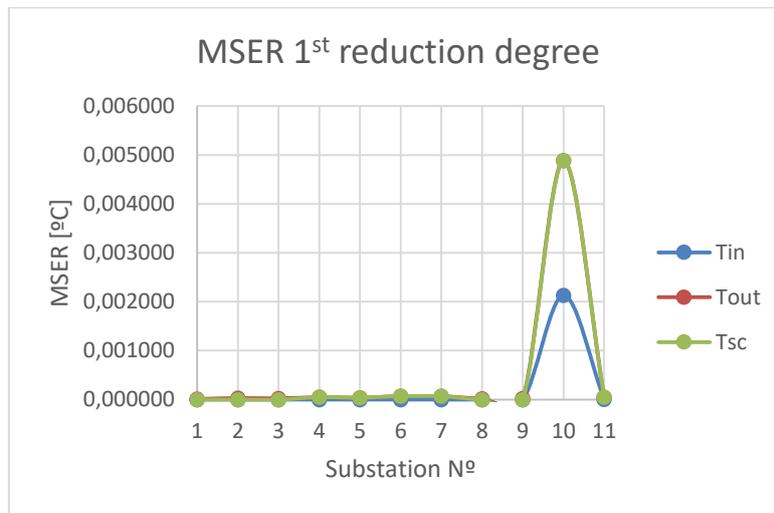
% The equivalent structure with the higher reduction degree is modified and
% saved to use it in the simulator
Pipes_3= Transform_Pipesdata(Pipes,Conf);
Conf_3=Conf;
[PipesOpt_3,ConfOpt_3]= Transform_for_Opti (Pipes_3,Conf_3);
save('PipesOpt_3.mat','PipesOpt_3');
save('ConfOpt_3.mat','ConfOpt_3');

```

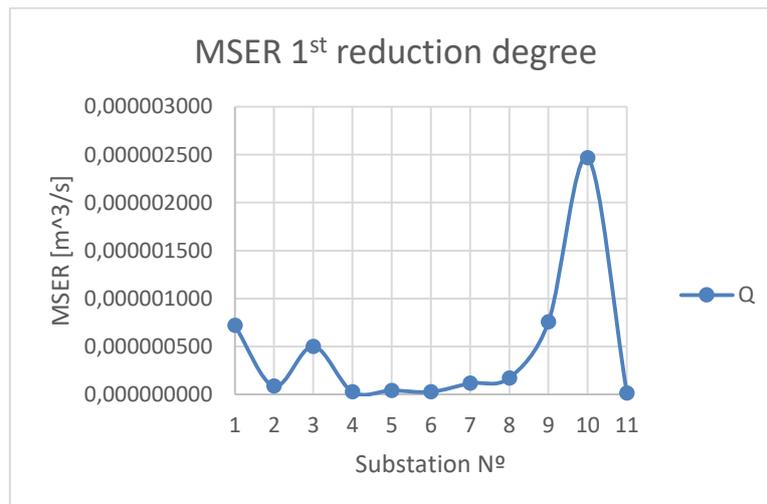
Figure 0.5: Series substations calculation

Appendix 2: 1st reduction degree results

- Hydraulic and thermal simulation:
 - MSER:

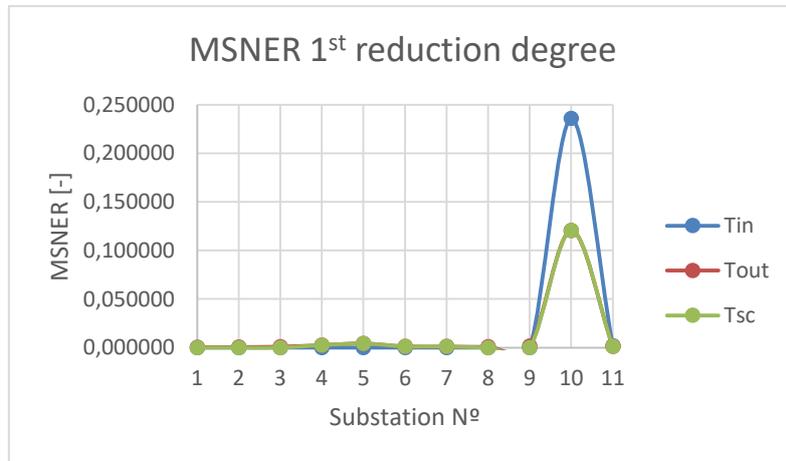


Graph 0.1: MSER 1st reduction degree Tin, Tout and Tsc

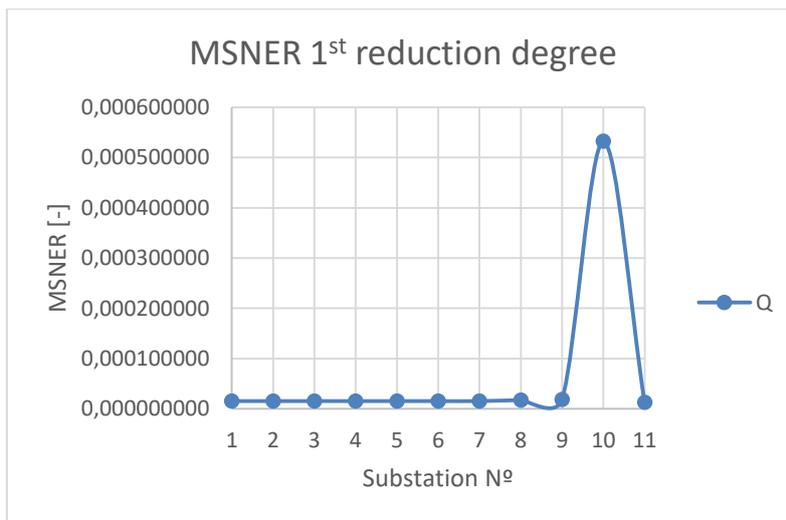


Graph 0.2: MSER 1st reduction degree Q

○ MSNER:

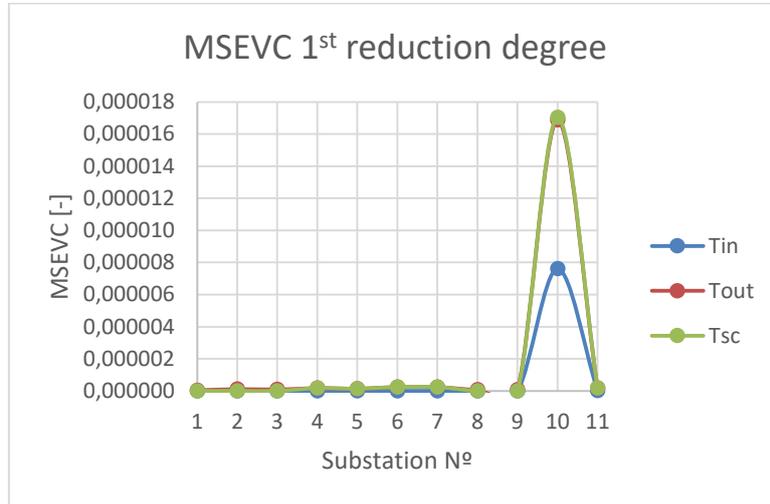


Graph 0.3: MSNER 1st reduction degree Tin, Tout and Tsc

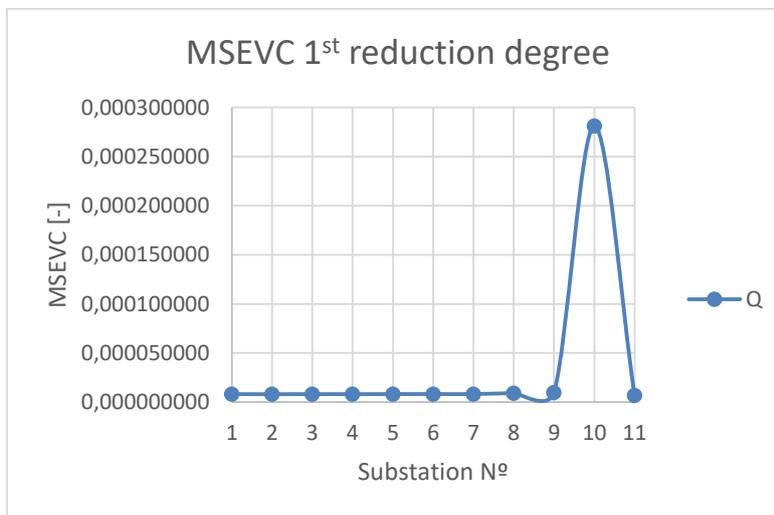


Graph 0.4: MSNER 1st reduction degree Q

○ MSEVC:



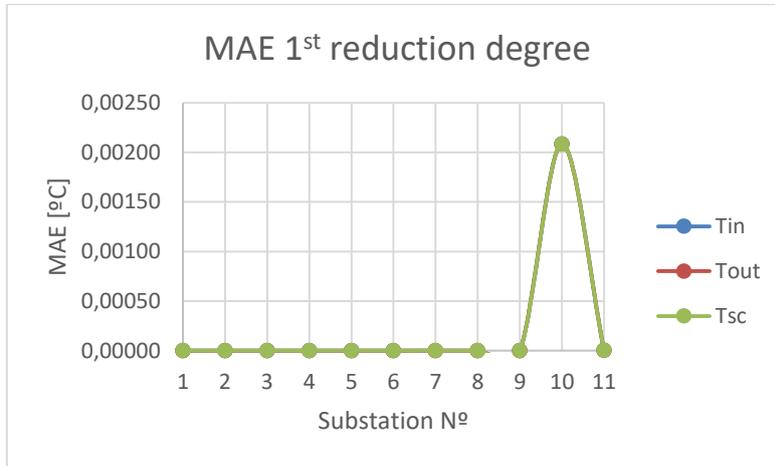
Graph 0.5: MSEVC 1st reduction degree Tin, Tout and Tsc



Graph 0.6: MSEVC 1st reduction degree Q

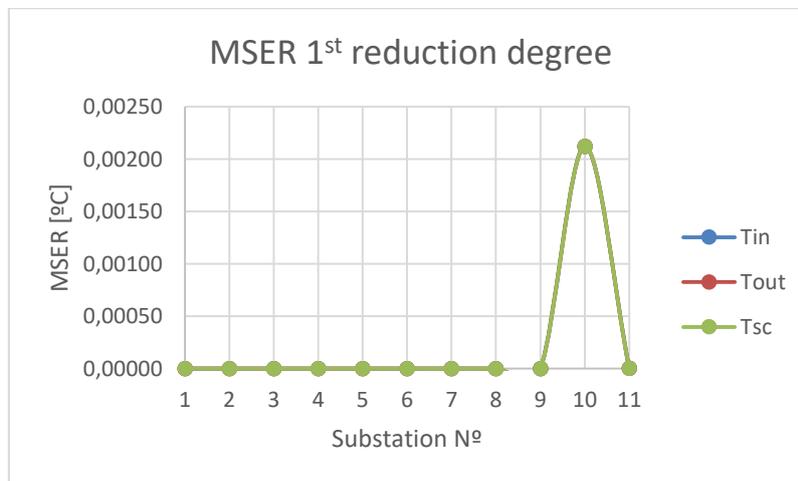
- Thermal simulation:

- MAE:



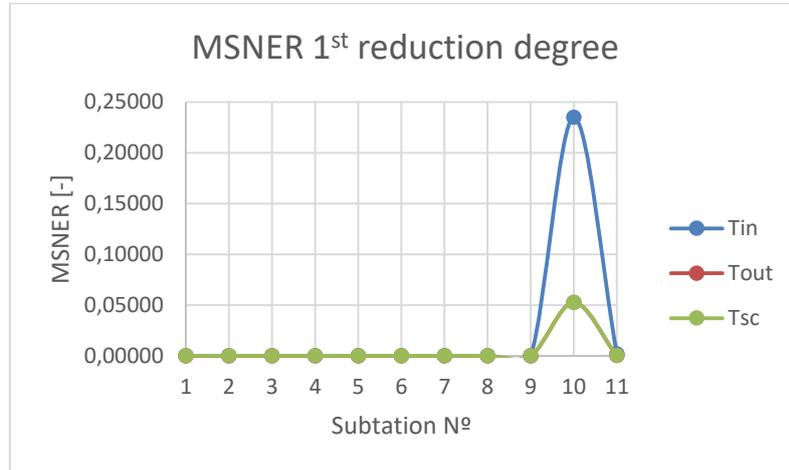
Graph 0.7: MAE 1st reduction degree Tin, Tout and Tsc

- MSER:



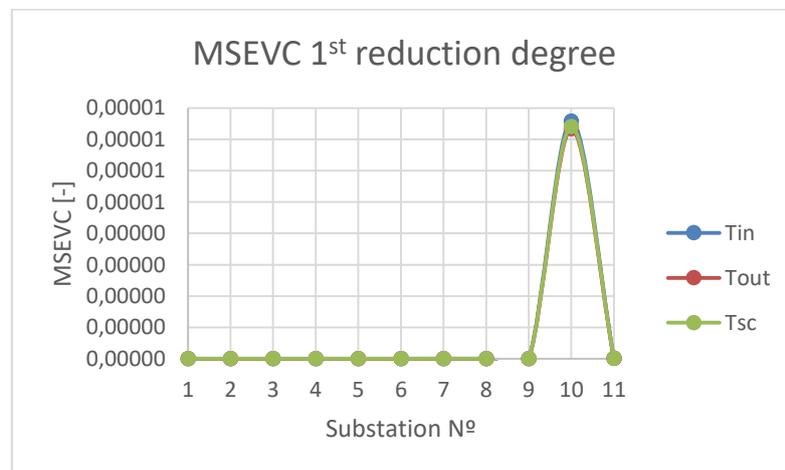
Graph 0.8: MSER 1st reduction degree Tin, Tout and Tsc

○ MSNER:



Graph 0.9: MSNER 1st reduction degree Tin, Tout and Tsc

○ MSEVC:

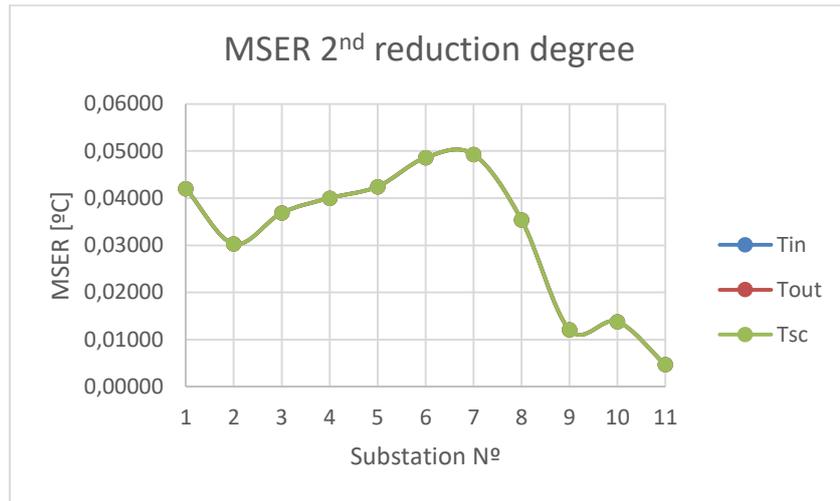


Graph 0.10: MSEVC 1st reduction degree Tin, Tout and Tsc

Appendix 3: 2nd reduction degree results

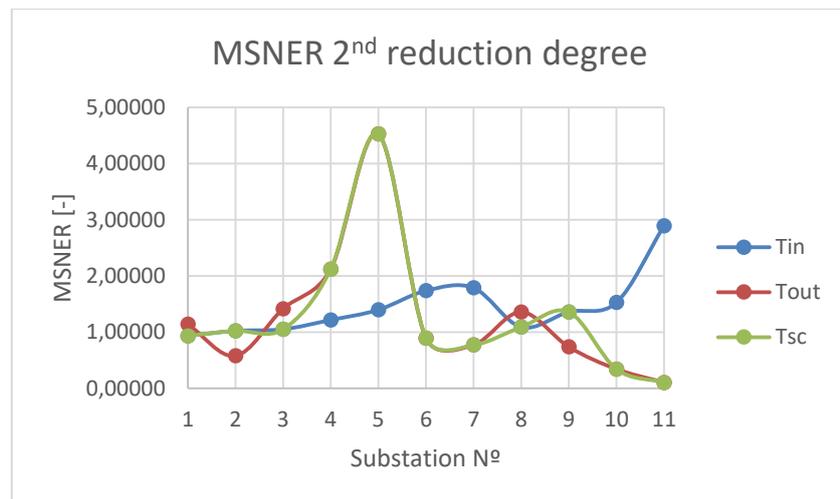
- Thermal equivalent network for DM and GM:

- MSER:



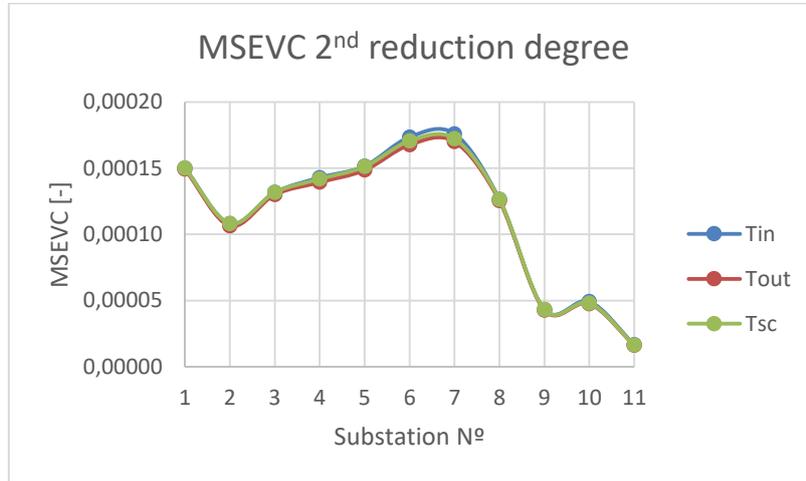
Graph 0.11: MSER 2nd reduction degree Tin, Tout and Tsc

- MSNER:



Graph 0.12: MSNER 2nd reduction degree Tin, Tout and Tsc

- MSEVC:

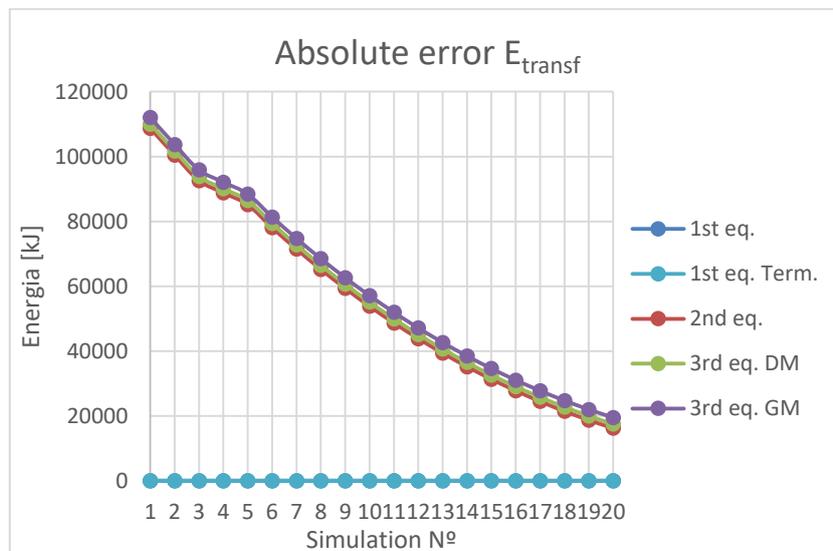


Graph 0.13: MSEVC 2nd reduction degree Tin, Tout and Tsc

Appendix 4: Other results and errors

- Thermal equivalent network for DM and GM:

- AE E_{transf} :



Graph 0.14: AE E_{transf} in kJ