DESIGN OF WATER DISTRIBUTION SYSTEM BY OPTIMIZATION USING RELIABILITY CONSIDERATIONS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

TEVFİK AKDOĞAN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
DEPARTMENT OF CIVIL ENGINEERING

APRIL 2005

Approval of the Graduate School of Natural And Applied Sciences

Prof. Dr. Canan Özgen
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Erdal Çokça
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Nuri Merzi
Supervisor

Examining Committee Members

Prof. Dr. Suha Sevük (METU, CE) _________________________

Assoc. Prof. Dr. Nuri Merzi (METU, CE) _________________________

Prof. Dr. Melih Yanmaz (METU, CE) _________________________

Assist. Prof. Dr. Ayşe Burcu Altan Sakarya (METU, CE) ______________________

İlker Eker, M.S. (ASKİ) _________________________

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Name, Last name : Tevfik Akdoğan

Signature :

ABSTRACT

DESIGN OF WATER DISTRIBUTION SYSTEM BY OPTIMIZATION USING RELIABILITY CONSIDERATIONS

Akdoğan, Tevfik
Department of Civil Engineering
Supervisor : Assoc. Prof. Dr. Nuri Merzi

April 2005, 91 pages

In spite of a wide research, design of water distribution networks are not realized using optimization techniques. One reason for this fact is, design of water distribution networks is evaluated, mostly, as a least-cost optimization problem where pipe diameters being the only decision variables. The other motivation for preferring the traditional modeling practice is that, existing optimization algorithms are not presented to the user as friendly as it should be.

In fact, water distribution systems are very complex systems such that it is not easy to obtain least-cost design systems considering other constraints such as reliability, in addition to classical constraints related to hydraulic feasibility, satisfaction of nodal demands and requirement of nodal pressures. This study presents a user-friendly package concerning the design of water distribution networks by optimization using reliability considerations; this works employs the algorithm proposed by Goulter and Coals (1986). At the end, a skeletonized network design is offered; various costs are estimated in regard to the degree of reliability.

Keywords: Water Distribution Systems, Linear Optimization, Reliability, Water Distribution Network of Ankara.

ÖZ

ŞEHİR SU ŞEBEKELERİNİN GÜVENİLİRLİK DAHİLİNDE OPTİMİZASYON KULLANILARAK TASARLANMASI

Akdoğan, Tevfik
İnşaat Mühendisliği Bölümü
Tez Yöneticisi : Doç. Dr. Nuri Merzi

Nisan 2005, 91 sayfa

Kapsamlı araştırmalara rağmen, optimizasyon teknikleri şehir su şebekelerinin tasarımında uygulanmamaktadır. Bunun temel nedeni, şehir su şebekelerinin tasarımının, sadece, boru çapları dikkate alınarak ve minimum maliyet hedefi gözetilerek bir optimizasyon çalışmasının gerçekleştirilmesidir. Geleneksel model uygulamalarının tercihindeki diğer neden ise var olan optimizasyon algoritmalarının olması gerektiği kadar kullanıcı kolaylığı sağlamamasıdır.

Gerçekte, şehir su şebekeleri oldukça karmaşık bir yapıya sahip oldukları için, noktasal su taleplerinin ve su basınçlarının karşılanması gibi klasik hidrolik verimlilik sınırlamalarının yanı sıra, minimum maliyetin ötesinde, mesela güvenilirliğin dikkate alınması kolay olmamaktadır. Bu çalışma, kullanıcı kolaylığı sağlayan ve güvenilirliği göz önünde bulundurarak, şehir su şebekelerinin tasarımını, lineer optimizasyon metoduyla gerçekleştiren bir program sunmaktadır. Çalışmada Goulter ve Coals'un (1986) sundukları algoritma kullanılmaktadır. İskeletleştirilmiş bir şebekenin tasarımı ve bu şebeke için güvenilirlik derecesine bağlı olarak elde edilmiş çeşitli maliyet hesaplamaları çalışmanın sonunda yer almaktadır.

Anahtar Sözcükler: Şehir Su Şebekesi, Lineer Optimizasyon, Güvenilirlik, Ankara Su Şebekesi

To My Fiancée, Neslihan Şalcı

ACKNOWLEDGMENTS

Thesis subject was proposed by Assoc. Prof. Dr. Nuri MERZİ. The author would like to express sincere appreciation to Assoc. Prof. Dr. Nuri Merzi for his valuable supervision, precious help, invaluable suggestions and continuous support throughout this study.

This study was supported by the Department of Civil Engineering, Middle East Technical University. The author would like to thank Department of Civil Engineering for their support during study.

The author also would like to express his gratitude to his family, for their supports, and encouragement.

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CHAPTER 1

INTRODUCTION

A water distribution system is a hydraulic infrastructure that conveys water from the source to the consumers; it consists of elements such as pipes, valves, pumps, tanks and reservoirs.

The most important consideration in designing and operating a water distribution system is to satisfy consumer demands under a range of quantity and quality considerations during the entire lifetime for the expected loading conditions. Also; a water distribution system must be able to accommodate abnormal conditions such as breaks in pipes, mechanical failure of pipes, valves, and control systems, power outages, malfunction of storage facilities and inaccurate demand projections. The possibility of occurrence of each of these deficiencies should be examined to determine the overall performance and thereby the reliability of the system. In general, reliability is defined as the probability that the system performs successfully within specified limits for a given period of time in a specified environment. As it is defined above, reliability is the ability of a system to provide adequate level of service to the consumers, under both normal and abnormal conditions. However, there is still not a convenient evaluation for the reliability of water distribution systems.

Traditionally, a water distribution network design is based on the proposed street plan and the topography. Using commercial software, the modeler simulates flows and pressures in the network and flows in and out to/from the tank for essential loadings. In this exercise, the modeler depends basically on his/her experience. However, even a small network containing pipes at the order of thirty can require millions of combinations of pipes not including pumps, tanks and valves. It is scarcely possible that a modeler, using traditional modeling practices, finds the optimum solution even for a small network concerning a least cost design. That's why, optimization techniques are applied for the design of water distribution networks.

Most of the optimization programs define the design problem basically as minimizing the pipe cost subjected to (1) the satisfaction of the velocity and the pressure constraints, (2) the satisfaction of nodal demands. However, modelers need to take into account, especially, reliability considerations and monetary limitations also.

Optimization of a water distribution system is quite complicated due to nonlinear relationships between parameters. Recently, significant amount of research has been performed on the optimal design of water distribution networks. Some of the first studies utilized linear programming (LP); later studies applied nonlinear programming (NP) and Genetic algorithm studies (GA).

Significant amount of research about optimization techniques for design of water distribution networks has been performed for years and there exist theories about optimization. But, many of these theories can not be modeled due to complexity of methods and difficulty of technical application of these theories to real networks. Nowadays, it is easier to model these optimization theories by the help of computers. As the cities grow, the importance of managing capital and maintenance costs of larger networks necessitates using of optimization techniques.

There are various researches about water distribution system reliability based optimization. Reliability based optimization of water distribution systems requires combination of an optimization algorithm with a method for estimating reliability. Goulter and Coals (1986) studied "quantitative approaches to reliability assessment in pipe networks". In this work, their study is improved and then modeled as a computer program to design any water distribution system. Objective of this program is to apply Goulter and Coals' (1986) theory to several water distribution networks: a skeletonized form of the pressure zone N8 (Ankara Water Distribution Network) is designed under various reliability levels.

In Chapter 2, a short review of optimization techniques of water distribution networks and water distribution system reliability is accomplished. In Chapter 3, methodology of linear programming which is used in the Case Study is presented. In Chapter 4, the application of the methodology based on Goulter and Coals (1986) is described. Design and analysis studies on sample water distribution networks are included in Chapter 5. Finally, conclusions are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Optimization Studies in Water Distribution Networks

In this chapter, a short review of optimization techniques of water distribution networks and water distribution system reliability is given. There are various applications of optimization methods concerning water distribution networks. These applications can be classified roughly into three classes: (1) calibration studies, (2) Operation studies, (3) Design / Extension / Rehabilitation studies.

2.1.1 Calibration Studies

Constructing a calibrated hydraulic network model consists of adjusting the selected parameters by comparing their measured and calculated values. If selected parameters of the network are pipe roughness and nodal demands, a procedure should be carried out in order to determine specific roughness values for the pipes and specific nodal demands for the nodes which will minimize the differences between measured (at the field) and calculated (using the hydraulic model) values. In the optimization-based models, the objective function (the difference between measured and calculated values) is minimized while satisfying constraints, which describe the feasible solution (Ormsbee et al. (1989); Lansey and Basnet (1991)).

Deciding for sampling locations for making measurements of pressure is another issue in calibration. Walski (1983) proposes that measurements should be made near large demands and near the boundary of the pressure zone; furthermore, it was advised that sampling points should be away from sources. However, it is difficult to decide for the exact location of sampling points; because, to calibrate a hydraulic model, test data should have already been obtained (sampling points' locations should be fixed beforehand). On the after hand, calibration parameters (resistance coefficients and nodal demands) can be obtained if the test locations were determined. Consequently, an iterative procedure should be realized, taking into account the sensitivity of the network.

The processes of selecting sampling points are accomplished by Bush and Uber (1998), Piller, et al. (1999), Meier and Barkdoll (2000) among others.

2.1.2 Operation Studies

Generally energy costs form a large percentage of the total expenditure of the water utilities. It is critical to organize the operation of all the pumps to minimize energy consumption. Jowitt and Germanopoulos (1992) propose a linear programming (LP) model whereas Yu et al (1994) and Percia et al. (1997) propose a nonlinear programming (NP) model among others. The basic advantage of LP is the possibility of using commercial software and finding global optimum; on the other hand, the loss of information through the linearization process is the main disadvantage.

2.1.3 Design of Optimal Water Distribution Networks

The general water distribution network design problem aims minimizing the whole network cost, since these systems are costly infrastructures. However optimization of a water distribution system is quite complicated due to nonlinear relationships between parameters. Recently, significant amount of research has been performed on the optimal design of water distribution networks. One of the first computerized optimization study was accomplished by Schanke and Lai (1969). Walski (1985) reviewed approximately hundred studies concerning optimization since then. During the next fifteen years, another notable increase in this field was observed. Study of famous optimization problems such as New York tunnel problem (Schanke and Lai, 1969), and various real systems (Jacobsen et al., 1998) were realized among others. According to Walski (2001), the algorithms which were developed until then do not simulate the whole course of the design. For example, (1) reliability considerations developed so far were not applied realistically (2) Monetary constraints was not included, (3) Benefits were not considered at all. As Walski (2001) mentions, because of these reasons and unfriendly packaging of the related software, engineers continue to design using traditional tools.

Number of theories coupled with the availability of inexpensive powerful hardware, the development of theories in the last three decades has improved considerably the ability to simulate hydraulic behavior of large water distribution networks (Rossman, et al. 1993). These models play an important role in layout, design and operation of water distribution systems. Selection of pipe diameters from a set of commercially available diameters to form a water distribution network of least capital cost has been shown to be a hard problem. The cost of maintenance and operation of a water distribution system may be considerable, but still one of the main costs is that of the pipelines themselves. In recent years a number of optimization techniques have been developed primarily for the cost minimization aspect of network planning, although some reliability studies and stochastic modeling of demands have been attempted.

Some of the first studies utilized which linear programming were performed by Alperovits and Shamir (1977); Quindry et al. (1981), and Shamir and Howard (1985). While later studies applied nonlinear programming (NP) Su, et al. (1987); Lansey and Mays (1989); Xu and Goulter (1999), or chance constrained approaches Lansey and Mays (1989) to the pipe network optimization problem. Much of the recent literature has utilized genetic algorithms for the determination of low cost water distribution network design and they have been shown to have several advantages over more traditional optimization methods (Simpson et al. (1994); Savic and Walters (1997)).

Linear optimization methods have been widely studied for the case of determining optimal design of water distribution networks. Alperovits and Shamir (1977) studied a method called linear programming gradient (LPG) method, by which optimal design of a water distribution system can be obtained. Operation of the system under each of a set of demand loading is considered explicitly in the optimization.

2.2 Water Distribution System Reliability

The American Water Works Association (1974) defines a water distribution system as one "including all water utility components for the distribution of finished or potable water by means of gravity storage feed or pumps through distribution-equalizing storage." Both cost of capital for first set up and cost of operation, maintenance and repair for the time water distribution network service to end users are large; designers try to reduce total cost of system. But this is a very difficult process to obtain minimal cost solution for a water distribution system because of the large number of parameters affecting cost. While optimizing a system, designer must take some expected and unexpected loading conditions into consideration to ensure delivery of water to end user. The most important consideration in the design and operation of a water distribution system is to satisfy consumer demands under a range of desired quantity and quality during the systems' entire lifetime for the expected loading conditions. Also water distribution system must be able to accommodate abnormal conditions such as breaks in pipes, mechanical failure of pipes, valves, and control systems, power outages, malfunction of storage facilities and inaccurate demand projections. The possibility of occurrence of each of these deficiencies should be examined to determine the overall performance and thereby the reliability of the system. In general, reliability is defined as the probability that the system performs specified limits for a given period of time in a specified environment. As it is defined above reliability is ability of systems to provide adequate level of service to system consumers, under both normal and abnormal conditions. However there is still not convenient evaluation for water distribution system reliability as there are many measures of reliability. A review of the literature, Mays, (1989) reveals that no universally acceptable definition or measure of the reliability of water distribution system is currently available.

2.3 Incorporation of Reliability in the Least-cost Design of Looped Water Distribution Networks.

Over the past years, considerable effort has been devoted to the development of optimization algorithms and models for the design of water distribution networks. Many of these theories have the objective of minimizing the both capital and operating costs. (Alperovits and Shamir, 1977; Quindry et al., 1981; Shamir and Howard (1985); Lansey and Mays, 1989; Eiger et al., 1994; Simpson et al., 1994; Savic and Walters, 1997) However, in practice, the optimal design of a water distribution network is a complex multiple objective process involving trade-offs between the cost of the network and its reliability, Xu and Goulter, (1999). Reliability incorporated optimization of water distribution systems requires combination of an optimization algorithm with a method for estimating reliability..

The term ‘‘reliability’’ for water distribution networks does not have a well-defined meaning. Nevertheless, it is generally understood that reliability is concerned with the ability of the network to provide an adequate supply to the consumers, under both normal and abnormal operating conditions (Goulter, 1995).

The first explicit considerations of probabilistic issues in the reliability of water distribution networks were reported by Kettler and Goulter (1983), who included the probability of pipe breakage as a constraint in an optimization model for the design of pipe networks. Then, Goulter and Coals, (1986) developed a quantitative approach to reliability measure in an optimized looped network. This approach begins by obtaining an “optimal” layout design through linear programming. Then, approach addresses the probability of isolating a node through simultaneous failure of all links connected directly to that node. The probability of failure of individual links is modeled using the Poisson probability distribution.

CHAPTER 3

METHODOLOGY OF LINEAR PROGRAMMING

This methodology, which seeks to determine the pipe sizes and associated lengths so as to minimize the cost of the system while satisfying hydraulic criteria and reliability requirements, is derived from a model developed by Goulter and Coals (1986) which in turn is originated from an earlier model developed by Alperovits and Shamir (1977), and described below.

Optimization tries to find best diameters for network links to reach optimum result. In this method, assumed unknown parameter for any link is not the pipe diameter but the lengths of the available pipe diameters, X_{jk}.

Objective Function:

Minimize $$C = \sum_{j=1}^{NL} \sum_{k=1}^{n(j)} c_{jk} \cdot X_{jk} \qquad (3.1)$$

Subject to the following constraints:

1. Length: the sum of the lengths of pipe in each link must equal the total length of the link where a link represents a pipe connecting two nodes directly.

$$\sum_{k=1}^{n(j)} X_{jk} = L_j \quad \text{For all links j} \qquad (3.2)$$

2. Head loss: minimum and maximum permissible head at each demand point or node must be satisfied.

$$H_o - \sum_{j \in p(n)} \sum_{k=1}^{n(j)} J_{jk} \cdot X_{jk} \geq H_{n_{\min}} \quad \text{For all nodes n} \tag{3.3}$$

$$H_o - \sum_{j \in p(n)} \sum_{k=1}^{n(j)} J_{jk} \cdot X_{jk} \leq H_{n_{\max}} \quad \text{For all nodes n} \tag{3.4}$$

3. Loop: for a looped system, the total head loss around a loop must equal zero.

$$\sum_{j \in p'(b)} \sum_{k=1}^{n(j)} J_{jk} \cdot X_{jk} = 0 \tag{3.5}$$

4. Non-negativity:

$$X_{jk} \geq 0 \quad \text{For all } j \text{ and } k \tag{3.6}$$

5. Reliability: a measure of reliability is incorporated into this constraint set by Equation 3.7, which limits the expected (average) number of breaks in given time period in any link

$$\sum_{k=1}^{n(j)} r_{jk} \cdot X_{jk} \leq R_j \quad \text{For all links } j \tag{3.7}$$

where

C_{jk} : cost of pipe of diameter k in link j ($/km)
C : total cost of the system ($)
H_{nmin} : minimum allowable head at node n (m)
H_{nmax} : maximum allowable head at node n (m)
H_o : original head at source (m)
J_{jk} : hydraulic gradient for pipe diameter k in link j (m/km)
L_j : total length of link j (km)
$n(j)$: number of different pipe diameters in link j
NL : total number of links within the system
$p(n)$: links in the path from source to node n
$p'(b)$: links in the path associated with net head loss B_p
r_{jk} : expected number of breaks/km/year for diameter k in link j
R_j : maximum allowable number of failures per year in link j
X_{jk} : length of pipe of diameter k in link j (km)
j : link index
k : diameter type index

CHAPTER 4

MODELING STUDY: CATE

Application of the methodology described in Chapter 3 is a difficult procedure even for a two-looped small network due to:

- Variety of parameters.
- The modification in the constraint equations for different cycles for the same water distribution network (because, head loss constraint, (Equation 3.3 and 3.4) may be changed for different cycles because of change in flow directions in the pipes).
- The transfer of input/output data between the hydraulic network solver and the linear optimization software is required in each cycle.
- The application which is time consuming (and it is easy to make errors).
- The difficulty of modification or change of the objective function and constraint equations for different water distribution networks.

To eliminate the drawbacks described above, a program is formed, named CATE. An easy and quick application of the theory to any water distribution network can be achieved by employing CATE.

4.1 Components of CATE

CATE is a program that is coded in C ++ to perform application of the methodology described in Chapter 3. CATE uses engines of two other programs, EPANET, EPANET programmer Toolkit and Lindo API. EPANET is free hydraulic network solver software provided by Environmental Protection Agency (EPA). Lindo API is a commercial linear optimization program. CATE includes three subroutines called CATE code 1, 2 and 3. Functions of each subroutine and the algorithm of CATE are explained below. Figure 4.1 presents the general procedure followed by CATE.

EPANET: EPANET operates under Windows 95/98/NT/XP; it performs extended period simulation of hydraulic and water-quality behavior within pressurized pipe networks. A network may consist of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of chemical species throughout the network during a simulation period comprised of multiple time steps. In addition to chemical species, water age and source tracing can also be simulated.

The Windows version of EPANET provides an integrated environment for editing network input data, running hydraulic and water quality simulations, and viewing the results in a variety of formats. These include color-coded network maps, data tables, time series graphs, and contour plots.

EPANET was developed by the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory. It is public domain software that may be freely copied and distributed.

EPANET PROGRAMMER TOOLKIT: EPANET is a program that analyzes the hydraulic and water quality behavior of water distribution systems. The EPANET Programmer's Toolkit is a dynamic link library (DLL) of functions that allows developers to customize EPANET's computational engine for their own specific needs. The functions can be incorporated into 32-bit Windows applications written in C/C++, Delphi Pascal, Visual Basic, or any other language that can call functions within a Windows DLL. The Toolkit DLL file is named EPANET2.DLL and is distributed with EPANET. The Toolkit comes with several different header files, function definition files, and .lib files that simplify the task of interfacing it with C/C++, Delphi, and Visual Basic code.

EPANET programmer toolkit provides the execution of hydraulic network analysis, without using EPANET interface. To define network topology properties, schematic input is not required in toolkit; text input is enough to define network to hydraulic solver. As well as, the outputs of the hydraulic analyses are available in text format with toolkit.

LINDO API: LINDO (Linear, INteractive, and Discrete Optimizer) is a convenient, but powerful tool for solving linear, integer, and quadratic programming problems.

CATE CODE 1: This function prepares input file for Lindo API by using the output file provided by EPANET. Objective function and linear constraints described in the methodology section are formed within this code.

CATE CODE 2: This function extracts optimized diameters from Lindo API and replaces the diameters in previous EPANET input file by these values; in other words it creates new input file for EPANET and runs the modified network with these new inputs. LINDO may result one, two or more diameter for one link, this code eliminates the diameters and results with the longest pipe diameter.

CATE CODE 3: This function compares new directions of flow with previous ones. If they are all same, it stops the program; it means that the optimized network is reached. If not, it return to step one with the modified output file provided by CATE code 2 (output file obtained in step 8).

4.2 The Procedure Followed by CATE

The algorithm flowchart describing CATE's procedure is presented in Figure 4.1. There are totally eleven basic steps in the procedure. In this study, one cycle of progress from step 1 to step 11 is called a "run".

Step 1 is the place for data input, afterwards EPANET proceeds to step 2 with this data. Results are obtained in step 3. Then, linear optimization objective function and constraints are formed in step 4 and LINDO runs with the prepared input file, in step 5. Output of LINDO is evaluated in step 6 and 7, and then new network is formed in step 8. In step 9, hydraulic analysis of the network is performed. Step 10 is the decision place to continue or stop the run.

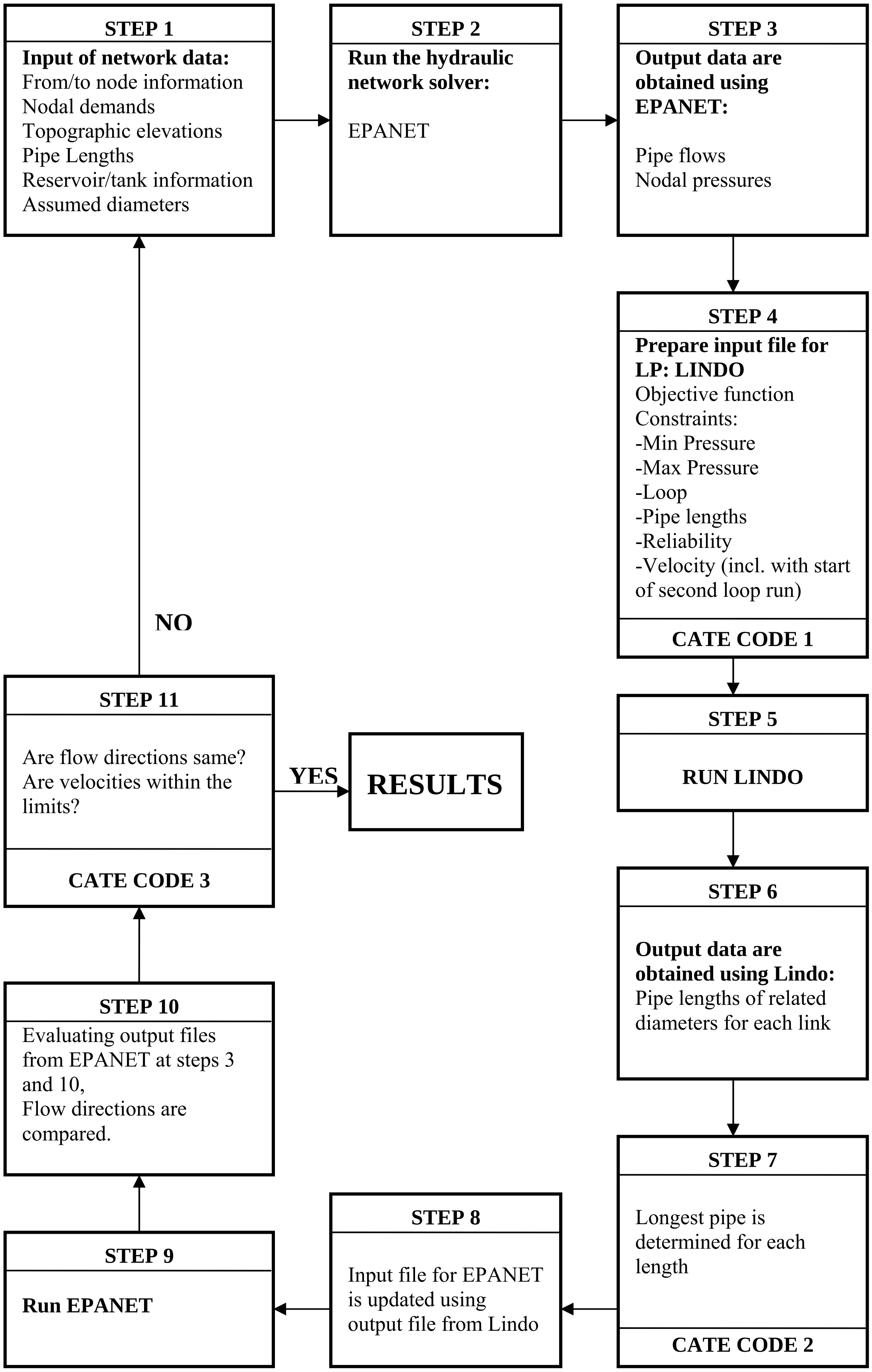


Figure 4.1 Algorithm Flowchart of CATE

4.3 Algorithm of CATE

In this section, eleven steps of the algorithm of CATE are explained in further details.

4.3.1 Step 1 of the Algorithm: Forming Input Files

To start with the design of any water distribution network with CATE, user prepared input files for the network are required. These files are; deneme.inp, pipeTypes.txt and loops.txt.

Deneme.inp is the text input file of EPANET, includes water distribution network properties. This file is used for input file for network properties and contains information about:

- Junction topographical elevations and flow demands,
- Reservoir elevations,
- Pipe lengths, assumed diameters, roughness, and topology properties.
- Hydraulic analysis options.

Deneme.inp file can be created from EPANET command menu. Initially, EPANET must be installed to computer (EPANET 2.0, User Manual). Afterwards, the water distribution network that is intended to be designed should be created in EPANET. See Figure 4.2 for EPANET interface.

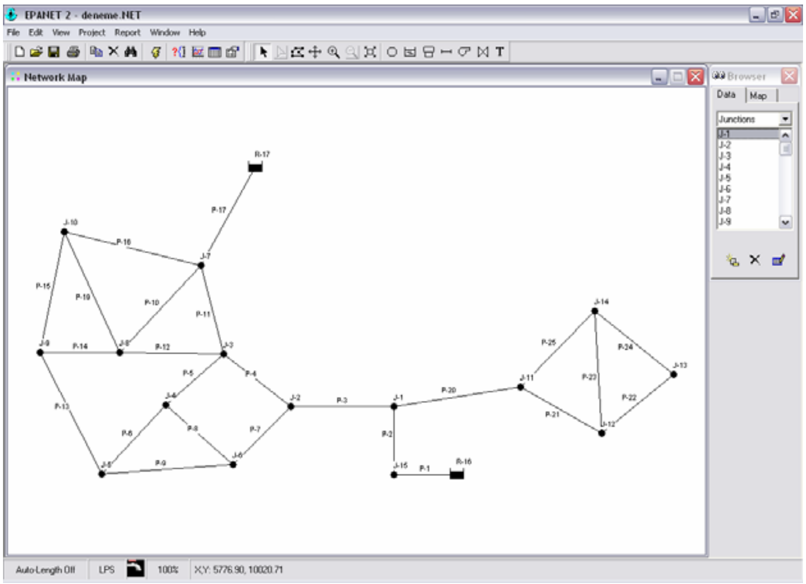


Figure 4.2 EPANET Interface

Deneme.inp file can be created from file>export>network pull down menu of EPANET, see Figure 4.3.

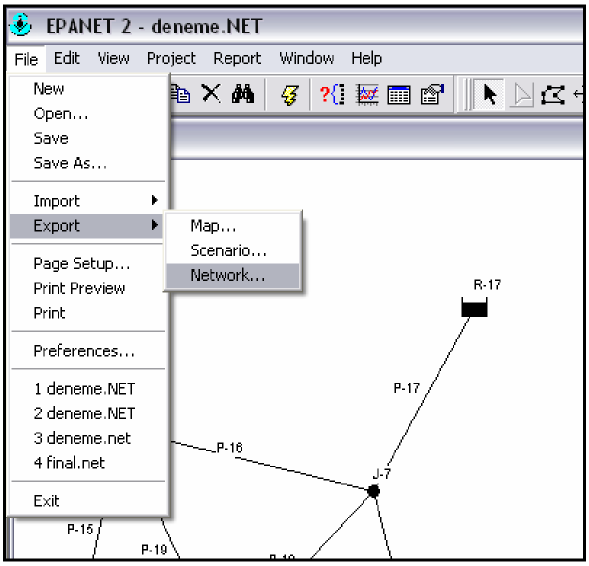


Figure 4.3 Export of Network file

In this version CATE cannot identify loop structure of water distribution network by itself; hence a loop identifying file must be defined by user. Loop.txt file contains loop number and pipes and junctions that constitute loops. This file introduces the loop structure to CATE.

```
8
3 10 19 8 14 9 15 10
3 10 16 7 10 8 19 10
3 7 11 3 12 8 10 7
5 3 5 4 6 5 13 9 14 8 12 3
4 3 4 2 7 6 8 4 5 3
3 4 8 6 9 5 6 4
3 14 24 13 22 12 23 14
3 14 23 12 21 11 25 14
```

Figure 4.4 Loop.txt File

Structure of the loop file:

The number in the first line indicates the total number of loops in the water distribution network. The second and following lines indicates each loops' structure. One line is used for one loop, and the number of lines can not exceed the total number of loops indicated in the first line. First character of these loop lines defines the total number of pipes that constitute these loops. Following characters defines node and pipe ID in order with the link continuity. One blank space must be left between each character.

The Loop.txt file displayed in Figure 4.4 is described below as an example.

First Line: This line shows number of loops in the water distribution network; and indicates that there are 8 loops in the network.

Second line: This line describes the loop in Figure 4.5.

Second line, first character: Number of pipes in the loop is defined with first character. In the example, number of pipes is equal to 3.

Second line, second character: ID of initial junction of the loop is defined with this character. Any junction in the loop can be selected by user as start junction for the loop, then the continuity must not be disturbed while selecting following pipes and junctions until last pipe. The direction of the loop can be defined as clockwise or counterclockwise.

Second line, third character: ID of adjacent pipe to initial selected pipe is defined with this number.

Defining of the adjacent junction and pipe ID's must continue according to described criteria up to starting Junction ID.

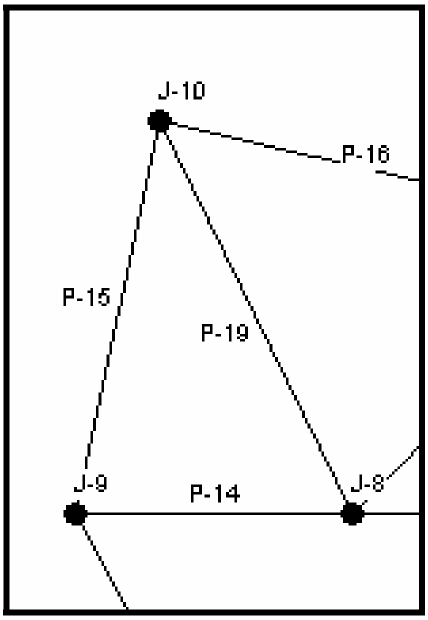
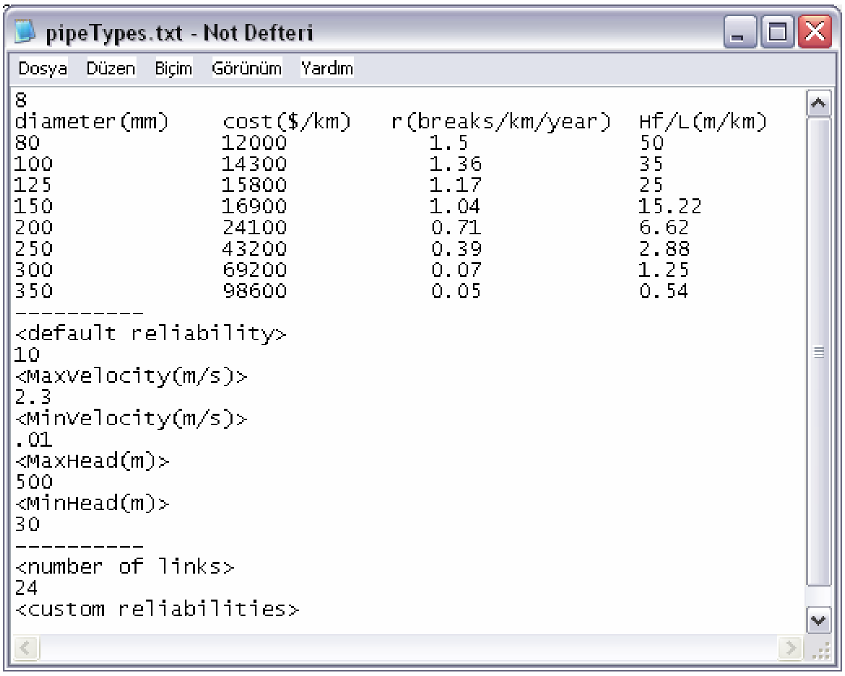


Figure 4.5 Loop Scheme

Last input file, pipeTypes.txt is used to define constraints and commercial pipe types available for the design, see Figure 4.6.

Detailed definition of pipeTypes.txt file is described below:

- Number of available commercial pipe types defined in the first line.
- Properties of available pipes defined in adjacent lines. Defined properties of the pipes are: diameter of pipes, unit cost of pipes ($/km), statistical breaks of pipes (breaks/km/year), and head loss gradients of the pipes (m/km).
- After than, default reliability constraint of the network links are indicated in the next line.
- Subsequently, allowable minimum and maximum velocity limits are defined in the following lines.
- Then, allowable maximum and minimum pressure heads are defined in the next lines.
- Afterward, number of links in the network is defined.
- Finally custom reliabilities can be defined in the following lines.



```
8
diameter(mm)    cost($/km)   r(breaks/km/year)  Hf/L(m/km)
80              12000           1.5             50
100             14300           1.36            35
125             15800           1.17            25
150             16900           1.04            15.22
200             24100           0.71            6.62
250             43200           0.39            2.88
300             69200           0.07            1.25
350             98600           0.05            0.54
-----------
<default reliability>
10
<MaxVelocity(m/s)>
2.3
<MinVelocity(m/s)>
.01
<MaxHead(m)>
500
<MinHead(m)>
30
-----------
<number of links>
24
<custom reliabilities>
```

Figure 4.6 pipeTypes.txt file

Table 4.1 Expected Number of Breaks per km per year

Pipe Size (mm)	r - expected number of breaks/km/yr
100	1.36
150	1.04
200	0.71
250	0.39
300	0.07
350	0.05

Kettler and Goulter (1983)

Table 4.2 Hydraulic Loss Gradients according to recommendations of AWWA

Hydraulic Gradient, acc. to AWWA recommendations	
Diameter(mm)	**J (m/km)**
80	50.00
100	35.00
125	25.00
150	15.22
200	6.62
250	2.88
300	1.25
350	0.54

4.3.2 Step 2 of Algorithm: Network Hydraulic Analysis by EPANET

In this step, EPANET analyzes network defined by deneme.inp file.

4.3.3 Step 3 of Algorithm: Output of Hydraulic Analysis by EPANET

In this step output of the hydraulic analysis is obtained and stored in the cache memory by CATE.

4.3.4 Step 4 of Algorithm: Prepare Input file for LP – CATE Code 1

In this step, CATE generates objective function and constraints, and then converts them into a format appropriate for input file of to Lindo API.

CATE Code 1 gets information about;

- Number of links, number of pipe types, properties of pipe types, velocity head, pressure head and reliability constraints from pipeTypes.txt file.
- Loops information from loops.txt. file.
- Direction of flow information in the network from the cached hydraulic analysis report obtained in the previous step.

After getting information, CATE Code 1 generates objective function and constraints for optimization.

Objective function and constraint equations try to find best diameters for network links to reach the optimum result. Note that, in this approach, assumed unknown parameter for any link is not the pipe diameter but the lengths of the available pipe diameters defined in the pipeTypes.txt file. CATE finds out lengths of predefined available pipe diameters for each link.

In reference with the objective function (equation 4.1),

$$C = \sum_{j=1}^{NL} \sum_{k=1}^{n(j)} c_{jk} \cdot X_{jk} \tag{4.1}$$

CATE generates objective function for network.

where

C : total cost of the system ($)

C_{jk} : cost of pipe of diameter k in link j ($/km)

n(j) : number of different pipe diameters in link j
NL : total number of links within the system
X_{jk} : length of pipe of diameter k in link j (km)
j : link index
k : diameter type index

X_{jk} is the length unknown for each diameter in each link, and C_{jk} is the cost of the associated diameter types defined in pipeTypes.txt file.

The basic assumption of the approach of this study is to divide any link into the number of available pipe diameter types, and to define one unknown for each divided part. Unknowns are the lengths of the associated diameter types. And the cost function is equal to the summation of the cost of all parts that are calculated by multiplying of unit cost of pipe type and length.

Example:
Assume that predefined available diameters for the sample link between junction A and junction B in Figure 4.7 are: 100, 150, 200, 250, and 300 mm; and associated cost and lengths for these diameter types are C_{11}, C_{12}, C_{13}, C_{14}, C_{15} and X_{11}, X_{12}, X_{13}, X_{14}, X_{15}.

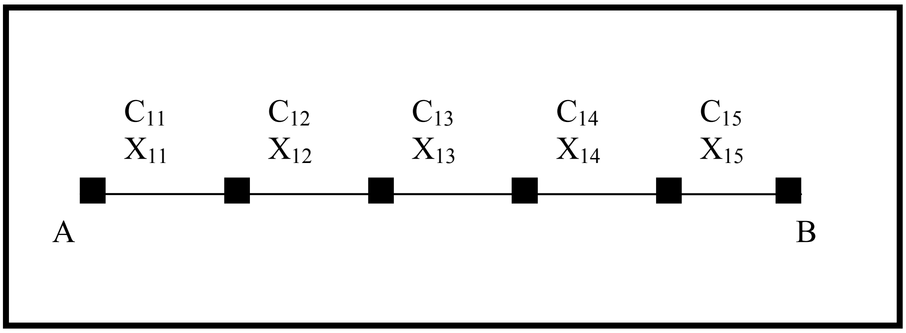


Figure 4.7 Link between Junction A and B

Objective function for the sample link is:

$C_{11}*X_{11} + C_{12}*X_{12} + C_{13}*X_{13} + C_{14}*X_{14} + C_{15}*X_{15}$

First Constraint, Equation 4.2, states that the sum of the length of pipes in each link must equal the total length of the link where a link represents a pipe connecting two junctions directly.

$$\sum_{k=1}^{n(j)} X_{jk} = L_j \quad \text{For all links j} \tag{4.2}$$

where

L_j : total length of link j (km)
n(j) : number of different pipe diameters in link j
X_{jk} : length of pipe of diameter k in link j (km)
j : link index
k : diameter type index

First constraint for the sample link in Figure 4.7 is equal to:
$X_{11} + X_{12} + X_{13} + X_{14} + X_{15}$ = Total length of the link.

Second Constraint defines limitations for minimum and maximum permissible head at each demand point or node. (Head Equations, See Equations 4.3 and 4.4)

$$H_o - \sum_{j \in p(n)} \sum_{k=1}^{n(j)} J_{jk} \cdot X_{jk} \geq H_{n_{\min}} \quad \text{For all nodes n} \tag{4.3}$$

$$H_o - \sum_{j \in p(n)} \sum_{k=1}^{n(j)} J_{jk} \cdot X_{jk} \leq H_{n_{\max}} \quad \text{For all nodes n} \tag{4.4}$$

Where

$H_{n\min}$: minimum allowable head at node n (m)

H_{nmax} : maximum allowable head at node n (m)
H_o : original head at source (m)
J_{jk} : hydraulic gradient for pipe diameter k in link j (m/km)
n(j) : number of different pipe diameters in link j
p(n) : links in the path from source to node n
X_{jk} : length of pipe of diameter k in link j (km)
j : link index
k : diameter type index

While generating the head equations for any node, all pipes from reservoir to that node must be known. Since all pipes in the pathway between reservoir and node are required to form energy equation. TRAVERSE, a CATE subfunction, selects the path to all nodes from the reservoir. Then, CATE generates equations for all paths from the reservoir to the nodes.

Example:

Network in Figure 4.8 consists of a reservoir and junctions connected by pipes. Sub function TRAVERSE determines path from reservoir to junctions A, B, C, D, and E to write head equations between them.

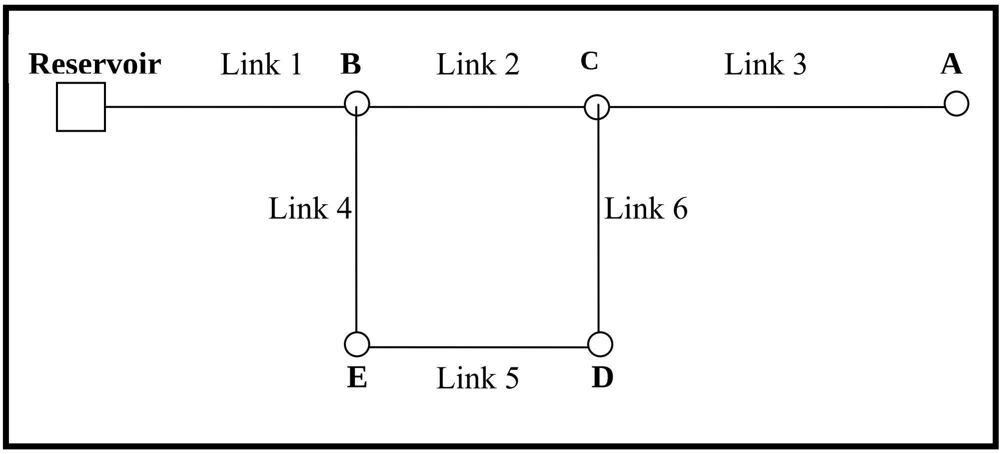


Figure 4.8 Paths from Reservoir to Junctions

Path from reservoir to junction B is equal to:
Reservoir – Link 1 – B

Path from reservoir to junction C is equal to:
Reservoir – Link 1 – Link 2 – C

Path from reservoir to junction A is equal to:
Reservoir – Link 1 – Link2 – Link3 – A

Path from reservoir to junction E is equal to:
Reservoir – Link 1 – Link4 – E

Path from reservoir to junction D is equal to:
Reservoir – Link 1 – Link2 – Link6 – D

There exists other alternatives for the paths to junction A, C, D, and E. TRAVERSE determines one of the alternatives and does not include other alternatives as head equation.

Link 6 is never passed along with the alternative displayed above. This does not mean that, head equation for link 6 is not included with the alternative above. Link 6 will be included in third constraint, loop equation.

Head equation for junction A is equal to:

Head @ Reservoir
(±) Unit Head loss of diameters for pipe types used in link 1 * length of pipe types
(±) Unit Head loss of diameters for pipe types used in link 2 * length of pipe types
(±) Unit Head loss of diameters for pipe types used in link 3 * length of pipe types
≥ Minimum permissible head. @ junction A
AND
≤ Maximum permissible head @ junction A

Plus and minus signs indicate addition or subtraction according to flow direction through the link. If travel direction is same with flow direction, sign is minus else plus. CATE obtains directions of flow in all links from previous EPANET analysis and determines the correct sign.

Third Constraint defines the loop continuity, Equation 4.5, the total head loss around a loop must equal zero.

$$\sum_{j \in p'(b)} \sum_{k=1}^{n(j)} J_{jk} \cdot X_{jk} = 0 \quad \text{For a loop} \tag{4.5}$$

where

J_{jk}	: hydraulic gradient for pipe diameter k in link j (m/km)
n(j)	: number of different pipe diameters in link j
X_{jk}	: length of pipe of diameter k in link j (km)
j	: link index
k	: diameter type index

In this version CATE cannot identify loop structure of water distribution network by itself; hence a loop identifying file must be defined by user. Loop.txt file contains total loop number and pipes and junctions that constitute loops. This file introduces loop structure to CATE while running.

CATE starts from any point on loop, travel through pipes one after another in loop, ends travel at starting point. While CATE travels from a node to another node, generates equations of head losses.

Example:
The network in Figure 4.9 has a loop and the head equation for that loop is sampled below.

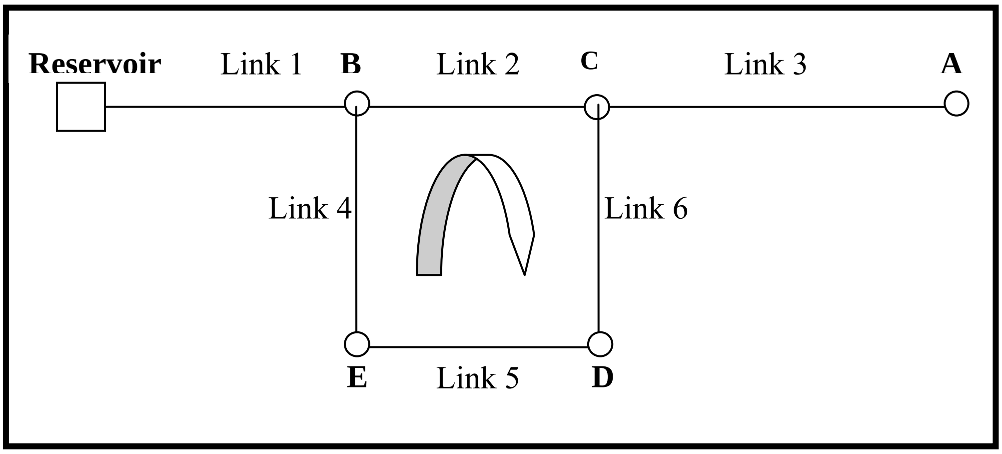


Figure 4.9 Loop Equation

Loop equation for the sample loop in Figure 4.9 is equal to:

Head @ Junction B

(±) Unit Head loss of diameters for pipe types used in link 2 * length of pipe types

(±) Unit Head loss of diameters for pipe types used in link 6 * length of pipe types

(±) Unit Head loss of diameters for pipe types used in link 5 * length of pipe types

(±) Unit Head loss of diameters for pipe types used in link 4 * length of pipe types

= 0

Flow directions in the links are important again as in second constraint. If travel direction is same with flow direction CATE assign sign as minus else plus. CATE obtains directions of flow in all links from previous EPANET Analysis and determines correct sign.

In the fourth constraint, Equation 4.6, CATE forces all variables to be greater than or equal to zero. (Non-negativity of variables)

$$X_{jk} \geq 0 \quad \text{For all } j \text{ and } k \tag{4.6}$$

where

X_{jk} : length of pipe of diameter k in link j (km)

j : link index

k : diameter type index

A measure of reliability is incorporated into fifth constraint, Equation 4.7, which limits the expected (average) number of breaks in given time period in any link.

$$\sum_{k=1}^{n(j)} r_{jk} \cdot X_{jk} \leq R_j \quad \text{For all links } j \tag{4.7}$$

where

r_{jk} : expected number of breaks/km/year for diameter k in link j
R_j : maximum allowable number of failures per year in link j - user defined
X_{jk} : length of pipe of diameter k in link j (km)
n(j) : number of different pipe diameters in link j
j : link index
k : diameter type index

CATE obtains breaks/km/year values for each pipe type from pipeTypes.txt file then generates constraints for reliabilities of each link.

Velocity control of the links, with respect to predefined maximum velocity limit, is granted with the sixth constraint; this constraint is activated in the second run of CATE. According to the results obtained in the first run, CATE determines the links that have velocity smaller than the minimum velocity limit and generate a constraint to increase flow velocity in these links.

In the second run, CATE finds out velocities from the previous EPANET hydraulic analysis and checks; whether velocities are under minimum limit or not and determines links which have velocities under limit. Then, it determines used diameter for that link and prevent using of this diameter and larger diameters for the next run.

Velocity control of the links, with respect to predefined minimum velocity limit, is granted with seventh constraint, this constraint activates in the second run of CATE.

According to the results obtained in the first run, CATE determines the links that have velocity greater than the maximum velocity limit and generates a constraint to decrease flow velocity in these links.

In the second run, CATE finds out velocities from the previous EPANET hydraulic analysis and checks; whether velocities are over maximum limit or not and determines links which have velocities over limit. Then, it determines used diameter for that link and prevent using of this diameter and smaller diameters for the next run.

4.3.5 Step 5 of Algorithm: Execution of LINDO

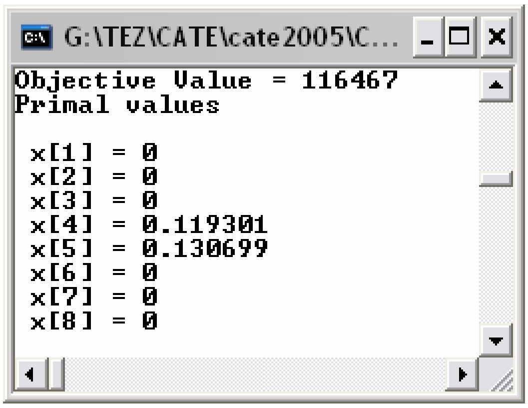
In this step Lindo API linear optimizer computes optimum solution according to given input file that is prepared in step 4.

4.3.6 Step 6 of Algorithm: Output of LINDO

Lindo API linear optimizer determines the pipe lengths for the used diameters and prints them.

4.3.7 Step 7 of Algorithm: Diameter Election – CATE Code 2

While optimizing the network, CATE determines one, two or more pipe diameters for any link. As it seen in the Figure 4.10, CATE finds two types of diameter for a link.



```
Objective Value = 116467
Primal values

 x[1] = 0
 x[2] = 0
 x[3] = 0
 x[4] = 0.119301
 x[5] = 0.130699
 x[6] = 0
 x[7] = 0
 x[8] = 0
```

Figure 4.10 Optimization Result: Lengths of Diameter Types

119.3 m for pipe type 4
130.7 m for pipe type 5

Then, in this step, CATE eliminates short links and outcomes longest pipe diameter as pipe diameter of that link. Because a link in EPANET can not split into two or more pipes with different diameters.

In the above example, type 4 is eliminated by CATE and pipe type 5 resulted as link diameter.

4.3.8 Step 8 of Algorithm: Input for EPANET

CATE extracts selected diameters in the seventh step and replaces the diameters in previous EPANET input file with these new diameters and creates new input file for EPANET.

4.3.9 Step 9 of Algorithm: Analysis with EPANET

CATE runs EPANET with new input prepared in step 8.

4.3.10 Step 10 of Algorithm: Analyzing Flow Directions

In this step CATE evaluates the results of last (in step 9) and first (in step 2) EPANET analysis, and then compares the flow directions obtained in two different analyses for each pipe.

4.3.11 Step 11 of Algorithm: Final Check – CATE Code 3

In this step CATE checks two criteria:

- Are flow directions same between two analyses for each pipe?
- Are velocities in between the limits?

Flow directions: CATE compares new directions of flow with previous ones. If they are all same, answer to question is “YES”. If not, it returns to step 1 with the modified output file provided by CATE code 2 (output file obtained in step 8).

Velocities: CATE controls velocities with according to minimum and maximum limits. If velocities are in limit, answer to question is “YES”. If not, it returns to step 1 with the modified output file provided by CATE code 2 (output file obtained in step 8).

If answers to all questions are “YES”, CATE finalizes the optimization.

4.4 Execution of CATE

By using software CATE, any water distribution network can be designed with respect to constraints defined by user. The procedure of the program algorithm and input file preparing are defined in the previous section.

In the present version of CATE, pump and tank elements, which are basics for a water distribution network, are not available. But reservoir element can be used instead of these elements with some reservations.

CATE does not have any interface for the purpose of input, but the inputs are text files, and easy to prepare. The most complicated input, water distribution network properties can be defined as schematic or text file in the CATE. And the results of the design can be displayed as schematic or tabular.

CATE can be executed by just clicking on the cate.exe in the program folder, after copying all input files to that folder.

CHAPTER 5

CASE STUDY

5.1 Description of Study Networks

In this section, two water distribution networks are designed using CATE. One of these networks is two looped network supplied by gravity by a reservoir that is used in the study of “Design of Optimal Water Distribution Systems” by Alperovits and Shamir (1977).

The other sample network is the highly skeletonized N8 network, which is a pressure zone that belongs to the northern supply zone of Ankara.

5.2 Design of Two-Looped Alperovits and Shamir (1977) Network

In this section input forming and design procedure of sample two-looped network is presented in detail. After having accomplish the analysis of the sample network, results are compared with the results of Alperovits and Shamir (1977)

5.2.1 Network Properties

Sample network is a two looped network supplied by gravity from a reservoir that is used in the study of “Design of Optimal Water Distribution Systems”, Alperovits and Shamir (1977). The network consists of 8 pipes, 6 junctions, and a reservoir. The scheme of the network is presented in Figure 5.1.

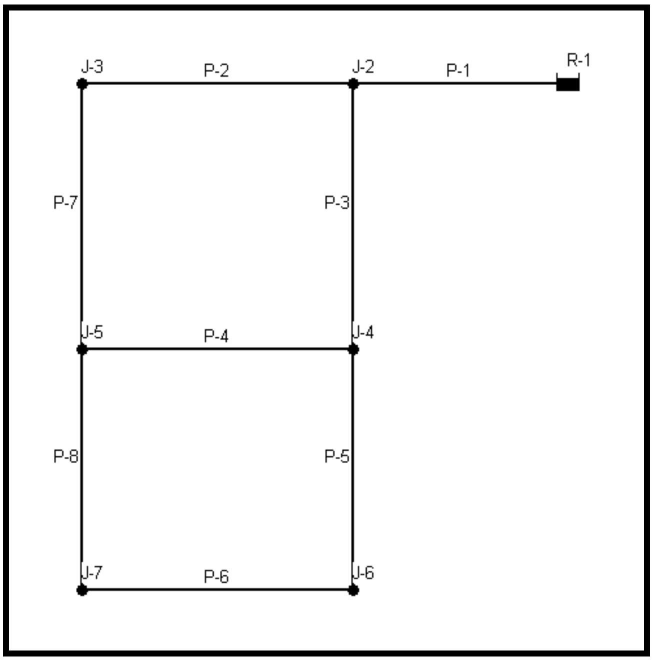


Figure 5.1 Two Looped Sample Network

Nodal weights, demand values and topographical elevations of sample network are tabulated in Table 5.1.

Table 5.1 Sample Network Table: Junction Properties

Junction	**Nodal Demands**			**Topographical Elevation (m)**
	Nodal Weights	**Qpeak (m^3/hr)**	**Qpeak (lt/sec)**	
1		**-1120.0**	**-311.11**	**210.00**
2	0.089	100.0	27.78	150.00
3	0.089	100.0	27.78	160.00
4	0.107	120.0	33.33	155.00
5	0.241	270.0	75.00	150.00
6	0.295	330.0	91.67	165.00
7	0.179	200.0	55.56	160.00
Total	**1.000**	**1120.0**	**311.11**	

Pipe length and roughness values of the sample network are tabulated in Table 5.2.

Table 5.2 Sample Network Table: Link Properties

Pipe	Length (m)	C (Hazen Williams coefficient)
1	1000	130
2	1000	130
3	1000	130
4	1000	130
5	1000	130
6	1000	130
7	1000	130
8	1000	130

5.2.2 Design Results of Alperovits and Shamir (1977) Study

In this optimization study the unit inch is used for the diameter values. Available diameters of pipes in the unit inch and millimeter for optimization are tabulated in Table 5.3. Pipe cost is unitless for the available pipes in Alperovits and Shamir (1977) sample.

Table 5.3 Diameters and Pipe Costs for Sample Network

Diameter (inch)	Diameter (mm)	Accepted Diameter (mm)	Cost / m
4	101.6	100	11
6	152.4	150	16
8	203.2	200	23
10	254.0	250	32
12	304.8	300	50
14	355.6	350	60
16	406.4	400	90
18	457.2	450	130
20	508.0	500	170

The results of the sample design are tabulated in Table 5.4. It can be seen that there are more than one pipe assigned for some links in the results. This means that Alperovits and Shamir (1977) optimization technique can be resulted in a way that, one link can be originated from two different pipe types. The cost of the network is calculated in Table 5.4, by taking different pipe types into consideration. Total cost of the network is 479525.

Table 5.4 Alperovits and Shamir Design Results

Link	**Total Length (m)**	**Segment 1**			**Segment 2**			**Link**
		Diameter (inch)	**Length (m)**	**Pipe Cost**	**Diameter (inch)**	**Length (m)**	**Pipe Cost**	**Link Cost**
1	1000	18	744.00	96720	20	255.97	43515	140235
2	1000	8	996.37	22917	6	3.61	58	22974
3	1000	18	999.98	129997	0	0.00	0	129997
4	1000	6	680.62	10890	8	319.38	7346	18236
5	1000	16	1000.00	90000	0	0.00	0	90000
6	1000	10	215.06	6882	12	784.94	39247	46129
7	1000	6	999.99	16000	0	0.00	0	16000
8	1000	6	990.91	15855	4	9.06	100	15954
							Total Cost	**479525**

Optimization using CATE is performed twice, with exact fit of these diameters in mm unit and their approximate fit in mm unit. Accepted diameters in mm unit are presented in Table 5.3. First Design is performed with exact diameters, used in previous study realized by Alperovits and Shamir. The second design is performed with approximate commercial diameters in mm, near to available diameters in Alperovits and Shamir (1977). Two design and their results are presented in the following sections.

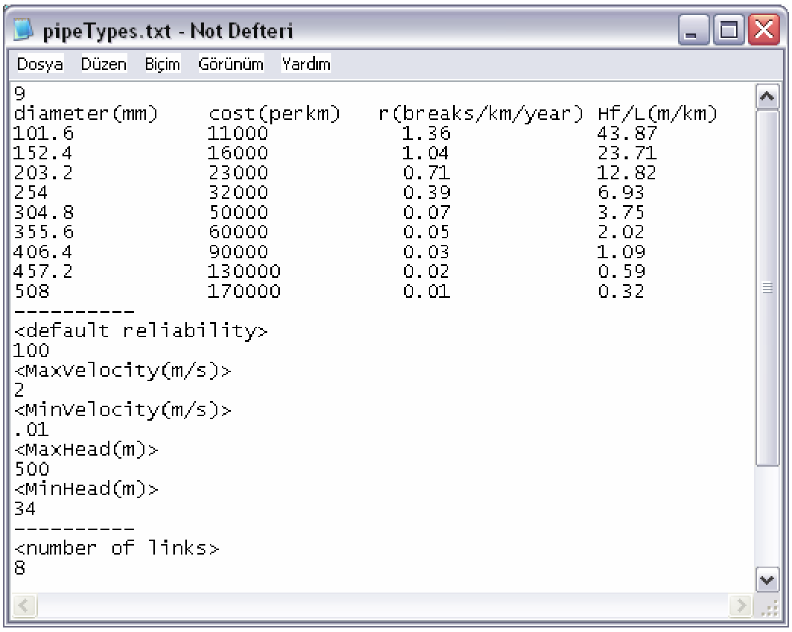
5.2.3 First Design of Alperovits and Shamir (1977) Sample Network by CATE

The design is performed with exact diameters in this section.

5.2.3.1 Input Files for Alperovits and Shamir (1977) Sample Network

Three input files are prepared for CATE. These are pipeTypes.txt, loops.txt and deneme.inp files.

Pipe type input file, pipeTypes.txt, includes information about available pipe diameters for the design and their properties (pipe unit cost, pipe statistical break rates, and pipe hydraulic gradients), maximum and minimum velocity limits, maximum and minimum pressure head limits and reliability limits for links. This file for Alperovits and Shamir (1977) network is displayed in Figure 5.2.



```
9
diameter(mm)    cost(perkm)    r(breaks/km/year)  Hf/L(m/km)
101.6           11000            1.36             43.87
152.4           16000            1.04             23.71
203.2           23000            0.71             12.82
254             32000            0.39             6.93
304.8           50000            0.07             3.75
355.6           60000            0.05             2.02
406.4           90000            0.03             1.09
457.2           130000           0.02             0.59
508             170000           0.01             0.32
----------
<default reliability>
100
<MaxVelocity(m/s)>
2
<MinVelocity(m/s)>
.01
<MaxHead(m)>
500
<MinHead(m)>
34
----------
<number of links>
8
```

Figure 5.2 Pipe Type Input File for Sample Network Design 1: pipeType.txt

Loop Input file, loops.txt, contains information about number of the loops and their topology properties. Loop file for Alperovits' network is presented in Figure 5.3.

```
2
4  2  3  4  4  5  7  3  2  2
4  4  5  6  6  7  8  5  4  4
```

Figure 5.3 Loop Input File for Sample Network Design 1: loop.txt

To define network properties for CATE, sample water distribution network is created in EPANET, and then deneme.inp file is created from file>export pull down menu of the EPANET software. Deneme.inp file includes junction, reservoir, pipe properties, hydraulic options for analysis, and topological properties of pipes.

5.2.3.2 Design Constraints

Design constraints to be respected by CATE while reaching optimum solution for the network design are:

1) Velocities in pipes should be in the range of:

$V\ (m/s) < 2\ m/s$

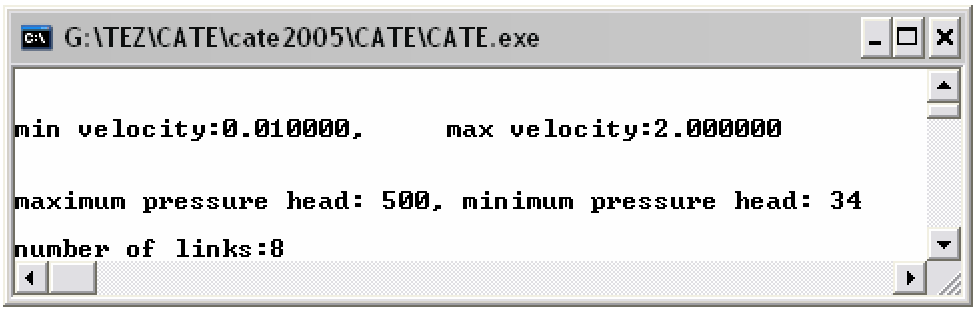
2) Available pipe diameters in inch are 4, 6, 8, 10, 12, 14, 16, 18, and 20.

3) Allowable minimum pressure limit is taken as:

$34\ m < P/\gamma\ (m)$

5.2.3.3 Design Procedure

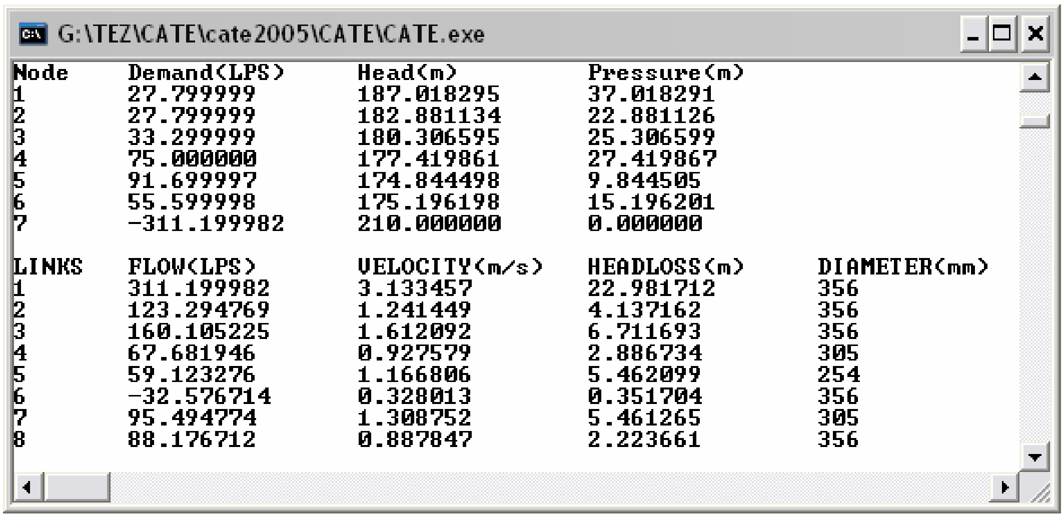
In this section, the design procedure for the network is described. For the design of the network, peak demand values are used. CATE scans network properties and constraints from input files and starts the design procedure with user command. The final design is achieved after several runs of CATE. Steps until the final design can be analyzed easily by user.



```
min velocity:0.010000,     max velocity:2.000000

maximum pressure head: 500, minimum pressure head: 34

number of links:8
```

Figure 5.4 Start Page of CATE for Sample Network Design 1

Figure 5.4 is the starting page of CATE. In the first page, CATE prints constraints used for the design of the network.

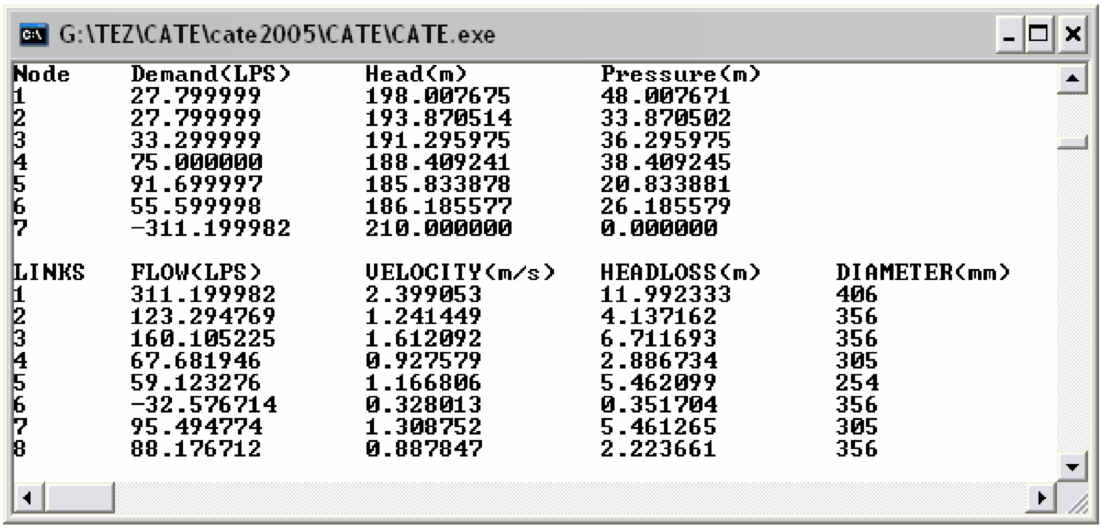


```
Node      Demand(LPS)      Head(m)          Pressure(m)
1         27.799999        187.018295       37.018291
2         27.799999        182.881134       22.881126
3         33.299999        180.306595       25.306599
4         75.000000        177.419861       27.419867
5         91.699997        174.844498       9.844505
6         55.599998        175.196198       15.196201
7         -311.199982      210.000000       0.000000

LINKS     FLOW(LPS)        VELOCITY(m/s)    HEADLOSS(m)      DIAMETER(mm)
1         311.199982       3.133457         22.981712        356
2         123.294769       1.241449         4.137162         356
3         160.105225       1.612092         6.711693         356
4         67.681946        0.927579         2.886734         305
5         59.123276        1.166806         5.462099         254
6         -32.576714       0.328013         0.351704         356
7         95.494774        1.308752         5.461265         305
8         88.176712        0.887847         2.223661         356
```

Figure 5.5 The Result of the First Run of CATE for Sample Network Design 1

Figure 5.5 presents selected diameters and hydraulic analysis results of nodes and links of the network at the end of the first run of CATE. These values are hydraulic grade line, pressure heads of nodes, velocities and head losses at links. In the first run of CATE, velocity constraints are not included. CATE builds velocity constraints in the second run for the first time according to the result of the first run. As it seen in the Figure 5.5, velocity of pipe 1 is greater than the upper velocity limit (3.13 m/sec. > upper velocity limit = 2.0 m/sec.)

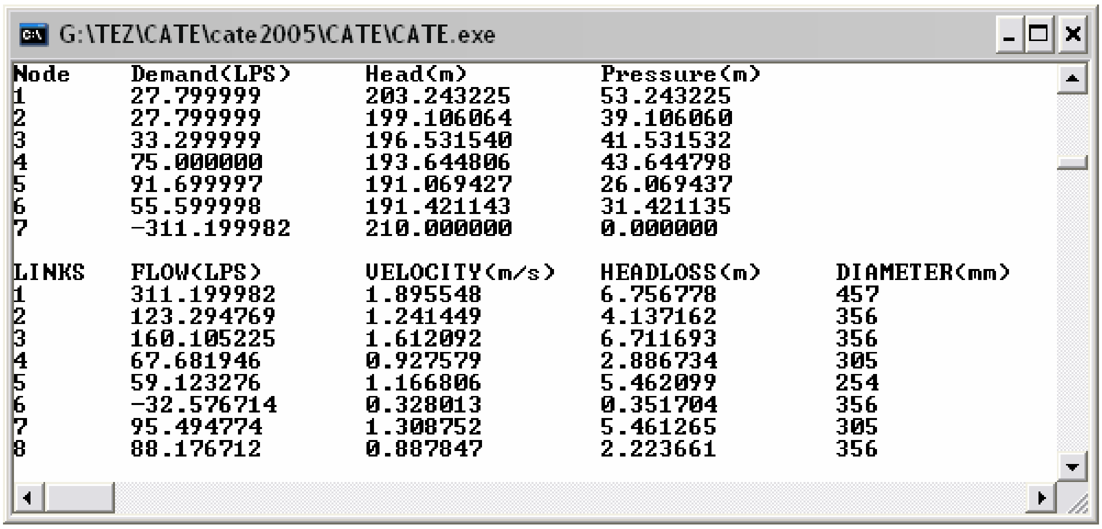
CATE performs runs, until all the results are in the range of the given constraints. In this network, the number of runs is three. At the end of the third run the results are in the range of predefined constraints.



```
Node    Demand(LPS)     Head(m)         Pressure(m)
1       27.799999       198.007675      48.007671
2       27.799999       193.870514      33.870502
3       33.299999       191.295975      36.295975
4       75.000000       188.409241      38.409245
5       91.699997       185.833878      20.833881
6       55.599998       186.185577      26.185579
7       -311.199982     210.000000      0.000000

LINKS   FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1       311.199982      2.399053        11.992333       406
2       123.294769      1.241449        4.137162        356
3       160.105225      1.612092        6.711693        356
4       67.681946       0.927579        2.886734        305
5       59.123276       1.166806        5.462099        254
6       -32.576714      0.328013        0.351704        356
7       95.494774       1.308752        5.461265        305
8       88.176712       0.887847        2.223661        356
```

Figure 5.6 The Result of the Second Run of CATE for Sample Network Design 1

Figure 5.6 presents selected diameters and hydraulic analysis results of node and link values of the network at the end of the second run of CATE. Velocity constraints are included in the second run of CATE. As well as the velocity of the pipe 1 is decreased due to the increase of pipe diameter of pipe 1. In the first run, velocity in the pipe 1 was over maximum velocity limit, and CATE increased diameter to 406 mm to decrease the velocity.



```
Node      Demand(LPS)     Head(m)         Pressure(m)
1         27.799999       203.243225      53.243225
2         27.799999       199.106064      39.106060
3         33.299999       196.531540      41.531532
4         75.000000       193.644806      43.644798
5         91.699997       191.069427      26.069437
6         55.599998       191.421143      31.421135
7         -311.199982     210.000000      0.000000

LINKS     FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1         311.199982      1.895548        6.756778        457
2         123.294769      1.241449        4.137162        356
3         160.105225      1.612092        6.711693        356
4         67.681946       0.927579        2.886734        305
5         59.123276       1.166806        5.462099        254
6         -32.576714      0.328013        0.351704        356
7         95.494774       1.308752        5.461265        305
8         88.176712       0.887847        2.223661        356
```

Figure 5.7 Final Run Results of CATE for Sample Network Design 1

Figure 5.7 presents results for the final run of CATE. The results of the final run are appropriate according to constraints and CATE finalize the design by third run.

<u>Cost, obtained at successive runs</u>:

Cost of first run	: 441550
Cost of second run	: 459389
Cost of final run	: 492905

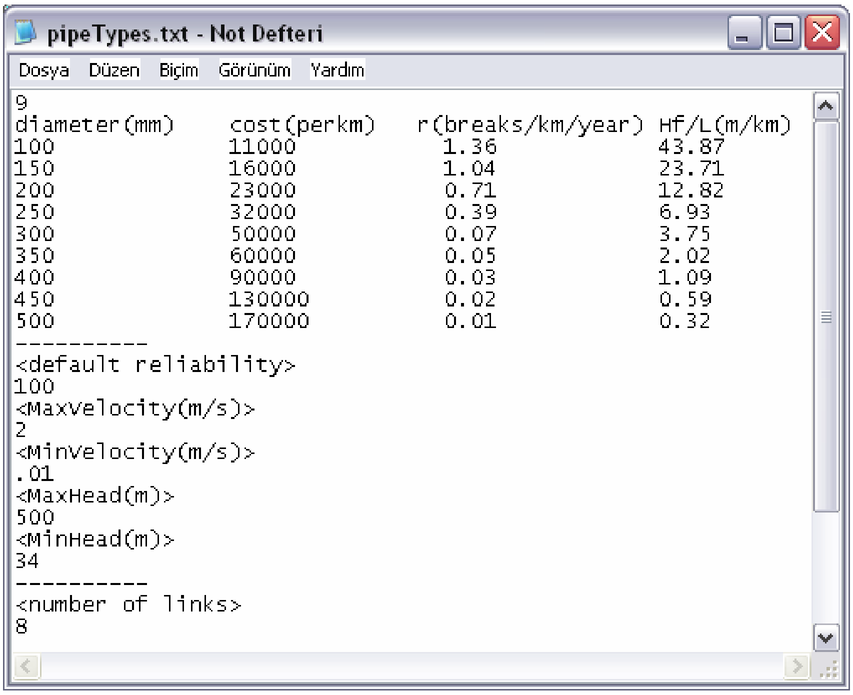
5.2.4 Second Design of Alperovits and Shamir Sample Network

Design with approximate diameters is performed in this section.

5.2.4.1 Input Files for Alperovits and Shamir Sample Network

Three input files are prepared for CATE. These are pipeTypes.txt, loops.txt and deneme.inp files.

Pipe type input file, “pipeTypes.txt”, includes information about available pipe diameters for the design and their properties (pipe unit cost, pipe statistical break rates, and pipe hydraulic gradients), maximum and minimum velocity limits, maximum and minimum pressure head limits and reliability limits for links. This file for Alperovits’ network is displayed in Figure 5.8.



```
9
diameter(mm)    cost(perkm)   r(breaks/km/year) Hf/L(m/km)
100             11000           1.36            43.87
150             16000           1.04            23.71
200             23000           0.71            12.82
250             32000           0.39            6.93
300             50000           0.07            3.75
350             60000           0.05            2.02
400             90000           0.03            1.09
450             130000          0.02            0.59
500             170000          0.01            0.32
----------
<default reliability>
100
<MaxVelocity(m/s)>
2
<MinVelocity(m/s)>
.01
<MaxHead(m)>
500
<MinHead(m)>
34
----------
<number of links>
8
```

Figure 5.8 Pipe Type Input file for Sample Network Design 2: pipeTypes.txt

Loop Input file, loops.txt, contains information about number of the loops and their topology properties. Loop file for Alperovits' network is presented in Figure 5.9.

```
2
4  2  3  4  4  5  7  3  2  2
4  4  5  6  6  7  8  5  4  4
```

Figure 5.9 Loop Input File for Sample Network Design 2: loops.txt

To define network properties for CATE, sample water distribution network is created in EPANET; deneme.inp file is created from file>export pull down menu of the EPANET software. Deneme.inp file includes junction, reservoir, pipe properties, hydraulic options for analysis, and topological properties of pipes.

5.2.4.2 Design Constraints

Design constraints to be respected by CATE while reaching optimum solution for the network design are:

1) Velocities in pipes should be in the range of:

$V \text{ (m/s)} < 2 \text{ m/s}$

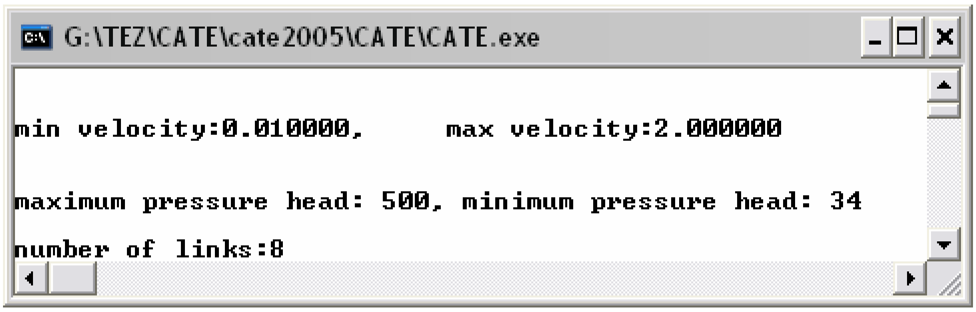
2) Available pipe diameters in mm are 100, 150, 200, 250, 300, 350, 400, 450, and 500.

3) Allowable minimum pressure limit is taken as:

$34 \text{ m} < P/\gamma \text{ (m)}$

5.2.4.3 Design Procedure

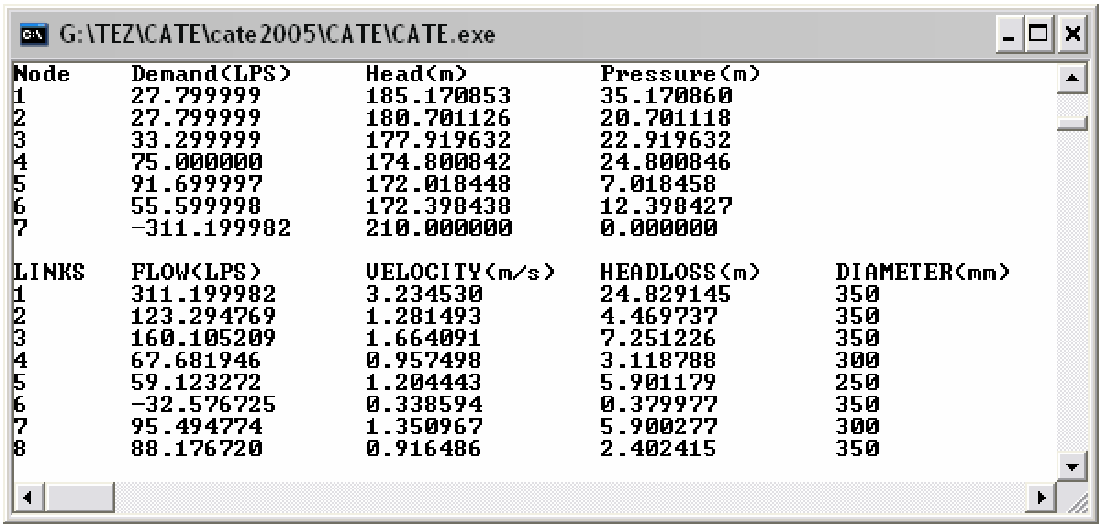
In this section, design procedure for the network is described. For the design of the network, peak demand values are used. CATE scans network properties and design constraints from input files and starts design procedure with user command. The final design is achieved after several runs of CATE. Steps until the final design can be analyzed easily by user.



```
min velocity:0.010000,     max velocity:2.000000

maximum pressure head: 500, minimum pressure head: 34

number of links:8
```

Figure 5.10 Start Page of CATE for Sample Network Design 2

Figure 5.10 is the starting page of CATE. In the first page, CATE prints constraints used for the design of the network.

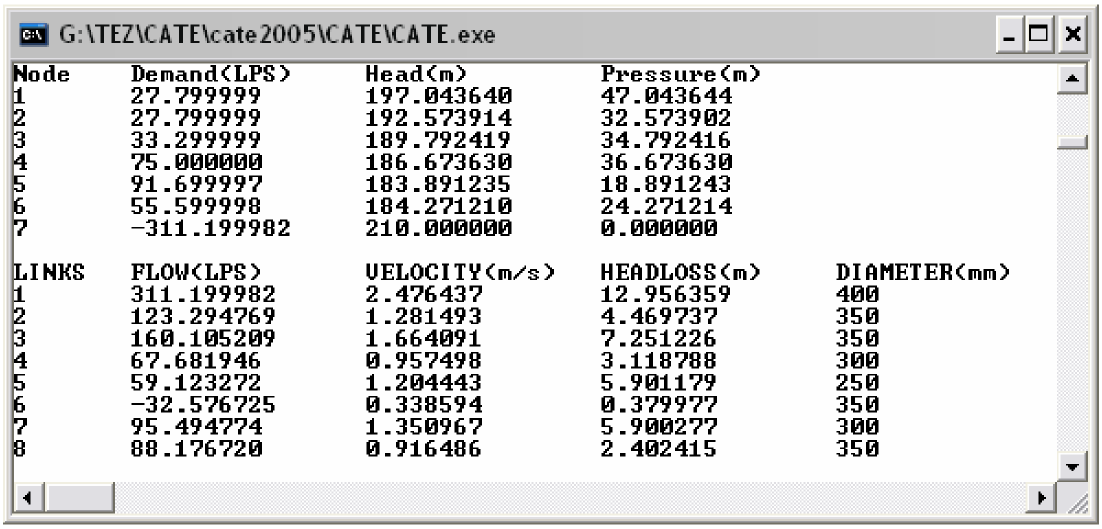


```
Node    Demand(LPS)     Head(m)         Pressure(m)
1       27.799999       185.170853      35.170860
2       27.799999       180.701126      20.701118
3       33.299999       177.919632      22.919632
4       75.000000       174.800842      24.800846
5       91.699997       172.018448      7.018458
6       55.599998       172.398438      12.398427
7       -311.199982     210.000000      0.000000

LINKS   FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1       311.199982      3.234530        24.829145       350
2       123.294769      1.281493        4.469737        350
3       160.105209      1.664091        7.251226        350
4       67.681946       0.957498        3.118788        300
5       59.123272       1.204443        5.901179        250
6       -32.576725      0.338594        0.379977        350
7       95.494774       1.350967        5.900277        300
8       88.176720       0.916486        2.402415        350
```

Figure 5.11 The Result of the First Run of CATE for Sample Network Design 2

Figure 5.11 presents selected diameters and hydraulic analysis results of nodes and links of the network at the end of the first run of CATE. These values are hydraulic grade line, pressure heads of nodes, velocities and head losses at links. In the first run of CATE, velocity constraints are not included. CATE builds velocity constraints in the second run for the first time according to the result of the first run. As it can be seen in the Figure 5.11, velocity of pipe 1 is greater than the upper velocity limit (3.23 m/sec. > upper velocity limit = 2.0 m/sec.)

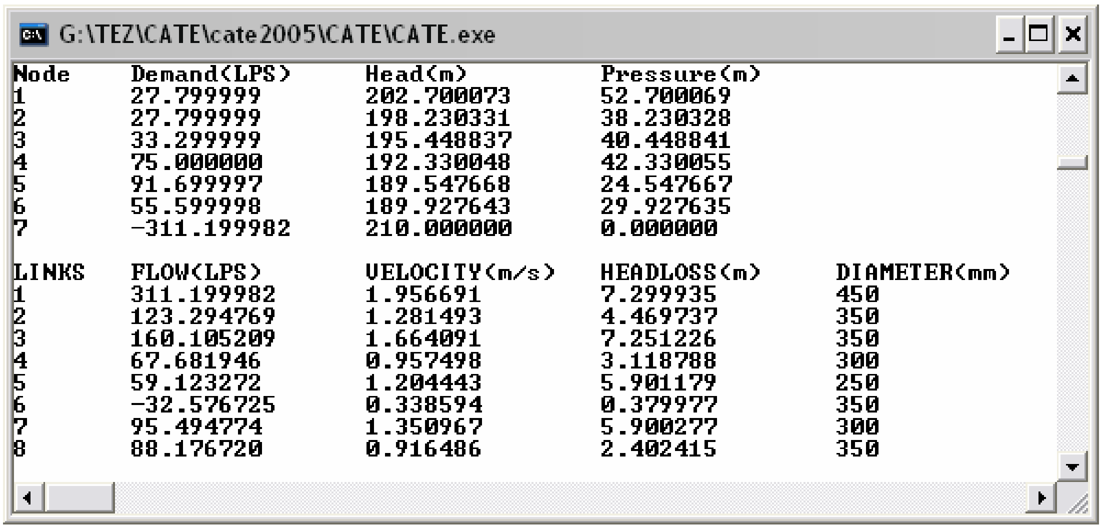
CATE performs runs, until all results are in the range of the given constraint. In this network, the number of runs is three. At the end of the third run the results are in the range of predefined constraints.



```
Node      Demand(LPS)     Head(m)         Pressure(m)
1         27.799999       197.043640      47.043644
2         27.799999       192.573914      32.573902
3         33.299999       189.792419      34.792416
4         75.000000       186.673630      36.673630
5         91.699997       183.891235      18.891243
6         55.599998       184.271210      24.271214
7         -311.199982     210.000000      0.000000

LINKS     FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1         311.199982      2.476437        12.956359       400
2         123.294769      1.281493        4.469737        350
3         160.105209      1.664091        7.251226        350
4         67.681946       0.957498        3.118788        300
5         59.123272       1.204443        5.901179        250
6         -32.576725      0.338594        0.379977        350
7         95.494774       1.350967        5.900277        300
8         88.176720       0.916486        2.402415        350
```

Figure 5.12 The Result of the Second Run of CATE for Sample Network Design 2

Figure 5.12 presents selected diameters and hydraulic analysis result of node and link values of the network at the end of the second run of CATE. Velocity constraints are included in the second run of CATE. As well as the velocity of the pipe 1 is decreased due to the increase of pipe diameter of pipe 1. In the first run, velocity in the pipe 1 was over maximum velocity limit, and CATE increased diameter to 400 mm to decrease velocity.



```
Node      Demand(LPS)     Head(m)         Pressure(m)
1         27.799999       202.700073      52.700069
2         27.799999       198.230331      38.230328
3         33.299999       195.448837      40.448841
4         75.000000       192.330048      42.330055
5         91.699997       189.547668      24.547667
6         55.599998       189.927643      29.927635
7         -311.199982     210.000000      0.000000

LINKS     FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1         311.199982      1.956691        7.299935        450
2         123.294769      1.281493        4.469737        350
3         160.105209      1.664091        7.251226        350
4         67.681946       0.957498        3.118788        300
5         59.123272       1.204443        5.901179        250
6         -32.576725      0.338594        0.379977        350
7         95.494774       1.350967        5.900277        300
8         88.176720       0.916486        2.402415        350
```

Figure 5.13 Final Run Results of CATE for Sample Network Design 2

Figure 5.13 presents result for the final run of CATE. The results of the Final run are appropriate according to constraints and CATE finalize the design by third run.

Cost, obtained at successive runs:

Cost of first run : 441550
Cost of second run : 492905
Cost of final run : 492905

5.2.5 Comparison of Results

In this section previous optimization results of the sample network, Alperovits and Shamir (1977), and two new optimizations carried out by CATE are compared. The first and second designs of CATE have the same cost, 492905, according to the defined pressure head and velocity constraints. Alperovits and Shamir (1977) optimization cost is 479525 that is 2.6 % less than the result obtained with CATE.

The basic reason for the differences between two results is probably due to the assumed constant J, hydraulic loss gradient, values for each of pipe diameters.

Results of CATE optimizations are same but the input pipe diameters are different in the two optimization. Despite the small differences between diameters, CATE optimizes same result in each case; thus, the costs of the optimizations are same. The difference of the diameters affects the hydraulic result of the two cases. In the first design result, velocities are under limit, and minimum pressure head is 26 m, that is allowable for the design. Again, velocities are under the limit in the second design, but the number of pressure heads less than 30 m is two, one of 29.9 m, allowable one for design, and the other is equal to 24.5 m, not allowable for the design.

Reliability constraints are not activated for this optimization. Reliability constraint effects are available for the next case study.

5.3 Design and Analysis of N8 Network

In this section, creation of input files for network then design and analysis procedure of N8 network is presented in detail.

5.3.1 Network Properties

Highly skeletonized N8 network consists of 25 pipes, 15 junctions, a tank, a reservoir and a pump. Since, including of a tank and a pump in the network is not available in this version of CATE, these items are assumed as reservoir (water supplying elements that have constant water level). Skeletonized scheme of N8 network is displayed in Figure 5.14. R-17 symbolizes an assumed reservoir instead of a tank. The pump near the reservoir 16 is cancelled by transferring pump head value to R-16.

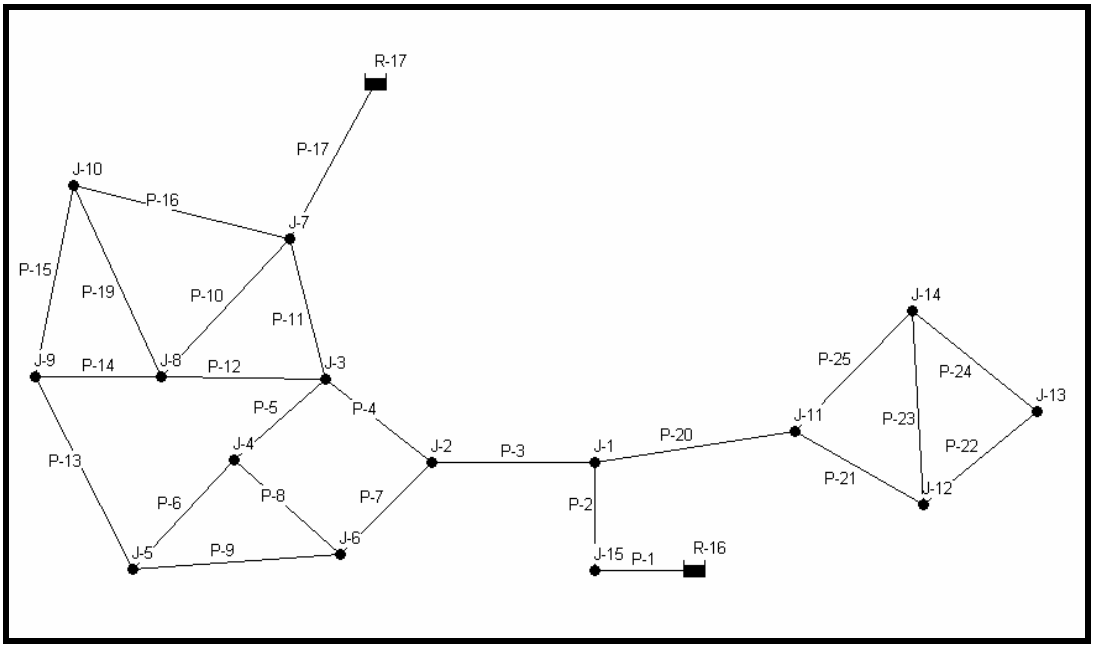


Figure 5.14 Skeletonized Form of N8 Network

Table 5.5 N8 Network Table: Junction Properties

		Nodal Demands						Topographical Elevation (m)
Node	**Nodal Weights**	**Q_{peak} (m^3/min)**	**Q_{max} (m^3/min)**	**Q_{night} (m^3/min)**	**Q_{peak} (lt/sec)**	**Q_{max} (lt/sec)**	**Q_{night} (lt/sec)**	
1	0.029	0.2356	0.1571	0.0314	3.93	2.62	0.52	1063.72
2	0.079	0.6419	0.4279	0.0856	10.70	7.13	1.43	1105.05
3	0.113	0.9181	0.6121	0.1224	15.30	10.20	2.04	1092.66
4	0.061	0.4956	0.3304	0.0661	8.26	5.51	1.10	1090.11
5	0.071	0.5769	0.3846	0.0769	9.61	6.41	1.28	1072.95
6	0.061	0.4956	0.3304	0.0661	8.26	5.51	1.10	1108.05
7	0.107	0.8694	0.5796	0.1159	14.49	9.66	1.93	1110.77
8	0.100	0.8125	0.5417	0.1083	13.54	9.03	1.81	1097.11
9	0.079	0.6419	0.4279	0.0856	10.70	7.13	1.43	1084.01
10	0.128	1.0400	0.6933	0.1387	17.33	11.56	2.31	1099.95
11	0.036	0.2925	0.1950	0.0390	4.88	3.25	0.65	1075.70
12	0.050	0.4063	0.2708	0.0542	6.77	4.51	0.90	1108.01
13	0.029	0.2356	0.1571	0.0314	3.93	2.62	0.52	1073.80
14	0.057	0.4631	0.3088	0.0618	7.72	5.15	1.03	1078.50
Total	**1.000**	**8.1250**	**5.4167**	**1.0833**	**135.42**	**90.28**	**18.06**	

Nodal weights, nodal demands and topographical elevations of N8 network are tabulated in Table 5.5.

Pipe length and roughness values of N8 network are tabulated in Table 5.6.

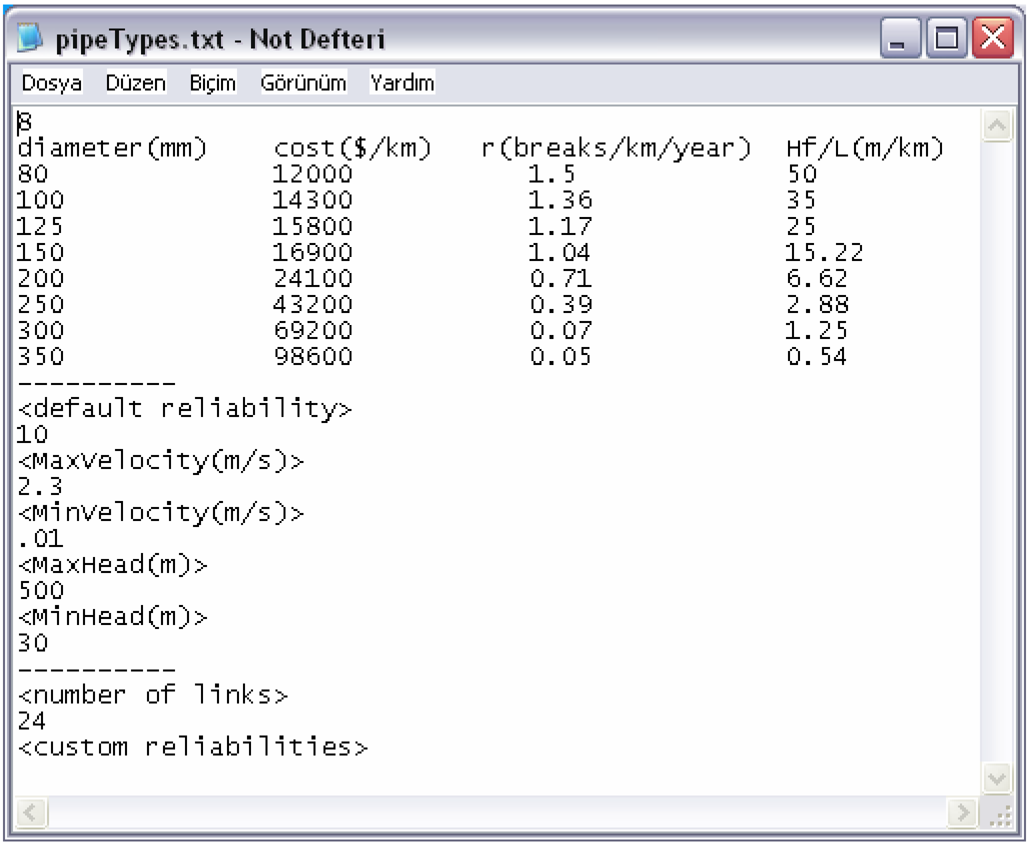
Table 5.6 N8 Network Table: Link Properties

Pipe	Length (m)	C (Hazen Williams coefficient
1	250	140
2	250	140
3	200	140
4	200	140
5	200	140
6	200	140
7	300	140
8	250	140
9	300	140
10	200	140
11	200	140
12	200	140
13	500	140
14	300	140
15	300	140
16	400	140
17	500	140
18	600	140
19	500	140
20	500	140
21	200	140
22	200	140
23	300	140
24	200	140
25	300	140

5.3.2 Input Files

Three input files are prepared for CATE. These are pipeTypes.txt, loops.txt and deneme.inp files.

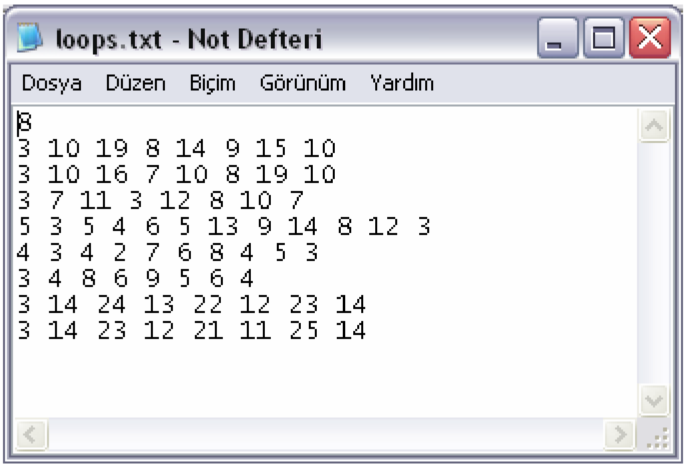
Pipe type input file, pipeTypes.txt, includes information about available pipe diameters for design and their properties (pipe unit cost, pipe statistical break rates, and pipe hydraulic gradients), maximum and minimum velocity limits, maximum and minimum pressure head limits and reliability limits for links. This file for N8 network is displayed in Figure 5.15.



```
8
diameter(mm)    cost($/km)   r(breaks/km/year)   Hf/L(m/km)
80              12000           1.5              50
100             14300           1.36             35
125             15800           1.17             25
150             16900           1.04             15.22
200             24100           0.71             6.62
250             43200           0.39             2.88
300             69200           0.07             1.25
350             98600           0.05             0.54
----------
<default reliability>
10
<MaxVelocity(m/s)>
2.3
<MinVelocity(m/s)>
.01
<MaxHead(m)>
500
<MinHead(m)>
30
----------
<number of links>
24
<custom reliabilities>
```

Figure 5.15 Pipe Type Input File for N8 Network: pipeType.txt

Loop Input file “loops.txt” contains information about number of the loops and their topology properties. Loop file for N8 network is presented in Figure 5.16.



```
8
3 10 19 8 14 9 15 10
3 10 16 7 10 8 19 10
3 7 11 3 12 8 10 7
5 3 5 4 6 5 13 9 14 8 12 3
4 3 4 2 7 6 8 4 5 3
3 4 8 6 9 5 6 4
3 14 24 13 22 12 23 14
3 14 23 12 21 11 25 14
```

Figure 5.16 Loop Input File for N8 Network: loops.txt

To define network properties to CATE, firstly N8 water distribution network is created in EPANET and deneme.inp file is created from file>export pull down menu of the EPANET software. Deneme.inp file includes junction, reservoir, pipe properties, hydraulic options for analysis, and topological properties of pipes.

5.3.3 Design Constraints

Design constraints to be respected by CATE while reaching optimum solution for N8 network are:

1) Velocity constraint:

$V\ (m/s) < 2.3\ m/s$

2) Available pipe diameters in mm are 80, 100, 125, 150, 200, 250, and 300.

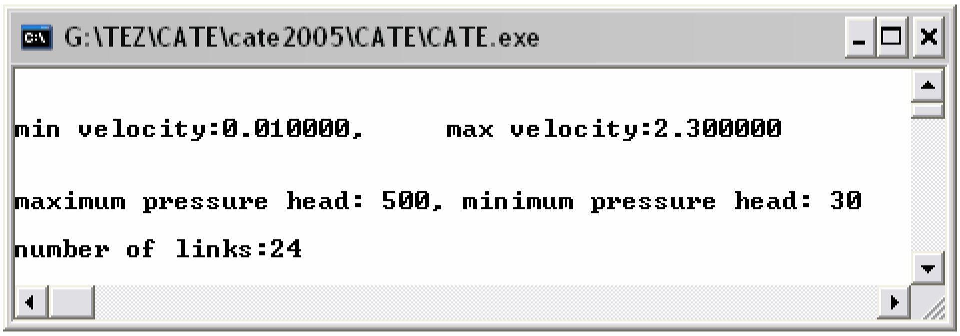
3) Allowable minimum pressure head:

$30\ m < P/\gamma\ (m)$

These constraints are defined to CATE in pipetype.txt input file.

5.3.4 Design Procedure

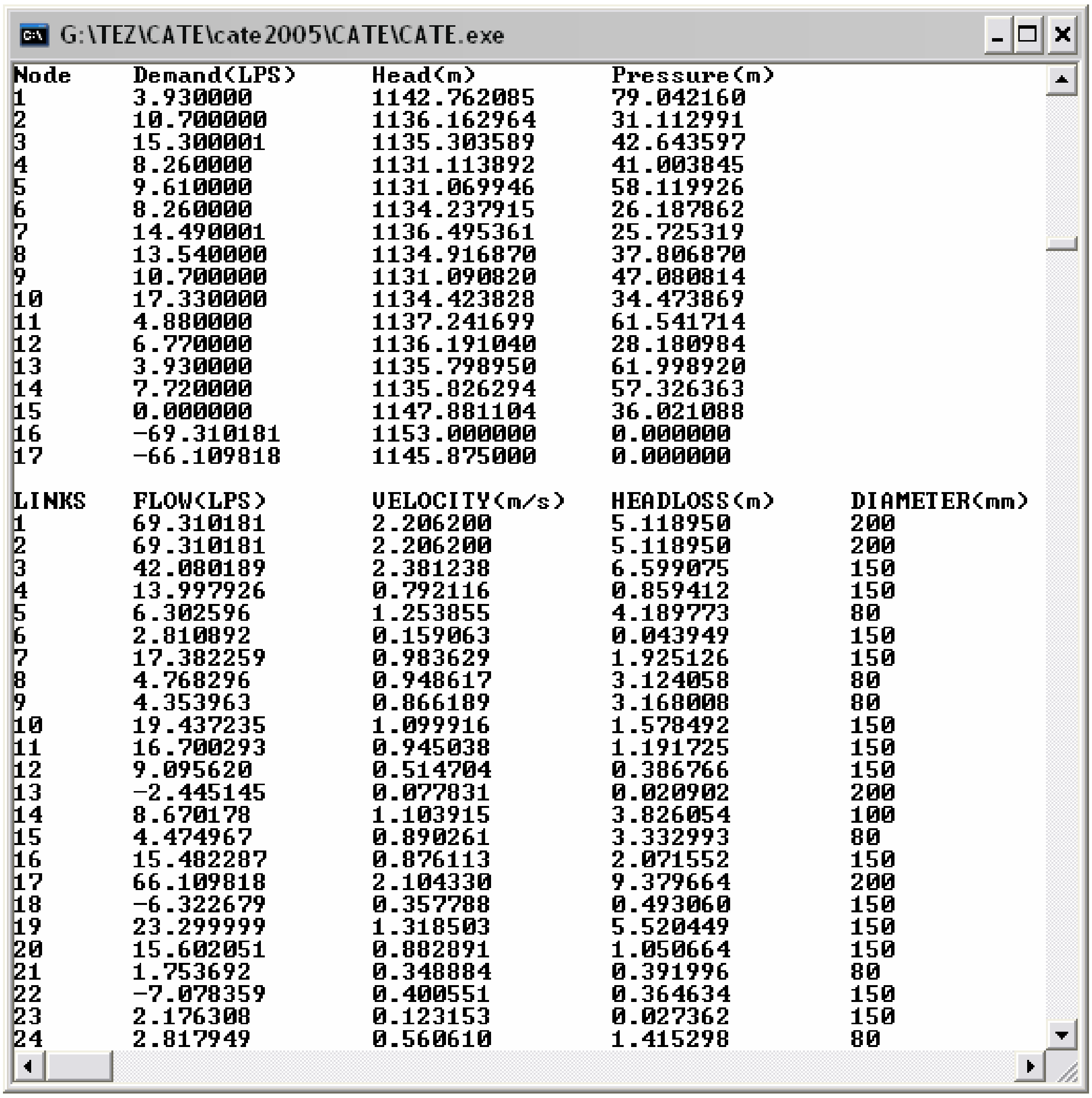
In this section design procedure of N8 network is described. For the design of the network, peak demand values are used. CATE scans network properties and constraints from input files and starts design procedure with user command. The final design is achieved after several runs of CATE. Steps until the final design can be analyzed easily by user.



```
min velocity:0.010000,     max velocity:2.300000

maximum pressure head: 500, minimum pressure head: 30
number of links:24
```

Figure 5.17 Start Page of CATE for N8 Network Design

Figure 5.17 is the starting page of CATE. In this first page, CATE prints constraints defined for the network.

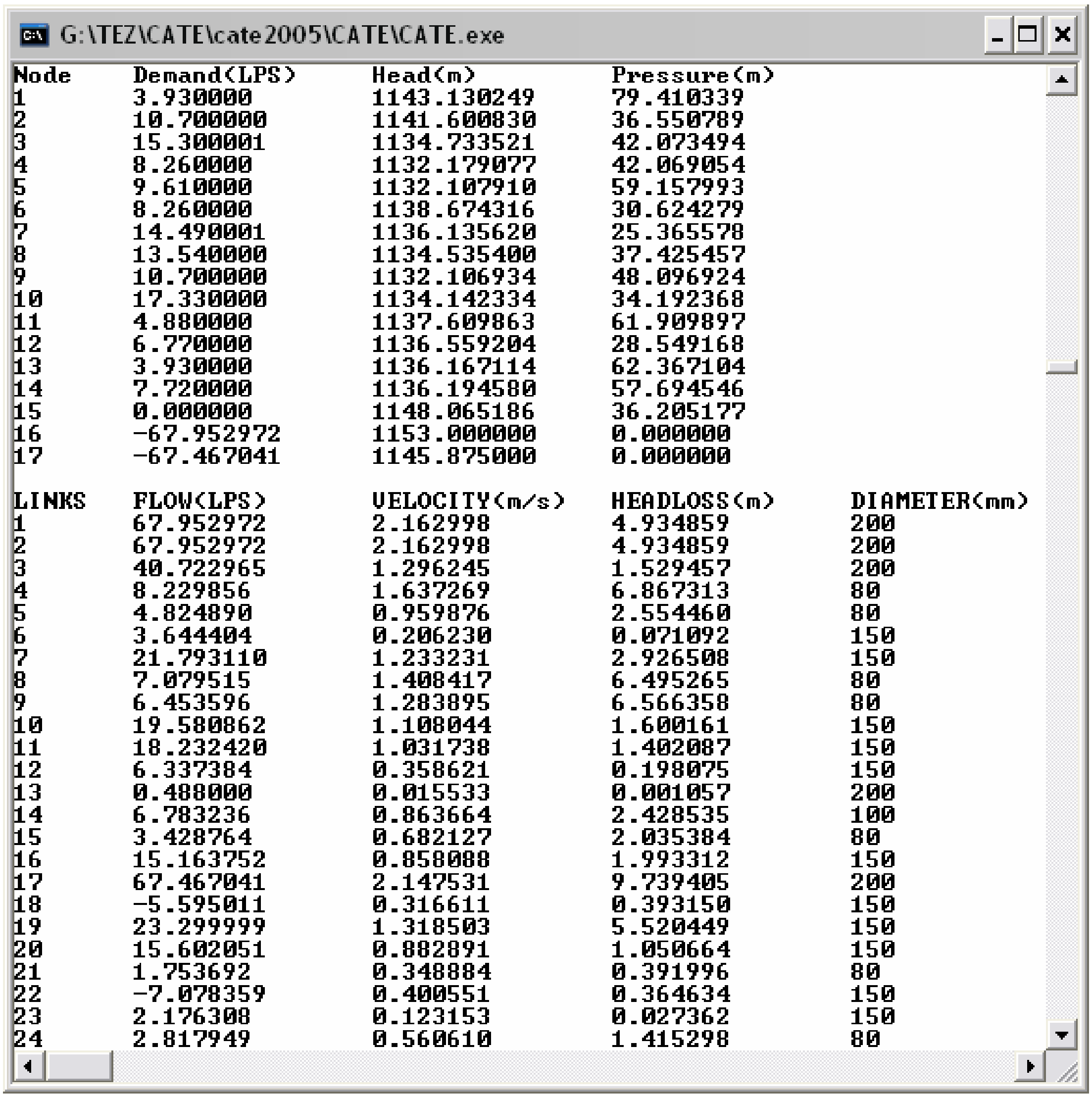


```
Node      Demand(LPS)      Head(m)          Pressure(m)
1         3.930000         1142.762085      79.042160
2         10.700000        1136.162964      31.112991
3         15.300001        1135.303589      42.643597
4         8.260000         1131.113892      41.003845
5         9.610000         1131.069946      58.119926
6         8.260000         1134.237915      26.187862
7         14.490001        1136.495361      25.725319
8         13.540000        1134.916870      37.806870
9         10.700000        1131.090820      47.080814
10        17.330000        1134.423828      34.473869
11        4.880000         1137.241699      61.541714
12        6.770000         1136.191040      28.180984
13        3.930000         1135.798950      61.998920
14        7.720000         1135.826294      57.326363
15        0.000000         1147.881104      36.021088
16        -69.310181       1153.000000      0.000000
17        -66.109818       1145.875000      0.000000

LINKS     FLOW(LPS)        VELOCITY(m/s)    HEADLOSS(m)      DIAMETER(mm)
1         69.310181        2.206200         5.118950         200
2         69.310181        2.206200         5.118950         200
3         42.080189        2.381238         6.599075         150
4         13.997926        0.792116         0.859412         150
5         6.302596         1.253855         4.189773         80
6         2.810892         0.159063         0.043949         150
7         17.382259        0.983629         1.925126         150
8         4.768296         0.948617         3.124058         80
9         4.353963         0.866189         3.168008         80
10        19.437235        1.099916         1.578492         150
11        16.700293        0.945038         1.191725         150
12        9.095620         0.514704         0.386766         150
13        -2.445145        0.077831         0.020902         200
14        8.670178         1.103915         3.826054         100
15        4.474967         0.890261         3.332993         80
16        15.482287        0.876113         2.071552         150
17        66.109818        2.104330         9.379664         200
18        -6.322679        0.357788         0.493060         150
19        23.299999        1.318503         5.520449         150
20        15.602051        0.882891         1.050664         150
21        1.753692         0.348884         0.391996         80
22        -7.078359        0.400551         0.364634         150
23        2.176308         0.123153         0.027362         150
24        2.817949         0.560610         1.415298         80
```

Figure 5.18 Result of First Run of CATE for N8 Network

Figure 5.18 presents selected diameters and hydraulic analysis results of nodes and links of the network at the end of the first run of CATE. These values are hydraulic grade line, pressure heads of nodes, velocities and head losses at links. In the first run of CATE, velocity constraints are not included. CATE builds velocity constraints in the second run for the first time according to the result of the first run. As it can be seen in the figure 5.18, velocity of pipe 3 is greater than the upper velocity limit (2.38 m/sec. > upper velocity limit = 2.3 m/sec.)

CATE performs runs until all results are in the range of the given constraint. In N8 network, number of runs is three. At the end of the third run the results are in the range of predefined constraints. To design such a looped network is very difficult and time consuming without a model program like CATE; CATE is convenient for any looped or branched network, namely there is no need to modify CATE to solve another network. It is enough to change only input files.



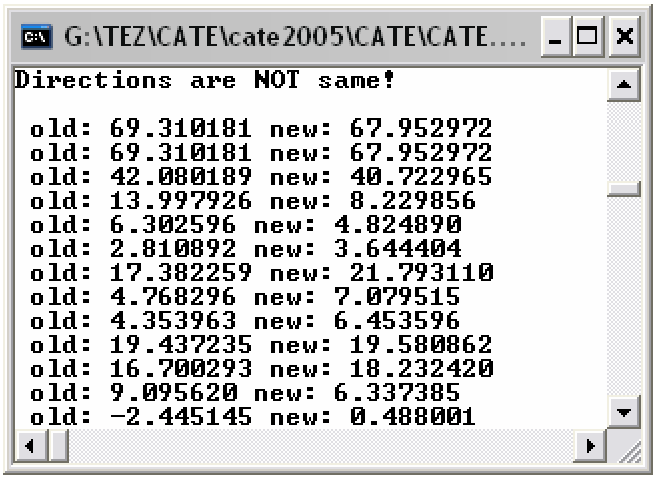
```
Node    Demand(LPS)     Head(m)         Pressure(m)
1       3.930000        1143.130249     79.410339
2       10.700000       1141.600830     36.550789
3       15.300001       1134.733521     42.073494
4       8.260000        1132.179077     42.069054
5       9.610000        1132.107910     59.157993
6       8.260000        1138.674316     30.624279
7       14.490001       1136.135620     25.365578
8       13.540000       1134.535400     37.425457
9       10.700000       1132.106934     48.096924
10      17.330000       1134.142334     34.192368
11      4.880000        1137.609863     61.909897
12      6.770000        1136.559204     28.549168
13      3.930000        1136.167114     62.367104
14      7.720000        1136.194580     57.694546
15      0.000000        1148.065186     36.205177
16      -67.952972      1153.000000     0.000000
17      -67.467041      1145.875000     0.000000

LINKS   FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1       67.952972       2.162998        4.934859        200
2       67.952972       2.162998        4.934859        200
3       40.722965       1.296245        1.529457        200
4       8.229856        1.637269        6.867313        80
5       4.824890        0.959876        2.554460        80
6       3.644404        0.206230        0.071092        150
7       21.793110       1.233231        2.926508        150
8       7.079515        1.408417        6.495265        80
9       6.453596        1.283895        6.566358        80
10      19.580862       1.108044        1.600161        150
11      18.232420       1.031738        1.402087        150
12      6.337384        0.358621        0.198075        150
13      0.488000        0.015533        0.001057        200
14      6.783236        0.863664        2.428535        100
15      3.428764        0.682127        2.035384        80
16      15.163752       0.858088        1.993312        150
17      67.467041       2.147531        9.739405        200
18      -5.595011       0.316611        0.393150        150
19      23.299999       1.318503        5.520449        150
20      15.602051       0.882891        1.050664        150
21      1.753692        0.348884        0.391996        80
22      -7.078359       0.400551        0.364634        150
23      2.176308        0.123153        0.027362        150
24      2.817949        0.560610        1.415298        80
```

Figure 5.19 Result of Second Run of CATE for N8 Network

Figure 5.19 presents selected diameters and hydraulic analysis result of node and link values of the network at the end of the second run of CATE. Velocity constraints are included in the second run of CATE. The velocity of the pipe 3 is in the range of given constraints also (under the upper limit of 2.3 m/sec). Other difference between first and second run is the pipe diameter of the third link. In the first run, velocity in the pipe 3 was over maximum velocity limit, and CATE increased the diameter to 200 mm to decrease the velocity. Increase of that pipe diameter changed network pressure balance and CATE changed another pipe diameter to decrease network cost within constraints range. Diameter of pipe 4 is decreased to 80 mm from 150 mm.

The result of the second run is appropriate according to constraints but CATE performs another run because of the inequality of design equations with the results of output network. CATE controls if the flow directions are same between hydraulic analysis of CATE output network and linear optimization equations of LINDO input created according to previous output network, at the end of each run (Step 11 of algorithm). If the flow directions are not same, CATE repeats run.

After the second run, CATE performs a hydraulic analysis with EPANET and determines flow directions in pipes. CATE compares these flow directions with linear optimization equations' results that are used for design of the second run. CATE finds out that flow direction of pipe 13 is changed, and repeats the run. In Figure 5.20 old and new flow directions are presented and it can be seen that flow direction in pipe 13 is reverse compared to the previous design result. In the figure below the minus sign before flow rate states reverse flow direction.



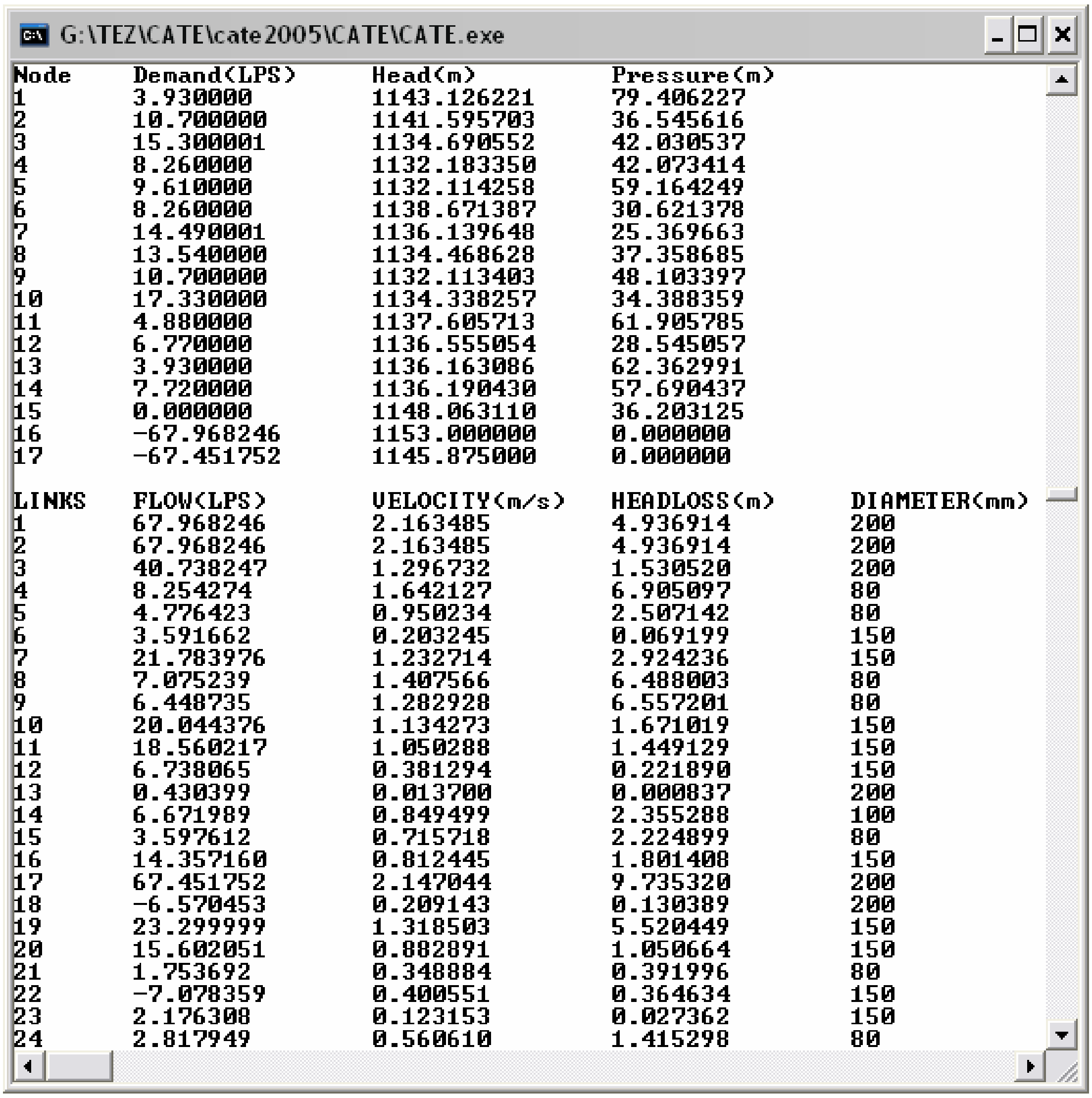
```
Directions are NOT same!

 old: 69.310181 new: 67.952972
 old: 69.310181 new: 67.952972
 old: 42.080189 new: 40.722965
 old: 13.997926 new: 8.229856
 old: 6.302596 new: 4.824890
 old: 2.810892 new: 3.644404
 old: 17.382259 new: 21.793110
 old: 4.768296 new: 7.079515
 old: 4.353963 new: 6.453596
 old: 19.437235 new: 19.580862
 old: 16.700293 new: 18.232420
 old: 9.095620 new: 6.337385
 old: -2.445145 new: 0.488001
```

Figure 5.20 Flow Direction Control in CATE for N8 Network Design

Figure 5.21 presents selected diameters and hydraulic analysis result of node and link values of the network at the end of final run of CATE. All velocity and Pressure head results are in range defined by constraints.

Cost, obtained at successive runs:

Cost of first run : 120455 $
Cost of second run : 121411 $
Cost of final run : 116467 $

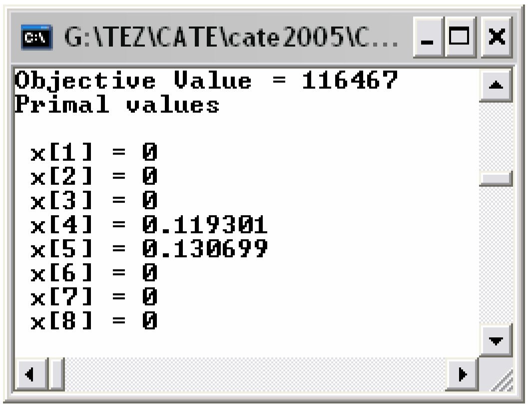


```
Node      Demand(LPS)        Head(m)            Pressure(m)
1         3.930000           1143.126221        79.406227
2         10.700000          1141.595703        36.545616
3         15.300001          1134.690552        42.030537
4         8.260000           1132.183350        42.073414
5         9.610000           1132.114258        59.164249
6         8.260000           1138.671387        30.621378
7         14.490001          1136.139648        25.369663
8         13.540000          1134.468628        37.358685
9         10.700000          1132.113403        48.103397
10        17.330000          1134.338257        34.388359
11        4.880000           1137.605713        61.905785
12        6.770000           1136.555054        28.545057
13        3.930000           1136.163086        62.362991
14        7.720000           1136.190430        57.690437
15        0.000000           1148.063110        36.203125
16        -67.968246         1153.000000        0.000000
17        -67.451752         1145.875000        0.000000

LINKS     FLOW(LPS)          VELOCITY(m/s)      HEADLOSS(m)        DIAMETER(mm)
1         67.968246          2.163485           4.936914           200
2         67.968246          2.163485           4.936914           200
3         40.738247          1.296732           1.530520           200
4         8.254274           1.642127           6.905097           80
5         4.776423           0.950234           2.507142           80
6         3.591662           0.203245           0.069199           150
7         21.783976          1.232714           2.924236           150
8         7.075239           1.407566           6.488003           80
9         6.448735           1.282928           6.557201           80
10        20.044376          1.134273           1.671019           150
11        18.560217          1.050288           1.449129           150
12        6.738065           0.381294           0.221890           150
13        0.430399           0.013700           0.000837           200
14        6.671989           0.849499           2.355288           100
15        3.597612           0.715718           2.224899           80
16        14.357160          0.812445           1.801408           150
17        67.451752          2.147044           9.735320           200
18        -6.570453          0.209143           0.130389           200
19        23.299999          1.318503           5.520449           150
20        15.602051          0.882891           1.050664           150
21        1.753692           0.348884           0.391996           80
22        -7.078359          0.400551           0.364634           150
23        2.176308           0.123153           0.027362           150
24        2.817949           0.560610           1.415298           80
```

Figure 5.21 Final Run Results of CATE for N8 Network Design

In the design of the network, CATE determines one, two or more pipe diameters for one link initially. For example: as it can be seen in the Figure 5.22 CATE assigned two types of diameter for first link.

119.3 m → for pipe type 4 (150 mm)
130.7 m → for pipe type 5 (200 mm)



```
Objective Value = 116467
Primal values

 x[1] = 0
 x[2] = 0
 x[3] = 0
 x[4] = 0.119301
 x[5] = 0.130699
 x[6] = 0
 x[7] = 0
 x[8] = 0
```

Figure 5.22 Final Run Results for N8 Network Design: CATE Result for Link 1

Then, while finalizing results, CATE eliminates short links and outcomes longest pipe diameter as pipe of that link. For link 1, type 4 is eliminated by CATE and pipe type 5 resulted as link 1 diameter type. Final result of the pipe diameter of link 1 is 200 mm presented in Figure 5.21.

Cost presented in CATE is calculated before diameter elimination with partial diameters. Cost of final design, after elimination, with one type diameter for one link is tabulated in Table 5.7.

Table 5.7 Cost of Final Design of N8 Network

Pipe	Length (m)	Diameter (mm)	Unit Cost of Diameter ($/km)	Link Cost ($)
1	250	200	24100	6025
2	250	200	24100	6025
3	200	200	24100	4820
4	200	80	12000	2400
5	200	80	12000	2400
6	200	150	16900	3380
7	300	150	16900	5070
8	250	80	12000	3000
9	300	80	12000	3600
10	200	150	16900	3380
11	200	150	16900	3380
12	200	150	16900	3380
13	500	200	24100	12050
14	300	100	14300	4290
15	300	80	12000	3600
16	400	150	16900	6760
17	500	200	24100	12050
18	0	0	69200	0
19	600	200	24100	14460
20	500	150	16900	8450
21	500	150	16900	8450
22	200	80	12000	2400
23	200	150	16900	3380
24	300	150	16900	5070
25	200	80	12000	2400
			Total Cost	**130220**

5.3.5 Improving of N8 Network and Analysis of Improved Design under Several Loading Conditions

N8 Network is designed for the peak hour loading conditions in the design part already presented in Section 5.3.4. In this section, designed diameters will be improved for peak hour loading conditions to obtain desired flow ratio between reservoirs.

Desired flow ratio between reservoirs in the peak hour is:

* Reservoir 16 (Pump) should produce approximately maximum day flow. (5,417 m^3/min)

* Rest of the required flow (Q_{peak}-Q_{max}) should be delivered by the reservoir 17 (tank). (2,708 m^3/min)

Qpeak = 1.5*Qmax: Pump should produce : 1 flow
Tank should produce : 0.5 flow for the peak case.

By this ratio of the flows in between R-16 and R-17 in the peak hours, recharge of R-17 (tank) will be obtained in night loading conditions hours.

To provide this condition diameter of pipe line between R-16 (Pump) and R-17 (Tank) are increased. New diameter values for the mainline between reservoirs are tabulated in Table 5.8.

Table 5.8 New Diameters for Mainline

Pipe	Designed Diameter (mm)	Improved Diameter (mm)
1	200	250
2	200	250
3	200	250
4	80	250
11	150	250
17	200	250

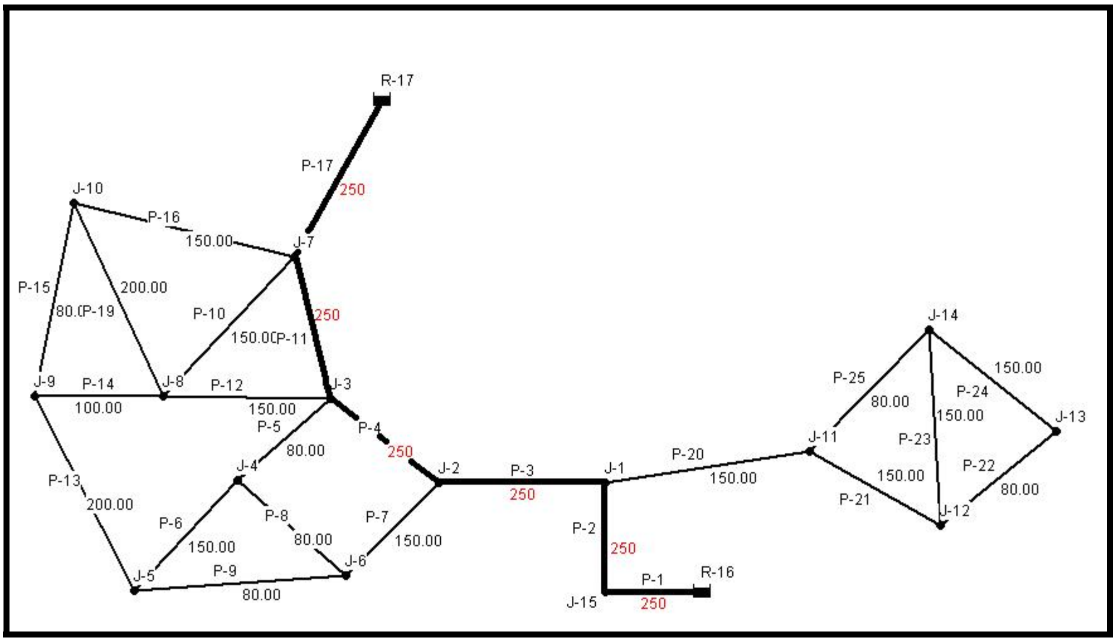


Figure 5.23 N8 Network: New Diameters for Mainline

After the change of diameters in the mainline between reservoirs, N8 network is analyzed for peak, maximum day with fire and night demand flows with EPANET software. The analysis results are described in the following sections.

5.3.5.1 Analysis of Improved System for the Peak flow demands

The new network obtained by improving of mainline diameters is controlled according to peak demand values. Analysis Results of N8 network with peak demand flows are tabulated in Table 5.9 and Table 5.10.

Table 5.9 Peak Demand Analysis for N8 Network: Junction Report

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc 1	1063.72	3.93	1146.62	82.90
Junc 2	1105.05	10.70	1145.23	40.18
Junc 3	1092.66	15.30	1144.71	52.05
Junc 4	1090.11	8.26	1140.13	50.02
Junc 5	1072.95	9.61	1140.07	67.12
Junc 6	1108.05	8.26	1143.29	35.24
Junc 7	1110.77	14.49	1144.70	33.93
Junc 8	1097.11	13.54	1143.64	46.53
Junc 9	1084.01	10.70	1140.09	56.08
Junc 10	1099.95	17.33	1143.37	43.42
Junc 11	1075.70	4.88	1141.09	65.40
Junc 12	1108.01	6.77	1140.04	32.03
Junc 13	1073.80	3.93	1139.65	65.85
Junc 14	1078.50	7.72	1139.68	61.18
Junc 15	1111.86	0.00	1149.81	37.95
Resvr 16	1153.00	-96.59	1153.00	0.00
Resvr 17	1145.88	-38.83	1145.88	0.00

It is obtained that, pressure heads at junctions for peak analysis are over minimum pressure limit.

Table 5.10 Peak Demand Analysis for N8 Network: Pipe Report

Link ID	Length m	Diameter mm	Roughness	Flow LPS	Velocity m/s
Pipe 1	250	250	140	96.59	1.97
Pipe 2	250	250	140	96.59	1.97
Pipe 3	200	250	140	69.36	1.41
Pipe 4	200	250	140	41.21	0.84
Pipe 5	200	80	140	6.61	1.32
Pipe 6	200	150	140	3.15	0.18
Pipe 7	300	150	140	17.45	0.99
Pipe 8	250	80	140	4.80	0.96
Pipe 9	300	80	140	4.39	0.87
Pipe 10	200	150	140	15.71	0.89
Pipe 11	200	250	140	-3.54	0.07
Pipe 12	200	150	140	15.75	0.89
Pipe 13	500	200	140	-2.06	0.07
Pipe 14	300	100	140	8.32	1.06
Pipe 15	300	80	140	4.44	0.88
Pipe 16	400	150	140	12.17	0.69
Pipe 17	500	250	140	38.83	0.79
Pipe 19	500	200	140	-9.60	0.31
Pipe 20	500	150	140	23.30	1.32
Pipe 21	200	150	140	15.60	0.88
Pipe 22	200	80	140	1.75	0.35
Pipe 23	300	150	140	-7.08	0.40
Pipe 24	200	150	140	2.18	0.12
Pipe 25	300	80	140	2.82	0.56

It is obtained that, velocities are in the range of limits.

Table 5.11 Final Cost of N8 Network After Improving Mainline

Pipe	Length (m)	Diameter (mm)	Unit Cost of Diameter ($/km)	Link Cost ($)
1	250	250	43200	10800
2	250	250	43200	10800
3	200	250	43200	8640
4	200	250	43200	8640
5	200	80	12000	2400
6	200	150	16900	3380
7	300	150	16900	5070
8	250	80	12000	3000
9	300	80	12000	3600
10	200	150	16900	3380
11	200	250	43200	8640
12	200	150	16900	3380
13	500	200	24100	12050
14	300	100	14300	4290
15	300	80	12000	3600
16	400	150	16900	6760
17	500	250	43200	21600
18	0	0	0	0
19	600	200	24100	14460
20	500	150	16900	8450
21	500	150	16900	8450
22	200	80	12000	2400
23	200	150	16900	3380
24	300	150	16900	5070
25	200	80	12000	2400
			Total Cost	**164640**

Increase in the mainline diameters increase the network total cost, new cost calculation is tabulated in Table 5.11.

5.3.5.2 Analysis of Improved System for the Maximum day with fire flow Demands

Two critical nodes, one is at the west and the other is at the east side of N8 network, are tested respectively with 30 lt/sec of fire flow in addition to maximum day demand.

- J-6 is selected as the most critical node in the west side.
- J-12 is selected as the most critical node in the east side.

To find out the most critical node for the fire case, all nodes are investigated. Then the node, which reduces the pressure heads of itself and other nodes' under limit or too much taken as critical node.

In the west side the nodes with pressure head near to lower limit are tested; these nodes are J-2 (P/γ=40.18m), J-6 (P/γ=35.24m), J-7 (P/γ=33.93m). After tests on each of these nodes, J-6 is taken as critical node.

In the east side the nodes are tested; these nodes are J-12 (P/γ=32.03m) and J-14 (P/γ=61.18m). After tests on these nodes, J-12 is taken as critical node.

Fire at Junction 6

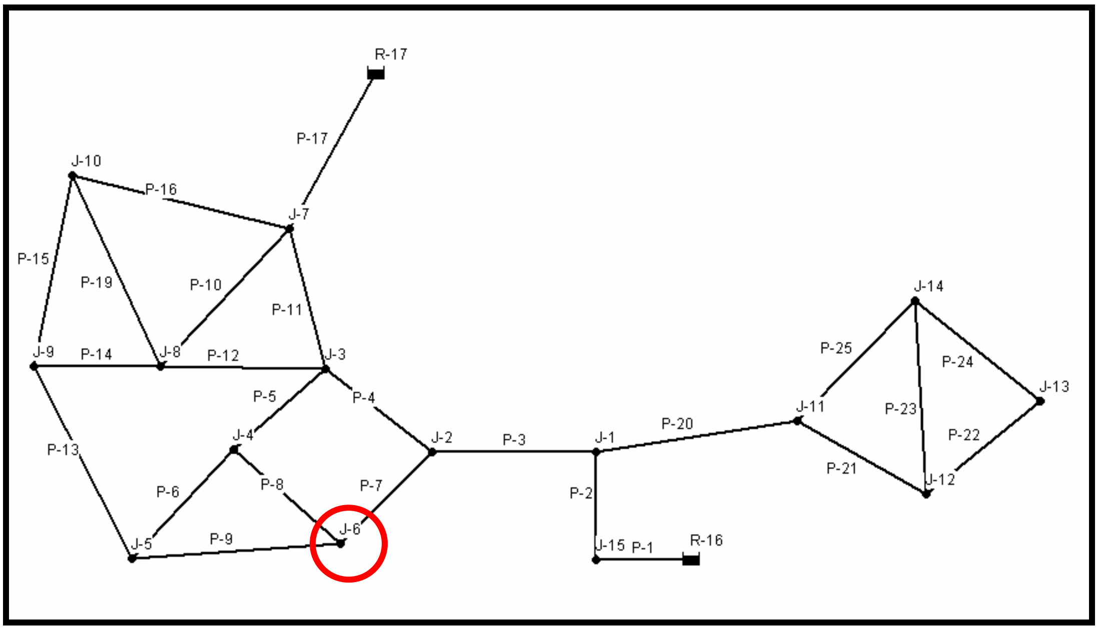


Figure 5.24 N8 Network: Fire at Junction 6

The network is analyzed with the fire flow of 30 lt/sec at junction 6 and junction results are tabulated in Table 5.12. Pressure Head at junction 6 is above limit of 15 m and there is no other junction that has pressure head under the limit of 30 m for the fire case. Minimum pressure head limit, 15 m, is originated from fire trunks' working pressure head.

Table 5.12 Junction Report of EPANET Analysis for Fire at Junction 6

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc 1	1063.72	2.62	1147.16	83.44
Junc 2	1105.05	7.13	1145.60	40.55
Junc 3	1092.66	10.20	1145.23	52.57
Junc 4	1090.11	5.51	1139.80	49.69
Junc 5	1072.95	6.41	1139.80	66.85
Junc 6	**1108.05**	**35.51**	**1139.42**	**31.37**
Junc 7	1110.77	9.66	1145.22	34.45
Junc 8	1097.11	9.03	1144.50	47.39
Junc 9	1084.01	7.13	1139.97	55.96
Junc 10	1099.95	11.56	1144.35	44.40
Junc 11	1075.70	3.25	1144.55	68.85
Junc 12	1108.01	4.51	1144.06	36.05
Junc 13	1073.80	2.62	1143.87	70.07
Junc 14	1078.50	5.15	1143.89	65.39
Junc 15	1111.86	0.00	1150.08	38.22
Resvr 16	1153.00	-92.08	1153.00	0.00
Resvr 17	1145.88	-28.21	1145.88	0.00

Fire at Junction 12

The network is analyzed with the fire flow of 30 lt/sec at junction 12 and junction results are tabulated in Table 5.13. Pressure Head at node 12 is 14.29 m, under limit of 15 m but allowable. And there is no other junction that has pressure head under the limit of 30 m for the fire case.

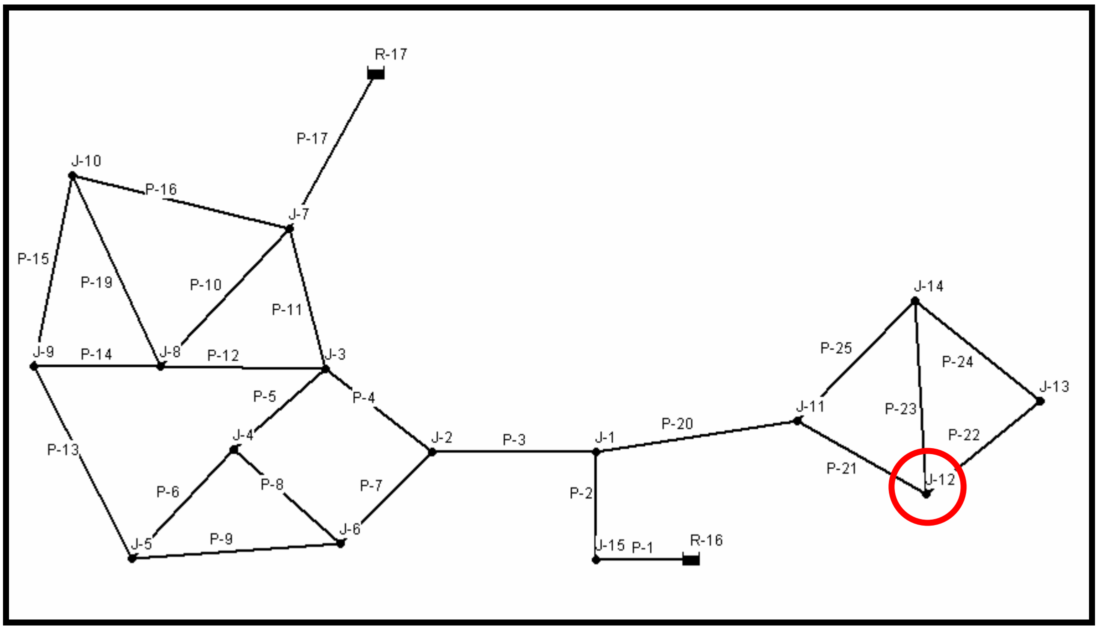


Figure 5.25 N8 Network: Fire at Junction 12

Table 5.13 Junction Report of EPANET Analysis for Fire at Junction 12

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc 1	1063.72	2.62	1146.49	82.77
Junc 2	1105.05	7.13	1145.75	40.70
Junc 3	1092.66	10.20	1145.45	52.79
Junc 4	1090.11	5.51	1143.30	53.19
Junc 5	1072.95	6.41	1143.28	70.33
Junc 6	1108.05	5.51	1144.83	36.78
Junc 7	1110.77	9.66	1145.44	34.67
Junc 8	1097.11	9.03	1144.94	47.83
Junc 9	1084.01	7.13	1143.28	59.27
Junc 10	1099.95	11.56	1144.82	44.87
Junc 11	1075.70	3.25	1127.40	51.70
Junc 12	**1108.01**	**34.51**	**1122.30**	**14.29**
Junc 13	1073.80	2.62	1122.25	48.45
Junc 14	1078.50	5.15	1122.28	43.78
Junc 15	1111.86	0.00	1149.75	37.89
Resvr 16	1153.00	-97.59	1153.00	0.00
Resvr 17	1145.88	-22.70	1145.88	0.00

5.3.5.3 Analysis of Improved System for Maximum Storage Replenishment: Night Case

In the night case analysis of the network, demand flows are considered as 20% of Q_{max}.

- Reservoir 16 (Pump) should produce approximately maximum day flow. (5,417 m^3/min)
- 80% of the flow that is produced by reservoir 16 (Pump) is used to fill the tank.

Table 5.14 Pipe Report of EPANET Analysis with Night Demand Flows

Link ID	Length m	Diameter mm	Flow LPS	Velocity m/s
Pipe 1	250	250	90.28	1.84
Pipe 2	250	250	90.28	1.84
Pipe 3	200	250	86.66	1.77
Pipe 4	200	250	77.80	1.58
Pipe 5	200	80	1.40	0.28
Pipe 6	200	150	3.58	0.20
Pipe 7	300	150	7.44	0.42
Pipe 8	250	80	3.29	0.65
Pipe 9	300	80	3.05	0.61
Pipe 10	200	150	-8.27	0.47
Pipe 11	200	250	-61.16	1.25
Pipe 12	200	150	13.20	0.75
Pipe 13	500	200	5.35	0.17
Pipe 14	300	100	-2.40	0.31
Pipe 15	300	80	-1.52	0.30
Pipe 16	400	150	-4.73	0.27
Pipe 19	500	200	-5.52	0.18
Pipe 20	500	150	3.10	0.18
Pipe 21	200	150	2.08	0.12
Pipe 22	200	80	0.23	0.05
Pipe 23	300	150	-0.94	0.05
Pipe 24	200	150	0.29	0.02
Pipe 25	300	80	0.37	0.07
Pipe 18	500	250	72.23	1.47

Table 5.15 Junction Report of EPANET Analysis with Night Demand Flows

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc 1	1063.72	0.52	1155.37	91.65
Junc 2	1105.05	1.43	1153.28	48.23
Junc 3	1092.66	2.04	1151.57	58.91
Junc 4	1090.11	1.10	1151.31	61.20
Junc 5	1072.95	1.28	1151.24	78.29
Junc 6	1108.05	1.10	1152.88	44.83
Junc 7	1110.77	1.93	1150.47	39.70
Junc 8	1097.11	1.81	1150.80	53.69
Junc 9	1084.01	1.43	1151.15	67.14
Junc 10	1099.95	2.31	1150.70	50.75
Junc 11	1075.70	0.65	1155.23	79.53
Junc 12	1108.01	0.90	1155.21	47.20
Junc 13	1073.80	0.52	1155.20	81.40
Junc 14	1078.50	1.03	1155.20	76.70
Junc 15	1111.86	0.00	1158.18	46.32
Junc 18	**1145.88**	**72.23**	**1146.74**	**0.87**
Resvr 16	1161.00	-90.28	1161.00	0.00

Junction and pipe report with night flows indicates that pressure head is greater than 0 m at junction 18 (Tank) and flow from tank to pump is 72.23 l/sec (80 % of maximum day flow) as needed for the night replenishment of the tank.

5.3.6 Reliability Analysis on N8 Network

The term ‘‘reliability’’ for water distribution networks does not have a well-defined meaning and measure. Nevertheless, it is generally understood that reliability is concerned with the ability of the network to provide an adequate supply to the consumers, under both normal and abnormal operating conditions, Goulter (1995). Adequate supply for consumers means to provide flow in required quantity and quality for consumers. Components of water quantity are flow and pressure in required range; quality implies acceptable physical and chemical conditions for water conveyed to consumers. Since there are many criteria affecting water quantity and quality, analysis of all criteria at the same time, to define reliability, is a very complex procedure. On the other hand, uncertainties of some parameters, like water demand of consumers, in water distribution systems, reveal the need of statistical measures incorporating with other reliability measures. Besides, measuring and evaluation of reliability without any reference point of measure is impossible. Stating of measure for evaluation "reliability of this network is 90 %" is meaningless. The true way to define measure is roughly; "more or less reliable according to another condition". It is say to that, measuring with relative to any other measure is more accurate. One another point is statement of measure for reliability of different parameters should be measured separately and cannot be merged in one reliability definition. For example; reliability measure for quality of water and water flow cannot be incorporated in one measure.

The reliability approach in CATE is related with pipe failure, which is affecting both water quality and quantity, does not consider the true issue of reliability by itself.

A measure of reliability is incorporated into this constraint set by Equation 5.1 in CATE, which limits the expected (average) number of breaks in given time period in any link

$$\sum_{k=1}^{n(j)} r_{jk} \cdot X_{jk} \leq R_j \quad \text{For all links } j \tag{5.1}$$

where

n (j) : number of different pipe diameters in link j

r_{jk} : expected number of breaks/km/year for diameter k in link j

R_j : maximum allowable number of failures per year in link j

X_{jk} : length of pipe of diameter k in link j (km)

j : link index

k : diameter type index

Expected numbers of breaks/km/year for types of diameters (r) are obtained from statistical archives, (Kettler and Goulter 1983). And maximum allowable number of failures per year in any link (R) is a user defined value for each link. By defining R value for a link, limiting of number of failures per year for that link is possible towards statistical r values of used pipe types. If you design network by limiting number of failures for a link with two different R values separately, you will have two designs that have different reliabilities relative to each other.

5.3.6.1 Case Study: Design with Reliability Constraint on N8 Network

In this section skeletonized N8 network, a pressure zone that belongs to the northern supply zone of Ankara, is analyzed with CATE to investigate reliability constraint effect on the network.

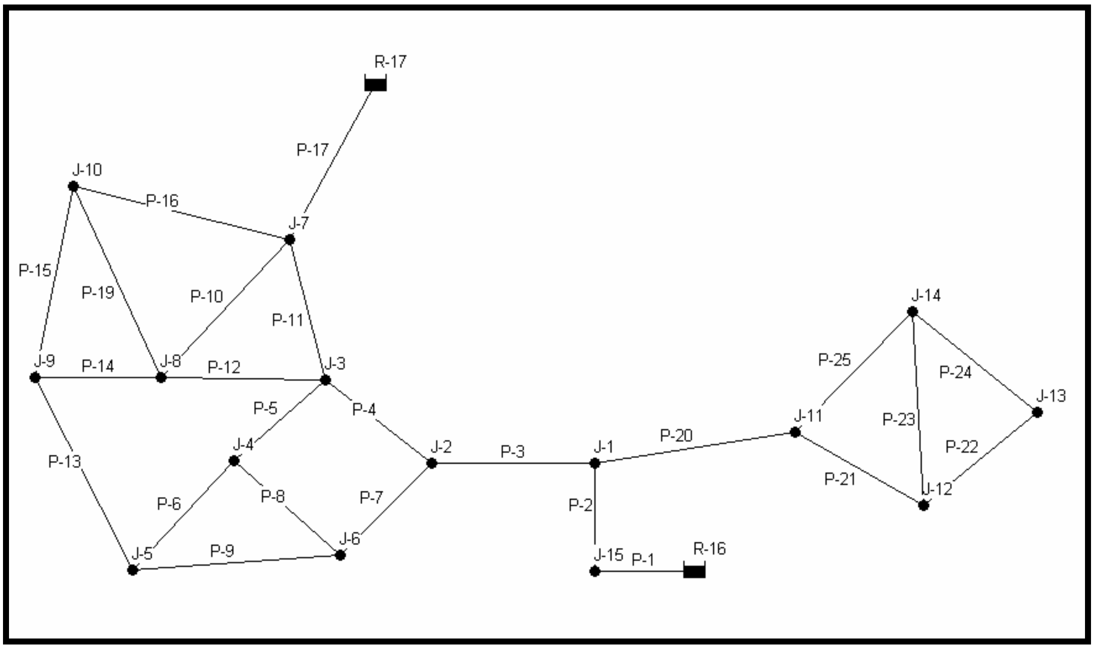


Figure 5.26 Skeletonized Form of N8 Network

Nodal weights, demand values and topographical elevations of N8 network are tabulated in Table 5.16.

Table 5.16 N8 Network: Junction Properties

		Demand						**Topographical Elevation (m)**
Node	**Nodal Weights**	**Q_{peak} (m^3/min)**	**Q_{max} (m^3/min)**	**Q_{night} (m^3/min)**	**Q_{peak} (lt/sec)**	**Q_{max} (lt/sec)**	**Q_{night} (lt/sec)**	
1	0.029	0.2356	0.1571	0.0314	3.93	2.62	0.52	1063.72
2	0.079	0.6419	0.4279	0.0856	10.70	7.13	1.43	1105.05
3	0.113	0.9181	0.6121	0.1224	15.30	10.20	2.04	1092.66
4	0.061	0.4956	0.3304	0.0661	8.26	5.51	1.10	1090.11
5	0.071	0.5769	0.3846	0.0769	9.61	6.41	1.28	1072.95
6	0.061	0.4956	0.3304	0.0661	8.26	5.51	1.10	1108.05
7	0.107	0.8694	0.5796	0.1159	14.49	9.66	1.93	1110.77
8	0.100	0.8125	0.5417	0.1083	13.54	9.03	1.81	1097.11
9	0.079	0.6419	0.4279	0.0856	10.70	7.13	1.43	1084.01
10	0.128	1.0400	0.6933	0.1387	17.33	11.56	2.31	1099.95
11	0.036	0.2925	0.1950	0.0390	4.88	3.25	0.65	1075.70
12	0.050	0.4063	0.2708	0.0542	6.77	4.51	0.90	1108.01
13	0.029	0.2356	0.1571	0.0314	3.93	2.62	0.52	1073.80
14	0.057	0.4631	0.3088	0.0618	7.72	5.15	1.03	1078.50
Total	**1.000**	**8.1250**	**5.4167**	**1.0833**	**135.42**	**90.28**	**18.06**	

Pipe length and roughness values of N8 network is tabulated in Table 5.17.

Table 5.17 N8 Network: Link Properties

Pipe	Length (m)	Hazen Williams Roughness
1	250	140
2	250	140
3	200	140
4	200	140
5	200	140
6	200	140
7	300	140
8	250	140
9	300	140
10	200	140
11	200	140
12	200	140
13	500	140
14	300	140
15	300	140
16	400	140
17	500	140
18	600	140
19	500	140
20	500	140
21	200	140
22	200	140
23	300	140
24	200	140
25	300	140

Pipe type input file, pipeTypes.txt, contains information about available pipe diameters for design and their properties (pipe unit cost, pipe statistical break rates, and pipe hydraulic gradients), maximum and minimum velocity limits, maximum and minimum pressure head limits and reliability limits for links.

In this case study about reliability on N8 network, groups of pipes' maximum permissible break rate per km per year values (R) are limited and the results are investigated. Then one pipe's R value is limited, and the results are examined as the second case study.

For the first case, selected pipes are pipe 4 and 5 in the west side of the N8 network, see Figure 5.27. Custom reliability values for these pipes are decreased to 0.18, See Figure 5.28. This means that, maximum number of breaks for pipe 4 and 5 are forced to be smaller than 0.18 per one year. In this case, pipe 4 and 5 will be forced to be formed from pipe diameters that will have break rate values smaller than 0.18.

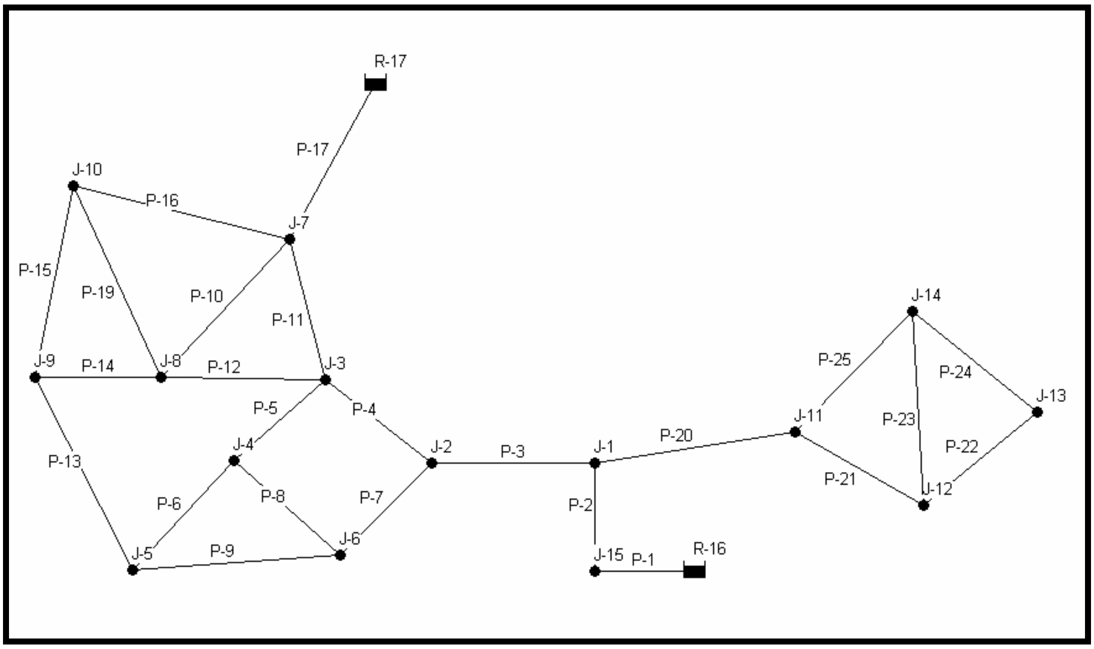
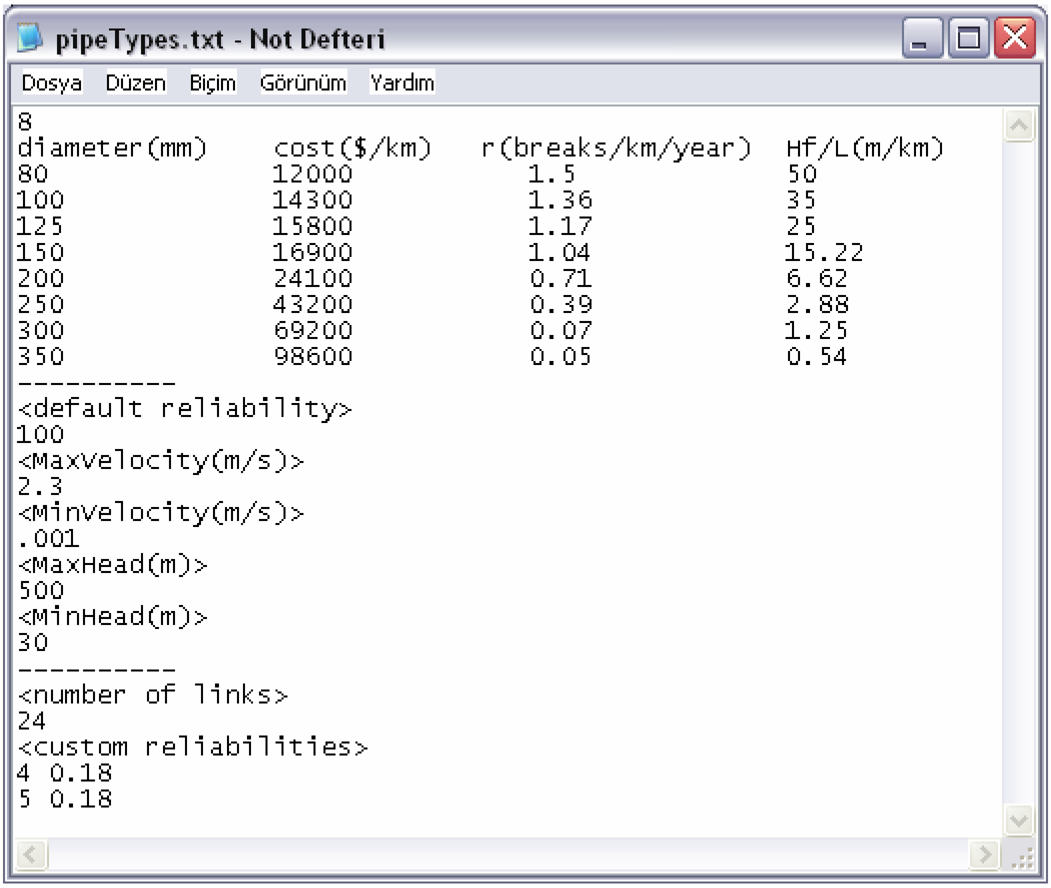


Figure 5.27 Skeletonized Form of N8 Network



```
8
diameter(mm)     cost($/km)    r(breaks/km/year)  Hf/L(m/km)
80               12000            1.5                50
100              14300            1.36               35
125              15800            1.17               25
150              16900            1.04               15.22
200              24100            0.71               6.62
250              43200            0.39               2.88
300              69200            0.07               1.25
350              98600            0.05               0.54
----------
<default reliability>
100
<MaxVelocity(m/s)>
2.3
<MinVelocity(m/s)>
.001
<MaxHead(m)>
500
<MinHead(m)>
30
----------
<number of links>
24
<custom reliabilities>
4 0.18
5 0.18
```

Figure 5.28 Pipe Type Input file for N8 Network Reliability Analysis 1: pipeType.txt

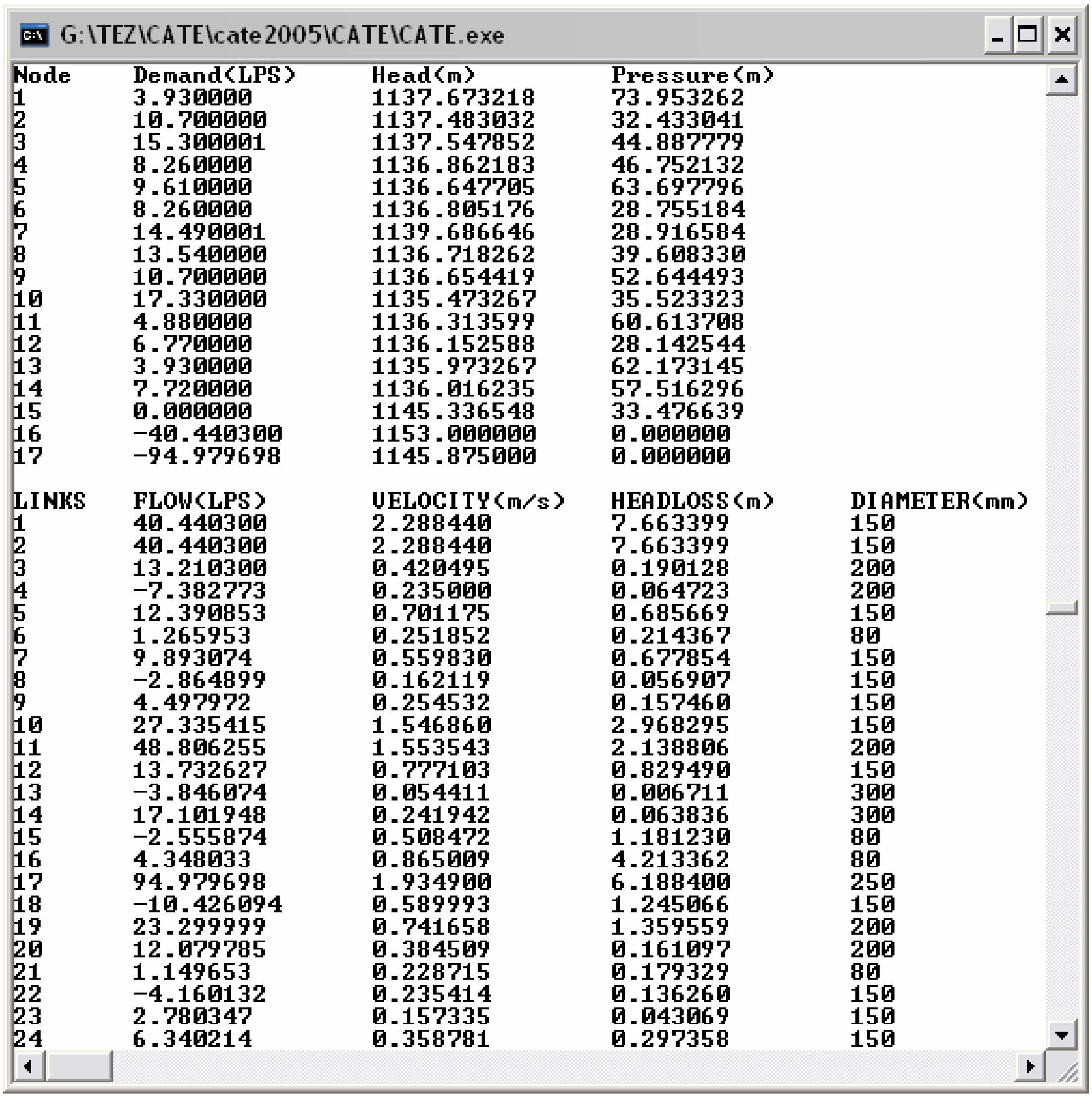
Design constraints to be respected by CATE while reaching optimum solution for N8 network are:

1) Velocity constraint: V (m/s) < 2.3 m/s

2) Available pipe diameters in mm are 80, 100, 125, 150, 200, 250, and 300.

3) Allowable minimum pressure head: 30 m < P/γ (m)

These constraints are defined to CATE in pipetype.txt input file.



```
Node    Demand(LPS)     Head(m)         Pressure(m)
1       3.930000        1137.673218     73.953262
2       10.700000       1137.483032     32.433041
3       15.300001       1137.547852     44.887779
4       8.260000        1136.862183     46.752132
5       9.610000        1136.647705     63.697796
6       8.260000        1136.805176     28.755184
7       14.490001       1139.686646     28.916584
8       13.540000       1136.718262     39.608330
9       10.700000       1136.654419     52.644493
10      17.330000       1135.473267     35.523323
11      4.880000        1136.313599     60.613708
12      6.770000        1136.152588     28.142544
13      3.930000        1135.973267     62.173145
14      7.720000        1136.016235     57.516296
15      0.000000        1145.336548     33.476639
16      -40.440300      1153.000000     0.000000
17      -94.979698      1145.875000     0.000000

LINKS   FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1       40.440300       2.288440        7.663399        150
2       40.440300       2.288440        7.663399        150
3       13.210300       0.420495        0.190128        200
4       -7.382773       0.235000        0.064723        200
5       12.390853       0.701175        0.685669        150
6       1.265953        0.251852        0.214367        80
7       9.893074        0.559830        0.677854        150
8       -2.864899       0.162119        0.056907        150
9       4.497972        0.254532        0.157460        150
10      27.335415       1.546860        2.968295        150
11      48.806255       1.553543        2.138806        200
12      13.732627       0.777103        0.829490        150
13      -3.846074       0.054411        0.006711        300
14      17.101948       0.241942        0.063836        300
15      -2.555874       0.508472        1.181230        80
16      4.348033        0.865009        4.213362        80
17      94.979698       1.934900        6.188400        250
18      -10.426094      0.589993        1.245066        150
19      23.299999       0.741658        1.359559        200
20      12.079785       0.384509        0.161097        200
21      1.149653        0.228715        0.179329        80
22      -4.160132       0.235414        0.136260        150
23      2.780347        0.157335        0.043069        150
24      6.340214        0.358781        0.297358        150
```

Figure 5.29 Final Run Results of CATE for the Design 1 of N8 Network with Reliability Constraints

Figure 5.29 presents selected diameters and hydraulic analysis result of node and link values of the network at the end of final run of CATE. All velocity and Pressure head results are in allowable range defined by constraints. Furthermore CATE assigns new diameters for pipe 4 and 5 due to custom reliability defined for them.

Table 5.18 Cost of Final Design of N8 Network: Comparison of Two Designs, with and without Reliability Constraint

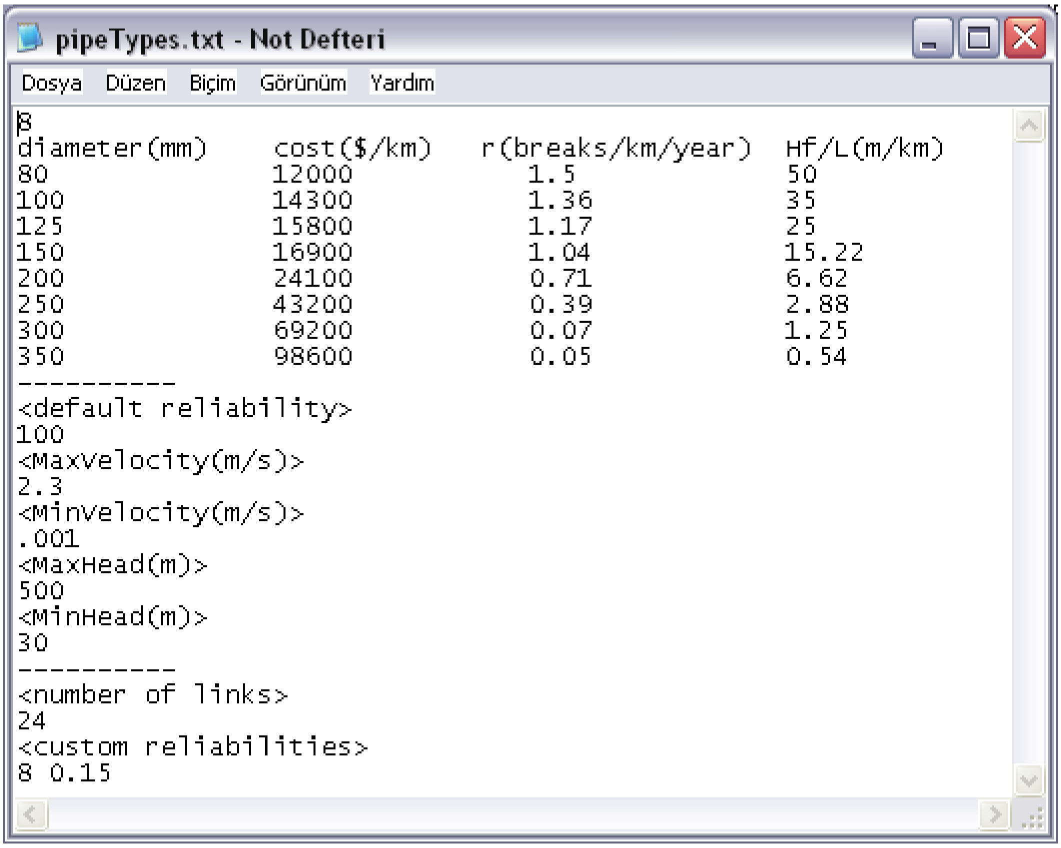
		Without Reliability Constraint			With Reliability Constraint		
Pipe	**Length (m)**	**Diameter (mm)**	**Unit Cost of Diameter ($/km)**	**Link Cost ($)**	**Diameter (mm)**	**Unit Cost of Diameter ($/km)**	**Link Cost ($)**
1	250	200	24100	6025	150	16900	4225
2	250	200	24100	6025	150	16900	4225
3	200	200	24100	4820	200	24100	4820
4	**200**	**80**	**12000**	**2400**	**200**	**24100**	**4820**
5	**200**	**80**	**12000**	**2400**	**150**	**16900**	**3380**
6	200	150	16900	3380	80	12000	2400
7	300	150	16900	5070	150	16900	5070
8	250	80	12000	3000	150	16900	4225
9	300	80	12000	3600	150	16900	5070
10	200	150	16900	3380	150	16900	3380
11	200	150	16900	3380	200	24100	4820
12	200	150	16900	3380	150	16900	3380
13	500	200	24100	12050	300	69200	34600
14	300	100	14300	4290	300	69200	20760
15	300	80	12000	3600	80	12000	3600
16	400	150	16900	6760	80	12000	4800
17	500	200	24100	12050	250	43200	21600
18	0	0	69200	0	0	69200	0
19	600	200	24100	14460	150	16900	10140
20	500	150	16900	8450	200	24100	12050
21	500	150	16900	8450	200	24100	12050
22	200	80	12000	2400	80	12000	2400
23	200	150	16900	3380	150	16900	3380
24	300	150	16900	5070	150	16900	5070
25	200	80	12000	2400	150	16900	3380
		Total Cost		**130220**	**Total Cost**		**183645**

Diameters of the pipe 4 and pipe 5 are increased to 200 mm and 150 mm with the effect of reliability constraint.

These pipes have the diameter 80 mm without reliability constraint design. When the R value is decreased to 0.18, CATE designs larger pipe diameters for these pipes to be under limit of 0.18 breaks per year for these links. This condition is not to say the design with small diameter pipe is not reliable and the design with larger diameter pipe is reliable. Only comment can be: “the second design with reliability constraint is more reliable according to the first design”.

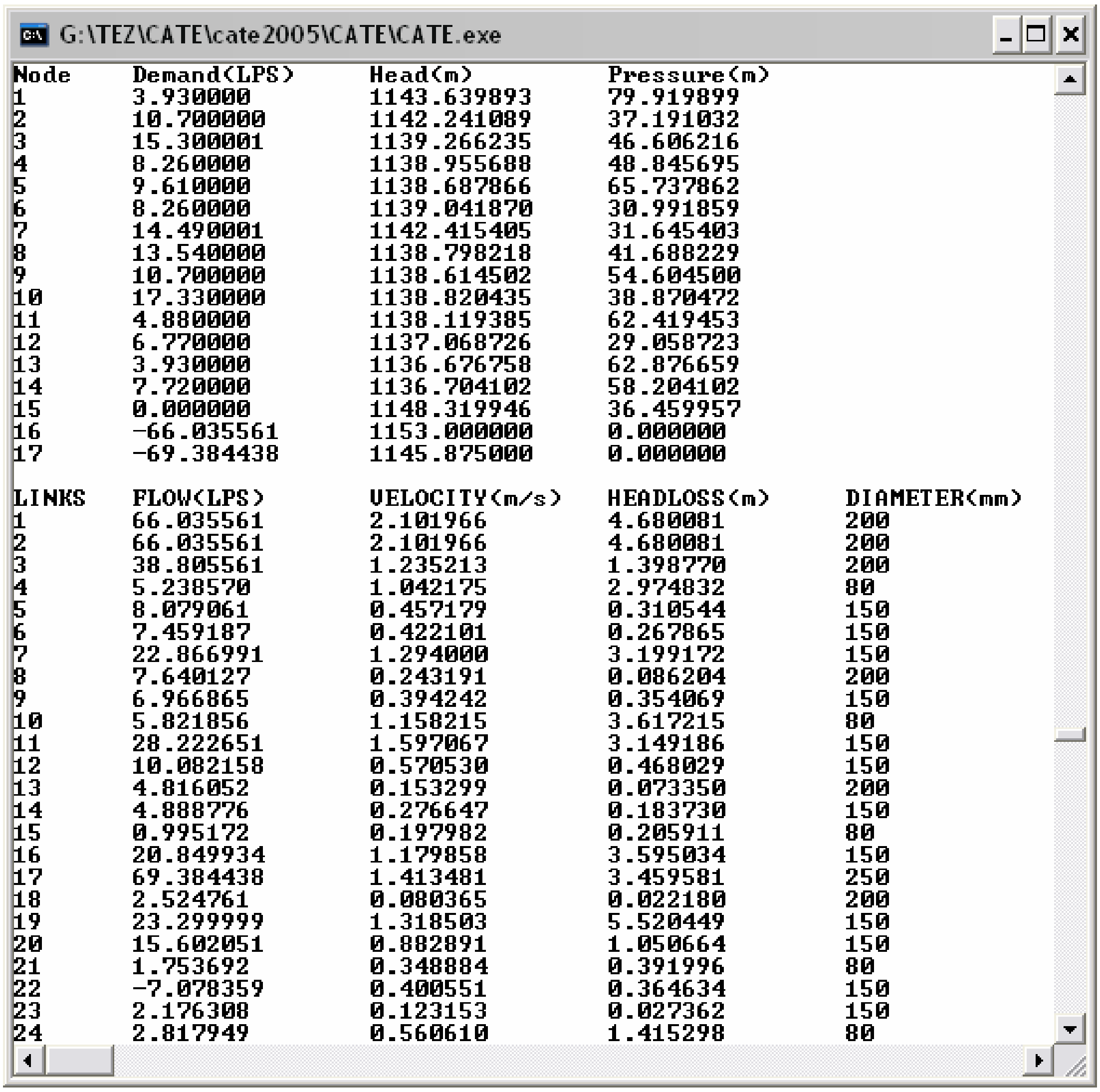
Besides, change in the diameter of pipes affect other links of the network and some other diameters are increased or decreased in the network, along with total cost of the network is increased to 183645 $. Comparison is tabulated in Table 5.18.

For the second case, selected pipe is pipe 8 in the west side of the N8 network, see Figure 5.27. Custom reliability value for the pipe is decreased to 0.15, See Figure 5.30. This means that, maximum number of breaks for pipe 8 is forced to be smaller than 0.15 per one year. In this case, pipe 8 will be forced to be formed from pipe diameters that will have break rate values smaller than 0.15.



```
8
diameter(mm)     cost($/km)   r(breaks/km/year)  Hf/L(m/km)
80               12000           1.5                50
100              14300           1.36               35
125              15800           1.17               25
150              16900           1.04               15.22
200              24100           0.71               6.62
250              43200           0.39               2.88
300              69200           0.07               1.25
350              98600           0.05               0.54
----------
<default reliability>
100
<MaxVelocity(m/s)>
2.3
<MinVelocity(m/s)>
.001
<MaxHead(m)>
500
<MinHead(m)>
30
----------
<number of links>
24
<custom reliabilities>
8 0.15
```

Figure 5.30 Pipe Type Input file for N8 Network Reliability Analysis 2: pipeType.txt



```
Node      Demand(LPS)     Head(m)         Pressure(m)
1         3.930000        1143.639893     79.919899
2         10.700000       1142.241089     37.191032
3         15.300001       1139.266235     46.606216
4         8.260000        1138.955688     48.845695
5         9.610000        1138.687866     65.737862
6         8.260000        1139.041870     30.991859
7         14.490001       1142.415405     31.645403
8         13.540000       1138.798218     41.688229
9         10.700000       1138.614502     54.604500
10        17.330000       1138.820435     38.870472
11        4.880000        1138.119385     62.419453
12        6.770000        1137.068726     29.058723
13        3.930000        1136.676758     62.876659
14        7.720000        1136.704102     58.204102
15        0.000000        1148.319946     36.459957
16        -66.035561      1153.000000     0.000000
17        -69.384438      1145.875000     0.000000

LINKS     FLOW(LPS)       VELOCITY(m/s)   HEADLOSS(m)     DIAMETER(mm)
1         66.035561       2.101966        4.680081        200
2         66.035561       2.101966        4.680081        200
3         38.805561       1.235213        1.398770        200
4         5.238570        1.042175        2.974832        80
5         8.079061        0.457179        0.310544        150
6         7.459187        0.422101        0.267865        150
7         22.866991       1.294000        3.199172        150
8         7.640127        0.243191        0.086204        200
9         6.966865        0.394242        0.354069        150
10        5.821856        1.158215        3.617215        80
11        28.222651       1.597067        3.149186        150
12        10.082158       0.570530        0.468029        150
13        4.816052        0.153299        0.073350        200
14        4.888776        0.276647        0.183730        150
15        0.995172        0.197982        0.205911        80
16        20.849934       1.179858        3.595034        150
17        69.384438       1.413481        3.459581        250
18        2.524761        0.080365        0.022180        200
19        23.299999       1.318503        5.520449        150
20        15.602051       0.882891        1.050664        150
21        1.753692        0.348884        0.391996        80
22        -7.078359       0.400551        0.364634        150
23        2.176308        0.123153        0.027362        150
24        2.817949        0.560610        1.415298        80
```

Figure 5.31 Final Run Results of CATE for the Design 2 of N8 Network with Reliability Constraints

Figure 5.31 presents selected diameters and hydraulic analysis result of node and link values of the network at the end of final run of CATE. All velocity and Pressure head results are in allowable range defined by constraints. Furthermore CATE assigns new diameters for pipe 8 due to custom reliability defined for it.

Table 5.19 Cost of Final Design of N8 Network: Comparison of Two Designs, with and without Reliability Constraint

		Without Reliability Constraint			**With Reliability Constraint**		
Pipe	**Length (m)**	**Diameter (mm)**	**Unit Cost of Diameter ($/km)**	**Link Cost ($)**	**Diameter (mm)**	**Unit Cost of Diameter ($/km)**	**Link Cost ($)**
1	250	200	24100	6025	200	24100	6025
2	250	200	24100	6025	200	24100	6025
3	200	200	24100	4820	200	24100	4820
4	200	80	12000	2400	80	12000	2400
5	200	80	12000	2400	150	16900	3380
6	200	150	16900	3380	150	16900	3380
7	300	150	16900	5070	150	16900	5070
8	**250**	**80**	**12000**	**3000**	**200**	**24100**	**6025**
9	300	80	12000	3600	150	16900	5070
10	200	150	16900	3380	80	12000	2400
11	200	150	16900	3380	150	16900	3380
12	200	150	16900	3380	150	16900	3380
13	500	200	24100	12050	200	24100	12050
14	300	100	14300	4290	150	16900	5070
15	300	80	12000	3600	80	12000	3600
16	400	150	16900	6760	150	16900	6760
17	500	200	24100	12050	250	43200	21600
18	0	0	69200	0	0	69200	0
19	600	200	24100	14460	200	24100	14460
20	500	150	16900	8450	150	16900	8450
21	500	150	16900	8450	150	16900	8450
22	200	80	12000	2400	80	12000	2400
23	200	150	16900	3380	150	16900	3380
24	300	150	16900	5070	150	16900	5070
25	200	80	12000	2400	80	12000	2400
		Total Cost		**130220**	**Total Cost**		**145045**

Diameter of the pipe 8 is increased to 200 mm with the effect of reliability constraint. Pipe 8 has the diameter 80 mm without reliability constraint design. When the R value is decreased to 0.15, CATE designs larger pipe diameter for this pipe to be under limit of 0.15 breaks per year for the link. This condition is not to say the design with small diameter pipe is not reliable and the design with larger diameter pipe is reliable. Only comment can be: “the second design with reliability constraint is more reliable with respect to the first design”.

Besides, change in the diameter of pipes affect other links of the network and some other diameters are increased or decreased in the network, along with total cost of the network is increased to 145045 $. Comparison is tabulated in Table 5.19.

CHAPTER 6

CONCLUSION

6.1 Summary of the Study

In this thesis, optimization and design of water distribution network study is performed. Previously studied methodology is modified and modeled for the study.

A computer program, CATE, is coded to apply methodology easily to any water distribution network. Manipulation of the program is explained using screenshot figures from the program. Theory of the program, which uses the linear optimization methodology to design water distribution networks, is explained.

6.2 Conclusion

Both the capital and maintenance cost of a water distribution network (not including operation cost) is tremendous. That's why; engineers are looking for new methods for the design of water distribution networks besides the traditional methods. In this study, a methodology is developed which uses an optimization procedure employing also reliability considerations (CATE). Objective function imposes minimization of the capital cost of the pipes, whereas reliability considerations are based on the mechanical failure of the pipes. LINDO was used for solving the linear optimization problem, whereas EPANET was employed as a hydraulic network solver.

A highly skeletonized form of a pressure zone (N8) of Ankara water distribution system is designed as a case study. Instead of using three static loadings or an extensive period simulation (EPS) loading as constraints, the design is realized at the basis of the peak hour loading using CATE; the necessary modification concerning the main line between the pump and the tank is accomplished using the night schedule of the pressure zone referring to an allowable velocity value throughout the main line.

Instead of studying a nonlinear problem, a linear form has been obtained where the pipe lengths were unknowns associated with the predefined diameters for the given links according to the street plan.

Although there was no universally accepted measure for reliability levels, already obtained design was altered for different reliability levels of some links. The cost increases as the reliability level increases. It is also observed that even the reliability level of one link increases, the diameters of one group of links increases.

6.3 Future Work

The future work for this study will mainly deal with the improvements of the computer program, which is coded in this study. The most important step for the future work is to include node isolation approach for the decision making process for improving the network if a limited amount of money is available.

Another important step for the program will be usage of pumps and tank elements in the network.

A more user friendly interface is aimed for the future versions of the program.

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