Designing a cost-effective and reliable water distribution network.

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Group 2

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Source: http://www.engineerguy.com/images/water-pipe.jpg

Summary

This report holds a description of a model, which should describe a cost-effective, and reliable water network. There are several nodes, which all demand a different amount of water. These nodes are mutually connected with water pipes, which can only change in diameter. This is important in this model because the diameter not only influences the water pressure inside the pipes but also the total cost of the water system.

In the early stage we defined concepts, properties and their relations in order to conceptualize our model. We explored two different ways of designing the distribution network, for instance loops and branches, and furthermore we made assumptions about the advantages and disadvantages of each case.

The next step was to find the appropriate formulas that are related to our concepts and check out how we can use them in a way the serves our model. Restrictions of the problem were taken into account and we proceed with calculations with the help of EPANET. With the help of EPANET we were able to make simulations and obtain results. These results were all met the restrictions we have from the initial problem and we manage to make a model that works and contributes efficiently the water along with cost-effectiveness.

Description of the modeling process: Definition phase

Context

In a mountainous area, water from a high positioned lake or reservoir may be distributed to lower regions through a network of steel or concrete pipes. The water velocity and flux depends of course on many characteristics of the used materials and of the geographical situation. We know the actual usage of water at certain tap points (nodes). Water can be tapped only if pressure is high enough. In an existing network of pipes we may consider adding extra pipelines to ensure the availability of water. We may also consider replacing current pipes by others of different quality or even design a new network from scratch.
In all cases we have to compare costs for the network comparing to the benefits. The bigger the network, the more it costs.

Source: TW-water network, project description, Oase (Accesed 17-2-2014)
Picture source: http://openwalls.com/image/24267/mountain_water_1920x1080.jpg

Problem Definition and Purpose

Our project aims to create a feasible water distribution network among communities with a certain demand for water. These communities are represented by nodes, which are connected by pipes. A reservoir supplies water for the complete network and has a certain pressure.

The goal of the assignment is to find the most efficient way to create a reliable water network. We are given a schematic with certain nodes and links with specific demands.

The problem is that designing a cost-effective and reliable water distribution network requires a proper selection of the pipes. In this case, reliability is defined by the capability of the pipes to hold up to a certain pressure. This depends of the proper selection of the diameter. The pressure and the velocity of the fluid in the pipes depend on the diameter, the roughness of the pipe and the material of the pipe and the density of the fluid. For this specific problem we don't consider "the roughness of the pipe" as the pipes are made of the same material.

Next to that the height of a certain node also influences the pressure that is needed to reach a certain flow rate. Our job is to optimize the water system to get the cheapest, yet most reliable network.

Sub-questions

Sub-questions were formulated in the early stage of our model. The purpose of that is to help us understand better the problem and focus on the essential information in order to proceed with the design of a cost-effective and reliable water distribution network.

Variables

1. What are the unknown variables-values?
2. Can we calculate them with the use of a formula and the known variables-values?

Routes

3. What are the possible routes and what's the most likeable route?
4. Does our model necessarily needs loops?

Picture source: https://s3.amazonaws.com/wetfeetproduction/articles/photos/476/original/BLG_pressure_reg20120816-17262-1uooufg.jpg?1345138945

Nodes

5. What nodes are 'most important' to look first?
6. Does a node need to be connected with more then one pipe?

Pipes

7. What pipe diameters can be used so that all restrictions are met?

Conceptualization

Concepts, properties, values and relations

Chart 1. Relations of the concepts and their properties.

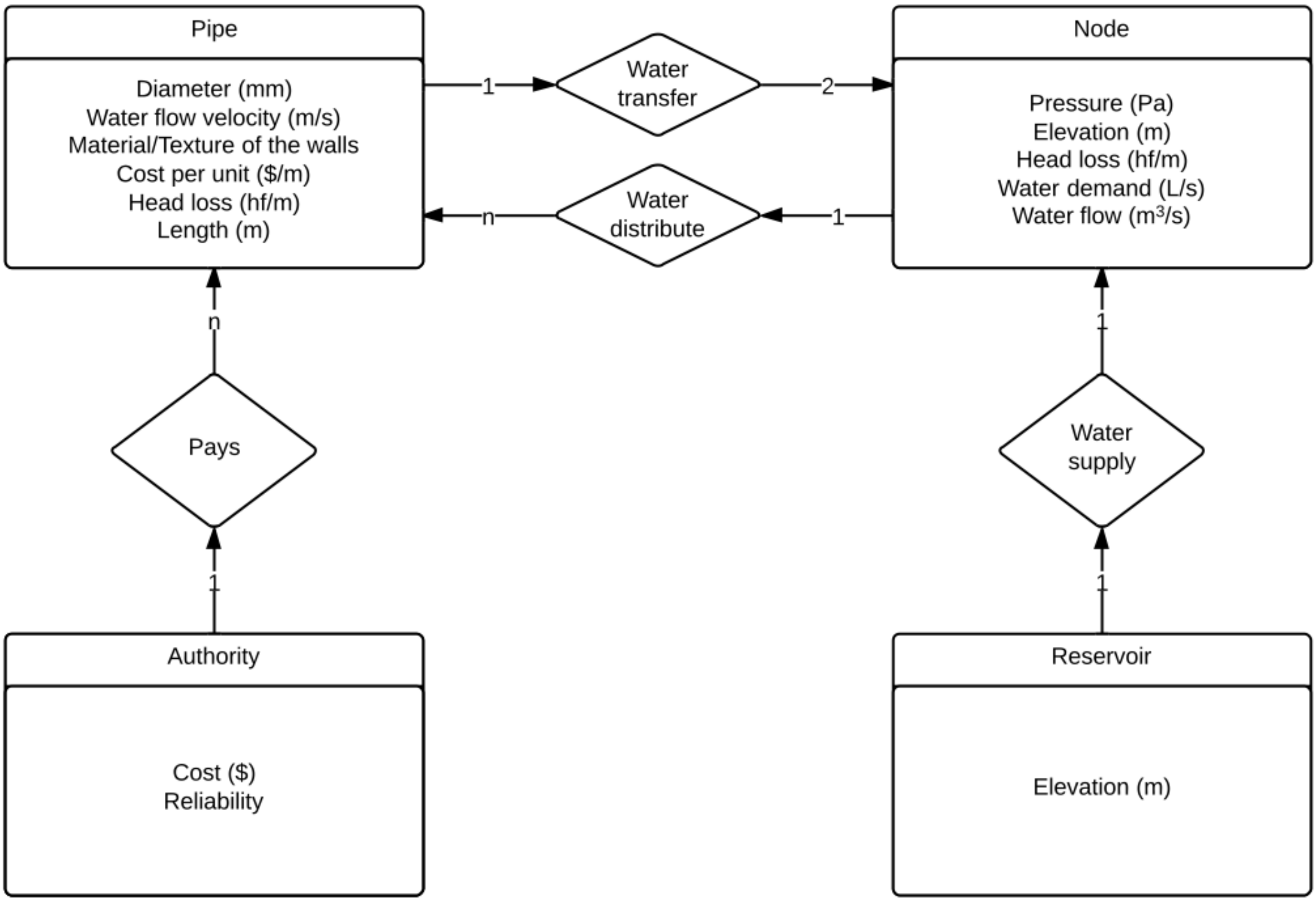


Table 1. Concepts, properties, values and units.

Concept	Properties	Values	Unit
Node	Water demand	{3.9, . . . , 45.0}	[L/s]
	Elevation	{0, . . . , 45}	[m]
	Pressure	{10, . . . ,100}	[Pa]
	Head Loss	{R+}	[hf/m]
Pipe	Diameter	{200, . . . , 450}	[mm]
	Roughness coefficient	{100, . . . , 140}	-
	Length	{130, . . . , 1070}	[m]
	Water velocity	{0.1, . . . , 3.0}	[m/s]
	Unit cost	{15.7652, . . . , 51.5675}	[$/m]
	Water flow	{R+}	[m^3/s]
	Head loss	{R+}	[hf/m]
Reservoir	Elevation	{60}	[m]
Authority	Cost	{R+}	[$]
	Reliability	{yes,no}	-

Pipe:

In this model, pipe is a concept. Changing the diameter or the length, adding or excluding water pipes will drastically alter the outcome of the model.

Diameter

The diameter is most likely to be the most important property of not only this concept but also the whole model because the main question and a large number of sub-questions are based on this property. The diameter determines the reliability of the specific water pipe and/or the water network as a whole.

Water velocity

Water velocity is highly related with pressure and it needs to be calculated in order to choose the diameter. Additionally, changes in diameter of the pipe affect the velocity and the pressure.

Roughness coefficient

Roughness coefficient gives an indication of the pipe inner-surface where the water flows. It is high related with the 'major loss' of energy. We decided that concrete is a proper material for our water pipes. We choose this material due to its low cost, chemical resistance and ease of jointing. Every material has a different roughness coefficient, which affects the velocity of the water that causes changes to the pressure of the pipe.

Length

Length is an important property as well. If we know the length of each pipe we are able to calculate energy losses due to friction within each pipe. That information helps us to analyze the water network.

Unit cost

The unit cost depends on the different diameters of the pipe and is the determinant for the diameter choice.

Node:

Nodes are the points in this model that have a certain demand of water. They are supplied with the demanded water through water pipes. Also they function as the connection points between different pipes.

Pressure

Dynamic pressure is very important for the reliability of the network as it indicates if the pressure exceeds the resistance of the pipe.

Elevation

Elevation is highly related to pressure. It is a driven factor of the choice of the diameter in order to achieve equal water supply throughout the network.

Minor loss

Minor loss is the energy loss that occurs when the water flow changes directions through the nodes.

Water demand

Every single node in the network demands a certain amount of water. It is an essential factor for the diameter selection.

Reservoir:

Reservoir is network's source of water.

Elevation

The reservoir has the higher elevation in our model. The elevation of the tank gives us a hint about the initial pressure of the model.

Authority:

The authority is responsible for the realization of a reliable water system.

Cost

Moreover it pays the total cost for the water network.

Reliability

The Authority is responsible for the construction of a reliable water network.

Picture source: http://www.britishdams.org/images/1st%20prize%20Craig%20Goff%20-%20Clywedog%20Dam.jpg

Formalization

Quantities and their relationships

Quantity	**SI unit symbol**	**Role**	**Category:**
Water demand	Q	Constant	III
Elevation	z	Constant	III
Pressure	p	Asked	II
Head loss	h_f	Intermediate quantity	IV
Diameter	d	To decide	I
Roughness coefficient	C	Constant	III
Water velocity	V	Asked	II
Length	l	Constant	III
Acceleration due to gravity	g	Constant	III
Hydraulic radius	R	Intermediate quantity	IV
Cross-sectional area of flow	A	Intermediate quantity	IV
Density	ρ	Constant	III
Cost	C	Asked	II

We assume the following relationships among quantities:

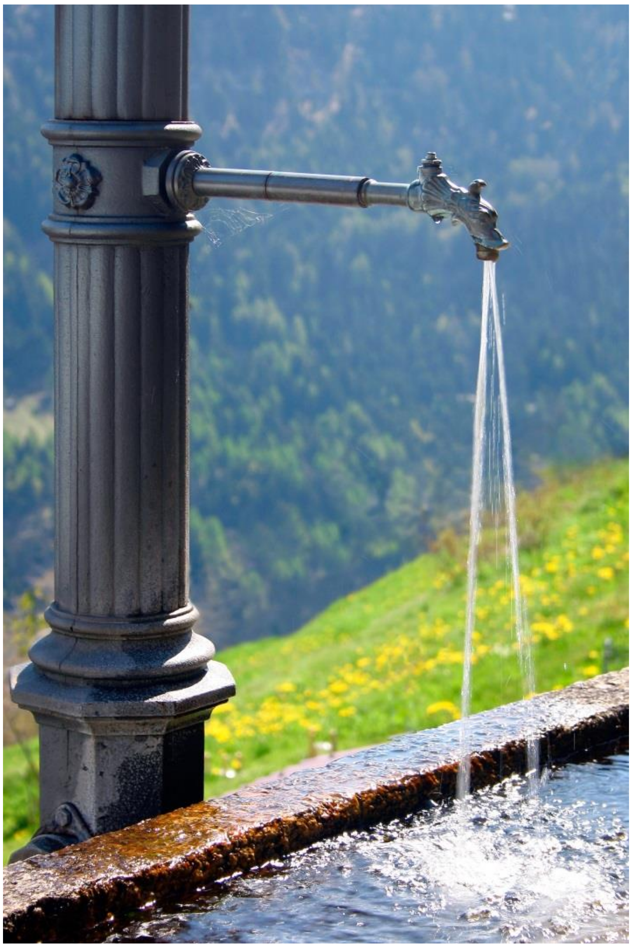
- The hydraulic radius is directly related with the diameter of the pipe that we will choose,
- The pressure at a certain node has a relation with the initial pressure and with the height difference of the reservoir,
- The choice of our diameter affects the velocity through hydraulic radius,
- The dynamic pressure is highly related with the velocity of the water,
- The head loss is highly related to the acceleration due to elevation on the pipe material and the elevation,
- The cost of a pipe is calculated by multiplying the length with the unit cost.

In our model we have the following restrictions:

- The velocity has the range $0{,}1 \leq V \leq 3{,}0$.
- The pressure difference it has to be more than 10m.

Approximations and assumptions

- Initially, the most important nodes to be taken into account are the elevated nodes. The higher elevated node indicates the initial pressure of our model.
- The elevation of the reservoir indicates the initial pressure of the model.
- From the range of the different velocities and pressures that the water has in our model among different pipes and nodes, the lowest velocity and pressure is where we have the highest elevation. That's an assumption we make according to Bernoulli's principle.
- Concrete is the appropriate material for designing a cost-effective and reliable water network.
- When water rises or drops through the pipes, changes in pressure and velocity will occur.
- Reaching a node with elevation demands more pressure.
- We assume the that water is fresh and it's density is 1000 kg/m^3.
- Every node can be connected with one pipe (branch network) as long as the requirements for designing a feasible water distribution network are met.
- We assume that minor loss is insignificant for our problem and doesn't affect our model.
- Each node can have two or more pipes with different diameters.
- All pipes are full of water.
- We assume that the given diameters are the inner diameters of the pipes.
- We assume that the nodes don't have a cost.
- The cost of building this network are ignored.



Picture source: http://upload.wikimedia.org/wikipedia/commons/8/8f/Fresh_water_fountain.jpg

Derivations

The hydraulic radius R is calculated by

$$R = \frac{A}{P}$$

where A is the cross sectional area and P the wetted perimeter.

In a case of a round tube we have as a cross sectional the area of a circle

$$A = \pi \, r^2$$

and as for the wetted perimeter we take into account the perimeter of a circle

$$P = 2 \, \pi \, r$$

so

$$R = \frac{\pi \, r^2}{2 \, \pi \, r} = \frac{r}{2}$$

where r is the radius of the pipe but since we have to deal with diameters, we also have to take into account that

$$r = \frac{d}{2}$$

Finally, the formula uses meters as a unit in order to calculate the hydraulic radius (R).
Since the pipe diameter is in millimetres we have to divide by 1000. Consequently we get

$$R = \frac{d}{4000}$$

The total cost (C) in dollars is calculated by the following formula:

$$C = D1 * M1 + D2 * M2 + D3 * M3 + D4 * M4 + D5 * M5 + D6 * M6$$

Legend	**Unit cost ($/m)**	**Legend: Total lenght of pipes with diameter**	**Diameter**
D1	15.7652	M1	200
D2	20.2867	M2	250
D3	24.7882	M3	300
D4	35.8312	M4	350
D5	44.5225	M5	400
D6	51.5675	M6	450

Dynamic pressure is an important aspect for our calculation and it is given by:

$$q = \frac{1}{2}\rho V^2$$

The determinant formula for the calculation of our model is the Hazen-Williams equation

$$V = k\, C\, R^{0.63}\, S^{0.54}$$

Bernoulli's principles states the suitable velocity and pressure in different elevation in order to have a constant flow

$$\frac{V^2}{2} + gz + \frac{p}{\rho} = constant$$

Special cases

To check that the given price is calculated correctly, we decided that we are going to calculate what the most expensive water network will cost, what the cheapest water network will cost and what the average water network will cost. This will be calculated by taking all the pipes multiply this with different pipe prices.

Diameter (mm)	Unit cost ($/m)
200	15.7652
250	20.2867
300	24.7882
350	35.8312
400	44.5225
450	51.5675

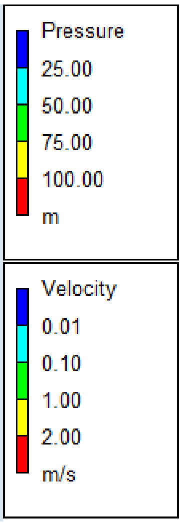
With loops

The total number of pipes is 29. That's the model with loops. The combined length of the pipes is 1180 meter.
The most expensive water network with the thickest pipes then will cost:
11180 x 51.5675 = 576524.65 $ ≈ 580 thousand dollars
The cheapest water network the thinnest pipes then will cost:
11180 x 15.7652 = 176254.94 $ ≈ 176 thousand dollars
Average price water network:
202 thousand dollars

Without loops

We will also calculate the price range for a network without loops. A network without loops consists out of 18 pipes with a total length of 7450 meter.
The most expensive water network without any loops and with the thickest pipes cost:
7450 x 51.5675 = 384,177.88 $ ≈ 384 thousand dollars
The cheapest network water network without any loops and with the thinnest pipes cost:
7450 x 15.7652 = 117,450.74 $ ≈ 117 thousand dollars
Average price water network
134 thousand dollars
This is the range the price range for the water network without loops. These ranges and averages will help us to check if our calculated prices are a bit plausible.

Estimates



In our model, the values that we get are the outcome of some formulas that are related to water network design process. Our calculations meet the criteria and the calculations that we had to cope with from the beginning.
Some of these limitations were: Minimum water velocity is set to 0.1 m/s; Maximum velocity 3.0 m/s; lower water pressure is set at 10 m. Pressures should be high enough to be adequately meet the node’s needs. Taking the elevation nodes into consideration we can optimize our network design by achieving higher flow-rate and that is quite crucial for an efficient planning. These estimations come from EPANET. When we run some analyses EPANET itself came with a certain range for the values. We used this legend to estimate the right values.

Regarding the distribution design, some assumptions are:

For branches:
Advantages
• It is a very simple method of water distribution. Calculations are easy and simple to do.
• Because of the use of fewer pipes, the flowrate through the pipes will be higher. Therefore the requirements of the lower velocity and minimum pressure will be easily met.
Disadvantages
• Branches are less reliable. One pipe breaks upstream and all the nodes 'below' it don't have water anymore

For loops:
Advantages
• Water reaches all points with minimum head loss.
• Is more reliable because the water has multiple routes to choose form.
Disadvantages
• Because this network requires more pipes, the costs will most probably be higher too.

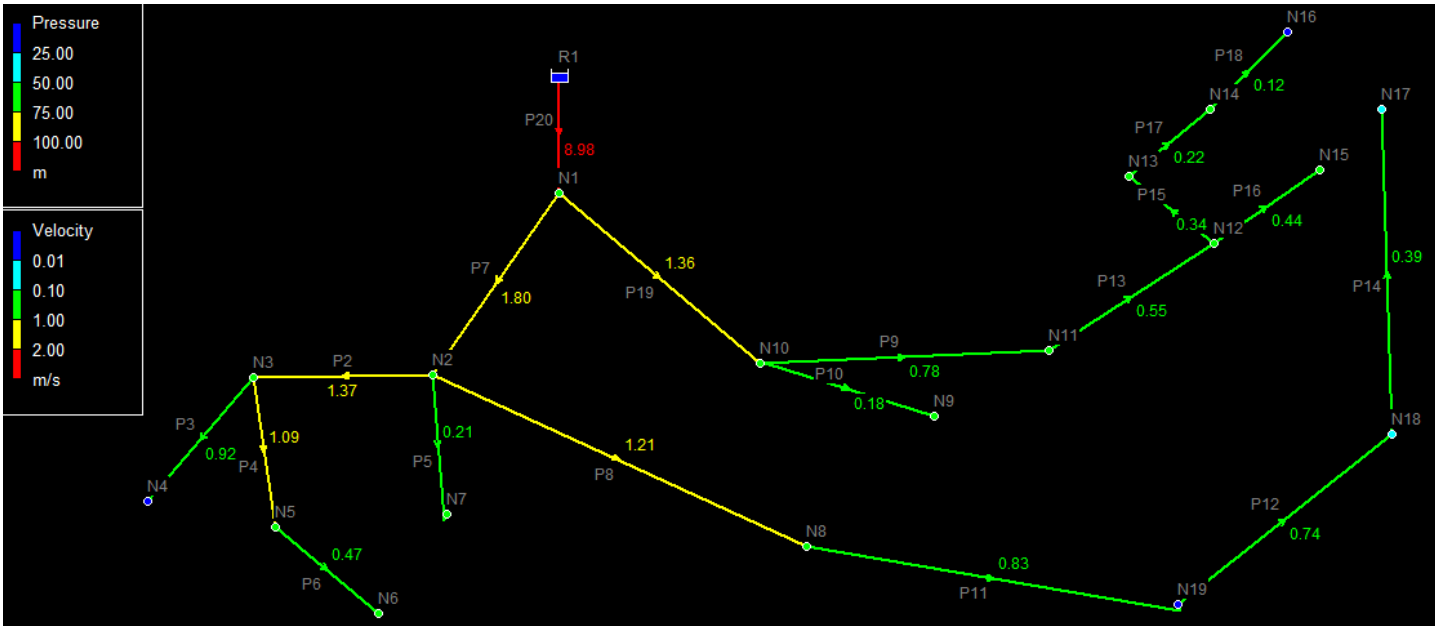
Picture source: http://www.wateryouthnetwork.org/wp-content/uploads/2013/01/water1-1024x640.jpg

Execution

Calculations / Implementation / Simulation

After working with EPANET we got some simulations and results. With EPANET we were able to experiment with different pipe diameters to see how much they influence each other and directly see if the resulting values meet the requirements.

Branch system



Network Table - Links

Link ID	Length m	Diameter mm	Velocity m/s	Unit Headloss	Friction Factor
Pipe P2	270	300	1.37	6.98	0.022
Pipe P3	480	250	0.92	4.13	0.024
Pipe P4	420	200	1.09	7.40	0.024
Pipe P5	210	200	0.21	0.34	0.031
Pipe P6	390	200	0.47	1.56	0.028
Pipe P9	600	350	0.78	2.04	0.023
Pipe P10	300	250	0.18	0.19	0.031
Pipe P11	1070	250	0.83	3.40	0.024
Pipe P12	870	200	0.74	3.59	0.026
Pipe P13	180	350	0.55	1.08	0.025
Pipe P14	570	200	0.39	1.09	0.028
Pipe P15	130	300	0.34	0.53	0.027
Pipe P16	260	200	0.44	1.39	0.028
Pipe P17	260	300	0.22	0.24	0.029
Pipe P18	300	200	0.12	0.13	0.034
Pipe P8	520	250	1.21	6.93	0.023
Pipe P7	140	350	1.80	9.73	0.021
Pipe P19	480	300	1.36	6.88	0.022
Pipe P20	0.1	200	8.98	366.35	0.018

Network Table - Nodes

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc N2	0	10.70	58.60	58.60
Junc N3	0	17.20	56.72	56.72
Junc N4	40	45.00	54.74	14.74
Junc N5	0	19.50	53.61	53.61
Junc N6	0	14.80	53.00	53.00
Junc N7	0	6.50	58.53	58.53
Junc N8	0	19.00	55.00	55.00
Junc N9	0	8.60	56.60	56.60
Junc N10	0	12.60	56.66	56.66
Junc N11	0	21.80	55.43	55.43
Junc N12	0	15.00	55.24	55.24
Junc N13	0	8.30	55.17	55.17
Junc N14	0	11.70	55.11	55.11
Junc N15	0	13.90	54.88	54.88
Junc N16	45	3.90	55.07	10.07
Junc N17	0	12.20	47.62	47.62
Junc N18	0	11.00	48.24	48.24
Junc N19	40	17.30	51.37	11.37
Junc N1	0	13.00	59.96	59.96
Resvr R1	60	-282.00	60.00	0.00

Costs in dollars:

Diameter 200 mm = 47612.48052 $

Diameter 250 mm = 48079.479 $

Diameter 300 mm = 28258.548 $

Diameter 350 mm = 32964.704 $

Total cost: 156,915.2115 $

Length in meters:

3020.1

2370

1140

920

Total length: 7450.1 meter

Validation and Verification; Accuracy and Precision

Validation

To validate the model we first looked in the early chosen Cat,-III quantities if they were correct.
The quantities Q, z, l, g and ρ are quantities which are common knowledge in the scientific world or quantities which were given to us to work with. Only the C quantity, roughness factor was a factor we need to look up and needed to choose. We then found that this quantity has a range from 100 – 140. It's not completely clear why this could vary but we made some assumptions regarding quantity:

- It could change over time
- Not every concrete pipe has the same C
- Within a pipe the C could vary

To tackle this problem we chose to use 120 as our C, as it is the average and for convenience.

The model behaves intuitively. The consistency of the model is good, because it behaves as it should behave. If we choose for bigger pipes, the velocity and the pressure will decrease but the model becomes more expensive and the other way around. Also the length of the pipes doesn't have a significant impact on the results, just as we expected. The pressure loss due to the length of the pipe has an average of **5.84%** of the total head. This can be measured by calculating the average head and head loss in every node and then determine its percentage considering the total head. This could change if we take a higher or lower roughness factor for the pipes. But due to the minor impact to our model we do not take it under consideration, as it wouldn't change much to the actual cost.

In our model is possible the final total cost calculation. The total cost lies in the early calculation of the possible total cost range (Maximal 384 thousand dollars, minimal 117 thousand dollars). So the Cat,-II quantities are conclusive.

Verification

The model is right because the outcome "Cost" (C) is in dollars. That is a dimension we can work with to draw conclusions from.

The values are all within the admitted bound of the conceptual model. So the model is verified to be a good model with good accuracy and precision.

Picture source: http://www.theconcretecompany.com/test/images/products05.gif

Discussion after the conceptual model

In our model, we calculate the most expensive and cheapest water network in order to see what is the cost of an average water network. Our purpose for that wasn't to design the most expensive or the cheapest network. The philosophy behind that was to check if the price of our network was plausible and furthermore strengthen our decision.
Head loss is divided in two main categories, major losses associated with energy loss per length of pipe and minor losses associated with bends fittings valves etc.
in our model, we took into consideration only the major losses even though in some occasions minor losses can exceed them.

Discussion after the Formal model

In our project, we had to work with an amount of concepts, properties and values. To achieve the models purpose, required calculations were made to find important values. Aside from calculations, the relations between these values related were established. In general, the results achieved, were an outcome of mathematical calculations depending on the predefined and estimated values. In the model the challenge was to make the model meet all requirements and to take any inaccuracies in account to calculate the overall inaccuracy of the model.
From a numerical point view, the results meet all the criteria of limitations and restrictions that were stated from the beginning and the outcomes of the calculations are considered correct and accurate enough. Furthermore, the results are sufficient to approach the initial problem effectively. Besides that, in the assignment there was the freedom to experiment more with the concepts.That meant that different setups could be analyzed to see what the influence was of this change on the total model outcome.Overall, the approach and results to design a reliable water distribution network are assumed adequate enough to make this a valid model.

Picture source: http://upload.wikimedia.org/wikipedia/commons/2/25/Constructing_natural_gas_pipe,_Finland.jpg

Discussion after the Result

We have verified that the results of our model are precise and accurate enough according to the assumptions we have made. But the model is only useable when people want to estimate the cost of the building materials, because we didn't include factors like employment costs, digging costs, 10% unanticipated costs etc. If they want to estimate the total cost of building a water network they can't use this model. Such model needs to incorporate a lot more factors then this model.

Discussion after the Solution of the Initial Problem

In the problem definition is stated that the model has to be a feasible water distribution network, so far we succeeded. All values we obtained were meeting the initial criteria and restrictions. We can conclude the model is feasible and reliable since we took everything into consideration.
Besides that we also succeeded to calculate the costs of our feasible network. We chose not to use loops but instead we just use a model with branches, so we left some pipes out that weren't needed. This lowers the costs and is easier for its realization.

Possibilities for improvement

There is always room for improvement when working on a project for almost two months. Our project had limited time and we never worked with water network distribution before. In the beginning everything was completely new and unfamiliar. This was our first attempt to analyze and optimize a solution in problem and overcome problems that we faced in our project.
The assignment was quite demanding and our time as bachelor's students is really limited. If we had more time the quality of our work in the report would be even better but still we are satisfied with the outcome. That doesn't mean that improvements can be done though.

What aspects of your work are you proud of?

We are proud of finding our own way through the assignment, which seemed difficult at the beginning but yet with collaborating and good thinking we came up with a good and feasible model. Another thing to be really proud of is that none of us had any previous knowledge on programming but still we made an efficient model including every element we need and all information we needed to gather.
We are also proud on the fact that we were able to work together without any complications and in a good and peaceful ambience; everyone worked really hard and we split the tasks fairly and together we established some good work.

What have you learned?

The first thing we learned was never to make a model without a purpose, if you do not work towards a certain purpose your model will never be as good as when you do, next to that your model will lack certain parts of critical information that make your model reliable. We also learned subtract valuable information out of the given information such as: properties, values, types and the relations between them. We learned to divide the quantities with their types into four different categories in a meaningful way. Moreover we learned a structured and rational methodology when working with a model in order to meet requirements and our goals.