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A Genetic Algorithm Technique to Optimize the Configuration of Heat Storage in District Heating Networks

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ABSTRACT

The technical and economic evaluation of heat storage layout and configuration in a district heating (DH) network are on the one hand parts of important aspects to optimize the heat production from the heat supplier's point of view. On the other hand, their roles to meet the demand of heat consumers are acknowledged.

Generally, the state of the art technique has considered three optional planning layouts for DH networks. A classical network with centralized heat storage at the Combined Heat and Power (CHP) plant, decentralized storages in the middle of the network, and decentralized small storages at the substations or in the customer building.

In this paper, through the use of genetic algorithm technique, a comparison of three different scenarios is presented to evaluate the optimal planning of heat storage layout in CHP-based DH supply systems according to economic and technical aspects of the network.

Keywords:

Genetic Algorithm;
Heat Storage;
DH Network;
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Abbreviations:

CHP = Combined heat and power
DH = District heating
DHS = District Heating System
GA = Genetic Algorithm
DHN = District Heating Network
DSM = Demand Side Management

1. Introduction

Various techniques and methodologies are proposed and presented in the recent years to manage the potential of the heat demand in District Heating System (DHS), in order to determine the optimal heat production of the heat plant and reduce the overcapacity of heat in the customer side. One of the important issues to be noticed is that there are at least

two approaches to be mentioned related to this issue, namely statistical and numerical approaches. The statistical approaches generally exploit extensive large data sets. Furthermore, the accuracy of the results relies on the quality of the statistical data set. The statistical method developed to minimize the supply temperature is performed e.g. in [1]. On the other side, the numerical approaches utilize calculation steps and mathematical operations to be performed. This will

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require extensive calculation time. Some examples for the dynamic optimization to determine the optimum supply temperatures and the optimum load distribution are found in [2]. The genetic algorithm technique tries to cover the advantages offered by both aforementioned approaches since it exploits heuristic data and compute those data to approximate the optimal solution, as we would like to apply this method mainly in this paper. The method is furthermore used to evaluate the benefit of different size of storages for the CHP system.

Several works are mentioned regarding the configuration of District Heating Network, some of them implemented genetic algorithm method. In [3] the configuration of the peak boiler related to its capacity and location is evaluated. Sakawa et al. applied the genetic algorithm to solve the operational planning problem of district heating and cooling units at a single location. This problem is formulated as a mixed 0–1 linear programming problem and approximately solved using GA. Other researcher such Li and Svendsen [4] optimized the DHN configuration using genetic algorithm which connect a single heat generation plant and the end users. Fang and Risto [5] optimized the supply temperatures of multiple heat plants (CHP) at different locations of the network and calculated optimal load allocation between the plants to minimize the combined production and distribution costs based on a static DH system model using GA. Samira et al. [6] used evolutionary algorithm to optimize the layout, the operation schedule and the temperatures of energy distribution pipelines. In [7] Molyneux et al. applied multi-objective and multi-modal evolutionary algorithm to facilitate the design and planning of a district heating network based on a combination of centralized and decentralized heat pumps combined with on-site cogeneration. Sakamoto et al. [8] optimized the operation schedule for on-line processing in the electric type district heating and cooling plant based on genetic algorithm. In the recent paper [9] Fang and Risto has developed CHP optimization model with heat storages to minimize the production cost and to maximize the revenue from power sales based on a sliding time window method.

As a matter of consideration, heat producers always want to initially start the production plant with lower operational cost. By estimating the heat demand, heat producers can avoid overproduction of heat. The advantages of heat demand management will enable the heat producers to schedule which production plant to be activated and coordinate the heat consumption at the customer side. This could be performed by utilizing the heat storages in the DH network. The novelty of this

study is that we implement a GA based method to analyse and compare the different layout of DH network with single CHP and heat storages in the network.

Heat storage is very useful to manage the heat demand as it collects heat for later use and can be integrated into a CHP system to enhance the energy efficiency [10]. On the one hand, the storages can be charged or discharged when the heat demand is low or high. On the other hand the heat storages are beneficial to operate when the spot price is low and the CHP can produce less power. Bachmaier et al. [11] has shown that the installation of a decentralized thermal energy storage is nearly as efficient as operating a central thermal storage. Therefore in this work we will investigate the characteristics of three different layout of heat storage in the District Heating Network to get better benefit of each alternative according to the available factors in the real condition.

Meanwhile, the heat load has exhibited non-linear, stochastic and dynamic behaviours, which needs an adaptive, robust and heuristic model to be developed. Genetic algorithm is part of metaheuristic algorithm to find a good near optimal feasible solution with a reduced computational time [12]. Therefore, in this paper a heuristic technique which utilizes genetic algorithm will be introduced as a new option for calculating the optimal configuration in the operational planning of the heat storage in the District Heating Network (DHN). Furthermore, three scenarios of heat storage configuration in the DHN including CHP will give more insights for the comparison of DHS performance.

2. Setting up three layout models of District Heating Network with heat storages

According to several discussions mentioning the typical DH Network configurations which combine heat storages and CHP Plant, mainly the centralized and decentralized network structure (see [9, 11, 13]), we could make three general assumptions for the network model, namely centralized, semi decentralized and full decentralized type of network. To provide a clear description of the aforementioned planning layout of district heating network with heat storages and CHP, we set up a virtual district heating network model. There are three scenarios regarding the configuration of district heating network with heat storages as follows:

1. Centralized heat storage (see Figure 1)
2. Semi decentralized heat storages (see Figure 2)
3. Full decentralized heat storages (see Figure 3)

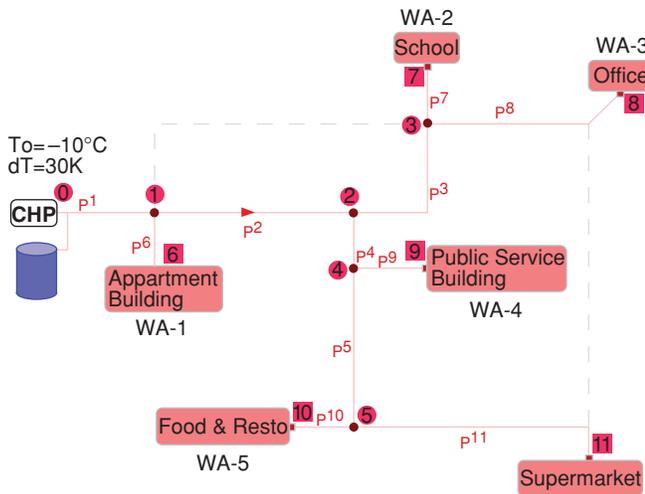


Figure 1: Virtual DH Network with centralized heat storage.

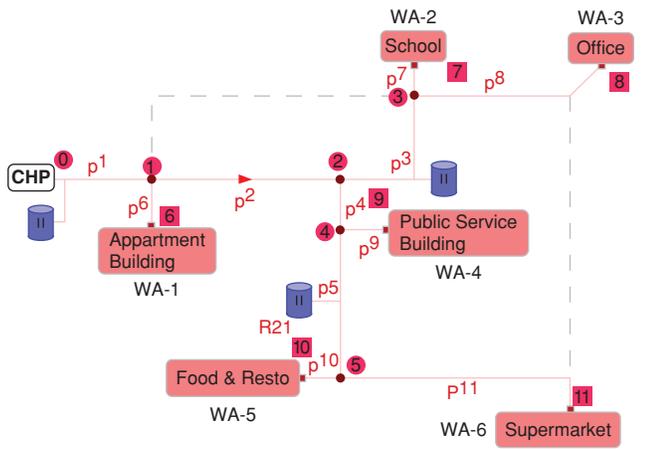


Figure 2: Virtual DH Network with semi decentralized heat storages.

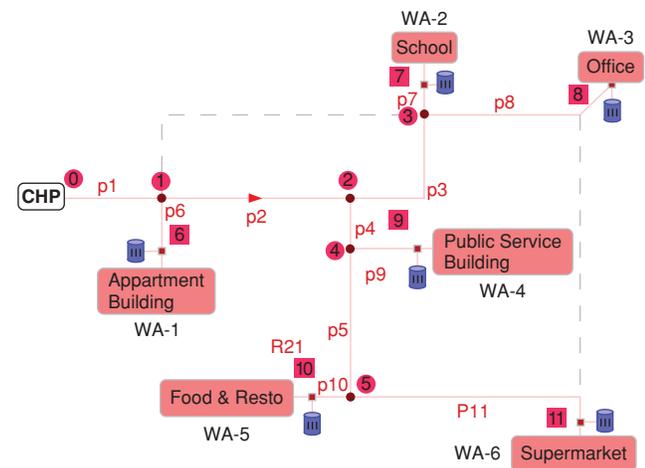


Figure 3: Virtual DH Network with full decentralized heat storages.

The topology of District Heating Network is represented by a graph model which provides the thermo-hydraulic computation to be performed within two consecutive steps. The first (central) step is the hydraulic modelling of the mass flows within the network, by inserting several boundary flow conditions at the customer side as well as the pressure and temperature constraints at the heat producer site.

This step determines all currents flowing through the pipes of the network. Simultaneously, determining the mass flow distribution in the district heating network gives the foundation of the thermal losses calculation within the network (see [14]).

2.1. Dimensioning the network parameters (pipe length, pipe diameter, consumer heat load)

The calculation of the hydraulic state in the district heating network has been treated within several papers and dissertations, for example [15, 16, 17, 18, 19]. Combining the hydraulic calculation of the pipe network and heat transfer theories enables the determination of the pipe dimensions according to the amount of the heat load entering the pipe. The resulting pipe diameter calculation will be further transferred into the cost function for the optimization procedure in the next step. By applying the techniques provided by genetic algorithm, the cost function in the DHN will be minimized.

2.2. Thermo-hydraulic simulation (heat loss, temperature loss)

In order to determine the volume of heat storages as well as the heat distribution, a thermo-hydraulic simulation is performed to calculate the static pressure and heat distribution in the network. The friction factor f generally has to be calculated as well, e.g. by the Darcy-Weißbach or Swamee-Jain correlation (see [17, 20]).

The conversion of the heat demand into a mass-flow boundary condition can be done by applying the first principle of thermodynamics, see again [17, 20].

2.3. Coupling of the thermal model

The thermal model is calculated by assuming a constant heat capacity c_p of the medium (water). After calculating temperature loss distribution in the network, it is very crucial to identify temperature drop in every single pipe.

The temperature drop inside each pipe is calculated by an exponential equation, see [21, 22]. Results of the thermal calculation is then combined with all heat demands to generate a yearly heat energy load in the network.

3. Calculation of heat customer load profile

Heat customer load profile is calculated according to the following steps:

1. Basic resources for the representation of heat consumer profile are taken from the consumer standard heat load profile given by BGW P2007/13 suggested by TU München, see [23].
2. Values of heat load data are computed for every hour for the whole year using the outer temperature data samples from

Deutscher Wetterdienst (Germany’s National Meteorological Service). The collected values are then scaled according to the type of the building with corresponding week factors and hour factors (see Figure 4) to generate the variation of customer heat load in the network during a year (in the total of 8760 hours).

3. The chosen heat consumers are classified according to the heat profile given by above resources, which yield the values shown in Table 1.

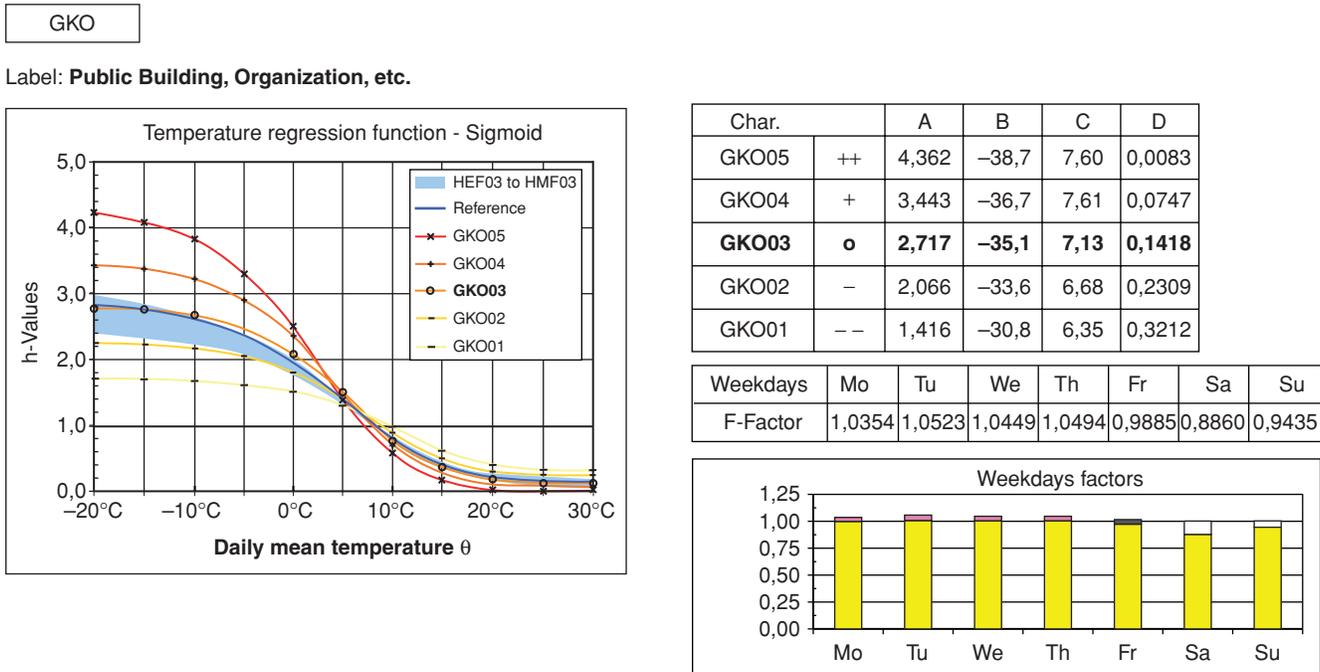


Figure 4: Example of parameters and factors according to the chosen building categories (translated from the German page).

Table 1: Heat load for each type of the building calculated in a year.

Nr	Consumer	Type of building	Arithmetical mean [kWh/m ² a]	Average area [m ²]	Total heat consumption [kWh]	Building Classification
1	Apartment	Privat Residential Building,	159	3,025	480,619	HMF
2	Supermarket	Retails, Wholesale, Shopping center	75	4,198	311,845	GHA
3	Public Building	Public Service Building	141	2,375	333,785	GKO
4	School	School in general (without swimming pool)	154	4,406	676,372	GKO
5	Resto	Public house, restaurant	130	2,300	299,512	GGA
6	Office	Normal administrative building	120	3,716	446,654	GBD

- Calculation of the hourly based heat load follows the equation:

$$Q_{\text{hour}} = KW * h(\varphi) * F * SF \quad (1)$$

where

- Q_{hour} : hourly value of the heat consumptions
- KW : customer individual value of the heat consumptions
- $h(\varphi)$: a value that depend on coefficient of the sigmoid function and daily average temperature
- F : week factor (depends on the building categories)
- SF : hour factor (depends on the building category, the daily average temperature and the time)

Parameters of the sigmoid function are given according to the building categories and calculated under the following equation:

$$h(\vartheta) = \frac{A}{1 + \left(\frac{B}{\vartheta - \vartheta_0}\right)^c} + D \quad (2)$$

The results of the total heat load duration in a year calculated for the network are given in the Table 1 and Figure 5. Yearly energy heat load is applied to determine the strategies or scenarios to fulfil the heat demand. The purple curve describes the profile of heat load duration including heat losses. The heat loads are ordered according to the amount of load in an hour-based, while the red curve describes the heat load duration without heat loss. The integral of the region under the curves

shows the amount of heat loads should be covered. The region under the green line shows the amount of based heat load normally covered by the CHP and the rest of the region between the green line and the curves are the heat load that should be covered by the heat storages or combined with heat boiler. After performing the calculation of heat load, it is now possible to determine the configuration and the volume of heat storages in the network.

4. Determining the heat storage layout and volumes

According to the day observation and the pressure loss distribution in the network, determination of the location and the volume of heat storage could be performed (see again Figure 1–3).

During winter, the heat consumption of the network is at maximal level as described in figure 6. Therefore the characteristic of the heat consumption line in a winter type day is very crucial as the basic calculation of the heat storage volume. In figure 7 a typical daily heat loads in the DH Network for aforementioned heat consumers are reordered, which is represented by the black curved. The green area describes the base heat load supplied by CHP. In this case, the integral of the heat consumption pattern in a day is calculated and summed up as the maximum load of the heat storage (see Figure 7).

Based on the amount of heat required to load and unload in the storage, in combination with the following equation

$$Q_{\text{sp}} = M_{\text{sp}} C_{p_{\text{sp}}} dT_{\text{sp}} = V_{\text{sp}} \rho_{\text{sp}} C_{p_{\text{sp}}} (T_{1\text{sp}} - T_{2\text{sp}}) \quad (3)$$

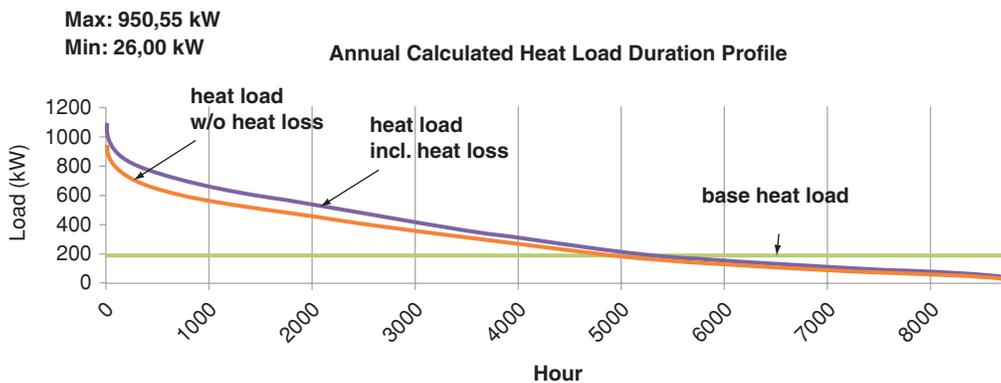


Figure 5: Profile of the heat load duration calculated in a year.

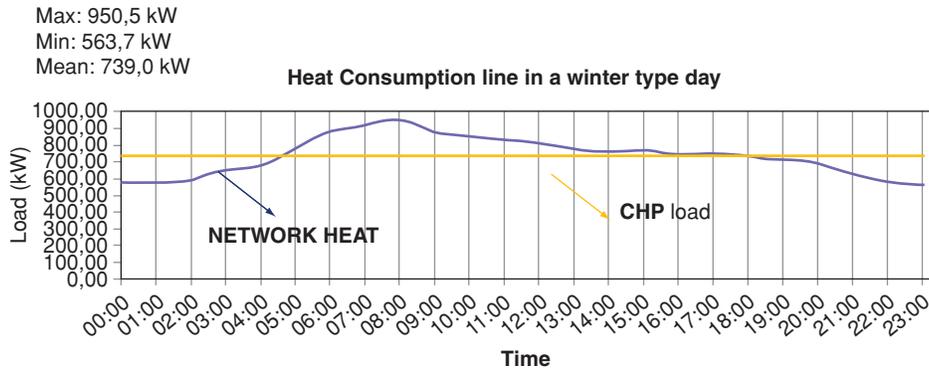


Figure 6: Characteristics of heat consumptions in the network during a winter day.

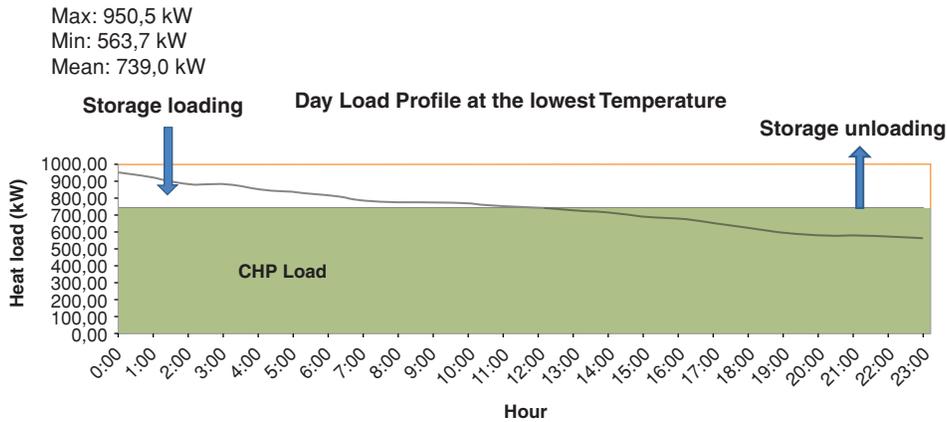


Figure 7: The heat loads are reordered according to the duration of heat consumptions.

- $Q_{sp}[\text{kJ}]$: heat capacity of the storage
- $M_{sp}[\text{kg}]$: mass of the storage
- $C_{p,sp}[\text{kJ/kg}\cdot\text{K}]$: specific heat of storage media (water)
- $dT_{sp}[\text{K}]$: temperature difference in the storage
- $V_{sp}[\text{m}^3]$: volume of the storage
- $\rho_{sp}[\text{kg/m}^3]$: density of the storage media
- $T_{1sp}[\text{°C}]$: temperature of loaded storage
- $T_{2sp}[\text{°C}]$: temperature of unloaded storage,

the heat capacity of heat storages in the network could be estimated.

5. Generating nonlinear cost function

The cost function consists of three main components in the network, the heat production component which is represented in this case by the CHP, the heat distribution in the network, and the heat storages. The cost function for CHP is derived by calculating the function of CHP performance toward its price for every kilowatt

performance ($f(\text{Performance})$). This dependency is described in Figure 9. Meanwhile, the cost function for the heat storage is determined by the function of the storage volume toward its price ($f(\text{Volume})$)(see Figure 8). For the heat distribution network, there are many references that can be referred for calculation of the cost

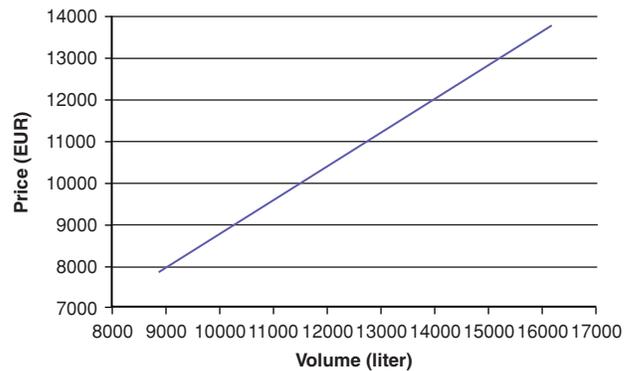


Figure 8: Linear Cost function of heat storage, see [25].

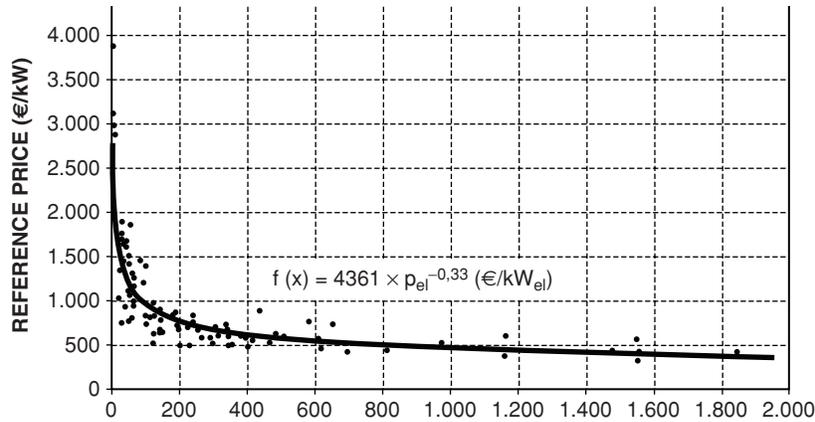


Figure 9: Cost function for CHP, see [26].

function in the heat distribution component. One of these references is described in [24], where all of the components in the network (pipe diameter, pump, investment cost, etc.) are being considered. In a general equation, the cost function is represented by the following term:

$$\sum f_{\text{cost}}(\text{CHP}) + f_{\text{cost}}(\text{DHS}) + f_{\text{cost}}(\text{Heat Storage}) \quad (4)$$

The generated nonlinear cost function model would be minimized in the optimization process by utilizing the genetic algorithm technique. Each element of the cost function is the following:

1. $f_{\text{cost}}(\text{CHP})$ is the function of the electrical power of CHP

$$f1(p_{el}) = 4361 * p_{el}^{-0.33}, \quad p_{el}: \text{electrical power} \quad (5)$$

2. $f_{\text{cost}}(\text{DHS})$ is the function of the pipe inner diameter d

$$f2(d) = [I_1 / \ln((4H_p)^y (d^{-y} + (2\Delta x_i)^{1-y} d^{-1}))] + I_3 d^{-(5+b+c)} + A_9 d \quad (6)$$

where

- Δx_i : insulation thickness (m)
- d : pipe inner diameter (m)
- a, b and c** : coefficients determined by curve fitting (dimensionless)
- H_p : burial depth to pipe centerline (m)

while I_1 represents the cost of heat loss, I_3 and A_9 represent the maintenance cost and capital cost of the supply and return pipe respectively.

3. $f_{\text{cost}}(\text{Heat Storage})$ is the function of the heat storage volume (m^3)

$$f3(\text{Vol}) = 0.375 * \text{Vol} + 3538.7 \quad (7)$$

The sum of those equations yields a nonlinear equation which is then applied in the genetic algorithm as the objective function.

6. Optimization with genetic algorithm

Genetic algorithm is a meta-heuristic algorithm mimics the evolution strategy from nature which is adapted into computational steps to find a solution in a more natural way. This method has been introduced by Goldberg [12]. One of the genetic algorithm applications is to get an optimal solution of an optimal combinatorial problem which has many possibilities of solution. A solution generated in the genetic algorithm is defined as chromosome and a group of the chromosomes are called a population.

A chromosome is generated from components which so-called a gene. Its value could be a numeric, binary, symbols or character, depends on the problem being solved. The chromosomes will experience the evolution simultaneously. This step is defined as a generation. In every generation, the value of chromosomes are evaluated to determine their level of success toward the proposed problem (objective function) using a measure which so-called a fitness. To choose the good chromosomes for the next generation, a process called selection is performed. The chromosomes which have a high value of fitness have bigger chance to be chosen in the next generation. New chromosomes called offspring are reproduced by performing a mating between chromosomes in the same generation. This process is called crossover. The other mechanism which is called a

mutation is represented by changing of the gene in the chromosome with random values.

In this work, the function implements the classical genetic algorithm and the nonlinear cost function mentioned in the previous section (the summation of equation (5) – (7)) is set up as the objective function. The generated components or variables are represented with binary and integer encoding. The fitness of the generated chromosomes is determined by calculating the values which minimize the total cost function of the network.

The objective function is subjected to the constraints according to the thermo-hydraulic conditions for the three network layouts. In this method we define the range of values for a decision variable by setting the lower bound and upper bound of the variable. It is important to pick meaningful bounds for the decision variables so that the calculation doesn't waste time exploring solutions that are not meaningful. The defined ranges of values are the following:

- The capacity performance of CHP (in kW)

$$P_{\min} < P_j < P_{\max}, \text{ for } j \text{ in each layout} \quad (7)$$
- The volume of heat storage (in m³)

$$V_{\min} < V_j < V_{\max}, \text{ for } j \text{ in each layout} \quad (8)$$
- The available pipe diameter (m) subjected to the commercial pipeline

$$d_{\min} < d_j < d_{\max}, \text{ for } j \text{ in each layout} \quad (9)$$

- The network maximum allowable pressure drop

$$\Delta p_i < \Delta p_{\text{critical}}, \text{ for } j \text{ in each layout} \quad (10)$$
- The pipeline maximum allowable velocity

$$v_j < v_{\text{limit}}, \text{ for } j \text{ in each layout} \quad (11)$$

The parameters and the range of values used in this method during the calculation are the following:

- Population size: 100
- Crossover probability: 0.7
- Mutation probability: 0.03
- Number of Generation: 1000
- $P_{\min} = 50 \text{ kW}; P_{\max} = 500 \text{ kW}$
- $V_{\min} = 1 \text{ m}^3; V_{\max} = 100 \text{ m}^3$
- $d_{\min} = 0.06 \text{ m (DN 20)}; d_{\max} = 0.508 \text{ m (DN 50)}$
- $\Delta p_{\text{critical}} = 200 \text{ kPa}$
- $v_{\text{limit}} = 2 \text{ m/s}$

Summary of the genetic algorithm method used in this work is illustrated in Figure 10, as follows:

1. The initial population can be generated by randomizing the genes for each chromosome of the initial population. In this step we generate chromosomes from the genes which represented by the parameters in the objective functions, e.g. a, b, c, etc. according to the range of parameters defined previously.
2. Fitness evaluation is performed by calculating the objective function of the chromosome generated earlier. The fitness is evaluated according to the formula **fitness= (1/(1+objective_func))** and the

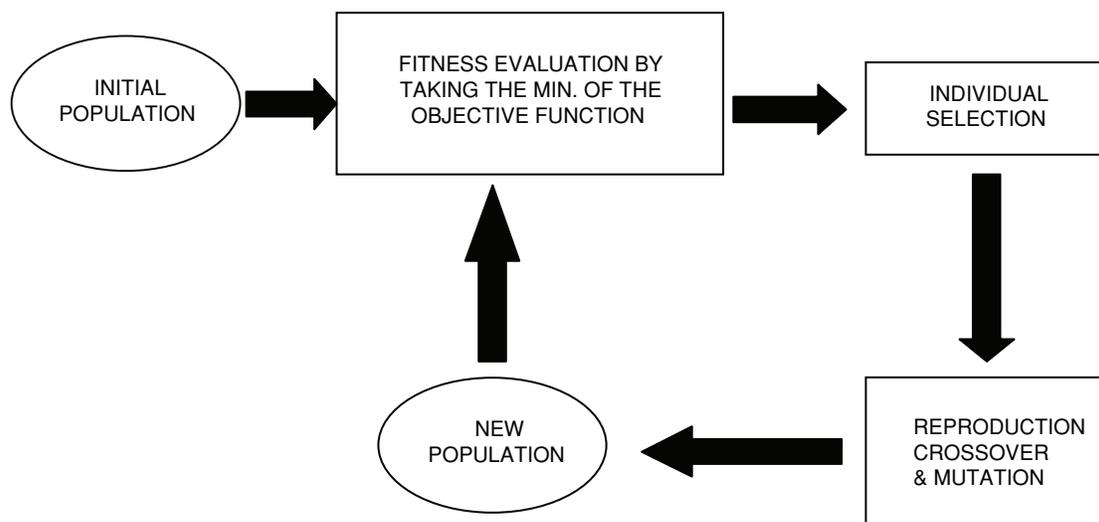


Figure 10: Genetic algorithm procedures to minimize the cost function.

probability of the chromosome is calculated by $P[i]=fitness[i]/total_fitness$, for every **chromosome**[i]. The fitness of the chromosome shows that the chromosome has higher probability value to be chosen in the next generation.

3. The selection process is performed such that the chromosome which has a small value of the objective function has higher probability to be chosen. This could be done by calculating cumulative probability and comparing it with a random value for choosing the best chromosome in the new population.
4. The next steps are the reproduction of random value to choose a position from the parent chromosome for exchanging the gene. Number of chromosomes which experience the crossover are influenced by the crossover probability. Mutation process is done by replacing a chosen gene randomly with a new randomized value. The numbers of mutated gene in a population are determined by mutation probability. The results of crossover and mutation process are then given to the new population.
5. After performing the previous steps we have finish the first iteration for generating a new generation. This process will be repeated until the maximum generation is reached.

7. Result and discussion

To get the result as proposed in the section 1, the main step to be performed in the calculation is to find the

optimal CHP capacity, the pipe diameter and the volume of heat storage which minimize the cost function. This will be performed for each scenario of the network, namely the network with centralized, semi decentralized and full decentralized heat storages. The constraint values are obtained from the thermo-hydraulic calculation in each of the scenarios, which will give the range of possible values for the CHP capacity, pipe diameters and heat storage volumes in the network.

Minimizing the cost function with respect to those three variables is equivalent to minimizing the total cost function. Therefore, after obtaining the best values for those variables we can proceed to solve equations (5) – (7) as well as to get the minimal sum of the cost function in every network layout.

By considering simultaneity factor of one, several points are to be mentioned according to the result described in the figure 11:

- Network type 1 (centralized heat storage) has overall the lowest investment cost, but it requires more heat energy production. It means that more excess heat is produced within the network. Consequently, more losses caused by the waste of heat energy are unavoidable.
- Network of type 2 has medium efficiency of cost and energy, but it depends on the installation, the volume of the heat storage and its location as well. There are still open questions, whether this type of network could be optimized more intensively in order to perform the same energy efficiency as the network type 3. One of the possibilities is by integrating intelligent control in the heat producer

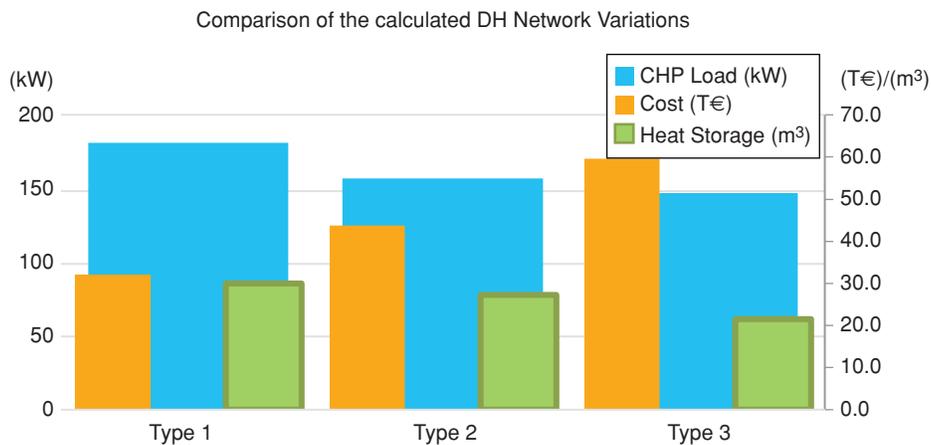


Figure 11: Comparison of three different scenarios of DH Network with heat storages.

- side and utilizing heat demand's forecasting and adaptive controlling in the consumer side.
- The energy efficiency is improved by network type 3 (decentralized heat storage), although it needs higher initial investment. On the other side, the heat production could be minimized along with the time. The higher cost invested in the initial phase will be paid off by low operation of the heat production.
- Although network type 3 requires higher initial cost, but one of its advantage is to improving more security of heat supply for the heat customer. By unexpected accident, (e.g. sudden damage at the pipe network, extreme temperature drop etc.) the heat storages will provide a quick solution to handle the heat demand required by the customer.

8. Conclusions and prospects

This work is focused mainly on the comparative study of three different layout of DHN with combining heat storage and CHP Plant using the genetic algorithm technique. As the real experiment data is not available, three virtual networks are setup and the calculation is performed using standard profile taken from references and the comparison of qualitative analysis for every type of network is carried out. Therefore, this study is intended to give a first overview about the choice of suitable DH network layout according to the conditions given by the location of the network as well as the related financial factors.

As prospective, there are some points needed to be underlined for the future works:

- This paper provided some procedures and considerations regarding the optimization of district heating network using CHP with integration of the heat storages in three different layouts.
- Detail calculation of the storage volume could be optimized by utilizing genetic algorithm method.
- Improving degree of control on the heat customer side (demand side management) increases efficiency of the heat production. This could be achieved effectively through implementation of the decentralized heat storages (network type 3).
- Combination of heat resources (solar cell, geothermal, etc.) and heat storages in the network is possible and could be optimized by applying the same technique.

- Other layout combinations (close loop, more renewable heat sources extension) should be investigated for further research as well.
- Comparing the result with operational data of the heat production plant is recommended to improve optimization level, data integration and performance testing.

Furthermore, a validation of the simulation result regarding the combination of heat sources and customers from real data for the next step is foreseen.

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