TO REHABILITATION STRATEGY OF DISTRICT HEATING IN TRANSITION ECONOMIES

Nuorkivi A.E.
Laboratory of Energy Economics and Power Plant Engineering
Department of Mechanical Engineering,
Helsinki University of Technology,
P.O. Box 4100, 02015 TKK (Espoo),
Finland,
E-mail: arto.nuorkivi@tkk.fi

ABSTRACT

The collected district heating (DH) rehabilitation experiences in economies in transition (ET) in Europe, financed by international financing institutions (IFI), were analyzed. Linear regression analysis was used when assuming the benefits gained by investments in new pipelines, pumps, heat exchanger stations (substations), heat metering, temperature controllers, thermostatic radiators valves and heat cost allocators. Based on the outcome, a computerized dynamic model over time span was created by means of linear (LP) and non-linear (NLP) programming under the GAMS[1] programming environment that, based on the analyzed experience, can optimize the DH rehabilitation strategy for a given number of years in other DH systems being candidates for comprehensive rehabilitation. The model was successfully tested in a Russian type system.

INTRODUCTION

In most of Europe and Central Asia, DH with long and large underground pipelines is the major heating mode of buildings. Out of the total residential and public heating market in Europe DH covers 70% in Russia and Lithuania, 68% in Latvia, 53% in Poland, 52% in Estonia, and 50% in Denmark and in Finland, for instance.

In the ETs, however, the DH systems are in poor condition. The DH network damages in Russia, for example, have reached the annual frequency of 2 damages per km; a very high number and equal to the Warsaw DH system before the rehabilitation started in 1991. The DH system of Warsaw used to represent a kind of negative benchmarking in early 1990's with the thermal

losses about six times, water losses even 80 times, and the number of the human resources at least five times higher than in the modern systems. After almost two decades since initiated rehabilitation, a large number of DH systems still wait for rehabilitation. In Russia alone, some 50,000 DH systems in about 10,000 towns and cities deteriorate fast. Due to industrial collapse, many of those systems may not be eligible for rehabilitation. The economic living conditions have become questionable in the long term and people have started moving elsewhere in search of work.

Rehabilitation of DH systems, where economic and sustainable, requires private sector participation (PSP) in ETs due to insufficiency of the resources of the IFIs and the local authorities. In order to address some of the barriers faced by the private sector, an analysis of the already completed rehabilitation cases, financed by the World Bank, and development of a strategic planning tool using the results of the analyses was considered useful. A simple linear regression analysis of the material measures, e.g. the investments, and the obtained economic benefits of the completed projects has given estimates about the relations between the individual measures and the related benefits. The author has had an opportunity to participate in preparing and using the database of the World Bank, the largest co-financier of the rehabilitation cases so far, comprising the analysis results of the completed rehabilitation cases, located in Poland and the Baltic States.

Thermal losses of residential buildings related to centralized heating, consumer substations and heating networks, extended lifetime of the fixed assets – mainly underground piping - due to improved circulation water quality and rehabilitated pipelines, reduced water flows due to increased temperature difference prevailing between the supply and return pipe, reduced overall water temperature levels as a means to reduce

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[1] General Algebraic Modelling System, initially developed by the World Bank but later commercialized with Gams International, Inc.

thermal losses and to improve economy of cogeneration of heat and power (CHP), for example, were analyzed.

Using the analyzed information about the benefits provided by the completed projects, a dynamic model consisting of LP and NLP was created by means of the GAMS programming tool.

The Model produces an optimal rehabilitation strategy for the case system, either from the financial or the economic point of view as selected. On the strategic level, the Model aims at optimizing the measures and the scheduling to rehabilitate a DH system in any city in the ETs under some restrictions to be discussed later in the document. Eligible measures consist of various investments in frequency controlled pumping, large, medium and small pipelines, consumer substations with/without heat exchangers and temperature controllers, network sectioning valves, CHP development, heat metering and DSM as well as of immaterial measures.

The model performance has been demonstrated in a fictive Russian DH system. Due to the basis of analyzed data and the testing results, the model may offer encouraging opportunities to assist private sector and other financiers in planning DH rehabilitation in ETS on strategic level.

The research study was presented and defended in public as Doctoral Thesis in 2005 [6].

NOMENCLATURE

Alphabetical

c	[-]	Component of the thermal chain
e	[-]	Natural constant equal to 2.71
Q	[GWh]	Heat energy
R	[%]	Rehabilitation rate
t	[a]	Time

Greek characters

Θ	[-]	Benefit weighing function
β	[%]	Relative potential of savings in need of resource
η	[%]	Efficiency of the energy system component
π	[-]	Equivalent to 3.14…

Subscripts

de	Sales (demand)
dh	DH
ℓ	Losses
ne	Network
o	Base or reference year before rehabilitation has started
pr	Production

SCOPE OF RESEARCH

The DH system is the least known part for the PSP in the DH/CHP chain, starting from the fuels and reaching the end user, since

1. The network is mainly underground, geographically large and invisible, and therefore, the technical condition cannot be directly assessed; and
2. Little measured data is available about the various losses of the network and the consumer equipment. Typically, the heat production and water consumption are measured only at the heat sources but neither in the network nor at the consumer side.

Therefore, DH rehabilitation planning at present is based on fuzzy or no information. In order to have a holistic optimization of the entire system, a computerized Model was considered useful for PSP. The Model would use existing data, reasonably reliable estimates of those parameters not measured, and other experiences on immaterial benefits achieved. The Model should produce a strategic plan for DH rehabilitation helpful for PSP.

All domestic hot water (DHW) is excluded as well, because most of the customers are equipped with DHW supply from the DH system and no major rehabilitation needs are indicated there, except elimination of the group substations (GS).

Elimination of GSs and small boilers fueled with solid fuel have been excluded from the Model building due to their location specific features.

METHODOLOGY

Regarding the methodology, three approaches were used to design the tool, the Model, for rehabilitation strategy planning of the DH systems in the ETs as follows:

1. Economic and Environmental Analyses of Completed Projects

The outcome of the five Polish and four Baltic rehabilitation cases was analyzed from economic and environmental point of view. The final result of rehabilitation was verified to the alternative business as usual, in other words, the business was compared with and without rehabilitation. The analyzed benefits of the rehabilitation including other lessons learned were further developed in the two other approaches described below.

2. Questionnaire Analysis on Immaterial Measures

The goal was to find a quantitative relation between the immaterial and material measures and related benefits in order to have a holistic prioritization of all major measures, both material and immaterial ones. Therefore, a questionnaire analysis was found necessary in order to evaluate the impacts of the immaterial measures comprising education, co-operation, small investments in IT systems and maintenance practices. By means of the questionnaire, the task was to find out benefits and lessons learned from the large projects already completed or being completed shortly. Two prioritizations were made: first, the immaterial versus the material set of measures, and second, the individual measures inside the immaterial set of measures. The priorities were then used to model the impact of the immaterial measures in the Model on general level. The questionnaire analysis is excluded in the paper on hand.

3. Model for Rehabilitation Strategy

Development of a Model was considered useful for planning a rehabilitation strategy. The task of the Model is to produce an optimal rehabilitation strategy for the case system, either from the financial or the economic point of view. On the strategic level, the Model aims at optimizing the measures and the scheduling to rehabilitate a DH system in any city in the ETs under some restrictions to be discussed later in the document. Eligible measures consist of various investments in frequency controlled pumping, large, medium and small pipelines, consumer substations with/without heat exchangers and temperature controllers, network sectioning valves, CHP development, heat metering and DSM as well as of immaterial measures. The measures are used to improve the DH system economy. Based on the measures to be implemented, the energy

system economy will be improved by reduced thermal, electricity and water losses, reduced flue gas emissions, reduced need of heat production capacity and both HR and repair works under the prevailing financial constraints. Moreover, the system economy may be improved by means of additional sales of heat and electric energy as well as of extended lifetime of the fixed assets. The Model has been documented, adjusted to the analyzed experience and demonstrated in a fictive case in Appendices 4, 5 and 6 respectively.
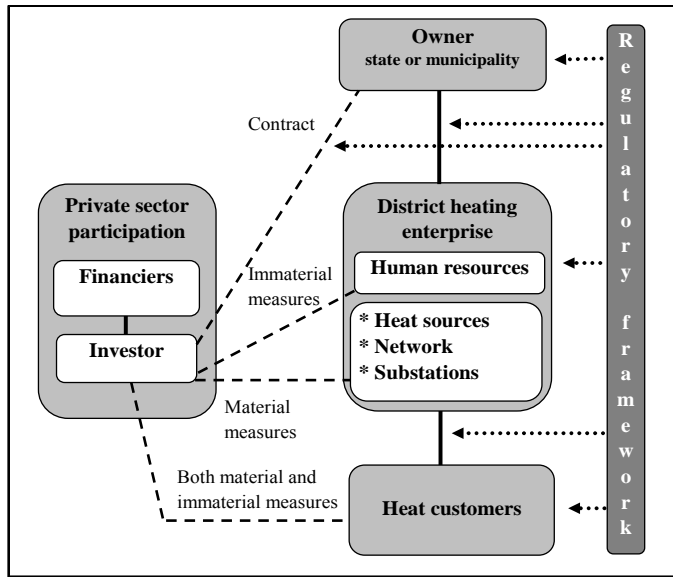
**Figure 1** A typical regulatory framework of the DH in an ET.

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The main conditions in designing the rehabilitation strategy are:
1. Predicting the heat load by means of the expansion rate, connection rate and the availability rate. However the DHW rate that is specific for a few countries only has been left for later development of the Model;

2. Limited financing available at the local district heating enterprise (DHE) and its owner;
3. Requirements and restrictions of financing at any potential investor and financier;
4. Low affordability of the customers preferring a low heat tariff level;
5. Unknown optimal order and quantity of a variety of investment options;
6. Uncertain quantitative importance, design and timing of the immaterial measures; and,
7. In general, incomplete institutional framework for PSP, either foreign or domestic, as addressed separately in the Handbook (Author, 2002).

As presented in Figure 1, the regulatory framework of DH in an ET is out of the influence of PSP. The local regulator stipulates the rights and responsibilities of the owner, PSP, the DHE and the customers. A financier may fund the measures of the investor but not the ones of the DHE, because the DHE cannot offer eligible guarantees for the financier. The investor shall enter in a contract with the owner of the DHE in order to carry out material measures in heat sources, network and the substations as well as immaterial measures to improve HR productivity of the DHE. The Model is aimed at improving the quality and focus of the measures and alleviating risks related to the contract.
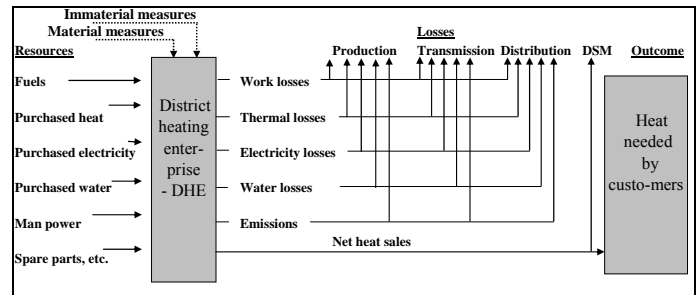
Figure 2 The loss flows of resources in a district heating system.

FLOWS OF LOSSES
Despite of offering an efficient infrastructure for energy supply, the DH system has a number of loss flows in operation, particularly in the ETs. Figure 2 above lists the main resources, identifies the flows of lost resources and yields the final energy sales to the customers. The main flows of losses are as follows:
1. The work related losses are due to low productivity of using the HR in energy production, heat transmission and distribution;
2. Thermal transmission losses in pipelines are caused by the poor or missing thermal insulation of the pipelines, holes of insulation in valves, pumps and compensators, and in ventilation of chambers. High thermal losses at the heat sources are caused by poor combustion efficiency;
3. Electricity losses in DH pumping, despite being mainly used for compensation of the friction in pipelines, are due

to poor efficiency of the pumps and couplings, low cooling, high roughness of pipes and excess pressure difference of the consumer equipment;

4. Water losses are caused by leaks in the network, heat exchangers and in control equipment, but mainly by illegal tapping at the consumer side;

5. The undesired environmental impacts (losses) are caused by the various emissions, mainly CO_2, SO_2, NO_x and dust;

6. Frequent replacement of materials – pipelines, heat exchangers, boilers – due to short lifetime causes maintenance costs; and,

7. Excess heat production capacity typically existing in the DH systems is a reason for excess maintenance costs.

MODEL STRUCTURE FOR PLANNING OF REHABILITATION STRATEGY

The Model aims at optimizing the measures to rehabilitate a DH system in any city in the ETs on a robust level. Such measures consist of a variety of both material and immaterial measures. The material measures include rehabilitating large, medium, and small pipelines, consumer substations, network sectioning valves, CHP development, heat metering and DSM measures, as well as taking into account the total impact of the immaterial measures. The DH system economy will be improved by reducing thermal, electricity and water losses of the system as well as the need of HR and replacement investments by means of the measures under the financial and the physical constraints.

The overall structure of the developed Model follows the general energy system modeling [2,3].

The economic conclusions have been drawn from the case analyses [4,6,7,8,9,10]. The conclusions have given the Model input data of the expected savings in use of the resources as functions of the completed measures.
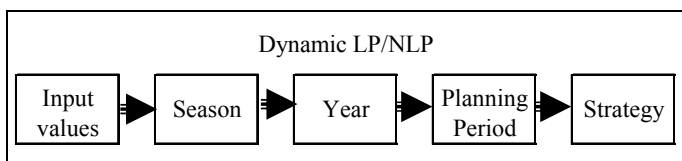

Figure 3 Timely structure of the Model.

BENEFITS DEPENDING ON REHABILITATION RATE

The benefits accrue in a variety of ways depending on the type of the particular measure. The most essential investments comprise boilers at heat sources, pipelines in the network and control systems in the substations. Such investments comprise the bulk of the costs in any comprehensive rehabilitation project, typically more than 90% of the total costs. Due to their high volume, the dependence of the expected benefits on the rehabilitation rate deserves a closer focus.

The Benefits depending on the rehabilitation rate R indicate the impact of the investments on the benefits of any component. For instance, investments in the worst pipes have a higher IRR than replacing all the pipes of the system. On the contrary, replacing only a few substations may have a lower IRR than replacing the bulk of the substations, which finally would

change the operation mode from the production to the demand driven one.

The benefits are assumed as functions of the rehabilitation rates. The functions of the LP Model consist of both truly linear and linearized ones, whereas non-linear functions are also included in the NLP Model.
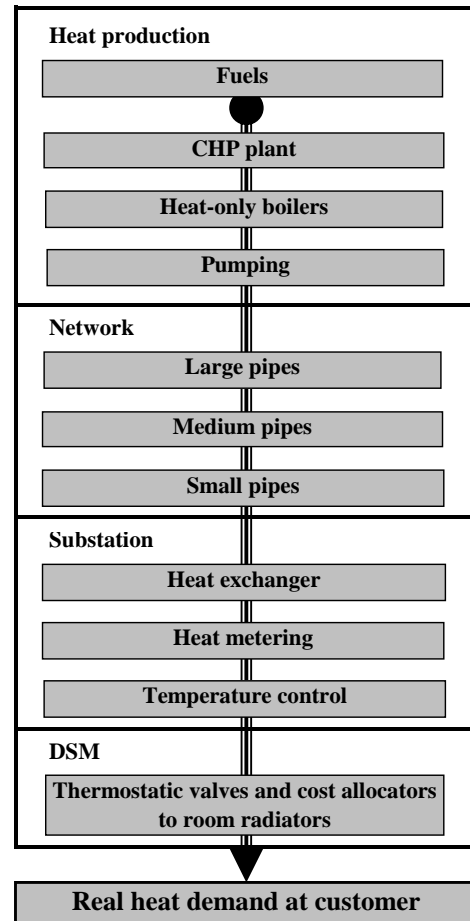

Figure 4 Thermal chain of components in the Model.

The positive variable R(c,t) specific to any component c has a range from zero to one. The benefit depends on the value of R(c,t). In LP the dependence is a linear, whereas in NLP a non-linear benefit function of the type of either a trigonometric (1), a logarithmic (2) or an exponential (3) one has been selected. The selection is based on the author's understanding and experience about the behavior of various ways of benefit accrual expressed in mathematical approximations, and not on any tests. Therefore, the approximations do not simulate the real behavior in an accurate manner but are assumed to be better than the linear approximations. The selected function types for such approximation are expressed below:

$$\Theta(c,t) = 1 - \cos(\tfrac{1}{2}\,\pi\,R(c,t)) \tag{1}$$

$$\Theta(c,t) = \lg(10\,R(c,t) + 1) \tag{2}$$

$$\Theta(c,t) = 0.1 / (0.1 + 10\ e^{(-10\ R(c,t))}) \tag{3}$$

With the conservative trigonometric function (1), the benefits of HR start accruing slowly and are delayed after the rehabilitation measures have been executed. The benefits lag behind the implemented measures but reach the final value when the R reaches the value 1. The trigonometric function simulates (i) the behavior of labor unions, since the HR reduction may not be allowed instantaneously following the investment measures, (ii) and moreover, may not be reasonable, because implementation of the investments requires temporarily more HR to install, supervise and tune the new equipment in the rehabilitation phase than to use them later in the O&M phase.

By means of the logarithmic function (2) the benefits start accruing fast, as the earlier rehabilitated pipes and boilers most likely have been in the worst condition. Therefore, the early rehabilitation of such worst equipment would yield higher relative benefits than those to be rehabilitated later on and, often being in a relatively good technical shape.

With the exponential function (3), the benefits start accruing slowly at first. The factor Θ lags behind the value of R until about 0.4, after which the values of Θ exceed the value of R. Such a benefit function is typical for the temperature controllers in substations: The R has to reach a critical mass before the system operation turns from the production to the demand driven mode.

THERMAL EFFICIENCY OF DISTRICT HEATING

In the thermal chain, one has to insert two estimate sets of the thermal loss percentages, two estimates for each component of the Model. The first set of estimates reflects the loss percentage values in the base year and the second set reflects the ones expected in the target year. A parameter β_c will be calculated for each component as a difference between the base year and target year values in order to express the relative thermal saving potential related to rehabilitation of the particular component.

In NLP, the heat energy transfer in the thermal chain is characterized by means of the recursive formula as follows:

$$Q(c,t) = \eta_o(c)\ Q(c-1,t) + \beta_{dh}(c)\ \Theta(c,t)\ Q(c-1,t) \tag{4}$$

In the NLP, the benefit weighing function Θ has been used instead of the rehabilitation rate, because the benefits are assumed to accrue in different nonlinear ways depending on the component.

For LP, the above formula has been linearized in order to avoid the product of the two time dependent variables, Θ and Q, by means of the three first terms of the Taylor series method [1].

$$\begin{aligned} Q(c,t) = \ &\eta_o(c)\ Q(c-1,t) + \beta_{dh}(c)\ [R(c,t)\ Q(c-1,0) + \\ &R_o(c,t)\ (Q(c-1,t) - Q(c-1,0)) + (R(c,t) - \\ &R_o(c,t)\ Q(c-1,t))\ ] \end{aligned} \tag{5}$$

Where $Q(c,t)$ means the heat energy at the output of component c during the year t, $\eta_o(c)$ the efficiency of the component c during the base year o, $\beta_{dh}(c)$ the potential of thermal energy savings at component c as inserted by means of the sets of estimates, and, $R(c,t)$ the rehabilitation rate of component c at the end of year t.

The formulas (4) and (5) indicate that the Model is dynamic; the achieved level of rehabilitation in a year creates the basic value for additional rehabilitation in the consecutive year throughout the selected period of years. In the Model, the level of the rehabilitation rate, as a variable ranging from 0 to 1, reflects the relative level of the investments in any component of the thermal chain.

Thermal losses of the thermal chain are assumed as the difference of the heat energy of the second component, heat production, and the last component, the heat sales, as follows:

$$Q_l(t) = Q_{pr}(t) - Q_{de}(t) \tag{6}$$

CONSTRAINTS OF MODEL

The Model, merely being a simulation of the real world, cannot be exact and accurate. The Model structure has been designed and the parameters adjusted in order to reflect the real world rehabilitation process in a reasonable extent and accuracy. However, the Model has been compressed to contain the most essential features of the rehabilitation, which should be sufficient to analyze most rehabilitation cases in a reasonable accuracy.

The Model can be used in most of DH systems in the ETs with the exceptions as follows:

1. The heat load pattern is simple dividing the annual heat demand to four seasons. Such a simplification creates inaccuracy to real fuel consumption, but may be sufficient when comparing alternative investment strategies;

2. The Model expects that both DHW and SH are supplied by the DH system. In some countries such as China [11,12] and Serbia [5], the DHW is usually not supplied by the DH system but either by individual solutions in apartments or not at all. Such DH systems without including the DHW services are rather rare in the ETs, thus not necessarily requiring the DHW rate to be included in the Model;

3. The energy sources are modelled in a rather simple way. Only one fuel per source is possible. The annual maintenance planning is excluded from the scope of the Model. Such deficits in the Model do not have any significant impact on the rehabilitation planning in the strategic time frame;

4. The Model contains the most simplified pattern of a CHP process, because the focus has been in the network and the substations rather than in energy production. Therefore, any investments aside from the DH circulation pumps and entire CHP plants should be planned separately. Only one CHP plant at the time can be included in the Model, which is typical in the smaller systems, presumably more attractive to Finnish financiers than the large systems;

5. The Model does not have any link to hydraulic analysis of the heating network. The large, medium and small pipelines in the Model are connected to each other in the order of the size without any link to the real network

topography. Therefore, the sizing and location of the pipelines for rehabilitation must be designed separately;

6. The water losses and water temperatures do not have direct relation to thermal transmission and distribution losses in the Model, even though such relation physically exists. The water temperatures are used for quantifying the electricity generation at the CHP plant. The thermal losses of the chain, however, are allocated to (i) the temperature related, (ii) the water loss related and (iii) to the base losses as a result of the optimization, thus compensating the neglected physical relation; and,

7. The Model is idealistic in a number of respects, which however, is typical for the planning tools designed for the strategic level.

Regardless the obvious benefits of using such Model some restrictions prevail, which cannot be included into the Model, for instance, as follows:

1. An elimination program for small polluting boilers should be developed separately by means of a spreadsheet tool;
2. A transition program for heat distribution from the 4-pipe to the 2-pipe system should be developed separately by means of spreadsheet tool; and,
3. A program for interconnecting a variety of local heating networks needs to be designed by means of hydraulic simulation.

EXAMPLE OF MODEL ADJUSTMENT TO REALITY

As an example of the model adjusted to the reality, the thermal transmission losses were obtained from six reference cities as presented in Table 1 below.

Table 1 The level of the thermal network losses of the network on the case year ($Q_{l,ne}$) and on the base year ($Q_{l,ne,o}$) depending on the network rehabilitation rate (R_{ne}).

DHE	$Q_{l,ne}/Q_{l,ne,o}$	R_{ne}
a	100 %	0 %
b	20 %	100 %
c	49,7 %	30 %
d	58,4 %	18 %
e	56,3 %	12 %
f	79,4 %	10 %
g	83,0 %	18 %
h	44,8 %	58 %

The linear regression formula based on the values given in Table 5.3 above with correlation of 0.89 is as follows:

$$Q_{l,ne}(t) / Q_{l,ne,o} = 0.93 - 0.84 \, R_{ne}(t) \quad\quad (7)$$

In creating the above formula, the weighing of the first row (a) in Table 1 is five times more than the consecutive rows down. The weighing is necessary as the thermal losses are

100% of the value of the base year while the rehabilitation rate is zero.

Another reference point, row (b) in Table 1, is assumed as an ideal situation when the entire network is rehabilitated (rehabilitation rate 100%). The network losses in large modern networks (Helsinki, for instance are about 5% of the produced heat energy, thus about a quarter of the initial level of the rehabilitated cases. In the system of Helsinki, however, there are still both preinsulated and mineral wool insulated pipelines, thus not yet being completely ideal. Therefore, the ideal target level of thermal losses is set at 20% of the initial thermal losses, when 100% of the network is rehabilitated.

A similar linear regression was formed to the other relations prevailing between the measures, such as investments in heat exchangers, pipes, control valves, heat meters and pumps, as well as to the various types of losses, such as fuel, water, electricity, maintenance work and spare part resources, as was illustrated in Figure 2.
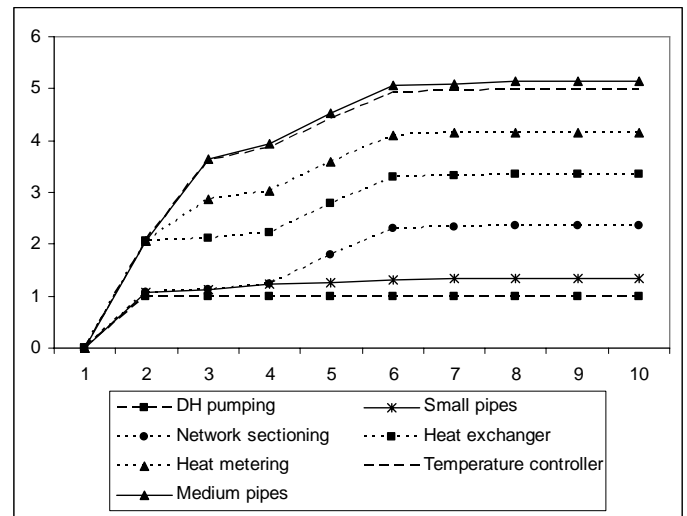
Figure 5 Example of rehabilitation rates of various components in thermal chain in the course of year of rehabilitation.

CONCLUSIONS

In Figure 5, and example of an optimal rehabilitation strategy based on economic terms is presented. It indicates that first heat metering and temperature controllers in consumer substation and apartment together with consumption based billing should be introduced in order to involve customers in energy saving. In a financial modelling, however, the pipelines and heat exchanger would be prioritized to DSM measures, thus reflecting the primary interest of the DHE to improve its business. In the example, the rehabilitation rate of pipelines does not exceed 10% level, because the main benefits are often obtained by replacing the worst pipelines in the systems, about 10% of the total length, and thereafter, the incremental benefits may not exceed the incremental investment costs.

Heating of room space and domestic hot water is a necessity in most northern countries in the world. DH is a largely adopted practice and recognized as the least-cost solution to serve more than 100 million people Europe, but too often with poor

performance. In general, the objectives of DH rehabilitation are to provide the customers with heating services that meet the requirements of economy, affordability, technical performance and environmental sustainability. In order to meet the objectives PSP is considered necessary. The PSP, however, faces a number of barriers. Some of the barriers can be addressed by means of more accurate strategic planning of the rehabilitation projects.

In this research, a Model was developed and demonstrated to assist potential investors and financiers in strategic planning of the DH system rehabilitation in the ETs. The need of such assistance is both urgent and crucial, because, first, the existing systems deteriorate fast as they have been maintained at necessary annual repair level only, but lack any considerable upgrading for a decade or longer, second, on the northern globe the availability of heating is an even more important necessity facilitating the human life than the availability of electric energy, and third, involvement of the PSP is necessary to foster rehabilitation but requires new means in order to manage a variety of risks related to such rehabilitation.

The Model is aimed at addressing a number of barriers that the investor faces while considering a DH system rehabilitation, for instance, as follows:

1. Improving accuracy and focus in planning of material measures taking the impacts of the immaterial ones into account, which improves the feasibility of rehabilitation;
2. Assisting in the least costs analysis of the existing system while suggesting a sustainable rehabilitation strategy;
3. Managing the financial risk of investments, because the materialized experiences from the completed comprehensive rehabilitation projects have been incorporated to the Model;
4. Reducing the costs of financing, because the Model will assist in risk mitigation; and,
5. Sizing the rehabilitation measures according to the affordability and quality requirements of the heat customers.

The Model in its current status of development has been designed to focus on the core needs of the investors to improve rehabilitation economy. In the future, the Model may be developed to a more detailed level and be extended to cover new features as follows:

1. Heat load duration: the heat load part may be extended from the current four-seasonal block pattern to a more detailed one by means of connecting the Model to a separate heat load model;
2. Energy Production: Expansion of the Model to cover more features in the heat production. Such features, as mentioned before already, consist of issues such as double fuel, several CHP units and maintenance planning;
3. DHW rate. The DH system does not usually supply DHW services in a few countries such as Serbia & Montenegro and China. Possible extension of the DH services to cover DHW as well offers interesting business opportunities;
4. DC rate: Similarly, district cooling could be a business opportunity in the future, when expanding CHP business becomes actual; and,

5. Steam rate: Analysis of steam network, usually operated with the DH systems in parallel, may become possible in the Model in some extent. Usually, the objective in Europe has been to get rid of the steam systems and either convert the customers to water system to provide them with customer-specific steam generators whichever more economic. In China, however, comprehensive steam networks have been built to provide steam to industry, to absorption chillers and DHW in the commercial and public buildings as the water type DH is used for 3-4 months a year for SH alone.

Improved optimization of the investment operations on the strategic level will improve the economy of the investments, thus likely improving opportunities for economic CHP expansion and CO_2 emission reduction, as was aimed at with the research work.

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