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Decision-making process for addressing bottleneck problems in district heating networks

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ABSTRACT

Lower system temperatures in district heating (DH) grids are important factors for system efficiency. Lower system temperatures lead, for example, to lower heat losses and higher production unit efficiency. One obstacle to lower supply temperatures are so-called bottlenecks in DH networks. Bottlenecks are areas in DH networks of very low differential pressure, which makes it difficult to supply them with sufficient heat. There are many potential solutions to bottlenecks. However, the current decision-making process generally does not include every potential bottleneck solution and also often does not include every important factor that affects the outcome. The aim of this study is to propose a structured and general *modus operandi*, in order to identify the best bottleneck solution for a specific situation. In this study we conducted analyses of previous bottleneck studies, workshops and interviews. The results show a decision-making process developed to be a tool when choosing a bottleneck solution. Coupled to the decision-making process, a summary of the advantages and disadvantages of different factors and bottleneck solutions is presented, as well as a description of a real case in which the decision-making process is used.

Keywords:

District heating;
Bottlenecks;
Planning;
Optimisation;

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1. Introduction

District heating (DH) facilitates the use of renewable heat sources, excess heat and heat from, for example, combined heat and power units [1,2,3]. DH technology is currently going through a transition to the 4th generation of DH, which is described by Lund et al [4]. In this transition, lower system temperatures are vital parameters. According to a study on prosumers' impact on technical parameters in distribution networks, this will facilitate prosumer introduction to the DH network [5]. This is because of the increased efficiency of such installations when the supply temperature in the DH network is lower. This is for instance shown a study describing heat pumps that increase the temperature of prosumer excess heat [6] and in a study about solar collectors in district heating networks [7]. Lower system temperatures are also shown to increase the possibility of utilising waste heat and lead to higher efficiency in combined heat and power units and flue gas condensation [8,9]. Another important and current development in DH systems is that there is a change in the way in which energy systems are viewed, which is shown in many recent studies that describe smart energy systems and the 4th generation of district heating [10, 11, 12, 13]. Previously, energy systems were often regarded as separate systems focusing on, for example, electricity, heating and transport, whereas the new perception is a holistic view of a single integrated energy system. The aim of this development is to increase the efficiency of the systems and achieve an energy system based on 100% renewable energy sources. However, there are many obstacles that must be overcome to achieve efficient and smart DH networks, one of which are bottlenecks. Other examples being discussed include future heat savings [14] and thermal energy storage [15].

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Bottlenecks are areas in DH networks in which it is difficult to maintain a sufficiently high differential pressure, often due to high flow velocities in the pipes leading to the area. From an optimisation perspective, the area with the lowest differential pressure (dp) in a DH network may also be regarded as a bottleneck with regards to network optimisation. Such areas are also decisive for the supply temperature in DH networks. Thus, in order to be able to continuously decrease the supply temperature, it is important to always work on areas of weak dp and try to improve the conditions in such areas.

One research area associated with lower supply temperatures in DH networks concerns the effect of lower supply temperatures in existing DH network. This is studied, for example, by Rämä and Sipilä [16]. From a building perspective, it is possible to supply buildings with the correct amount of heat with a lower supply temperature, as shown by Skaarup Østergaard and S. Svendsen, who tests the effect of a lower supply temperature in five Danish single-family houses from the 1930s [17]. However, another study show that the reduced temperature difference that often arises leads to more pressure losses and therefore higher costs [18]. Furthermore, large and old DH networks often have a higher hydraulic resistance, which is discussed in a study on the utilisation of low-temperature industrial excess heat for district heating [19]. This results in even higher pressure losses in such systems. Thus, it may be both difficult and costly to reduce the supply temperature in existing DH networks that are dimensioned for a specific temperature difference. There are many studies that discuss the optimisation of DH pipes in low temperature DH networks, although often from a heat loss perspective [20, 21, 22]. Some studies on lower supply temperatures in DH networks also consider the changed pressure situation, but only regard classical solutions associated with the distribution part of the DH network, for example, a larger pipe dimension or more pumping [23, 24, 25, 26].

The present study seeks to broaden the view of the types of arrangements that could be made to optimise the pressure situation in DH networks, thereby also simplifying the introduction of lower supply temperatures. This holistic approach to bottlenecks and pressure problems in DH networks has been previously considered in some studies [27, 28, 29]. This holistic perspective is important for the introduction of DH with lower supply temperatures, as described by Li and Wang [30].

The results in [27] describe the present bottleneck situation in Swedish DH networks, the origin of these bottleneck problems, as well as which solutions that are most often used. The results show that 75% of the DH companies that responded have, or have had, bottleneck problems and that the origins of DH bottlenecks are most often expansion, densification and interconnection of DH networks. The most used bottleneck solutions are higher supply temperature, bigger pipe area, more pumping, increased cooling in substations, local heat supply (LHS) and demand side management (DSM). The results are collected via a literature study and a survey.

The results in [28] describe how well the most used solutions in [27] work in different network configurations, for example, in a ring feed network and in a network with large altitude differences. The results also show the cost of different solutions. Only direct costs are quantified, not costs and savings related to added values such as the possibility of lowering the supply temperature or using less pumping. The results are developed through simulation of a DH bottleneck situation in the DH simulation programme NETSIM [31] together with a cost study.

The results in [29] describe different risks, possibilities and added values coupled to the most used solutions in [27]. The results also show issues coupled to the economy of bottleneck solutions, the parameters taken into account when choosing a bottleneck solution and more detailed information about bottleneck origin. The results are developed through an in-depth interview study with six different Swedish DH companies and by simulations in the same simulation tool, NETSIM, that was used in [28].

The decision on which bottleneck or optimisation solution to choose often appears to be based on gut feelings and rough economic estimates, as shown in a previous bottleneck study [29]. The results of another bottleneck study indicate that the DH network is regarded as comprising three separate components (production, distribution and consumption) and not as a whole interconnected system that forms part of the energy system [27], which also reduces the number of imaginable solutions. This perspective and traditional way of doing things may therefore exclude potentially very favourable solutions, which affect both system efficiency, the environment and the economy.

Structured planning is regarded as being very important to achieving a renewable energy system [32]. Thus, the present study provides a decision-making process with regards to how to choose between different bottleneck solutions. Coupled to this process, the various advantages and disadvantages of a number of bottleneck solutions are illustrated and discussed to assist in analysing which bottleneck solutions could be performed and how they differ. An example case is also presented to demonstrate how to use the decision-making process. The results are partly based on the results in [27, 28, 29] and partly on workshops and interviews with experts in the field. The purpose of this methodology is to achieve as comprehensive results as possible by using all the knowledge in the separate papers regarding bottlenecks and complement it with expert knowledge.

A bottleneck solution may have many contradictory goals. Thus, the decision-making process is inspired by multi-criteria decision-making (MCDM) [33], which is a well-established tool used in many energy planning studies [34, 35, 36]. However, the proposed decision-making process has been simplified, compared to MCDM, in order to enhance its usability. For example, it does not involve any quantitative ranking system, except for in the part in which the economy is regarded, and potential bottleneck solutions are rejected throughout the decision-making process. A similar idea of decision-making process is proposed by Saleki [37] who uses it to identify the most optimal renewable building-integrated power source. However, this decision-making process is less detailed and is clearly focused on small-scale electricity generation.

2. Methodology

The results regarding the decision-making-process were developed in three steps. In the first step, previous bottleneck studies [27, 28, 29] were analysed and the relevant aspects of bottleneck solutions were analysed and categorised. Based on this, a preliminary decision-making process was outlined. In the second step, the decision-making process was presented, evaluated and improved in two workshops. The first workshop was conducted with DH experts from the same DH company but who had different positions. The decision-making process was then updated and presented, evaluated and improved again in the second workshop. This workshop was conducted with DH experts from different DH companies but who had roughly the same position. Through this procedure, the opinions and perceptions of both people in different positions within one company and from different companies could be obtained. This led to more varied input and thus more comprehensive results. All the companies involved in the workshops owned, managed and developed DH networks as one of their main tasks. They also handled data, administration and contact regarding DH consumers. In the first workshop, the participating DH experts comprised one energy system analyst, one person working with DH network support at the company, one optimisation manager and one plant manager for the distribution network. The head of the energy system analysis department was also supposed to participate but was prevented from doing so. Instead, her comments were provided by one of her employees. The DH experts in the second workshop were participants in a strategic council administered by Swedenergy. They all worked on the long-term development of their DH networks and represented DH companies in many different parts of the country. In the third step, the definitive decision-making process was developed using input from the workshops.

The results regarding the advantages and disadvantages of different bottleneck solutions were coupled to specific factors. The chosen factors were mainly outlined by analysing the risks and opportunities in [29] and encapsulating them in eight factors. The factors and their evaluation criteria can be seen in Table 1. Additional factors than those proposed could, of course, be relevant,

Table 1: Factors describing the potential advantages and disadvantages of bottleneck solutions, and their evaluation criteria

Factor	Evaluation criteria
Reliability	Considered the stability of the solution and whether it would be reliable enough as a single solution.
Simplicity	Considered how much work would need to be conducted to accomplish the solution.
Swiftness	Considered how quickly the solution could be introduced.
No investment cost	Considered whether there would be any substantial investment cost.
Costliness	Considered how costly the solution would be throughout its lifetime.
Additional customer interaction	Considered whether the solution would lead to customer interaction that was regarded as positive by customers.
Environmental outcome	Considered how the solution would affect environmental values.
No extra maintenance demand	Considered whether the solution would lead to greater or lesser maintenance demand in the DH network.

but the factors mentioned in Table 1 are nearly always important. In the workshops mentioned above, the different factors were evaluated for nine proposed bottleneck solutions. The preliminary results were initially outlined through polls and discussions in the two workshops. In the polls, all workshop participants assigned colours to the factors and bottleneck solutions. If a factor was regarded as an advantage for a bottleneck solution, it was assigned a green colour, if it was seen as a disadvantage for a bottleneck solution, it was assigned a red colour and if it was either an advantage or a disadvantage for a bottleneck solution, it was assigned a yellow colour. The combined colour results and the workshop discussions were then combined with input from previous bottleneck studies [27, 28, 29] into final results. The bottleneck solutions included were based on the most used bottleneck solutions in [27] but were customised in order to simplify the polling process. It is important to note that this evaluation was performed from a bottleneck solution perspective. A number of the solutions could also be applied to other important district heating issues, which could then change which advantages and disadvantages would be relevant.

The example case that describe how to use the decision-making process was developed by analysing a real bottleneck case in a Swedish DH network in an interview. The interviewees were representatives of the responsible DH company: one network analyst and one person working with DH network support at the company. The company had already performed all investigations and studies required beforehand and the interview considered the results of their investigations. Thus, no own studies regarding the case were conducted by the authors. The results regarding economy were discussed without numbers on the grounds of confidentiality. Bottleneck solutions that were not included in the rest of the results were included in the case interview. This was because the interviewed DH company had thought of more solutions than the ones investigated in the present study. These solutions were included in the case description as it was regarded as important to demonstrate that every DH developer could use the decision-making process independently of how the bottleneck area looks and which bottleneck solutions that are available.

The bottleneck case area discussed in the interview is called the Plateau and is a DH area comprising around 1250 consumers located in a larger DH network. It is situated close to the outskirts of the DH network but not on the very outskirts. The area is ring fed from several pipes from the large DH network. The heat demand for the Plateau for the design outdoor temperature (DOT) of –16 °C degrees was 24 MW. The heat demand for the large DH network was 850 MW for the same outdoor temperature. For the DOT, the supply temperature to the Plateau was 105 °C and the return temperature was 50 °C. The lowest differential pressure in the Plateau for the DOT was 44 kPa and the pressure gradients for the supply pipes were between 0 Pa/m and 300 Pa/m. The main bottleneck pipe was one of the pipes between the production unit and the Plateau area. The supply pressure gradient for this pipe was around 400 Pa/m. The lowest supply temperature for the Plateau during the year was 70 °C and the corresponding return temperature was 35 °C. The total length of the pipes in the Plateau was around 115 km.

3. Results and Analysis

In this section, the results regarding the advantages and disadvantages of different bottleneck solutions (Table 2) are presented first. This is followed by a presentation of the decision-making process (Figure 1). Lastly, a real bottleneck case in which the decision-making process is used in order to find the most optimal bottleneck solution is presented, to assist in showing how the other results might be used. The results are presented from a district heating developer perspective.

3.1. Advantages and disadvantages of bottleneck solutions

Table 2 shows the advantages and disadvantages of some frequently used bottleneck solutions. This table is intended to be helpful when working through the decision-making process and it provides a general picture of factors coupled to the studied solutions. If a factor is green, it is regarded as an advantage to the solution; if a factor is red, it is regarded as a disadvantage to the solution; and if a factor is yellow, the factor may be either advantageous or disadvantageous to the solution, depending on the situation and the local conditions. The colours are shown from the perspective of DH network developers because they will have the final mandate to implement the solutions. The general results for each solution are also described.

3.1.1. Increased supply temperature

Increased supply temperature achieved positive ratings for reliability, simplicity, swiftness and no investment costs. Nevertheless, it was a costly solution if not used for very short periods and in small networks, and gave no

Table 2: Advantages (green), disadvantages (red) and factors that can be both advantageous and disadvantageous (yellow) for some important factors and bottleneck solutions

	Increased supply temperature	Increased pipe area	Increased pump work – existing pump	Increased pump work – new distributed pump	Increased cooling	Local heat supply – liquid or gas fuel	Local heat supply – solid fuel	Local heat supply – prosumers	DSM
Reliability	green	green	green	green	yellow	green	green	red	yellow
Simplicity	green	red	green	red	yellow	yellow	red	yellow	yellow
Swiftness	green	red	green	red	yellow	yellow	red	yellow	yellow
No investment cost	green	red	green	red	yellow	red	red	yellow	yellow
Costliness	red	red	green	red	yellow	red	red	yellow	yellow
Additional customer interaction	red	red	red	red	green	red	red	green	green
Environmental outcome	red	yellow	red	red	green	red	yellow	green	green
No extra maintenance demand	yellow	yellow	yellow	red	green	red	red	yellow	yellow

additional customer interaction. Furthermore, the environmental outcome was often negative because of the increased heat losses and decreased efficiency in certain production units. The yellow colour for the no extra maintenance demand factor was based on the fact that a higher supply temperature was coupled to more wear on the pipes and thus more leaks, which increased the maintenance demand. However, this partly depended on how much and how often the supply temperature had to be increased, because multiple increases and decreases caused more wear on the pipes than occasional increases.

3.1.2. Increased pipe area

Increased pipe area was given a positive rating for reliability but was often complicated due to earthworks. The solution was also regarded as not being very swift, having a high investment cost and not engendering any additional customer interaction. The yellow colour for the environmental outcome factor depended on the material use and installation process affecting environmental factors, even if the operational situation and, thus, the operational environmental outcome of the DH network could be improved. The yellow colour for the no extra maintenance demand factor depended on whether a new pipe would be installed (extra maintenance demand) or an old pipe would be exchanged for a new, bigger pipe (equal or less maintenance demand).

3.1.3. Increased pump work – existing pump

Increased pump work with the existing pump was given positive ratings for reliability, simplicity, swiftness, no investment cost and costliness but gave no additional customer interaction. The extra electricity demand led to a poorer environmental outcome. The yellow colour for the factor no extra maintenance demand depended on more pump work possibly causing more wear on the pipes. However, as for the increased supply temperature solution, this depended on how, and the extent to which, this solution was used.

3.1.4. Increased pump work – new distributed pump

Increased pump work with a new, distributed pump was given a positive rating for reliability but a negative rating for all other factors as it was both costly, complicated to build and maintain, gave no additional customer interaction and used electricity, which negatively affected the environmental outcome.

3.1.5. Increased cooling

Increased cooling at the consumers was given positive ratings for additional customer interaction, environmental outcome and no extra maintenance demand. The yellow colour for the reliability factor depended on a high degree of cooling in substations being perishable, but the solution was reliable as long as the cooling was regularly checked. The yellow colour for the simplicity and swiftness factors depended on their outcome being partly determined by how many consumers would need to be involved, partly by whether the problems were easily fixed and partly by the consumers' attitude if the substations were consumer owned. Also, there could be a great deal of analytical work involved in identifying the right consumers and establishing how to decrease their return temperature. The no investment costs and costliness factors were yellow because their outcome depended on whether or not the company would pay something to achieve the decreased return temperature or whether the consumer only would pay. Furthermore, the analytical work could be costly in terms of person hours, which added uncertainty to the costliness factor.

3.1.6. Local heat supply – liquid or gas fuel

This solution was given a positive rating for reliability but a negative rating for the remaining factors, with the exception of simplicity and swiftness. It was namely a costly installation that would require maintenance. The environmental outcome depended on the fuel used and the fuel that was replaced. However, liquid and gas fuels usually referred to fossil fuels, which is why the outcome was usually negative for the environment. The yellow colour for the simplicity and swiftness factors depended on the installation of an extra production unit possibly being preceded by a difficult and slow permit process. If, however, the production unit was smaller and if it was not intended to be a permanent but rather an interim solution, the permit process could be much swifter and easier.

3.1.7. Local heat supply – solid fuel

This solution was given a positive rating for reliability but a negative rating for everything else, with the exception of the environmental outcome factor, as it was a costly installation that would require maintenance. The permit process for solid fuels was often more complicated than for gaseous or liquid fuels, which is why simplicity and swiftness were negatively rated. The yellow colour for the environmental outcome factor depended on the different outcomes, based on whether the solid fuel consisted of coal or wood-based products.

3.1.8. Local heat supply – prosumers

The prosumer solution was given a positive rating for environmental outcome and additional customer interaction but was not very reliable as a bottleneck solution. There were many factors that were assigned a yellow colour. One reason for the yellow colour for the simplicity and swiftness factors was that an agreement with the prosumer could be difficult and time consuming to achieve. However, if standard models were already in place, the process would be much faster and easier. Simplicity also received a yellow colour because it depended on how much work and adjustments the DH developer would need to make and also because the prosumer load could be difficult to manage with regards to, for example, supply temperature and temporal availability of heat. The yellow colour for the no investment cost and costliness factors depended on how the connection of the prosumers to the DH network and the agreement between the DH developer and the prosumer regarding, for example, connection cost would look. Another reason why costliness received a yellow colour was that it depended on the energy prices that were contracted. Lastly, the yellow colour for the no extra maintenance demand depended on that the maintenance demand could be both more and less extensive. It could be more extensive with increased control demand and valves that would require maintenance. It could also be less extensive if many new and more state of the art components were installed instead of retaining the old components.

3.1.9. Demand side management

DSM was given a positive rating for environmental outcome and additional customer interaction. The yellow colour for the reliability factor depended on the outline of the agreement with consumers and who had ultimate control of the load management affecting the reliability of this solution. The simplicity factor received a yellow colour because the simplicity of DSM varied depending on whether there were already general agreements in place that could be utilised or whether they would have to be developed, as well as whether the underlying control and IT system were in place or had to be developed. The same considerations explain why the swiftness, no investment cost and costliness factors received a yellow colour. The number of consumers who would need to be involved and the equipment that would need to be installed also affected the no investment cost and costliness factors. There were many reasons why the no extra maintenance demand factor received a yellow colour. Two reasons were that ownership of the equipment affected the amount of maintenance required and that the control and IT system would have to work properly. Another very important reason was that the need for IT safety would be very high for these types of systems, which could increase the maintenance demand.

3.2. Decision-making process

An illustration of the decision-making process can be seen in Figure 1. Explanations of the different steps are also described. The work process for the decision-making process starts at step 1 with a problem description and then follows each step until the basis for decision is reached. In the description of each step, the most important factors for this step from Table 2 have been denoted in order to help the reader connect the two instruments. Thus, input from Table 2 could be used in the evaluation of different bottleneck solutions. The overall idea of the decision-making process is to come up with as many bottleneck solutions as possible at the start of the process and then reject solutions that are not possible to implement or are considered less favourable, on a step-by-step basis.

The steps involved are those necessary in order to thoroughly evaluate the solutions, based on the workshops. The reason for the order of the steps is to facilitate an effective process. The idea is to eliminate solutions quickly during the process in order to conduct as few time-consuming evaluations as possible. If conducted correctly, reiteration of the steps should not be necessary. However, different DH developers may naturally use the decision-making process in a way that best suits their situation.

Step 1 – Problem description

First, a problem description must be performed in order to illustrate the issue. The following questions should be answered:

- What are the characteristics of the bottleneck area?
- What is the magnitude of the problem?
- Which is the probable cause of the bottleneck?

Step 2 – Inventory of bottleneck solutions

In the second step, an evaluation of available bottleneck solutions is to be performed. An example of a study necessary in this step is a literature study of the potential ways of regulating differential pressure in DH networks. This step will result in a list of bottleneck solutions. In

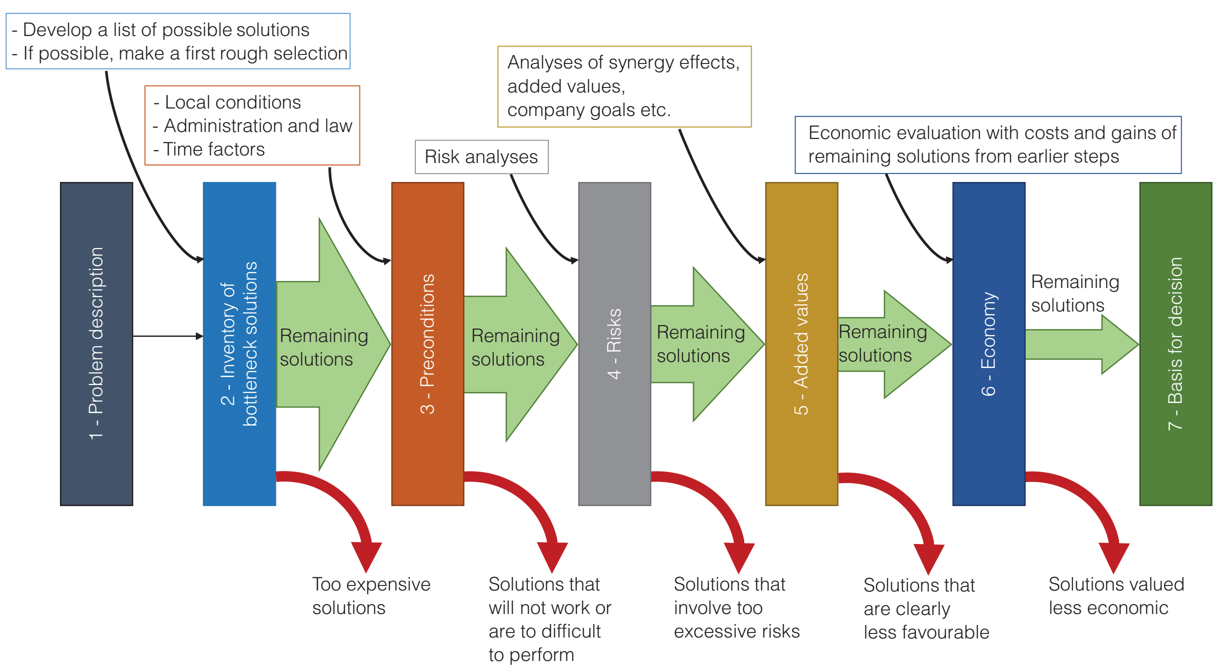

Figure 1: The proposed decision-making process for identifying the most optimal bottleneck solutions in DH networks

this step, experienced persons may already perform back-of-the-envelope economic calculations in order to reject solutions that will be too expensive. However, it is very important not to reject a solution that could turn out to be favourable. A factor in Table 2 that is particularly relevant to this step is costliness. The following questions should be answered:

- Which bottleneck solutions could theoretically be used?
- Could any of the solutions be rejected and, if so, which solutions?

Step 3 – Preconditions

In this step, the preconditions of the bottleneck area are to be investigated. Examples of such conditions include physical local conditions, administrative and legal conditions and time-bound conditions. Input data in this step include knowledge from network simulations, knowledge of the DH bottleneck area and consumers and knowledge of administrative and legal processes. In this step, all solutions which, for some reason, are not possible to implement are to be rejected. The factors in Table 2 particularly relevant to this step are swiftness and simplicity. The following question should be answered:

- Which bottleneck solutions are not possible to use as a solution for some reason (technical, legal, etc.)?

Step 4 – Risks

In this step, risk analyses and assessments are performed and bottleneck solutions with too high risks are rejected. The factors in Table 2 particularly relevant to this step are reliability, environmental outcome and no extra maintenance demand. The following question should be answered:

- Which bottleneck solutions are associated with too high risks to be used as bottleneck solutions?

Step 5 – Added values

In this step, analyses of added values are performed through, for example, network simulations, knowledge of the DH network and environmental calculations. All the added values coupled to the remaining solutions are to be considered and listed. If it is clear that some of the remaining bottleneck solutions become less favourable because of the lack of added values coupled to these solutions or the nature of the added values coupled to the other solutions, the less favourable solutions may be rejected. The factors in Table 2 that are particularly relevant to this step are additional customer interaction, environmental outcome and no extra maintenance demand. The following question should be answered:

- Which bottleneck solutions are clearly less favourable than others?

Step 6 – Economy

In the economy step, an economic evaluation of all remaining bottleneck solutions is performed. The reason why this is the last step, even though it is often regarded as the most important issue for DH developers [29], is that all information from previous steps is to be included in some way in the economic evaluation. Previous bottleneck studies namely show that there is a lack of a lifecycle perspective regarding bottleneck costs and savings [29], which could result in the most optimal bottleneck solution not being chosen. In this step, the bottleneck solutions that are too expensive are rejected. The factors in Table 2 particularly relevant to this step are no investment cost and costliness. The following questions should be answered:

- How much does each bottleneck solution cost during its lifetime, including all parameters, both costs and savings?
- Which bottleneck solutions are too expensive to implement?

Step 7 – Basis for Decision

This step marks the end of the decision-making process. There should now be sufficient information on the remaining bottleneck solutions to make an informed decision. If only one solution remains, the choice will be easy. If many solutions remain, the company will instead have to evaluate the solutions based on the information revealed earlier in the decision-making process. All factors in Table 2 are particularly relevant to this step.

3.3. Utilisation of the decision-making process in a real bottleneck case

The case results will be presented synoptically as the idea of the case description is to show an example of how the decision-making process could be used.

Step 1 – Problem description

The bottleneck area described in this case was called the Plateau. This was the area with the lowest differential pressure in the DH network and therefore the area that determined the prerequisites for many parameters in the DH system, such as pumping power and supply temperature. Over the last 10 years, new consumers have been connected in the area, which has increased the bottleneck problem. Further expansion of the Plateau and therefore also the installation of new consumers was planned for the future. In the Plateau, there were around 1250 DH consumers, many of them comprising one-family houses. There were many pipes leading to the Plateau, meaning that the Plateau was ring fed.

Step 2 – Inventory of bottleneck solutions

The bottleneck solutions investigated for this area comprised higher supply temperature, more pumping with the main pump, installation of a new distributed pump, bigger pipe area, local heat supply with a production unit or with prosumers, DSM, increased cooling at the consumers, local accumulator/accumulators and improved energy efficiency in the area. No solution was rejected in this step because there was insufficient knowledge of the solutions.

Solutions rejected: None

Step 3 – Preconditions

Solutions considered in this step: higher supply temperature, more pumping with the main pump, installation of a new, distributed pump, bigger pipe area, local heat supply with a production unit or with prosumers, DSM, increased cooling at the consumers, local accumulator/accumulators and improved energy efficiency.

It was not possible to use a higher supply temperature as a bottleneck solution because the supply temperature was already the highest possible.

It was not possible to use more pumping with the main pump as a bottleneck solution because the pump was already pumping at maximum capacity.

It was also not possible to use more pumping with a new, distributed pump as a bottleneck solution because simulations showed that this solution would be too complicated due to the many ring pipes to the Plateau. In order for the pump to increase the differential pressure sufficiently in the whole Plateau area, it would need to be located outside the Plateau. An issue with this location was that it would be very difficult, if not impossible, to be granted a permit to build a new pump station there.

A bigger pipe area could be a possible bottleneck solution in this area in the future, even though, according to the simulations, the pipe would have to be very long. The reason why this solution would have to be implemented in the future is that a permit was not granted to carry out earthworks in the streets in question in the coming few years because of street refurbishment work that has been planned for the future. There was, however, a good chance of being granted a permit to install new pipes during this refurbishment work.

Local heat supply with a production unit was a possible bottleneck solution. However, the Plateau was situated in a nature conservation area, why it was only possible to receive a temporary permit. The permit, moreover, would not apply to solid fuels due to increased transports and greater requirements for air purification coupled to this kind of heat supply unit. An electric boiler could not be installed in the Plateau due to limitations in the electric grid. A heat pump would have too low a coefficient of performance to be viable due to the high supply temperature needed. In addition, no heat sources were available for a heat pump in the Plateau. Prosumer heat sources were also not available. Simulations showed that only a small production unit could be installed due to the small size of the existing pipes. This meant that it would only be possible to install a small, gas or liquid fuel powered and temporary local heat supply unit.

DSM was a possible bottleneck solution but, according to the simulations, would not provide sufficient flow reduction in the future when new consumers would become connected to the DH network in the Plateau. This is primarily because in this area, the hourly peak heat power demand was only 10 % higher than the daily average heat power demand of the critical outdoor temperature.

More cooling at the consumers was a possible bottleneck solution but, according to simulations, it would not provide sufficient flow reduction in the future when new consumers would become connected to the DH network in the Plateau.

It was not possible to install a local accumulator or accumulators as a solution for the bottleneck problem in this area because it would be too difficult to load the accumulators. This was because of the shape of the heat demand curve.

Improved energy efficiency could be a possible bottleneck solution for this area.

Time factors important to this area were that solutions would have to be installed rather quickly in order to solve the bottleneck problem and that more extensive solutions would be needed in the future when more consumers were to become connected to the Plateau.

Solutions rejected: higher supply temperature, more pumping with the main pump, installation of a new, distributed pump, local heat supply running on solid fuel, local heat supply with prosumers, and an accumulator/accumulators.

Step 4 – Risks
Solutions considered in this step: bigger pipe area, local heat supply with a production unit running on gas or liquid fuel, DSM, increased cooling at the consumers and improved energy efficiency.

Risks associated with a bigger pipe area comprised the risk of not receiving a permit to carry out earthworks and personal safety risks when installing the pipe, particularly because of heavy traffic on the streets selected for the route of the pipe. Another important risk was the risk of the consumer base not developing as predicted.

One risk associated with local heat supply using a production unit running on gas or liquid fuel was that it was only possible to receive a temporary permit due to the Plateau being situated in a nature conservation area. Other risks included the risk for the local residents regarding noise and air pollution, increased maintenance demand, vulnerability to power failures and unfavourable environmental outcomes if the fuel would consist of fossil oil.

The main risk of DSM was that consumers would have final control of the equipment, meaning this solution could be unpredictable.

The main risk of increased cooling at the consumers, similarly to DSM, was that consumers would have final control of the equipment.

The main risk of improved energy efficiency was the control issue. However, for this solution, the energy company had no control at all of the solution, unlike for DSM and increased cooling at the consumers. All the company could do regarding improved energy efficiency was to run information campaigns.

The only risk that was deemed too large to accept was the risk of not having any control at all over the improved energy efficiency solution. This solution was therefore rejected as a bottleneck solution, but could be performed as a general strategy in the DH network. However, the uncertainty about the resulting energy savings was too significant to include possible energy savings derived from this solution in the bottleneck solution package.

Solutions rejected: improved energy efficiency
Step 5 – Added values
Solutions considered in this step: bigger pipe area, local heat supply with a production unit running on gas or liquid fuel, DSM and increased cooling at the consumers.

Some added values of a bigger pipe area was that this solution was very robust and provided the DH network with redundancy. Also, this was the only permanent solution that had the capacity to eliminate the bottleneck problem in the future, when the consumer base and the heat demand in the Plateau would increase.

One added value of local heat supply with a production unit running on gas or liquid fuel was that the fuel could be more environmentally beneficial than the existing peak fuels. Other added values were that total production capacity would increase, which would provide more peak heat capacity and therefore more redundancy in the DH network.

The added value of DSM was that this solution would increase contact with customers, which could lead to a better relationship between them and the company.

One added value of better cooling, similarly to DSM, was better customer contact. Other added values were that better cooling reduced the pumping power and created an increased yield of flue gas condensation throughout the entire year.

Solutions rejected: none
Step 6 – Economy
Solutions considered in this step: bigger pipe area, local heat supply with a production unit running on gas or liquid fuel, DSM and increased cooling at the consumers.

A new pipe area would be very expensive because a very long pipe would be required in order to solve the bottleneck problem.

A local heat supply unit would not be very expensive because of its small size. A gas powered heat supply unit would be less expensive than one running on liquid fuel due to the easily accessible gas network situated close to the heat supply location.

DSM would be favourable for the economy because it would not be a very expensive solution to install and would also generate savings coupled to the avoidance of short start-ups and stops of production units.

Increased cooling would also be favourable to the economy due to the positive effects on the DH network resulting from this solution and the fact that the company did not own the substations and would therefore not pay for any service or maintenance. For customers with a price model including a flow fee, this solution would often be economically viable because of the reduced heating costs.

Solutions rejected: local heat supply with a production unit running on liquid fuel

Step 7 – Basis for Decision

Solutions considered in this step: bigger pipe area, local heat supply with a production unit running on gas, DSM and increased cooling at the consumers.

In the basis for decision, four solutions were considered. Sooner or later the pipe area would have to be increased due to the expansion of the Plateau and the temporary permit for the local supply unit. However, economically, and in terms of knowledge of future plans, it would be better to postpone this large investment for as long as possible. In addition, it was not possible to connect a bigger pipe area immediately due to permit problems. Firstly, the company would thus improve the cooling at consumers and start up a DSM project in order to manage the current bottleneck problems. A small, temporary gas powered peak heating unit would also be installed to increase the redundancy in the Plateau and the DH network. A bigger pipe area would then be installed in the future when the other solutions were no longer sufficient to solve the bottleneck problem and the temporary peak heating unit would have to be phased out due to the temporary permit.

4 . Concluding discussion

The results describe a decision-making process regarding which DH bottleneck solution to choose. The decision-making process may also be used to choose which optimisation steps to implement. The advantages and disadvantages of different bottleneck solutions are also shown and coupled to the decision-making process. In addition, the results describe a real bottleneck case, in which the decision-making process is used to identify the most optimal solution. This is an example of how the decision-making process can be used.

This work is important because research shows that solutions with the highest potential in terms of efficiency, environmental gain and economy may be discarded if a systematic work process is not used. This could be because of the perception of DH systems as three separate systems (production, distribution and consumption) and decisions regarding which solution to choose often being made based on experience and with minimal resources being assigned to the decision-making process. Thus, the results in the present paper aim to shed light on bottleneck solutions other than conventional solutions and promote a systematised modus operandi in order to identify the most optimal bottleneck solution for a specific situation.

In the workshop discussions, it often seemed to be the case that little time and resources were dedicated to this kind of decision-making, even if there was a will and aim to conduct more thorough work and therefore be able to make more informed decisions. The proposed decision-making process helps with this issue as it presents a predetermined operating method that helps structure the work required. Thus, the work regarding how to start and perform the decision-making process can be eliminated.

Coupled to the lack of time and resources assigned to decision-making for companies, it is important for DH companies to regard this kind of work as a form of investment. It will probably lead to more suitable solutions being implemented and thus more efficient DH networks. From a broader perspective, this could lead to more efficient DH networks, with better environmental and economic outcomes, to the benefit of the entire energy system.

One interesting fact identified in the workshops is that the economic calculation is often performed as one of the first steps when choosing a bottleneck solution. In the proposed decision-making process, this is instead positioned as the last step before the decision-making. The reason for such a design is that factors other than only the direct costs of installing the solution may affect the economy and should be included in the calculation in order to make an informed decision. However, back-of-the-envelope calculations could be performed in an earlier stage in the process, although it is then important to not exclude solutions that could turn out to be favourable.

One disadvantage of the proposed decision-making process is that there is a risk of solutions being discarded too early in the process. Other disadvantages are that the decision-making process is not completely objective as it is the decision-maker who evaluates the input data, rates the solution partly quantitatively and partly qualitatively and decides which solutions should be rejected. However, the decision-making-process is thought to be a comprehensible tool that is actually going to be used by DH developers who have limited resources assigned to this kind of work. There is a risk that a more complex and complicated process will not be able to achieve this goal.

In this paper, the solutions are mainly discussed from a bottleneck solution perspective. Some of the possible solutions, for example, increased cooling at the consumers and improved energy efficiency, also form part of the long-term development strategy for DH networks. Performing these solutions as general development strategies rather than using them as a solution for a delimited bottleneck situation could be more complicated. For example, increased cooling at every consumer in a DH network could require handling larger amounts of data, thereby also creating a potential requirement for more automated processes. Improved energy efficiency in existing buildings in an entire DH network is also time-consuming and costly work. Nevertheless, such work is very important in order to decrease the system temperatures and thus achieve a more efficient DH network.

Potential future studies on DH bottlenecks include further comprehensive lifecycle cost analyses of different bottleneck solutions, as well as studies that investigate their environmental outcome. Studying the potential of lowering the supply temperature when introducing bottleneck solutions in different DH networks would also be an interesting part of the research field. Important future work would also be to validate that the decision-making process helps identify the bottleneck solution with the highest potential. This could be achieved through an extensive techno-economic evaluation of all possible bottleneck solutions or an evaluation study of real bottleneck cases in which the decision-making process is used.

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