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Optimal Phasing of District Heating Network Investments Using Multi-stage Stochastic Programming

Romain S. C. Lambert [a],*, Sebastian Maier[b], John W. Polak[c] and Nilay Shah[a]

a Centre for Process Systems Engineering, Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
b Department of Civil and Environmental Engineering and Grantham Institute – Climate Change and the Environment, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
c Centre for Transport Studies, Department of Civil and Environmental Engineering, and Urban Systems Laboratory, Imperial College London, South Kensington Campus, London SW7 2AZ, UK

ABSTRACT

Most design optimisation studies for district heating systems have focused on the optimal sizing of network assets and on the location of production units. However, the strategic value of the flexibility in phasing of the inherently modular heat networks, which is an important aspect in many feasibility studies for district heating schemes in the UK, is almost always overlooked in the scientific literature. This paper considers the sequential problem faced by a decision-maker in the phasing of long-term investments into district heating networks and their expansions. The problem is formulated as a multi-stage stochastic programme to determine the annual capital expenditure that maximises the expected net present value of the project. The optimisation approach is illustrated by applying it to the hypothetical case of the UK's Marston Vale eco town. It was found that the approach is capable of simulating the optimal growth of a network, from both a single heat source or separate islands of growth, as well as the optimal marginal expansion of an existing district heating network. The proposed approach can be used by decision makers as a framework to determine both the optimal phasing and extension of district heating networks and can be adapted simply to various, more complex real-life situations by introducing additional constraints and parameters. The versatility of the base formulation also makes it a powerful approach regardless of the size of the network and also potentially applicable to cooling networks.

Keywords:

District heating;
network expansion;
multi-stage;
phasing;

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1. Introduction

A number of optimisation based methods for the design of district heating systems have been proposed in the academic literature. These studies typically focus on the dimensioning of heat network and production assets, as well as the location of the production units, for optimal economic and environmental performance [1, 2, 3, 4, 5, 6]. Other research endeavours have looked into the question of expansion of existing district heating networks introducing metrics to assess economic viability [7] (e.g. the effective width) and making use of geographical information system (GIS) tools [8, 9, 10, 11, 12].However, one factor that is often overlooked in these studies is the stage-wise, time-dependent development and growth of heat networks. Heat networks 'phasing' is an important step in prefeasibility studies of heat networks schemes but its determination is usually not based on mathematical optimisation, so the optimality of the corresponding decisions is not guaranteed. The objective of phasing is to modulate capital outlay in order

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* Corresponding author e-mail: rl508@ic.ac.uk

to gradually develop a heat network as a function of available heat demand (the building loads that are ready for connection) and to minimize investment risk. In many UK feasibility studies, phasing typically consist of a cluster or 'seed' network and a set of future extension options for this seed network [19]. In order to improve the way in which phased investments are planned and executed, the influence of future heat demand and fuel prices uncertainties on the performances of district heating network investments might be taken into account when planning networks. Contrary to the classical net present value (NPV) approach, which treats the investment problem as if it was a now-or-never proposition, multi-stage stochastic programming [13, 14, 15, 16, 31] actively takes into consideration the possibility for the decision-makers to take recourse actions as more information about uncertain parameters becomes available. In this paper we propose the use of a simple multi-stage stochastic programming formulation for the optimal phasing of district heating networks. The type of uncertainty taken in consideration is heat demand uncertainty (whether a block of buildings will connect to the network or not) and fuel costs uncertainty which affect the production operation costs. The numerical examples demonstrate that a risk-aware decision maker investing in district heating networks under uncertainty can use this approach to determine not only the optimal growth of a network from a single heat source or separate islands of growth, but also the optimal marginal expansion of an existing district heating network.

The paper contains the following sections in addition to this Introduction: In Section 2, the overall approach to the optimal district heating network investment phasing problem is presented followed by a stochastic mixed integer linear programming formulation. In the third section, the approach is demonstrated on hypothetical case studies to illustrate different expansion patterns. Finally a discussion of the applicability, relevance and limitations of the method as well as some concluding remarks are provided in Section 4.

2. Methodology

The objective of this paper is to propose a model for the optimal phasing of district heating network investments. The emphasis of this approach is not set on the sizing of production units (e.g. gas engines) as this problem is typically a task which is carried out separately through a detailed analysis. The location of production units is not a key consideration either because this choice is often mainly driven by soft-engineering constraints, which significantly narrows down the set of available solutions. The key inputs of the optimisation problem are the annual and (diversified) peak demands of heat of blocks of buildings. These two parameters are used to estimate the network's capital and operational costs. As stated above, the capacity and capital cost of the heat sources will be considered as an input to the model. The only decision affecting these production units will be the date at which they are phased in.

In the proposed approach we use a two-step scheme. The first step performs a basic preliminary calculation of the size of the network pipe sections that minimizes capital cost and heat losses. The output of this first step is then used within the phasing problem, which determines the optimal key stages of development of the heat network. In order to address the problem of heat demand and fuel price uncertainty, the model is formulated as a multi-stage stochastic programming problem. Stochastic programming has been used to optimise investment under uncertainty of energy systems and infrastructures [13, 14, 15]. Unlike deterministic optimisation, stochastic programming can solve optimisation problems featuring uncertain parameters. As it is not possible to have access to the value of uncertain parameters (for instance future fuel prices or future heat demand), stochastic programmes are formulated to yield solutions that are feasible over a range of predefined scenarios (often discrete and portraying probability distributions) and which maximise the mathematical expectation of a cost function over a range of parametric realizations. A typical class of stochastic programming problems is that of multi-stage formulations [16] which are typically used to schedule investment decisions under uncertainty over some finite planning horizon.

In this paper we use a simple scenario-based formulation for combinations of heat demand and fuel price uncertainty scenarios. The possible effects of these two kinds of uncertainty are modelled through the use of a set of discrete scenarios based on forecasts from the UK's Department of Energy and Climate Change (DECC) [17]. The objective of the stochastic formulation will be to provide the best non regret phasing solution under uncertainty. In the following section, we present the equations defining the optimisation problem for each step.

2.1. Nomenclature

Here the notations used for the model description are listed:

Sets and indices:

$\mathcal{N}$	Set of candidate nodes
$\mathcal{P}$	Set describing the periods of the finite investment horizon
Ω	Set of possible (demand) scenarios
ε	Set of edges
r	Index of pipe diameters

Parameters:

C^{r}_{diam}	Cost per unit of length of laying a pipe of diameter r (£)
HeatlLosses$_{r}$	Heat losses per unit of length for a pipe of diameter r (W/m)
$C_{p,water}$	Water heat mass capacity (J/Kg.K)
ρ	Density of water (kg/m3)
$\lVert i,j \rVert$	Euclidian distance between nodes i and j (m)
PeakDemand$_{i}$	Peak heat demand for node i (MW)
ΔT_{peak}	Difference between forward and return temperature at peak load. (°C)
A	Adjacency matrix of the unoriented graph ($\mathcal{N}$, ε)
σ	Cost of building a pipe per unit of length (£/m)
HeatDemand$_{i,t,m}$	Heat demand at node i at time period t and in scenario m (MWh)
Heatprice$_{t,m}$	Heat sale price at time period t and in scenario m (£)
HeatLosses$_{i,j}$	Heat losses per unit of length for the pipe between nodes i and j (W/m)
BoilerProductionCosts$_{t.m}$	Boiler heat production cost at time period t and in scenario m (£)
WasteHeatPrice$_{t,m}$	Price of waste heat at time period t and in scenario m (£/KWh)
Availability$_{i,t}$	Binary parameter stating whether building i can be connected to the network at time t (equal to 0 if building is available for connection at time t)
NetworkCapexBudget$_{t}$	Maximum annual network investment budget (£)
MaximumBoilerOutput$_{i}$	Maximum annual load that boiler at location i can provide (MWh)
MaximumWHAnnualOutput$_{i}$	Maximum annual load that waste heat source at location i can provide (MWh)
MinLoadWasteHeat	Minimum annual load at which connection to waste heat source is feasible (MWh)
NetworkAssetLifetime	Lifetime of network assets, assumed longer than economic lifetime (years)
M	An arbitrarily large positive real number
i_{m}	Discount rate in scenario

Continuous variables:

$F_{i,j}$	Flow of heat at peak load between nodes i and j (MWh)
$v_{max,r}$	Maximum velocity of fluid in pipe of diameter r (m/s)
$\Delta P_{max,r}$	Maximum pressure drop of fluid in pipe of diameter r (Pa/m)
Re	Reynolds number
$v_{i,j}$	Velocity of water in pipe between nodes i and j (m/s)
$\Delta P_{i,j,r}$	Pressure drop in pipe of diameter r between nodes i and j (Pa/m)
$f_{i,j,r}$	Fannings friction factor for pipe of diameter r between nodes i and j
$R_{t,m}$	Revenue for period t and in scenario m (£)
$C^{net}_{t,m}$	Network costs (capital and operating) at time period t and in scenario m (£)

$\text{HeatRevenue}_{i,t,m}$	Heat revenue for node i at time period t and in scenario m (£)
$C^{repex,acc}_{t,m}$	Sum of all outgoing replacement costs at time period t and in scenario m (£)
$C^{repex}_{t,m}$	Anticipated annual replacement costs resulting from investments at time period t and in scenario m (£)
$C^{pr}_{t,m}$	Production costs (capital and operational) at time period t and in scenario m (£)
$Q_{i,t,m}$	Heat production for node i at time period t and in scenario m (MWh)
$Q^{boiler}_{i,t,m}$	Boiler heat production for node i at time period t and in scenario m (MWh)
$Q^{WH}_{i,t,m}$	Waste heat production for node i at time period t and in scenario m (MWh)

Binary variables:

$d_{i,j,r}$	Binary variable equal to 1 if nodes i and j are connected by a pipe of diameter r
$\forall i \in \mathcal{N}, t \in \mathcal{P}, m \in \Omega, N_{i,t,m}$	Binary variable taking the value 1 if node i is connected at time t in scenario m
$\forall i \in \mathcal{N}, t \in \mathcal{P}, m \in \Omega, \bar{P}_{i,t,m}$	Binary variable taking the value 1 if a plant is built on node i and connected at time t in scenario m
$\forall i \in \mathcal{N}, t \in \mathcal{P}, m \in \Omega, P_{i,t,m}$	Binary variable taking the value 1 if a plant *exists* at node i and is connected at time t in scenario m
$\forall i \in \mathcal{N}, t \in \mathcal{P}, m \in \Omega, E_{ij,t,m}$	Binary variable indicating whether node i and j are linked by a pipe with flow from i to j in period t and scenario m
$\forall i \in \mathcal{N}, t \in \mathcal{P}, m \in \Omega, \bar{E}_{ij,t,m}$	Binary variable indicating whether a pipe is built between node i and j with flow from i to j in period t and scenario m
$WH_{i,t,m}$	Binary variable representing existence of waste heat supply at location i time period t and in scenario m
$\overline{WH}_{i,t,m}$	Binary variable representing introduction of waste heat supply at location i at time period t and in scenario m

2.2. Built-out network sizing

In this section, we present the problem of optimal sizing of the heat network. This optimisation problem is similar to previous work in the literature [1]. It is presented here for completeness although it is not the main focus of this paper.

In this problem, it is assumed that the network is fully built out: All the building loads have been connected and appropriate heat sources are available at predefined locations with a predefined capacity. The network is designed under steady state diversified peak conditions to determine the sizing of the pipes. In order to avoid any redundancy with the second stage, we only consider a cost minimization problem.

$$z = c^{capex}_{network} = \sum_{l \in \varepsilon} \sum_{r \in R} d_{i,j,r} \cdot C^{r}_{diam} \cdot \|i, j\| \tag{1}$$

The capital cost of the heat network depends both on the length of the pipes and their diameter. A constraint is added to signify that only one diameter can be chosen for each pipe:

$$\sum_{r \in R} d_{i,j,r} \leq 1 \tag{2}$$

$$d_{i,j,r} + d_{j,i,r} = 1 \tag{3}$$

The fully built out network must respect the city layout (i.e. the adjacency matrix):

$$d_{i,j,r} \leq A_{i,j} \tag{4}$$

The flow of heat at each node depends on heat production and heat consumption at this node, as well as the heat losses:

$$\forall i, j, \in N, \sum_{j \in N} F_{i,j} - d_{i,j,r} \cdot \|i, j\| \cdot \text{HeatlLosses}_r \cdot = \sum_{j \in N} F_{j,i} + Q_i - \text{DiversifiedPeakDemand}_i \tag{5}$$

Hydraulic constraints:

The velocity of water in any given pipe is related to the diameter of the pipes as well as the heat flow:

$$\rho C_{p,water} v_l \cdot \Delta T_{peak} \cdot \pi r^2 \geq 4F_{i,j} - M(1 - d_{i,j,r}) \tag{6}$$

The water velocity is constrained according to engineering parameters for each diameter:

$$v_{i,j} \leq v_{max,r} + M(1 - d_{i,j,r}) \tag{7}$$

Maximum pressure drops are also taken into account according to diameter-dependent constraints:

$$k_r v_{i,j} - M(1 - d_{i,j,r}) \leq \Delta p_{max.r} \tag{8}$$

,where k_r is a linear coefficient relating pressure drops and velocity according to the Fanning's factor:

$$\Delta p_{i,j,r} = \frac{\rho f_{i,j,r} v_{i.j^2}}{2r} \tag{9}$$

where $f_{i,j,r}$ the Fanning's friction factor is approximated by the Haanland equation [19]:

$$f_{i,j,r} = \left[1.8 \cdot \log_{10} \left(\frac{6.9}{Re} + \left(\frac{\frac{k}{r}}{3.7} \right)^{1.11} \right) \right]^{-2} \tag{10}$$

Contrary to the work in [1], we only consider the minimizing of capital costs of the heat network. Note that this step could be replaced by more detailed hydraulic analyses, such as the ones typically conducted in feasibility studies. Its only purpose is to provide a basic estimate as input data for the phasing stage, since most of the network costs consist of civil-engineering and site development/planning costs rather than the cost of the pipes. Because uncertainty is considered in the second stage, estimates of network costs are deemed sufficient as a basic input.

2.3. Optimal phasing problem formulation

In this section, a formulation of the optimal network phasing problem is presented. The basic starting elements are a set of candidate "end-user" nodes to be connected and a set of allowable pipes (edges) and associated costs between these nodes. The edges correspond to possible routes for the district heating pipes, which are usually constrained by the city layout. These edges are assigned with a capital cost linked to the distances and size pipe.

Objective function

The objective function defines a multi-period calculation of the expected discounted cash flows of the district heating system:

$$\Theta = \sum_{t \in P} \sum_{m \in \Omega} \omega(m) \cdot \frac{CF_{t,m}}{(1 + i_m)^t} \tag{11}$$

This function consists of the probability weighted sum of discounted cash flows for all considered scenarios. The cash flows are composed of the sum of revenues from heat sales on the one hand and capital expenditure (capex) and operational expenditure (opex) on the other hand:

$$CF_{t,m} = R_{t,m} - C_{t,m}^{network,capex} - C_{t,m}^{production,capex} - C_{t,m}^{production,opex} - C_{t,m}^{repex,acc} \tag{12}$$

Revenues are the sum of heat sales for all the areas connected to the district heating network:

$$R_{t,m} = 0.95 \sum_{i \in N} N_{i,t,m} \text{HeatRevenue}_{i,t,m} \tag{13}$$

The coefficient of 0.95 accounts for 5% overhead administrative expenses. This is assumed without loss of generality, although this figure will be case-dependent. For a particular node, the heat revenue is the product of the heat demand and the heat price.

$$\text{HeatRevenue}_{i,t,m} = \text{HeatDemand}_{i,t,m} \ \text{HeatPrice}_t \tag{14}$$

The heat price is a constrained decision variable for the planners. In the UK, local authorities might assign different prices depending on the type of customer (e.g. social residential housing or commercial) [19]. The costs consist of the sum of capital costs and operational costs for both production and distribution (the network). Network costs in this model mainly consist of a conservative estimate of civil engineering works, estimated in the first step and which are linearly dependent on the distance.

$$C_{t,m}^{network,capex} = \sum_{i \in N} \sum_{j \in N} \text{PipeCost}_{i,j} \left(\bar{E}_{i,j,t,m} + \bar{E}_{j,i,t,m} \right) \tag{15}$$

In addition, we consider the situation in which an annual budget constraint determines the maximum capital outlay for network expansions:

$$\sum_{t\in P} C^{network,capex}_{t,m} \le \text{NetworkCapexBudget} \qquad (16)$$

Production costs consist of the capital costs to install a new production unit, $C^{production,capex}_{t,m}$ as well as maintenance and fuel costs:

$$C^{production,opex}_{i,t,m} = \text{BoilerProductionCosts}_{t,m}\; Q^{Boiler}_{i,t,m} + \text{WasteHeatPrice}_{t,m} \cdot Q^{WH}_{i,t,m} \qquad (17)$$

Anticipated future replacements costs are also taken into consideration: For a particular year t capital outlay, an annual replacement cost is calculated for future anticipated replacements costs and expenses related to this particular capital outlay:

$$C^{repex}_{t,m} = \frac{C^{network.capex}_{t,m}}{\text{NetworkAssetLifetime}}\left(+ \frac{C^{production.capex}_{t,m}}{\text{ProdAssetLifetime}} \right) \qquad (18)$$

For a given year t, the total replacement expense for all past capital investment outlays is calculated as:

$$C^{repex,acc}_{t_1,m} = \sum_{t\le t_1} C^{repex}_{t,m} \qquad (19)$$

Topology Constraints

Topology constraints consist of rules defining the way a network can be built, taking into account the city layout that stems from a given land-use.

Firstly, the potential existence of a pipe between two nodes implies these nodes are connected to the network, potentially as consumers or producers (unless they are intersection 'dummy' nodes with no heat production or demand):

$$\forall i,j \in N, t \in \mathscr{P}, m \in \Omega, E_{i,j,t,m} \le N_{i,t,m} \qquad (20)$$

$$\forall i,j \in N, t \in \mathscr{P}, m \in \Omega, E_{i,j,t,m} \le N_{j,t,m} \qquad (21)$$

Secondly, pipes can only exist in line with the city layout which is defined by the set of the allowable connections between nodes as defined by the adjacency matrix:

$$\forall i,j \in N, t \in \mathscr{P}, m \in \Omega, E_{i,j,t,m} \le A_{i,j} \qquad (22)$$

Similarly, a set of allowable plant locations is also defined for heat production.

$$\forall i, \in N, t \in \mathscr{P}, m \in \Omega, P_{i,t,m} \le y_i \qquad (23)$$

Although plant location is considered, in this paper, plant locations are not a key optimisation variable. Previous studies [1, 3, 4] have taken into account the optimal locations of plants to minimize operating costs. Although plant location does have an influence, its choice is usually constrained by the availability of a hosting site or land area as well as other soft-engineering constraints. Another rule-of-thumb will dictate that production units should be placed near large anchor loads to minimize heat losses. In our problem formulation, we consider binary variables defining the existence of pipes and the direction of heat flow in each pipe. For the calculation of the net peak heat flow the following constraint is imposed:

$$E_{i,j,t,m} + E_{j,i,t,m} \le 1 \qquad (24)$$

This will ensure that only a positive net heat flow is considered to represent the steady state of the heat network. Note that this does not exclude the possibility of having bidirectional flows under different heat load conditions (for example when during periods of lower heat demand) but only represents an annual aggregate flow.

Similarly, binary variables are defined for the construction of these pipes whose purpose is not to represent the existence at any given date, but the date at which they are built.

$$\bar{E}_{i,j,t,m} + \bar{E}_{j,i,t,m} \le 1 \qquad (25)$$

Chronology constraints

Chronology constraints concern the earliest connection dates for each cluster of demand:

$$\forall i \in N, t \in \mathrm{P}, m \in \Omega, N_{i,t,m} \le \left(1 - \text{EarliestConnection}_{\mathrm{l,t}}\right) \qquad (26)$$

Another chronology constraint states that a plant or a network section can only be built once:

$$\forall i \in N, m \in \Omega, \sum_{t \in \mathscr{P}} \bar{P}_{i,t,m} \leq 1 \tag{27}$$

$$\forall i, j \in N, t \in \mathscr{P}, m \in \Omega, \sum_{t \in \mathscr{P}} \bar{E}_{i,j,t,m} \leq 1 \tag{28}$$

Finally, construction constraints state that if an edge or a plant exists at time *t*, it has to have been built in one of the preceding periods $t_1 \in \{1, 2, \ldots, t-1\}$.

$$\forall i, j \in N, t \in \mathscr{P}, m \in \Omega, -\bar{E}_{i,j,t,m} + \sum_{t_1 \in \mathscr{P}, t_{1 \leq} t} \bar{E}_{i,j,t_1,m} \geq 0 \tag{29}$$

$$\forall i \in N, t \in \mathscr{P}, m \in \Omega, -P_{i,t,m} + \sum_{t_1 \in \mathscr{P}, t_{1 \leq} t} \bar{P}_{i,t_1,m} \geq 0 \tag{30}$$

Physical Constraints

In this model, physical constraints mainly consist of energy balances for each node of the heat network. The sum of inlet flows is equal to the sum of outlet flows, heat production at the node minus the energy consumed by the node:

$$\forall i, j \in N, t \in \mathrm{P}, m \in \Omega, \sum_{j \in N} F_{i,j,t,m} - \mathrm{HeatLosses}_{i,j} \|i, j\| \cdot E_{i,j} = \sum_{j \in N} F_{j,i,t,m} + Q_{i,t,m} + \mathrm{HeatDemand}_{i,t,m} N \tag{31}$$

In these constraints, specific heat losses per meter for each network section are taken into account. These depend on the diameter of the pipes in that specific section. To relate network section existence binary variables to the existence of a non-zero heat flow, some additional constraints are formulated. This '*big-M*' [4] constraints state that if a flow exists between nodes *i* and *j*, then pipes must exist at these locations:

$$\forall i, j \in N, t \in \mathscr{P}, m \in \Omega, ME_{i,j,t,m} \geq F_{i,j,t,m} \tag{32}$$

Similarly, if heat is produced at node *i* then it implies that node *i* is a plant site.

$$\forall i \in N, t \in \mathscr{P}, m \in \Omega, M.P_{i,t,m} \geq Q_{i,t,m} \tag{33}$$

Note that plant locations are also restricted to selected nodes that are available to host the plant:

$$\forall i \in N, t \in \mathscr{P}, m \in \Omega, P_{i,t,m} \leq \mathrm{ProductionLocation}_i \tag{34}$$

The relative contribution of waste and peak boilers heat at a certain production location is described in the following constraint:

$$Q_{i,t,m} = Q_{i,t,m}^{WH} + Q_{i,t,m}^{Boiler} \tag{35}$$

Both boilers and waste heat sources will be constrained by their maximum annual output, which is the maximum annual amount of heat that can be supplied by a given plant:

$$Q_{i,t,m}^{Boiler} \leq \mathrm{MaximumBoilerOutput}_i \tag{36}$$

$$Q_{i,t,m}^{WH} \leq \mathrm{MaximumWHAnnualOutput}_i \tag{37}$$

Another 'big-M' constraint is used to relate the existence of a waste heat recovery facility or plant to the production of waste heat at a given node *i*:

$$M \cdot \overline{WH}_{i,t,m} \leq Q_{i,t,m}^{WH} \tag{38}$$

Similarly to network trenches sections and production nodes, binary variables are used to represent both the existence and the decision to build or put in place a waste heat recovery facility:

$$\sum_{t \in \mathscr{P}} \overline{WH}_{i,t,m} \leq 1 \tag{39}$$

Another constraint is formulated to cap the proportion of heat that can be supplied from the waste heat sources:

$$\sum_{t \in \mathscr{P}} Q_{i,t,m}^{WH} \leq \alpha \sum_{t \in \mathscr{P}} Q_{i,t,m} \tag{40}$$

This equation relates to the fact that the waste heat, having a lower cost than "heat-only" boiler heat, will serve as a base load for the district heating system and that its limited annual output will entail topping up the heat production with "heat -only" boilers during peak demand. The coefficient α represents the maximum proportion of the load that can be provided by waste heat. This relative proportion between the two different types of heat sources will be determined separately based on an analysis of the load duration curve of the system. In this paper, however, it is considered as an input to the optimisation model. A constraint to restrict the introduction of a waste heat source recovery facility is presented below. This constraint states that a waste heat facility may only be introduced if a sufficient heat demand justifies it. This reflects the typical situation of UK district heating schemes where risk-averse local authorities will kick-start a seed network with "heat-only" boilers and introduce more expensive heat production units (such as CHP plants) only when sufficient heat demand is secured. This phasing approach is typically used by local authorities in the UK (see e.g. [19]) and its purpose is to minimize risk of capital outlay while facing uncertain demand.

$$Q_{i,t,m}^{WH} \geq \text{MinLoadWasteHeat} - M\left(1 - \overline{\text{WH}}_{i,t,m}\right) \quad (41)$$

Similarly to previous constraints, the following constraint relates to the existence of a waste recovery facility at time *t* to its introduction in a previous time period:

$$\forall i \in N, t \in \mathcal{P}, m \in \Omega, -WH_{i,t,m} + \sum_{t_1 \in \mathcal{P}, t_{1\leq} t} \overline{WH}_{i,t,m} \geq 0 \quad (42)$$

Non-anticipativity constraints

Non-anticipativity constraints are used to link the variables of the set of scenarios into a set of initial decision steps. This step will therefore be the best 'no-regret' decision for all scenarios considered. These constraints are applied to the binary variables which define production and consumer nodes, pipes and flows. Until uncertainty is revealed at time *T*, it is necessary to use a conservative approach that will be the best decision on average for all of the considered scenarios.

$$\forall i \in N, m \in \Omega, t \leq T, P_{i,t,m} = P_{i,t,m'} \quad (43)$$

$$\forall i \in N, m \in \Omega, t \leq T, N_{i,t,m} = N_{i,t,m'} \quad (44)$$

$$\forall i, j \in N, m \in \Omega, t \leq T, E_{i,j,t,m} = E_{i,j,t,m'} \quad (45)$$

$$\forall i, j \in N, m \in \Omega, t \leq T, \bar{E}_{i,j,1t,m} = \bar{E}_{i,j,t,m'} \quad (46)$$

$$\forall i \in N, m \in \Omega, t \leq T, Q_{i,t,m} = Q_{i,t,m'} \quad (47)$$

$$\forall i, j \in N, m \in \Omega, t \leq T, F_{i,j,t,m} = F_{i,j,t,m'} \quad (48)$$

$$\forall i, j \in N, m \in \Omega, t \leq T, \overline{WH}_{i,j,t,m} = \overline{WH}_{i,j,t,m'} \quad (49)$$

$$\forall i, j \in N, m \in \Omega, t \leq T, WH_{i,j,t,m} = WH_{i,j,t,m'} \quad (50)$$

In the following sections, our optimisation model is applied to hypothetical examples representing simplified typical urban situations.

3. Numerical Examples

In this section, the optimal phasing model is applied to theoretical examples. The assumptions for the different examples are presented in the next paragraph. Two situations will be considered: the development of a network from a single energy centre (or plant location) and the expansion of the network from initially isolated islands of growth. The influence of discount rates on the expansion patterns will also be presented.

3.1. Modelling Assumptions

- The peak demand is an input to the model and is assumed to be diversified. The calculation of the diversified peak demand from the peak demand of buildings will usually require an in-depth analysis of the various types of loads to be connected to the district heating network and the proportion of heat demand between space heating and hot water preparation The capital costs for the waste heat recovery system are assumed to be calculated separately. This is justified by the fact that the cost calculation of such a facility is case dependent and that the complexity of the financial evaluation cannot be accurately represented in the optimisation model.

- In this numerical example, we consider a UK baseline situation where natural gas is a prevalent fuel. A more realistic setting would consider the evolution of the national energy system and the possible introduction of competitive sources of heat, requiring specific calculation for the capital costs of production but this is not the object of this paper.
- This also avoids any loss of generality since the waste heat sources can be of a different nature such as industrial residual heat, waste heat from incinerators or from power stations etc. In the island growth case, it is assumed that gas boilers are pre-existent (typically associated to anchor loads) and that their over-capacity can be used to supply neighbouring loads for the early phasing stages of the seed network.
- One single price of heat is applied to all buildings and there is no differentiation by type of customer. This is a simplification: in Sweden, for example, various pricing mechanisms and tariffs are usually in place. Lower variable prices of heat are offered if the customer pays for the full cost of the connection to the building. More tariffs are being introduced by district heating companies in order to move from a 'one-size-fits-all' business model to a better value proposition in order to overcome stagnation. In the UK, in order to fight fuel poverty, local authorities differentiate between social housing and private buildings. In this example, a typical 2% annual increase is assumed, although it would be possible to choose to index the price of heat to the cost of individual boilers heating.
- In this study the equivalent utilisation period at peak demand for heat production is set to 870 hours. It is assumed that the waste heat source cannot supply more than 90% of required annual supplied heat.
- Location of production units is assumed a priori since it is in practice mainly determined by soft engineering constraints and an arbitrary set of plant node locations has been selected.
- Because accurate pumping costs are difficult to estimate and depend on complex hydraulic calculations, they are overestimated and included in the calculation of network trench costs. In this study, the costs of network sections are only indicative and their accurate calculation is not the subject of this paper and may be disregarded without loss of generality.
- Here we consider two different types of uncertainties. The first one is associated with the uncertain availability of several areas of heat demand represented by nodes: One area/building decides upon whether to connect to the network or not. In the case of a larger district heating scheme, the willingness of the buildings owners to connect will determine whether a district heating network section can be built in this area. The second type of uncertainty is that of gas prices, which are represented through a discrete set of gas price projections.
- In this study, the economic horizon for the calculation of the discounted cash flows is set to twenty years. It is assumed that the lifetime of network assets is higher and is set to 40 years (needed for the replacement cost calculations). The lifetime of the production facilities is set to 20 years.
- The cost of waste heat is assumed to equal half of the marginal cost of heat, which is based on the price of natural gas to reflect the current UK situation. The cost of waste heat will often depend on opportunity costs for the entity that supplies it. In the case of a waste incinerator, for example, it could be based on electricity that could have been supplied using the facilities' turbines, and the calculation will relate to the Z-factor of the facility (the Z-factor relates to the decrease of efficiency of electricity production for each additional unit of heat produced; consequently, the Z-factor can be used as an estimation of the opportunity cost of supplying heat rather than electricity).

3.2. Problem description

In this section some results are presented mainly to illustrate the various kinds of situations the optimisation model can address. In this paper we consider a topology consisting of both nodes and edges, which are represented by an adjacency matrix. The topology used in this paper is that of the proposed UK eco town of Marston Vale, which has been used to illustrate spatial modelling and optimisation models in other publications [4,6]. In this paper the topology of Marston vale is used for the sole purpose of illustrating the nature of results that can be generated by the proposed optimisation approach. The results presented below are case and parameter dependent and are not meant to represent an actual assessment of the real town.

Assigning heat demand to the 47 considered nodes, the cost minimization model of Section 2.2 is used to generate estimates for both pipe sizes and costs of the various network trenches. In Figure 3 it can be seen that oversizing some trenches (the main ‘artery’ of the network in Figure 3) is necessary to allow for possible future linking of separate island networks. Recall that this sizing is based on basic hydraulic calculations and merely an indicative input to the phasing optimisation problem.

In this example it is considered that a certain number of nodes may or may not connect in the future. It is therefore important to put in place a phasing strategy that will account for this uncertainty. The combination of future connection uncertainty and the uncertainty of future gas prices (four scenarios) is represented by a set of 16 scenarios (4 scenarios of gas price projection multiplied by 4 scenarios of heat demand). Each price projection scenario corresponds to a forecast of the UK’s department of energy and climate change [17].

The heat demand scenarios are constructed as follows: We consider a hypothetical situation in which two new developments (nodes) may or may not connect to the district heating network. The probability of connection is not known and assumed to be 50%. The connection uncertainty is revealed in year 4, which means planners have to take decisions that accommodate both outcomes for each development (the event of a connection for each node is independent of the other). Therefore four heat demand scenarios for the district heat network are constructed corresponding to the following situations: both uncertain nodes, only one of the two uncertain nodes, or none of the uncertain nodes decide to connect after year 4.

Another relevant situation, yet not treated in this numerical example is the case of continuous heat demand uncertainty. This type of uncertainty arises, for example, from inaccuracies in the estimation of heat demand profiles in a particular area comprising a large number of buildings, or the uncertainty of future (mainly space heating) demand resulting from efficiency gains of retrofitted buildings. In this case, a range of discrete scenarios would be created representing the estimated range of uncertainty of a set of anticipated trends (e.g. baseline, high level of refurbishment, medium level of refurbishment).

We illustrate the types of situations that can be examined using the proposed optimisation problem. Figures 4 and 5 show the two different expansion patterns: phasing from a single source of heat and phasing from separate islands of growth eventually linking into one single network in order to share access

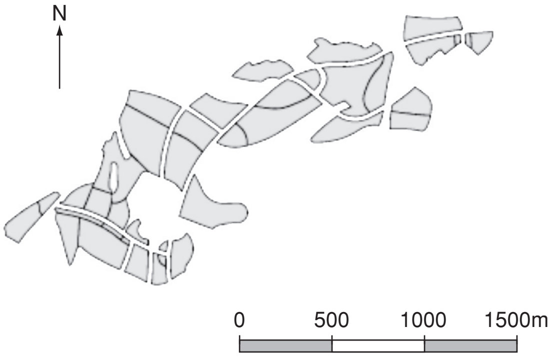

Figure 1: The city-layout of the Marston-Vale hypothetical case study.

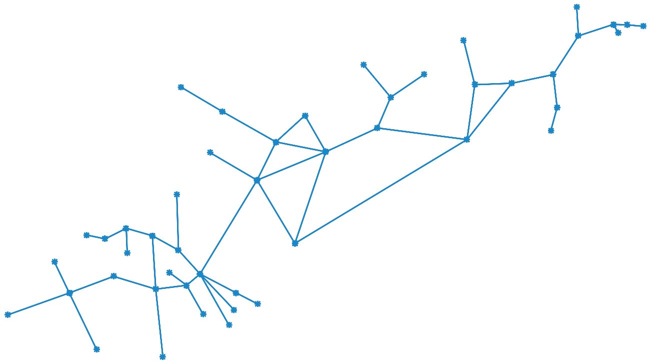

Figure 2: Topology of the city layout showing candidate end user nodes and allowable edges.

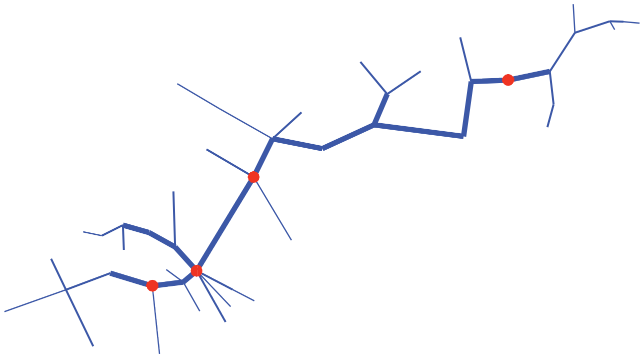

Figure 3: Pipe sizes for the district heating scheme. The required sizes for the different pipes are indicated on the blue edges. The red circles correspond to potential production sites.

to a waste heat source, respectively. These types of development patterns apply to district energy schemes of different sizes. It is important to note that it could also be used for district cooling applications; in which case, gas boilers would be replaced by absorption or compression chillers whereas free cooling sources (e.g. water bodies) would be considered to be the base-load of the scheme. Since a set of scenarios is considered, the evolution shown in Figures 4 and 5 display one possible outcome in the case of one of the considered scenarios. The first four steps of the evolution will be the same for all the scenarios as a result of the use of non-anticipativity constraints. The later stages (i.e. for the years 10 to 20) will be specific to the represented scenario and, for the sake of simplicity, the corresponding expansion strategies are not shown here. However, while none of the scenarios will exactly describe the future development, the optimisation over their expected value will allow for the anticipation of future possible outcomes, when assuming that the scenarios are sufficiently representative of possible future events.

In Figures 6 to 8, the influence of discount rates is displayed. The selected discount rates of 2%, 4.5% and 10% represent typical values for public companies, public-private partnership and private companies, respectively. The evolution of both annual heat flows and heat production output illustrate the stage-wise growth patterns of the considered heat network. This is in contrast to methodologies used in typical UK feasibility studies where expansions are determined a priori before the net present value (NPV) calculations are performed. In Figure 9 the corresponding investments and operation expenses of the cash flows are displayed. As expected, the importance of future cash flows decreases with an increase of discount rates. In that case, short term cash flows are prioritized. When maximising the expected NPV, the optimal solution will consist of expansion decisions that provide comparatively lower cash-flows in the longer term, but higher ones in the near term, thus compensating for decrease in future revenues. This is accompanied by a higher risk in the underlying cash flows due to the more aggressive expansion. In this case the NPV distribution across all scenarios tends to becomes more “fat tailed” with lower expected values, and a larger proportion of scenarios tends to be less favourable. In Figures 6 to 8 it can be observed that in the case of incremental investment into network expansion the discount rate has a strong influence on the growth patterns of the heat network, despite exhibiting a broadly similar final configuration. In other words, contrary to classical NPV analysis, variations in the required

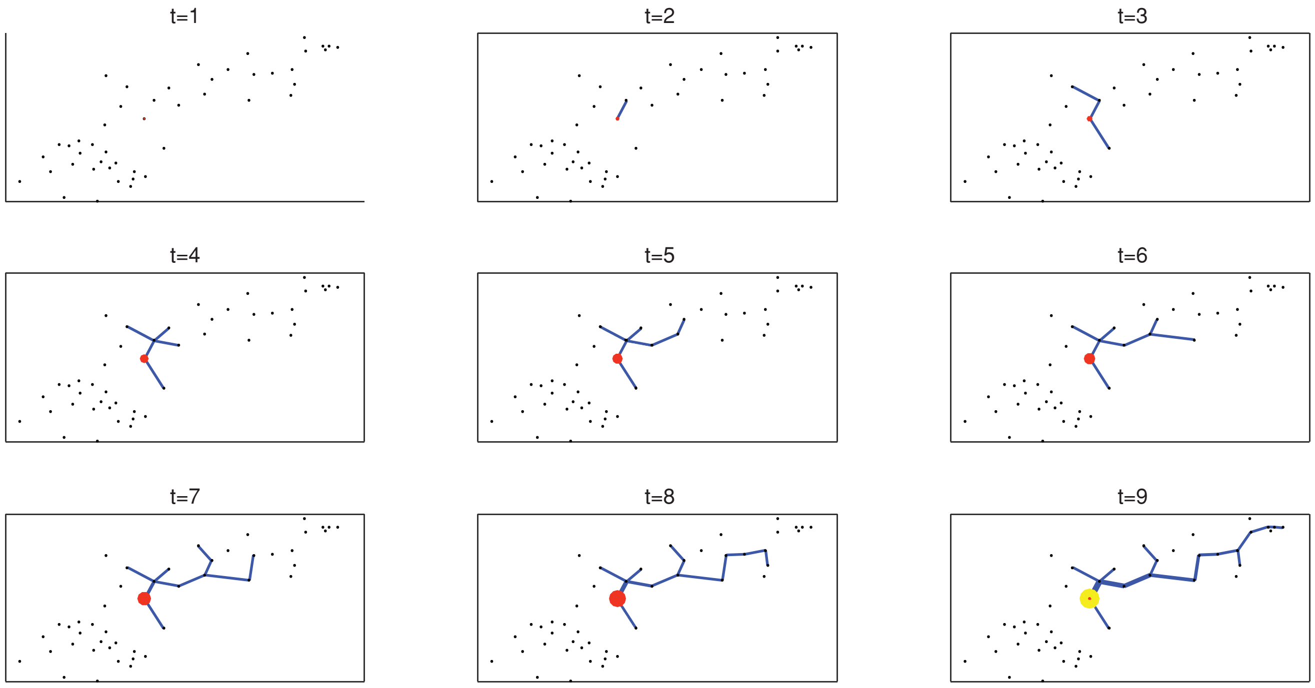

Figure 4: Optimal phasing from a single heat source location showing expansion from year 1 to year 9.

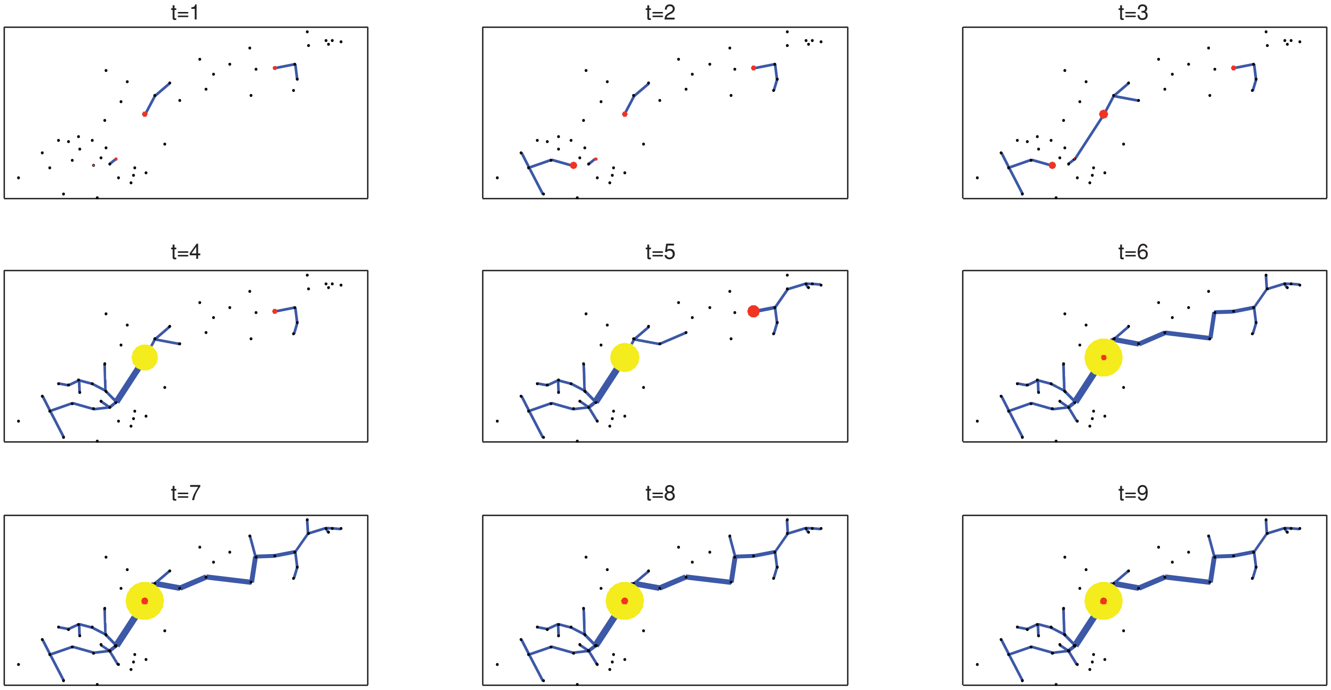

Figure 5: Optimal phasing from separate islands of growth gradually expanding and linking to capture waste heat (at a discount rate of 4.5%)

discount rate do not only result in the decreasing importance of net cash flows and postponement of predetermined investments over the time horizons, but also alter the scheduling of the discrete investment decisions. In the simple formulation presented in this paper, the range of solutions consists of an incremental network expansion, combined with an incremental increase of heat production and phasing of production assets. The advantage of simultaneously addressing annual heat production growth and network expansion lies in the fact that the phasing of additional production facilities is justified by the corresponding increase of the annual heat demand for the district heating scheme. Investments in new production assets are therefore directly commensurate to heat demand and not an arbitrary threshold. Clearly, the use of a stochastic formulation also allows for an adequate consideration of risks when sufficiently representative scenarios are used.

In classical Net present value analysis, the calculation of discounted cash flows is performed considering a fixed investment plan and predefined investment decisions. In the example situations shown in this paper, the NPV is maximised by the optimal choice of investment decisions. Since the investment decisions, due to the modularity of district heating development, produce different cash flows, that have an influence on network profitability, it can be seen that different discount rates will produce different expansion patterns.

4. Concluding Remarks

In this section, the relevance and applicability of the presented optimisation of district heating phasing are discussed.

The aim of the optimisation formulation and numerical example was to illustrate the usefulness of the method to determine the incremental, optimal evolution of heat networks in various cases: from a single source to separate islands of growth as well as expansion of an existing district heating network. Because of the simple formulation of the optimisation problem, it can easily be applied to schemes of various sizes and to district cooling networks. Large district heating systems typical to Scandinavia, could use a

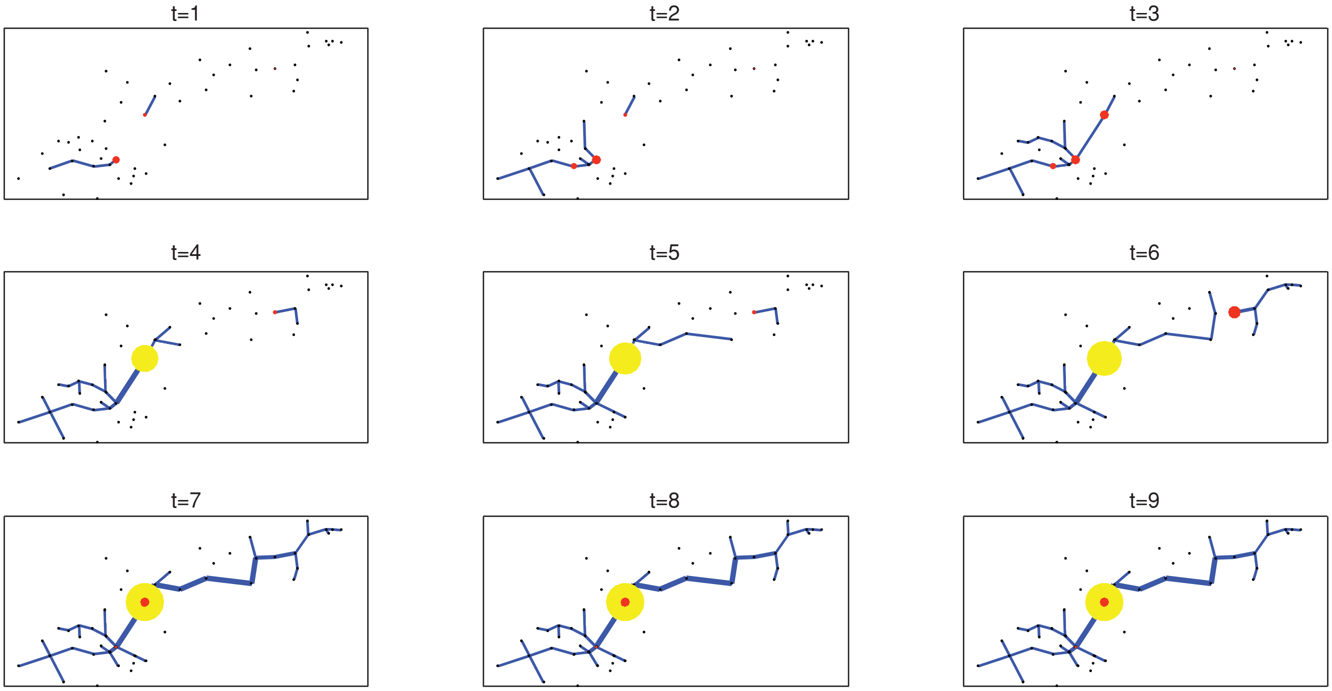

Figure 6: Islands of growth expansion with a discount rate of 2.5%

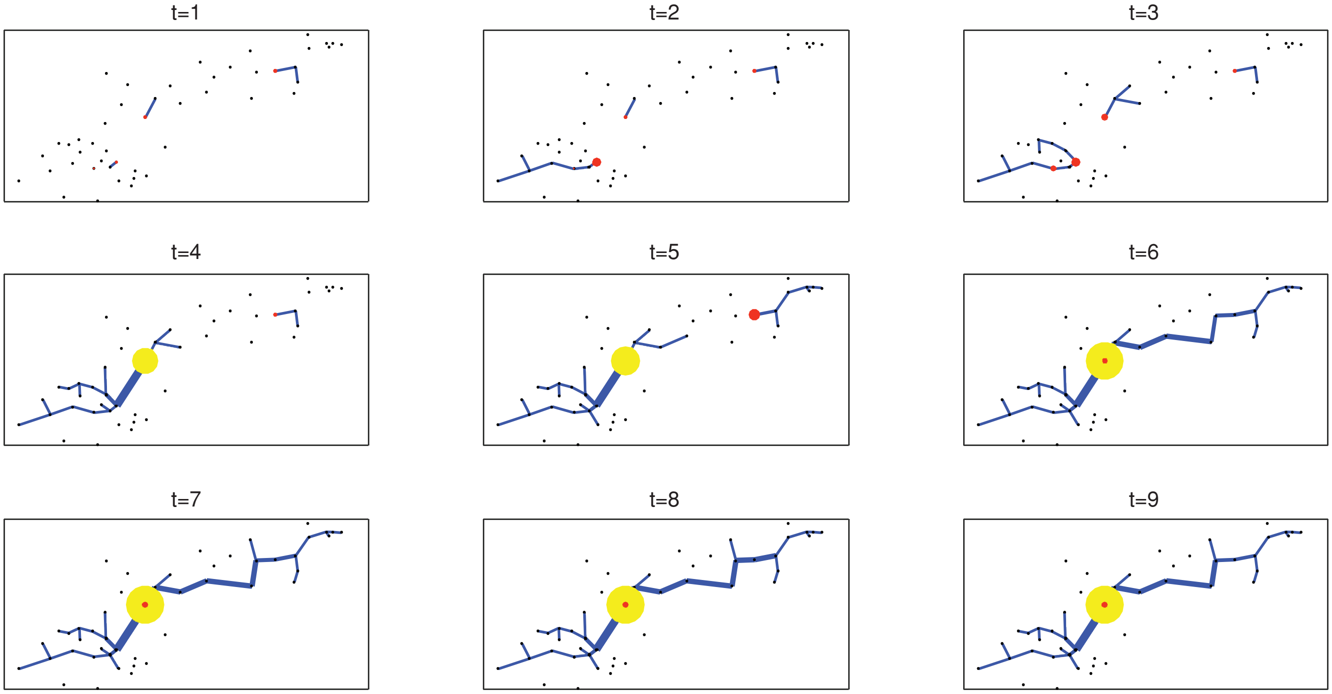

Figure 7: Islands of growth expansion with a discount rate of 10%

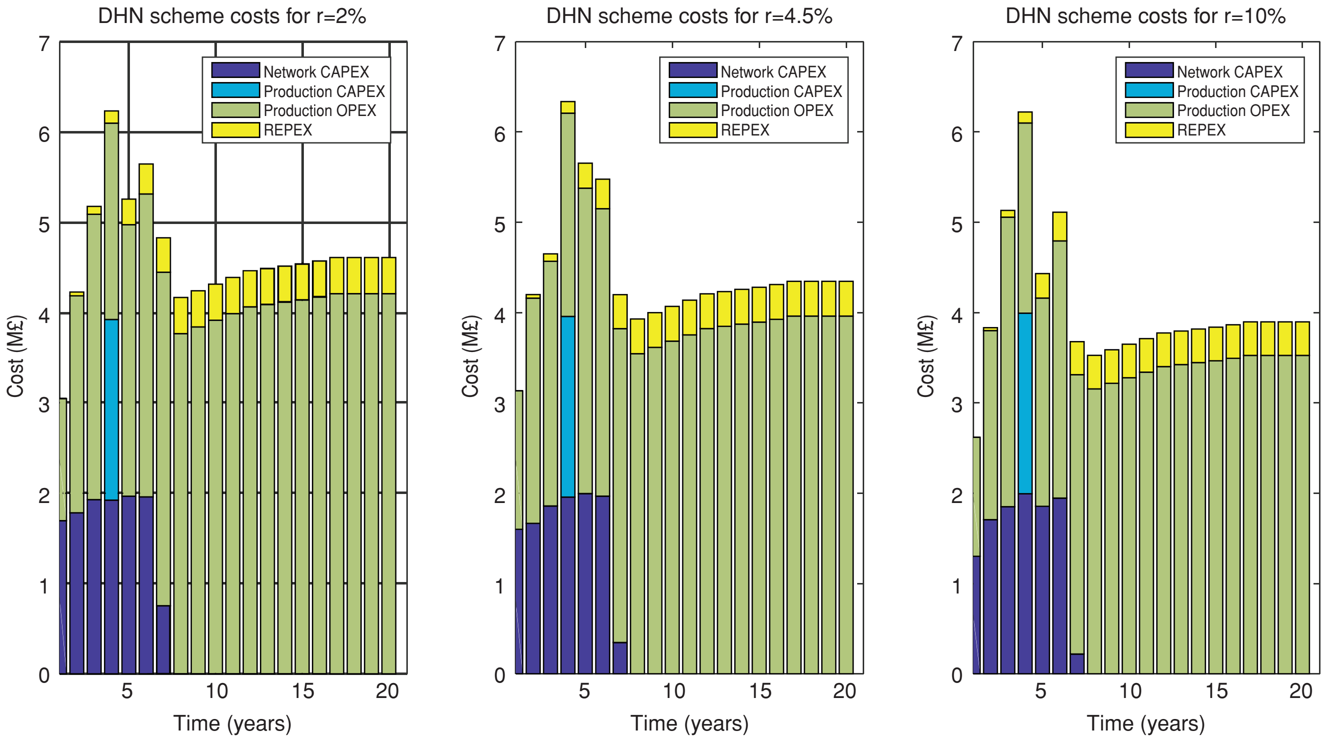

Figure 8: Costs of the district heating scheme for discount rates set to 2%, 4.5% and 10%.

similar approach to prioritize areas of development for their development activities related to district cooling networks. This situation is an example of heating network marginal extension. In the case of large existing separate schemes, the optimisation problem formulation could be used to anticipate the optimal future linking of the networks to efficiently integrate some new heat sources. The linking from island networks to one single large network is a pattern that has characterized Swedish district heating schemes around the time of the 1973 oil crisis, when separate community schemes were joined to be supplied by industrial waste heat. A current trend in mature large district heating systems is the creation of interconnected multi-municipal networks sharing production facilities for increased security of supply. Typical examples include the Helsingborg-Landskrona-Lund heat ring [21]. This latter situation could also be modelled with the presented approach since its validity does not depend on network size.

In areas with limited access to industrial heat, the same methodology could be applied in the case of renewable energy from such sources as municipal solid waste and biomass. Recent studies investigating the integration of alternative energy sources into DH systems include [29,30]. In these schemes, the cost of heat from the plant will be based on the opportunity cost of the reduction of electricity income corresponding to the heat to be supplied. This is explained by the fact that the heat is produced from a bleed from the steam turbine and the ratio of lost power to produced heat is represented by the ‘Z factor’. Examples of such schemes in London include the South East London CHP [22] in which French company Veolia invested in a heat network to supply Southwark housing estates. Another example is that of Edmonton energy from waste scheme [23], a 40 year old plant that will be supplying heat to the Upper Lee Valley heat network. The above discussion shows the universal nature of this type of phasing approach that, despite its simplistic formulation, can be applied to a wide range of district energy schemes.

In terms of planning decision making, the use of a sequential decision-making approach allows for the determination of expansion schedules that might not have been identified using arbitrary incremental network expansion. The presented approach could, in principle and subject to context adaptation, be used to show local authorities and planners how their district heating scheme might evolve over time. In the UK, for example, district heating schemes that are partially funded by public grants sometimes feature pre-existing building level community gas boilers from different locations instead of a single energy centre. This naturally leads to a larger number of potential island growth scenarios. In particular, the consideration of heat production increase and phasing of heat production facilities, in parallel to network growth, is one of the major strengths of the proposed approach. As explained above, the consideration of supplying the seed heat network with peak heat only gas boilers represents a typical UK situation where planners avoid the introduction of capital intensive heat sources until a sufficient heat load has been supplied. By using a sequential decision problem formulation it is possible to determine when it is optimal to introduce a new heat source given the achievement of an optimal annual heat demand threshold.

Clearly, practical application of the proposed approach to real life case studies will require specific and detailed studies of the load duration curves, production facilities, maintenance costs, hydraulics of the scheme under consideration. Other decisions such as flow temperature levels and storage require a more granular approach in their implementation (especially in the temporal domain). This is evidently not the subject of this paper. However, once accurate values for the costs of the scheme have been determined, it will be possible to use a similar approach to that proposed in this paper to determine the optimal phasing stages of the district heating network expansion. It is interesting to note that the formulation of the optimisation problem bears similarity to other investment problems typically formulated as knapsack problems [24], in which the value of an objective function is maximised by the selection of a number of investment options under a capital cost budget constraint.

In terms of managing uncertainties, there exists a number of options for potential improvements. First of all, with a better coverage of the range of future scenarios, including the use of stochastic evolution of heat demand characterized by increases in energy efficiency, connections lost to other types of heat supply systems, the infilling of current areas with new buildings etc. Another possibility will be the application of risk-averse objective functions, for example, based on dynamic risk-measures, or the application of real options analysis to value a portfolio of expansion options using Monte-Carlo simulation and approximate dynamic programming. The latter is the topic of future work for the authors of this paper.

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References

[1] Haikarainen C, Pettersson D, and Saxén H, An MILP Model for Distributed Energy System Optimization, Chemical Engineering Transactions 35 (2013). http://dx.doi.org/10.3303/CET1335049

[2] Li H, Svendsen S, District Heating Network Design and Configuration Optimization with Genetic Algorithm, Journal of Sustainable Development of Energy, Water and Environment Systems 1 (4) (2013) pages 291–303. http://dx.doi.org/10.13044/j.sdewes.2013.01.0022

[3] Pirouti M, Bagdanavicius A, Ekanayake J, Wu J, Jenkins N, Energy consumption and economic analyses of a district heating network, Energy 57 (2013) pages 149–159. http://dx.doi.org/10.1016/j.energy.2013.01.065

[4] Weber C, Shah N, Optimisation based design of a district energy system for an eco-town in the United Kingdom, Energy 36 (2) (2011) pages 1292–1308. http://dx.doi.org/10.1016/j.energy.2010.11.014

[5] Fazlollahi S, Becker G, Ashouri A, Maréchal F, Multi-objective, multi-period optimization of district energy systems: IV – A case study, Energy 84 (2015) pages 365–381 http://dx.doi.org/10.1016/j.energy.2015.03.003

[6] Voll P, Jennings M, Hennen M, Shah N, Bardow A, The optimum is not enough: A near-optimal solution paradigm for energy systems synthesis, Energy 82 (2015) pages 446–456. http://dx.doi.org/10.1016/j.energy.2015.01.055

[7] Persson U, Werner S, Heat distribution and the future competitiveness of district heating, Applied Energy 88 (3) (2011) pages 568–576. http://dx.doi.org/10.1016/j.apenergy.2010.09.020

[8] Nielsen S, A geographic method for high resolution spatial heat planning, Energy 67 (2014) pages 351–362. http://dx.doi.org/10.1016/j.energy.2013.12.011

[9] Finney K.N, Sharifi V.N, Swithenbank J, Nolan A, White S, Ogden S, Developments to an existing city-wide district energy network – Part I: Identification of potential expansions using heat mapping, Energy Conversion and Management 62 (2012) pages 165–175. http://dx.doi.org/10.1016/j.enconman. 2012.03.006

[10] Möller B, Lund H. Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. Applied Energy.;87(6) (2010) pages 1846–1857. http://dx.doi.org/ 10.1016/j.apenergy.2009.12.001

[11] Gils HC, Cofala J, Wagner F, Schöpp W. GIS-based assessment of the district heating potential in the USA. Energy. 58(1) (2013) pages 318–329. http://dx.doi.org/ 10.1016/j.energy.2013.06.028

[12] Persson U, Möller B, Werner S. Heat Roadmap Europe: Identifying strategic heat synergy regions. Energy Policy. 74 (2014;) pages 663–681. http://dx.doi.org/10.1016/ j.enpol.2014.07.015

[13] Zhou Y, Li Y. P., Huang G. H., A robust possibilistic mixed-integer programming method for planning municipal electric power systems, International Journal of Electrical Power & Energy Systems 73 (2015) pages 757–772 http://dx.doi.org/ 10.1016/j.ijepes.2015.06.009

[14] Zhou Z, Zhang J, Liu P, Li Z, Georgiadis M. C., Pistikopoulos E. N, A two-stage stochastic programming model for the optimal design of distributed energy systems, Applied Energy 103 (2013) pages 135–144. http://dx.doi.org/10.1016/ j.apenergy.2012.09.019

[15] Wu C. B., Huang G.H., Li W, Xie Y.L, Xu Y, Multistage stochastic inexact chance-constraint programming for an integrated biomass-municipal solid waste power supply management under uncertainty, Renewable and Sustainable Energy Reviews 41 (2015) pages 1244–1254. http://dx.doi.org/10.1016/ j.rser.2014.09.019

[16] Homem-de-Mello T, Pagnoncelli B.K., Risk aversion in multistage stochastic programming: A modeling and algorithmic perspective, European Journal of Operational Research, 249(1) (2016), pages 188–199, http://dx.doi.org/ 10.1016/j.ejor.2015.05.048

[17] Department of Energy and Climate Change (DECC) [online] Available:https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2014 [Accessed: 24-Jan-2016].

[18] Bird, R.B., Stewart, W.E. and Lightfoot, E.N. Transport Phenomena (Revised Second ed.). John Wiley & Sons. 2007 ISBN 978-0-470-11539-8.

[19] Redbridge Decentralised Energy Masterplan – Redbridge EMP.pdf. [Online].Available:http://www.london heatmap. org.uk/Content/uploaded/documents/Redbridge%20EMP.pdf [Accessed: 21-Oct-2015].

[20] Di Lucia L, Ericsson K, Low-carbon district heating in Sweden – Examining a successful energy transition, Energy Research & Social Science 4 (2014) pages 10–20, http://dx.doi.org/10.1016/j.erss.2014.08.005

[21] Landskrona Energi – Gemensam fjärrvärmeledning. (in Swedish)_ [Online]. Available:http: //www.landskronaenergi.se/ gemensam-fjarrvarmeledning-bra-for-skanes-miljo/ . [Accessed: 03-Mar-2016].

[22] South East London Combined Heat and Power - SELCHP - SELCHP. [Online]. Available: http://www.selchp.com/ [Accessed: 21-Oct-2015].

[23] North London Heat and Power Project. [Online]. Available: http://northlondonheatandpower.london/document-library/ options [Accessed: 03-Mar-2016].

[24] Kong X, Gao L, Ouyang H, Li S, Solving large-scale multidimensional knapsack problems with a new binary harmony search algorithm, Computers & Operations Research, 63 (2015), pages 7–22. http:// dx.doi. org/ 10.1016/j.cor.2015.04.018

[25] Arup, DENet – Decentralised Energy Networks Masterplanning Prefeasibility Tool. http://www.arup.com/ Projects/DENet.aspx [Accessed: 24-Jan-2016]

[26] Parsons Brinckerhoff – Royal Borough of Greenwich Energy Masterplan (2014) - http://www.londonheatmap.org.uk/ Content/uploaded/documents/Greenwich_EMP.pdf

[27] Parsons Brinckerhoff, Upper Lee Valley Decentralised Energy Network Pre-feasibility Study (2011). www.haringey 4020.org.uk/summary_-_ulv_enterprise.pdf[Accessed: 24-Jan-2016]

[28] CLASP. Procuring heat networks, - Learning from the Swedish Approach http://claspinfo.org/procuring-heat-networks-June2015 [Accessed: 03-Mar-2016]

[29] Margaritis N, Rakopoulos D, Mylona E, Grammelis P. Introduction of renewable energy sources in the district heating system of Greece. International Journal of Sustainable Energy Planning and Management. 4 (2014), pages 43–56. http://dx.doi.org/10.5278 /ijsepm. 2014.4.5

[30] Zhang J, Di Lucia L. A transition perspective on alternatives to coal in Chinese district heating. . International Journal of Sustainable Energy Planning and Management. 6 (2015), pages 49–68 http://dx.doi.org/10.5278/ijsepm.2015.6.5

[31] Zugno M, Morales J.M, Madsen H. Decision Support Tools for Electricity Retailers, Wind Power and CHP Plants Using Probabilistic Forecasts. International Journal of Sustainable Energy Planning and Management. 7 (2015), pages 19–36. http://dx.doi.org/10.5278/ijsepm.2015.7.3

[32] Poyri – The potential and costs of district heating networks. (2009) http://www.poyry.co.uk/sites/www.poyry.uk/files/ A_report_providing_a_technical_analysis_and_costing_of_DH networks.pdf [Accessed: 02-Mar-2016]

Appendix: Parameter values used in the presented numerical example

Table 1: Summary of sources for used parameters and datasets

Parameter	Source
Maximum pressure drop	[27]
Maximum velocities	[27]
District heating pipe costs as a function of length and diameter	[25]
Heat losses as a function of pipe diameter	[26]
Gas projection prices	[17]

Table 2: Heat Losses for varying diameters mains

Diameters (nominal internal mm)	Heat Losses (W/m)
150	20
200	25
250	28
300	35
350	42
400	49
450	53

Table 3: Maximum pressure drops and velocity as a function of pipe diameter

Pipe Size (nominal internal mm)	Maximum allowable pressure drop (Pa/m)	Maximum Velocity (m/s)
100	200	2
125	200	2.5
150	200	3
200	200	3
250	200	3.5
300	300	3.5
400	300	3.5
450	300	3.5

Table 4: Cost of laying out transmission pipes

Type	Pipe Size (nominal internal mm)	150	250	350	450
Green field	Cost (£/m)	870	1328	1663	2023
Brown field		920	1378	1719	2093
Hard urban		1862	2320	2820	3412
Hard sub-urban		1383	1841	2257	2741

Remark: These figures represent an urban situation which differs from green-field capital costs. UK network capital costs for layout pipes are very high compared to other northern European countries. In Sweden the cost of layout one meter of district heating pipes is of the order of SEK100. High network capital costs may explain the lower share of district heating for heat supply in the UK [32]. Recently, an initiative to create a procurement agency DEPA [28] (District energy procurement agency) inspired from the Swedish procurement agency VÄRMEK, and which will aim to reduce down procurement and contracting costs. The objective will be to enable UK local authorities to collectively negotiate equipment and services costs.