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District cooling network optimization with redundancy constraints in Singapore

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Abstract

This study presents a mathematical optimization model for planning topology and capacity of a district cooling network. The model relies on a mixed-integer linear programming formulation to find the most economic network layout while satisfying redundancy criteria against unavailability of cooling stations. The simplicity of the formulation makes it easy to embed in other models or to extend it to other redundancy cases.

The model is applied to a case study in the central business district of Singapore. Results show that district cooling is a profitable option for Singapore, especially due to its constant high cooling demand that is currently satisfied mainly through decentralized cooling units. This result generalizes to tropical cities world-wide with high cooling demand density.

Keywords: District cooling, Mathematical optimization, Mixed-integer linear programming, Redundancy

Introduction

District cooling has been established in many countries. Especially in bigger cities, it offers an energy efficient alternative to individual generation of cooling power at the site of customers. Even in a city like Munich, Germany, which is located in a temperate climate zone, several district cooling systems have already been installed successfully and maintained.

In contrast to Munich, in Singapore, warm and humid weather prevails all year long, which results in much higher demand for cooling and dehumidification both in residential and non-residential buildings. However, in most buildings, cooling power is generated by using small chillers that use air for re-cooling which is very inefficient. As a result, much electricity is used to operate the chillers. In this case study, we model a district cooling network for the central business district (CBD) of Singapore. We present several cases and a comparison to conventional individual cooling.

Singapore's CBD comprises mainly commercial buildings, e.g. shopping malls, hotels and office blocks, often with more than 50 floors. Thus, it stands in contrast to

other areas of Singapore which comprise more residential or industrial buildings. Due to the different type of use of commercial buildings with the air conditioning running all day long and amounting to approximately 50% of each building's energy demand, the introduction of district cooling could lead to tremendous energy savings.

Singapore already has a large underground district cooling system in the Marina Bay. The system contains two plants with a maximum of 330MW of cooling power. [1] According to the Singapore District Cooling Pte Ltd (SDC), a subsidiary of Singapore Power, energy savings amount to 40% which corresponds to the energy demand of 24 000 three-room flats operated by Singapore's Housing Development Board (HDB).

State of projects

Over the last decades, district cooling networks have been developed in several cities throughout Europe. Researches result in data shown in Table 1. Paris for example already started to supply in 1991 [2, 3]. Vienna has set the aim of installing 200MW district cooling power until the year 2020 ([4], p. 2). Stockholm has probably the biggest district cooling network today with a connected load of already 330MW, ranging from small (8kW) to large (7000kW) customers with an average load of about 500kW each [5]. Munich's district cooling network [6] is constantly growing and they have installed different kinds of

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Table 1 State of projects in European cities

City	[Sources]	Capacity (MW)	Energy (GWh/a)
Berlin	[27]	44	
Helsinki	[28, 29]	135	80
Munich downtown	[6]	15	
Munich groundwater	[6]	11.4	
Munich M-Campus (mixed form)	[6]	4.39	4.4
Paris	[2]	290	420
Stockholm	[5]	330	460
Vienna	[30]	113.3	

cooling in order to supply the best technology for each purpose.

State of research

This is a short summary of existing publications on district cooling in Singapore, district cooling in general, as well as similar or prominent approaches for district heating or more general multi-commodity district energy systems.

Cooling in Singapore

Apart from the aforementioned existing district cooling system [1], a recent study on Singapore [7] focused on comparing surface and subsurface cooling in tropical countries using an EnergyPlus model of a representative building. It concludes that an open-loop groundwater cooling system might be a better option for tropical cities like Singapore compared to conventional systems. The viability of district cooling in the CBD area of Singapore has already been assessed in a working paper [8] by Singapore Power Ltd.

District cooling

A thermal ice storage system and its influence on the cost-optimal design of district cooling distribution network is investigated [9] using non-linear optimization in two exemplary networks. It finds that ice storage can help reduce the required pipe diameters. A TRNSYS model is built to investigate a similar question [10] for a case study in Hong Kong; storage is not found to be an economically attractive option there.

A genetic algorithm is used [11] to assess the optimum shares of five building types to form a cooling load time series that is most suitable for district cooling. This approach was later embedded in an optimization scheme for a development project in South East Kowloon, Hong Kong. Another genetic algorithm was used by Feng and Long [12] to determine and compare piping layouts.

Khir [13] presents a mixed integer linear programming (MILP) model for designing district cooling system. It explicitly models flow rates, temperatures and pressures in a graph of arcs and nodes. Linearization of the physical constraints leads to a large amount of auxiliary variables. Both plant design and operation and network design can be optimized. However, to achieve a tractable problem size, those two subproblems are solved separately. However, this separation requires fixing the supply task. The paper also highlights the relationship with Steiner tree problems.

Södermann [14] presents a similar MILP model for designing district cooling systems in urban areas. It uses a linearized cost function for sizing equipment (plants, pipes, storages). A small set of representative load periods (8 in the example study) approximate the annual cooling load duration curve.

District heating

Due to the basic principle, district cooling and heating are comparable types of supply. In both types, with few central generation plants heat or cold is generated which is mostly transferred to water. This tempered water is transported through pipes to customers buildings. Having transferred the heat or cold to the buildings, the cooled or heated water returns to the generation plants where the process starts from the beginning. The biggest difference between both are the technologies used in generation plants, which is not the focus of this article.

Jamsek [15] presents a linear programming (LP) approach for determining cost-minimal pipe topology and capacity configuration for a given structure and cost data. A more conceptual, but worthwhile discussion of district heating and cooling systems is given by Rezaie [16].

Udomsri [17] presents and compares the different options to combine centralized and decentralized heating and cooling. It points towards solutions that use decentralized, thermally driven chillers to produce cooling on-site. This configuration can have advantages in regions with both heating and cooling demands throughout the year.

Multi-commodity district energy system

A detailed model on combined energy system planning for electric, heating and cooling demand is presented by Chinese from 2008 [18]. It presents a MILP model. A case study in Udine, Italy, is performed with 7 nodes and 41 individually weighted time steps to represent the seasonal demand characteristics of a full year.

A recent paper [19] investigates the case of combined district energy system for electricity, heating and cooling using a mixed integer linear optimization problem. Both spatial (7 nodes) and temporal (2 days in 48 time steps) resolution are low in the presented case study, but the

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non-linear performance of gas turbines is represented by a set of linearized constraints.

A broader review of computer models for renewable energy system analysis and optimization is provided by Connolly et al. [20]. Weber presents in her thesis [21] a comprehensive methodology to plan cost-optimal poly-generation energy systems.

This work

This paper presents the generalized version of a previously published model developed for planning of district heating distribution networks [22]. That model has then been adapted for optimization of district cooling systems and applied in a small case study for the city center of Munich [23].

Model

This section describes a mathematical optimization model to represent the planning task for a minimum cost district cooling network. Its main input is a connected graph of street segments that represent the discrete possible network parts. Each segment – called *edge* in the following – has the attributes length and a cooling demand that *may* (but does not have to) be satisfied by the district cooling network. A subset of the graph's *vertices* may provide cooling at fixed specific costs, representing (possible) cooling stations.

The model's main contribution lies in a simple representation of redundancy constraints by means of artificial time steps (or periods) with pre-determined reduced availability of cooling stations. This technique can easily be embedded into other optimization models and can increase the robustness of obtained solutions against equipment downtime due to outages or maintenance.

Overview

A brief conceptual overview on the model's inputs (parameters) and outputs (results) is given in Fig. 1. The presented optimization model, based on estimated (or known) cooling demand and a graph of possible segments to construct a cooling network, derives the cost-optimal size and topology of such a network. The objective function minimizes total costs (generation costs minus revenues), thus yielding the most profitable system design.
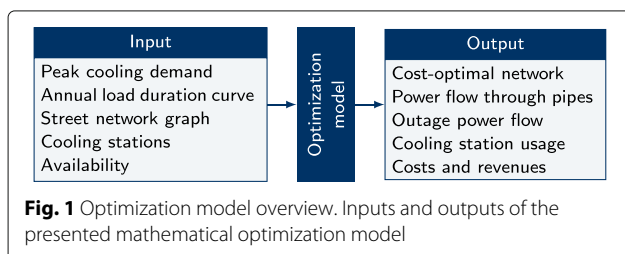

Fig. 1 Optimization model overview. Inputs and outputs of the presented mathematical optimization model

To improve performance for large study regions, the model employs a linearized cost function for sizing the thermal pipe capacity. Depending on the parameterization, one can either cautiously overestimate the real estimated costs or try to fit as closely the observed cost function. In the latter case, one typically slightly underestimates the cost of medium capacities, while overestimating the cost of small and large capacities.

Mathematical description

The presented model minimizes the total costs ζ of generating and distributing cooling through a district cooling network. The key result is the size and topology of the network, represented by the value of network capacity $\bar{\pi}$ (vector of all individual arc capacities $\bar{\pi}_{ij}$) in the optimal case:

$$\bar{\pi}^{\star} = \underset{\bar{\pi}}{\operatorname{argmin}} \ \zeta \qquad (1)$$

Sets

A district or city is represented as a graph of vertices and arcs. This graph is derived from the street network. It should be derived in such a way to include all considerable locations for network pipes. The spatial resolution can be chosen as fine as required. Here, it is on the level of building blocks, i.e. a single street segment between two intersections.

Let V be the set of vertices v_i, corresponding to connecting or terminating points of the graph. Set A of arcs then comprises ordered tuples of vertices $a_{ij} = (v_i, v_j)$ with $i \neq j$. A is symmetric, that means either both or none of the pair a_{ij} and a_{ji} are elements of A. For readability, the subscript $\circ_i$ is used to denote any parameter or variable that is defined over vertices $v_i \in V$, while $\circ_{ij}$ is used to denote a quantity defined over arcs $a_{ij} \in A$.

The set $V_0 \subseteq V$ defines so-called *source vertices*, which represent locations of possible cooling sources. Usually, the number of source vertices is low (≤ 10) compared to the size of the graph.

The neighbor sets N_i of a vertex v_i are defined by the indices of all vertices that are connected to it by an arc: $N_i = \{ k \mid a_{ki} \in A \}$.

Time is represented by a set T of discrete time steps t, which represent a small number of representative operational situations. The minimum viable number of time steps is two: one for peak demand with a duration of one to several hours, a second for the average annual load with a duration of the remaining year. A more comprehensive choice are three to four time steps: The third can refer to the all-year base load, while the fourth can be used to represent a common intermediate load level. Additional time steps need to be introduced if redundancy requirements are to be stated. Refer to the discussion of the parameter *availability* below for more details.

Parameters

The numerical given facts for this model are shown in Table 2. They are grouped by their defining domains. First are vertex parameters, then arc parameters, then constant or global parameters, and finally time-dependent parameters.

Vertices have a single parameter: their maximum power capacity $Q_i^{\max}$. It is the thermal output power given in kW for that location. All non-source vertices have this parameter set to 0.

Arcs have three main attributes: their length l_{ij} (m), the thermal peak demand d_{ij} (kW) of their adjacent buildings and g_{ij} (binary), which states whether a pipe already exists in this arc.

As secondary parameter, $C_{ij}^{\max}$ indicates the maximum thermal power capacity (kW) in an arc, which can be derived from the maximum available pipe diameter. For arcs with existing pipes ($g_{ij} = 1$), this value should be set according to the diameter of that existing pipe. As both arcs a_{ij} and a_{ji} refer to the same street segment, parameter values for both members are always identical.

Global parameters are technical and economic parameters that refer to the district cooling system as a whole.

Economic parameters are all costs and revenues. The investment costs are split into a fixed part c_{fix} and a variable part c_{var}. The fixed part, given in S$/m, captures all costs that are not dependent on the capacity of the pipe to be built, mainly earth works. The variable part,

given in S$/(kW m), refers to the capacity-dependent cost component of building a pipe. Both values must be tailored to the study area to compensate for differences in cost structure and availability of different pipe sizes. The same is true for the operation & maintenance (OM) cost parameter c_{om} in S$/m. In contrast to the fixed investment cost term, it is also to be paid for existing pipes. The cost for providing cooling c_v^{cool} here is dependent on the vertex to allow for representing cheap surface water cooling in contrast to more expensive re-cooling options.

The letter c and a subscript denote *economic parameters*. These are investment costs for building the pipe network c_{fix} and c_{var}, maintenance c_{om}, costs of providing c_i^{cool} cooling, and *revenue* for delivering c_{rev} cooling to consumers. While c_{fix} contains the size-independent costs (mainly earth works), c_{var} contains costs that are dependent on the thermal capacity (diameter) of the pipe.

Time-dependent parameters s_t and w_t represent scaling factor (dimensionless) and weight or duration (h) of a time step t. A value of $s_t = 1$ refers to peak demand, while smaller values correspond to moments of partial load. Together, these two parameters encode a *discretized annual load curve*.

Redundancy requirements can be stated in the model by setting the binary availability parameter y_{it} to value 0 in certain time steps for $1, 2, \ldots$ source vertices. If one time step for each foreseen failure configuration is introduced, a full $n - 1, n - 2, \ldots$ failure safety (against cooling source outages) can be enforced in the produced solution. Clarification: in the *conventional* time steps discussed above in paragraph time step set, the value $y_{it} = 1$ is to be set for all source vertices $v_i \in V_0$.

Variables

The main optimization task is to find values for the *binary* decision variable ξ_{ij}. If its value is one, a pipe is built in the street segment corresponding to the arc a_{ij}. For each time step, the actual use of a given pipe is decided by setting the binary pipe usage decision variable ψ_{ijt}. If its value is one, the pipe in arc a_{ij} is used in direction from vertex v_i to vertex v_j. Consequently, there must be a power flow π_{ijt}^{in} into the pipe. Simultaneously, a value $\xi_{ij} = 1$ requires that the demand d_{ij} of this arc has to be satisfied *at all times*. The power flow variable at the other end of the pipe is called π_{ijt}^{out}. Its value is determined by the ingoing power flow minus losses and demand.

The non-negative variable ρ_{it} represents thermal power output from a source vertex $v_i \in V_0$ at time t in kW. It is limited in value by the source vertex capacity parameter $Q_i^{\max}$ and possibly by the availability parameter y_{it}. Table 3 summarizes all model variables. The following line shows their domains, on which they are defined:

$$\zeta \in \mathbb{R} \qquad \xi_{ij}, \psi_{ijt} \in \{0, 1\} \qquad \bar{\pi}_{ij}, \pi_{ijt}^{\mathrm{in}}, \pi_{ijt}^{\mathrm{out}}, \rho_{it} \in \mathbb{R}_0^+.$$

Table 2 Optimization model parameters

Name	Unit	Description
c_{fix}	S$/m	Fixed investment costs
c_{var}	S$/(kW m)	Variable investment costs
c_{om}	S$/(m a)	Operation & maintenance costs
c_{rev}	S$/kWh	*Revenue* for cooling
w^{fix}	kW/m	Fixed thermal losses
w^{var}	kW/(kW m)	Variable thermal losses
b	—	Concurrence effect
q	—	Connect quota
u	1/a	Annuity factor for investment costs
c_i^{cool}	S$/kWh	Cooling costs at source vertices
$Q_i^{\max}$	kW	Source vertex capacity
l_{ij}	m	Arc length
d_{ij}	kW	Arc peak demand
g_{ij}	—	Existence of a pipe (1=yes, 0=no)
$C_{ij}^{\max}$	kW	Maximum pipe capacity
s_t	1	scaling factor
w_t	h	weight/duration
y_{it}	—	availability (1=yes, 0=no)

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Table 3 Optimization model variables

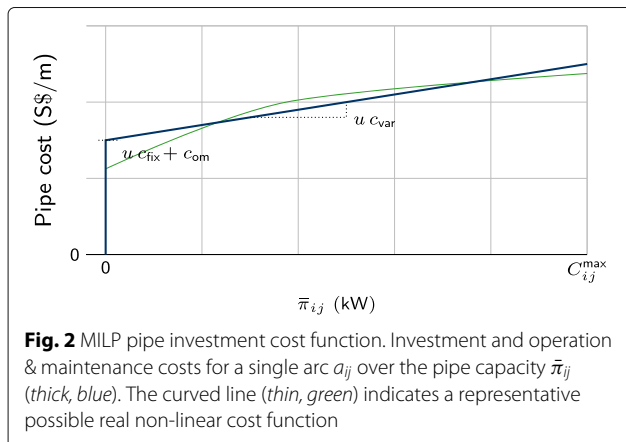| Name	Unit	Description
ζ	S$	Total system cost (Inv, O&M, Rev, Gen)
ξ_{ij}	—	Binary decision variable: 1 = build pipe
ψ_{ijt}	—	Binary decision variable: 1 = use pipe
$\bar{\pi}_{ij}$	kW	Thermal power flow capacity into arc a_{ij}
π_{ijt}^{in}	kW	Thermal power flow from v_i into arc a_{ij}
π_{ijt}^{out}	kW	Thermal power flow out of arc a_{ij} into v_j
ρ_{it}	kW	Cooling in source vertex v_i

Equations

Equations fall into two categories: The first is the cost function whose value is to be minimized. The second are constraints that codify all the previously discussed rules in mathematical form. By that, they define the region of feasible solutions, under which the solver selects a (close to) cost optimal solution.

The *cost function* value ζ is the sum of costs for providing cooling, minus revenue for that cooling. Network costs occur for building the network (annualized investment) and for operation & maintenance. The following *derived parameters* are introduced to shorten the definition of the cost function whose definition is given below: k_{ij}^{fix} (S$/a) and k_{ij}^{var} (S$/(kW a)) cover network costs (investment, O&M). k_{ij}^{cool} (S$/kWh) represents cooling generation costs, while r_{ij}^{cool} (S$/h) represents revenue for provided cooling. With these, the cost function is equal to

$$\zeta = \sum_{a_{ij} \in A} \left(k_{ij}^{\text{fix}} \xi_{ij} + k_{ij}^{\text{var}} \bar{\pi}_{ij} \right) + \sum_{\substack{v_i \in V \\ t \in T}} k_i^{\text{cool}} w_t \rho_{it}$$
$$- \sum_{\substack{a_{ij} \in A \\ t \in T}} r_{ij}^{\text{cool}} s_t w_t \xi_{ij}. \tag{2}$$

The first summand forms a piece-wise linear function that is depicted in Fig. 2. The plot also depicts that the

Fig. 2 MILP pipe investment cost function. Investment and operation & maintenance costs for a single arc a_{ij} over the pipe capacity $\bar{\pi}_{ij}$ (*thick, blue*). The curved line (*thin, green*) indicates a representative possible real non-linear cost function

linear approximation possibly over- and underestimates the cost of either small or large capacities. Depending on the parameterization, one can either force an optimistic (by deliberate underestimation) or cautious (by deliberate overestimation) planning decision. The linear approximation exhibits unsteady jump from zero to the fixed cost $u c_{\text{fix}} + c_{\text{om}}$ for any positive value of $\bar{\pi}_{ij}$ for any non-existing ($g_{ij} = 0$) pipe. The link between the binary decision variable ξ_{ij} and the continuous pipe capacity variable $\bar{\pi}_{ij}$ is enforced through Eqs. (8), (12), and (14) below.

These are the definitions for the four derived parameters used in the cost equation above. The division by value 2, common to all three arc parameters, compensates for the double-representation of one street segment $\{v_i, v_j\}$ as a pair two directed arcs a_{ij}, a_{ji}. More about this issue can be found at the explanation of the symmetry constraints (15) and (16) below. The cooling cost parameter k_i^{cool} is divided by the concurrence effect parameter b to remove the load reduction effect that is introduced in Eq. 10. In other words, the power flow that needs to be satisfied from a source vertex is lower by b than the *energy* flow that needs to be delivered. The division by b removes that difference in terms of costs.

$$\forall a_{ij} \in A: \quad k_{ij}^{\text{fix}} = \left[c_{\text{fix}} l_{ij} u (1 - g_{ij}) + c_{\text{om}} l_{ij} \right] / 2 \tag{3}$$

$$\forall a_{ij} \in A: \quad k_{ij}^{\text{var}} = \left[c_{\text{var}} l_{ij} u (1 - g_{ij}) \right] / 2 \tag{4}$$

$$\forall v_i \in V: \quad k_i^{\text{cool}} = c_i^{\text{cool}} / b \tag{5}$$

$$\forall a_{ij} \in A: \quad r_{ij}^{\text{cool}} = c_{\text{rev}} d_{ij} q / 2 \tag{6}$$

The *constraints* formalize all physical laws and technical rules that need to be satisfied by a feasible solution. The first constraint concerns energy conservation in vertices v_i, with respect to its neighbors N_i:
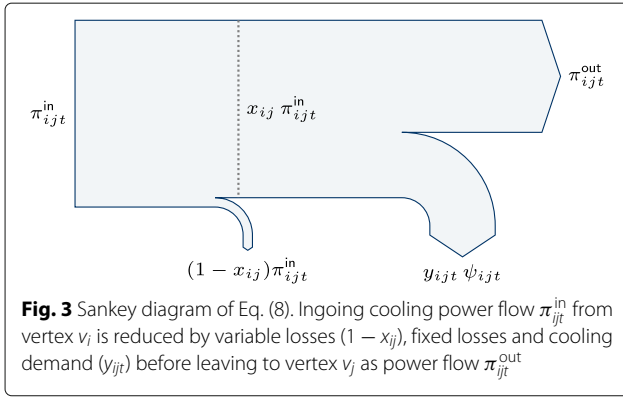
$$\forall v_i \in V, t \in T: \quad \sum_{n \in N_i} \left(\pi_{int}^{\text{in}} - \pi_{nit}^{\text{out}} \right) \leq \rho_{it} \tag{7}$$

This inequality is thus a relaxed version of the law of energy conservation. Relaxed, because it allows for power to vanish at any vertex. As power does not come for free, any solution returned by the solver will satisfy this constraint to equality. For all non-source vertices (i.e. $\rho_{it} = 0$), the difference between outgoing and incoming power must be smaller than or equal to zero. In source vertices, a positive difference may remain when it is met by an equal amount of input power ρ_{it} into the network at that vertex.

Demand satisfaction is the main *arc constraint*. It creates the logical connection between the discrete pipe usage decision ψ_{ijt} and the demand satisfaction. Like the cost equation, it relies on two derived parameters x_{ij} and y_{ijt}. This constraint is also graphically explained in Fig. 3.

$$\forall a_{ij} \in A, t \in T: \quad x_{ij} \pi_{ijt}^{\text{in}} - \pi_{ijt}^{\text{out}} = y_{ijt} \psi_{ijt} \tag{8}$$

Parameter x_{ij} refers to losses w^{var} that are proportional to the amount of power flow into the arc a_{ij}. Parameter

Fig. 3 Sankey diagram of Eq. (8). Ingoing cooling power flow π_{ijt}^{in} from vertex v_i is reduced by variable losses $(1 - x_{ij})$, fixed losses and cooling demand (y_{ijt}) before leaving to vertex v_j as power flow π_{ijt}^{out}

y_{ijt} refers to fixed thermal losses w^{fix} that only depend on the pipe length, not on the power flow, and the time-dependent demand $d_{ij} \cdot s_t$ that is further reduced by the concurrence effect b and the connect quota parameter q. In notation:

$$\forall a_{ij} \in A: \qquad x_{ij} = 1 - l_{ij} \, w^{\text{var}} \qquad (9)$$

$$\forall a_{ij} \in A, t \in T: \qquad y_{ijt} = b \, q \, d_{ij} \, s_t + l_{ij} \, w^{\text{fix}} \qquad (10)$$

Pipe capacity is a technical constraint that limits the power flow through a pipe by the built capacity. This is accomplished by first limiting the ingoing power flow into a pipe π_{ijt}^{in} by the built pipe capacity $\bar{\pi}_{ij}$. The second constraint is required to set the pipe usage decision variable ψ_{ijt}. Its value is forced to 1 if a flow in direction from v_i to v_j at time step t is required. The reason for this seemingly artificial constraint is explained in the following constraint.

$$\forall a_{ij} \in A, t \in T: \qquad \pi_{ijt}^{\text{in}} \leq \overline{\pi}_{ij} \qquad (11)$$

$$\forall a_{ij} \in A, t \in T: \qquad \pi_{ijt}^{\text{in}} \leq \psi_{ijt} \, C_{ij}^{\text{max}} \qquad (12)$$

Unidirectionality of the power flow π_{ijt}^{in} is required, as otherwise the solver would happily use a pipe's capacity in both directions simultaneously, which would not be physically possible. Therefore, the pipe usage decision variable ψ_{ijt} may only have the value 1 in one direction at any given time step t. This way, the direction of flow may change between time steps, but any given pipe may only be used in one direction at a given time.

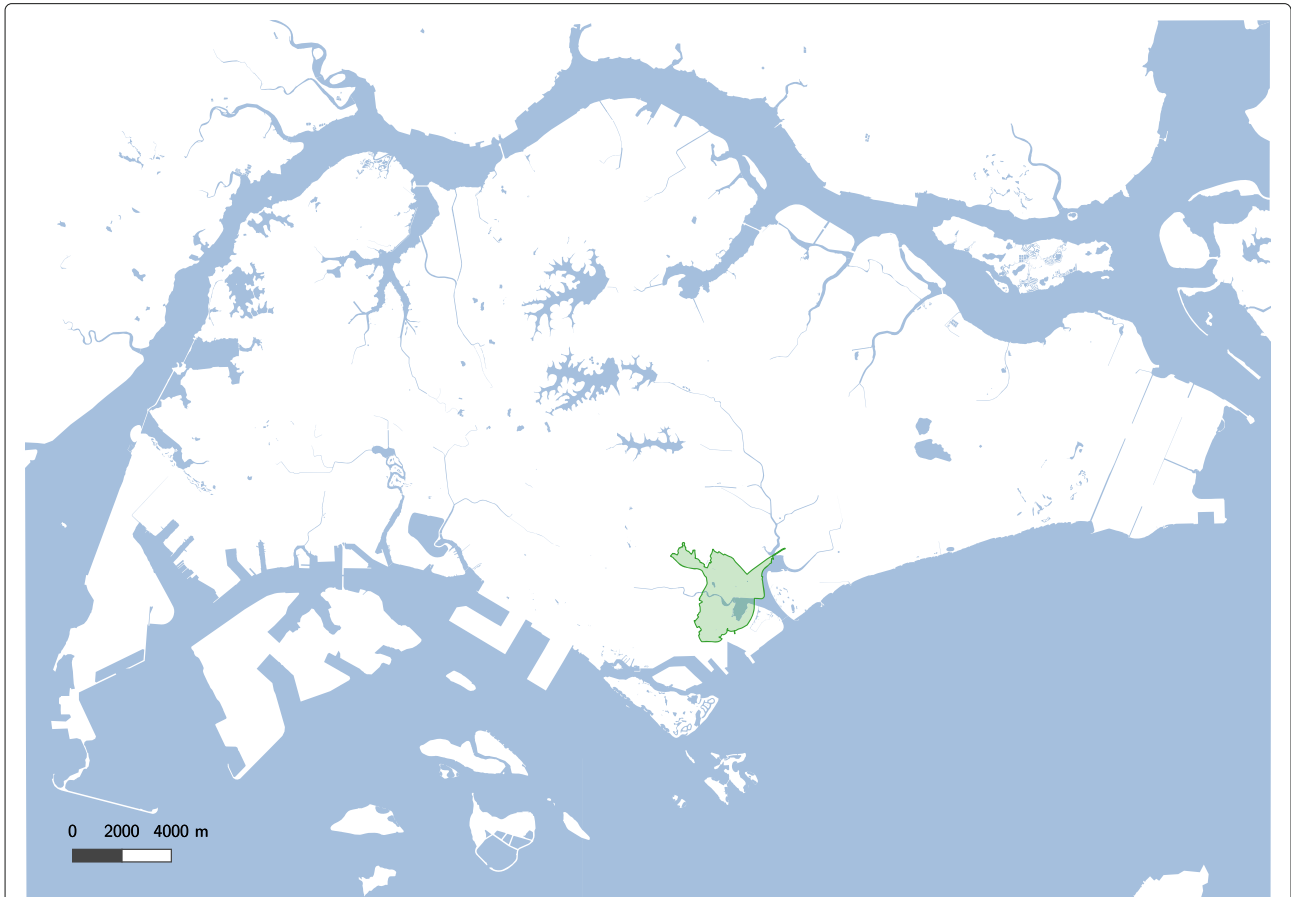$$\forall a_{ij} \in A, t \in T: \qquad \psi_{ijt} + \psi_{jit} \leq 1 \qquad (13)$$

Fig. 4 Study region within Singapore. The green outline shows the location of the CBD study region within the extent of Singapore. It covers the Marina Bay and follows Orchard Road to the north west

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Build capacity limits the pipe capacity variables to the maximum available diameter, whose capacity in kW is represented by parameter $C_{ij}^{\max}$. At the same time, this constraint sets the value of the building decision variable ξ_{ij}, if a non-zero pipe capacity $\bar{\pi}_{ij}$ is needed.

$$\forall a_{ij} \in A: \qquad \overline{\pi}_{ij} \leq \xi_{ij} C_{ij}^{\max} \qquad (14)$$

Symmetry of building decision are two constraints that enforce that the mathematically independent arcs a_{ij} and a_{ji} must have identical variable values for their pipe capacity $\bar{\pi}_{ij}$ and building decision ξ_{ij}. This way, a pipe can then be used in both directions at different time steps.

$$\forall a_{ij} \in A: \qquad \xi_{ij} = \xi_{ji} \qquad (15)$$
$$\forall a_{ij} \in A: \qquad \overline{\pi}_{ij} = \overline{\pi}_{ji} \qquad (16)$$

Use if built is the last piece in the puzzle to link the building decision ξ_{ij} to the pipe usage decision ψ_{ijt}. Up to this point, nothing in the formulation requires that the cooling demand of a customer is satisfied *at all times*. This constraint enforces exactly that, by requiring that the sum of $\psi_{ijt} + \psi_{jit}$ is greater or equal to 1, if a pipe is built along that arc. Otherwise, the condition should not be enforced. This is done by calculating the expression $(\xi_{ij} + \xi_{ji})/2$. It is equal to 1 if $\xi_{ij} = 1$, as Eq. (15) requires $\xi_{ij} = \xi_{ji}$. Otherwise, its value is equal to 0. In other words: if an arc is has a pipe, its demand must always be satisfied by a power flow from any of its two sides.

$$\forall a_{ij} \in A, t \in T: \qquad \psi_{ijt} + \psi_{jit} \geq (\xi_{ij} + \xi_{ji})/2 \qquad (17)$$

Source vertices is the last constraint. It limits the source vertex power flow ρ_{it} by its maximum allowed capacity $Q_i^{\max}$. The availability parameter y_{it} *usually* has value 1, except for special time steps in which the source vertex v_i is made unavailable by setting $y_{it} = 0$:

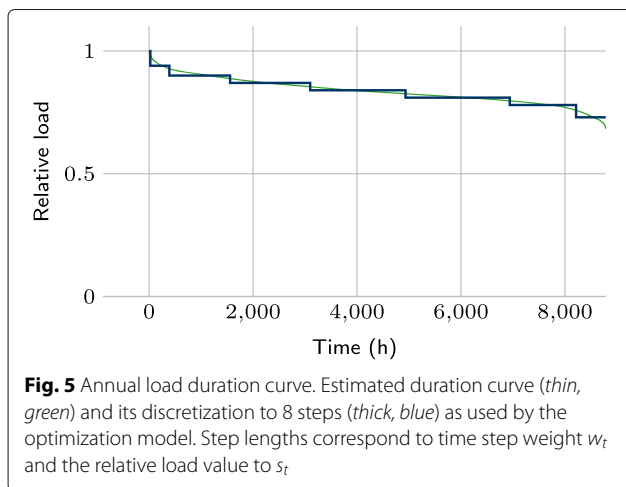$$\forall v_i \in V, t \in T: \qquad \rho_{it} \leq y_{it} Q_i^{\max} \qquad (18)$$

Table 4 Total floor area and cooling peak load by building type

Building type	Peak load (W/m^2)	Floor area (10^3 m^2)
Civic & community institution	112.5	529
Commercial	112.5	6685
Commercial & residential	100	1021
Educational institution	112.5	175
Health & medical care	125	40
Hotel	112.5	1605
Open space	0	22
Park	0	58
Place of worship	0	137
Reserve site	0	157
Residential	112.5	717
Residential/commercial (1st storey)	112.5	357
Sports & recreation	75	15
Transport facilities	0	29
Utility	0	43

Equations 2 to (18) together define a linear mixed-integer program, whose optimal solution is the desired vector of pipe capacities $\bar{\pi}^{\star}$, accompanied by optimal cooling power flows.

Case study

The presented model is applied on a potential supply area in the central business district of Singapore, as shown in Fig. 4. The first part describes how the input parameters were derived. Then the assumptions for a sensitivity analysis against conventional per-building cooling are described.

Fig. 5 Annual load duration curve. Estimated duration curve (*thin, green*) and its discretization to 8 steps (*thick, blue*) as used by the optimization model. Step lengths correspond to time step weight w_t and the relative load value to s_t

Table 5 Parameter values in case study

Name	Value	Unit
c_{fix}	7000	S\$/m
c_{var}	8e-4	S\$/(m kW)
c_{om}	80	S\$/(m a)
c_{rev}	0.14	S\$/kWh
w^{fix}	0.01	kW/m
w^{var}	1e-8	kW/(kW m)
b	0.9	—
q	1.0	—
u	0.091	1/a
c_i^{cool}	0.03 or 0.07	S\$/kWh

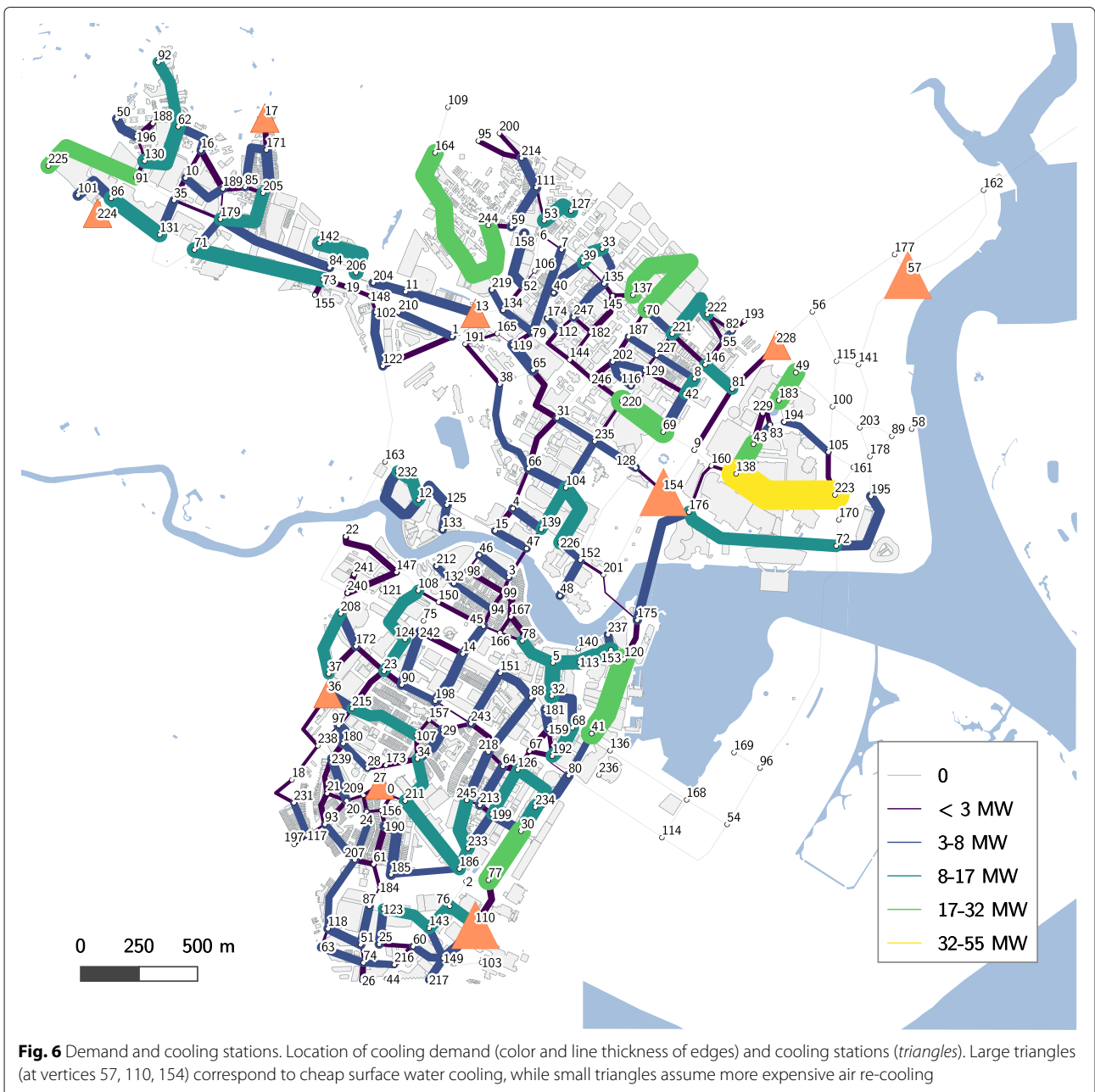Dorfner *et al. Future Cities and Environment* (2017) 3:1

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Load profile estimation

Due to lack of access to a load profile from Singapore, a known cooling load from Munich was extrapolated based on weather data in Singapore.

The district cooling system of Munich has mostly non-residential customers like shopping malls, offices, congress centers and smaller retail trades. Its usage type composition is therefore rather similar to Singapore's CBD. However, the buildings are much smaller and thus have a different surface to volume ratio and surface materials than the much higher buildings in Singapore's CBD.

To record and to utilize the optimization potential of this expanding system, in a detail data analysis a question amongst others was examined on which factors the customers cooling demand is depending. Furthermore the collected data serve as basis for the evaluation of the cooling demand in other cities like Singapore. Based on a period of two years up to 2015 the influence of temperature, humidity, insolation and the customer behavior itself was analyzed.

The strongest influence on the cooling demand is the temperature. The humidity plays a subordinated role in

Fig. 6 Demand and cooling stations. Location of cooling demand (color and line thickness of edges) and cooling stations (*triangles*). Large triangles (at vertices 57, 110, 154) correspond to cheap surface water cooling, while small triangles assume more expensive air re-cooling

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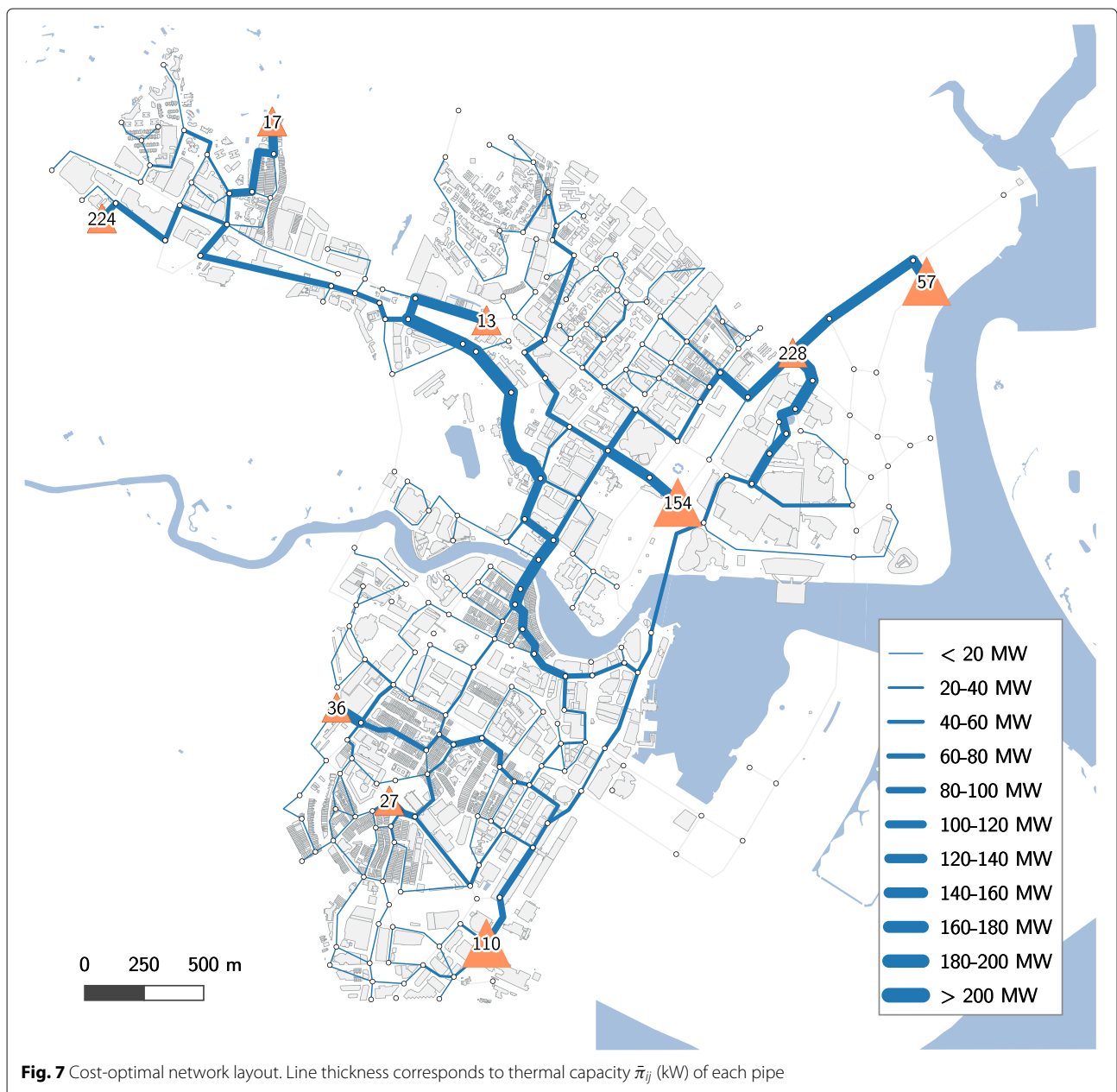
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Munich (but not in Singapore), cause of the temperate climate zone and the previous low dehumidification in the comfort zones. To count in this factor to the further customer and grid extension, the enthalpy of the outside air, as an index for the heat input to the buildings, is used as leading control parameter. The insolation has no considerable influence on the customers' requirements because of the good insulation of the rather new buildings and the shading situation in the densely built city center.

The second strongest influence factor on the cooling demand of the Munich costumers are the business hours. Due to the simultaneous public traffic in the shopping areas and offices as well as the highly volatile temperature profile of a day, the cooling demand is five times higher during the day than at night or on a holiday. This characteristic day-night cycle are also recorded in other Central European cities ([24], pp. 8, 80).

Using the high cooling demand during the business hours and the enthalpy dependence, a trend was generated for the customers' requirements. This trend line is combined with the climate records of Singapore to create an approximated annual load duration curve, shown in Fig. 5.

To reduce the temporal resolution for the optimization model to manageable sizes, this curve is discretized to 8

Fig. 7 Cost-optimal network layout. Line thickness corresponds to thermal capacity $\bar{\pi}_{ij}$ (kW) of each pipe

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individually weighted time steps, also shown. One 24 h long time step represents peak demand, while the other 7 steps have durations ranging from 390 h to 2006 h.
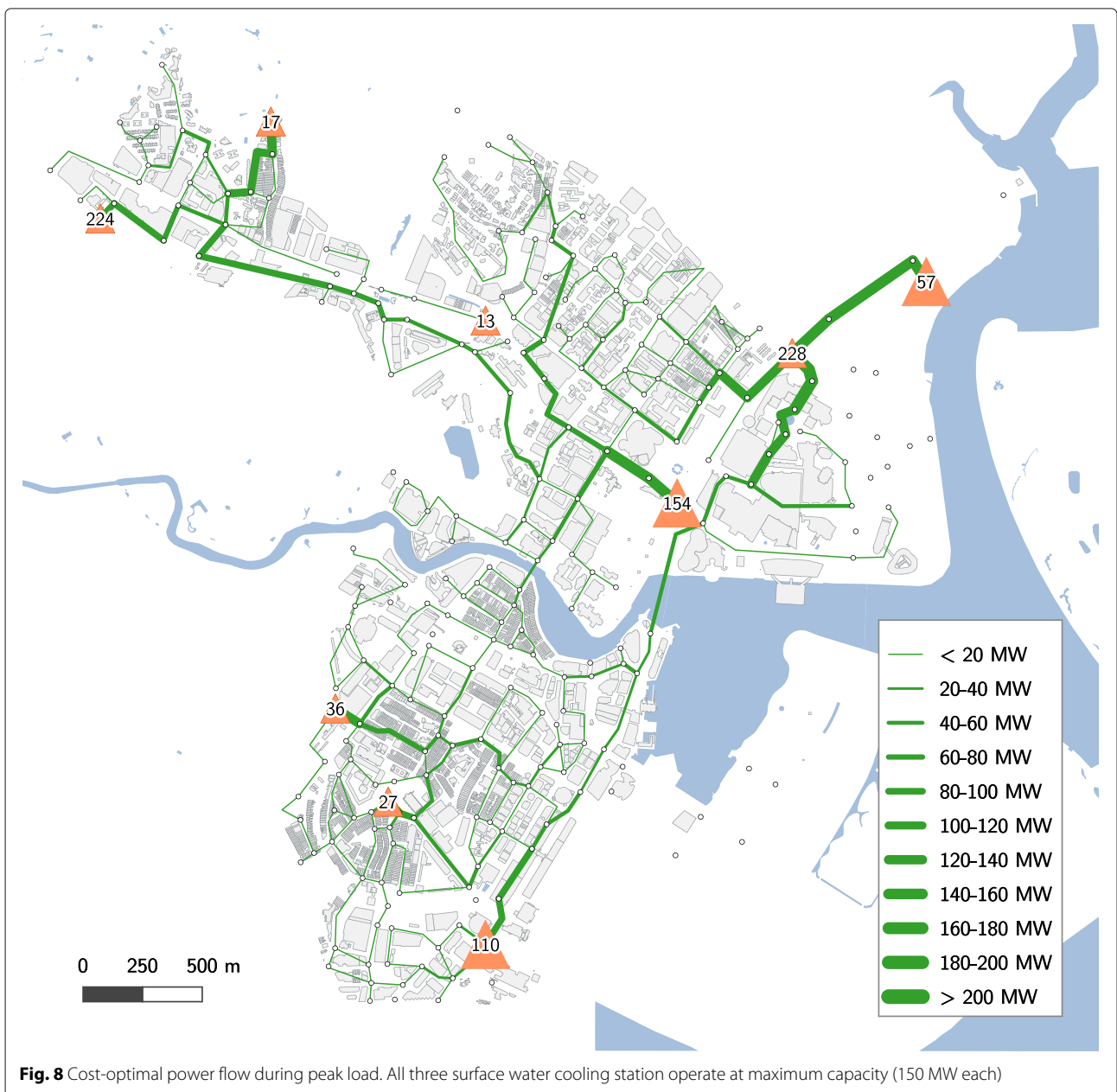
Annual cooling demand

Cooling demand is estimated based on previous work conducted by Böhme et al. [25]. There, a geographic dataset of buildings with gross floor area and usage type was prepared. The total floor area by building type (e.g. residential, commercial, ...) is summarized in Table 4. It also states the assumed design cooling loads, based on a mean design load of 112.5kW/m^2, estimated from

PengKee [8]. Building or area types with small total area were ignored. With those assumptions, a total summed peak cooling demand of 1241MW exists in the case study area.

Input data

The street graph is derived from OpenStreetMap data [26], processed using previously described [22] pre-processing steps using polygon skeletonization for simplifying the dense street network.

Cost data (given in S$) and technical parameters for this case study are summarized in Table 5. Pipe investment

Fig. 8 Cost-optimal power flow during peak load. All three surface water cooling station operate at maximum capacity (150 MW each)

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costs of 7000 S\$/m are the main cost driver on the supply side. This value is scaled to one year with an annuity factor

$$u = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{19}$$

with interest rate $i = 6.5\%$ and depreciation duration $n = 20a$, yielding a value of 0.091. Operation & maintenance are relatively cheap with annual 80 S\$/m. Cooling cost depends on the location of the cooling station. The large triangles in Fig. 6 show stations with access to surface water, which allows cheap re-cooling with an assumed

cost of 0.03 S\$/kWh. The other six cooling stations have higher costs of 0.07 S\$/kWh.

Scenarios
Base case
The base case is designed to show today's demand situation. In this scenario, the size and layout of a profitable district cooling network is to be determined.

In the base case, a revenue of 0.14 S\$/kWh is assumed. A sensitivity analysis with reduced revenues in steps of 0.02 S\$/kWh is also conducted to determine how sensitive the optimal network size is on the price for cooling.
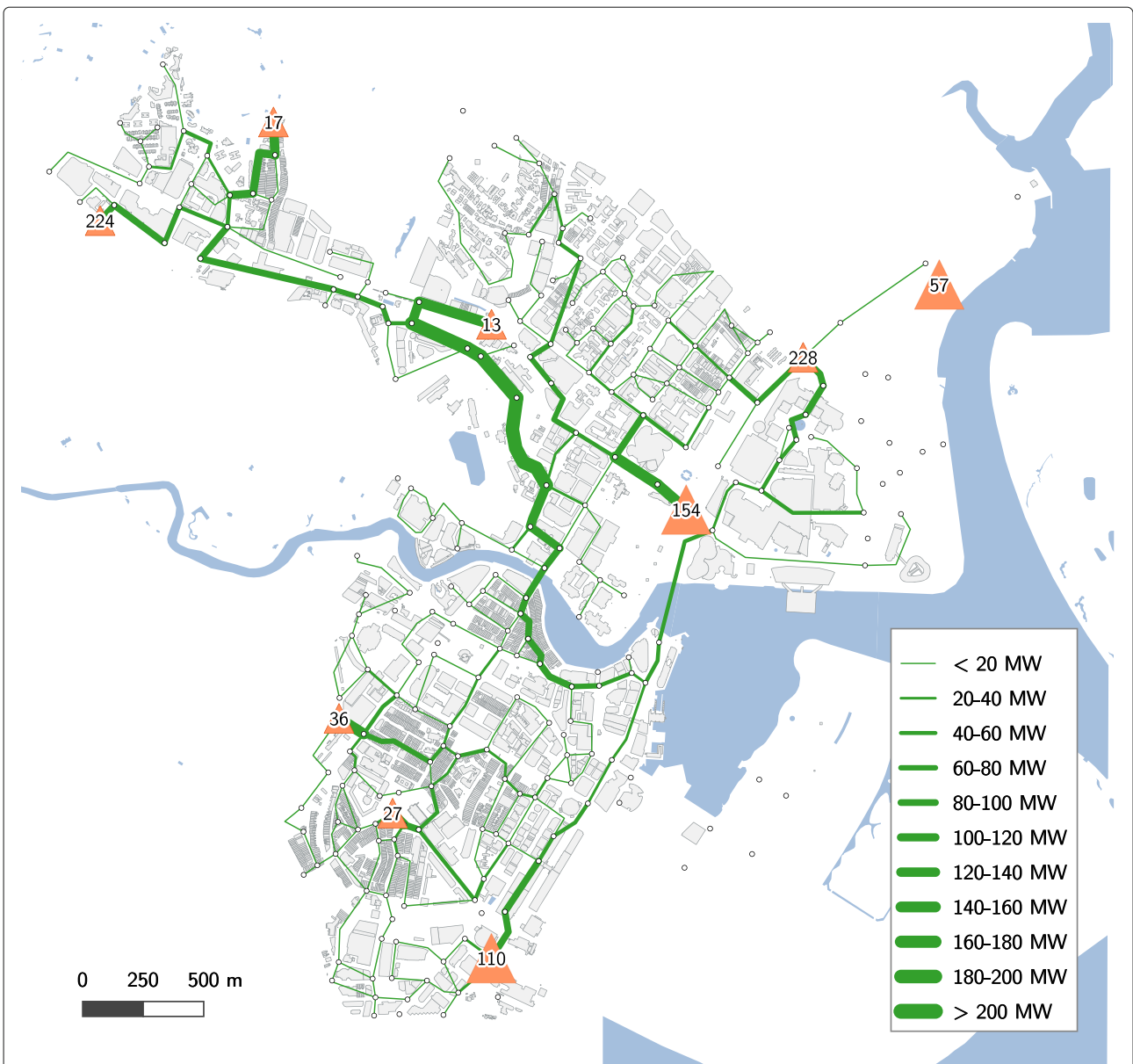
Fig. 9 Power flow during outage of cooling station at vertex 57. In this situation, the large pipe capacities south of vertex 13 are needed to transmit backup cooling power from the western three cooling stations to the central bay area

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Growing demand

In order to assess how the total cooling costs (generation and distribution) are affected by a possible demand growth in the study area, additional load is introduced in the edge (54, 114) in the south-eastern corner. It's value is changed from 0MW to 200MW with steps of 50 MW. As this step creates more load than the existing cooling stations could satisfy while satisfying the redundancy constraint, all cooling stations' capacity is increased by 50%.

Results

Base case

The resulting network for the base case is shown in Fig. 7. It shows a district cooling network that satisfies almost all (1240MW of 1241MW) cooling demand. In other words: under the presented cost assumptions and a cooling revenue of 0.14 S$/kWh, district cooling is an economically viable strategy. A sensitivity check with a reduced cooling revenue of 0.10 S$/kWh still leads to an almost full saturation of 1237 MW supplied demand. The unsatisfied demands are mainly short, isolated edges with low demand ($\leq 3MW$) that cannot offset the network investment cost. Only when revenue is further reduced, between 0.08 and 0.06 S$/kWh, the optimal network drops from satisfying 1200 MW to 0 MW. This value range thus can be taken as a lower bound for profitability of a district cooling system (under the given cost assumptions).

Figures 8 and 9 compare the cooling power flow in two of the 18 time steps considered for designing the network capacities in Fig. 7. The first situation shows the cost-optimal cooling power flow when all cooling stations are operational. The three cheap cooling stations (57, 110, 154) are delivering their full capacity of 150 MW each, while several of the other stations only run in partial load. The second situation in Fig. 9 shows how the redundancy requirement leads to the consideration of very different flow situations. Here, cooling station 13 now runs at full capacity and satisfies the middle of the study area.

Growing demand

The resulting cooling cost for gradually increasing the demand in edge (54, 114) for each case is shown in Fig. 10. The cooling cost here is calculated by dividing total costs for generation and network by the amount of provided cooling (in kWh). Cost for cooling grows slightly – along with demand – from approximately 0.045 S$/kWh to 0.048 S$/kWh in the case of additional 200MW peak cooling demand. This increase is caused by a higher utilization of the more expensive 0.07 S$/kWh cooling stations. The specific network costs actually exhibit a minor reduction as demand grows, but this effect is negligibly small here.

Fig. 10 Specific cooling costs for growing demand with original 0.03 and 0.07 S$/kWh cooling stations. Cost increase is caused by higher utilization of expensive cooling stations
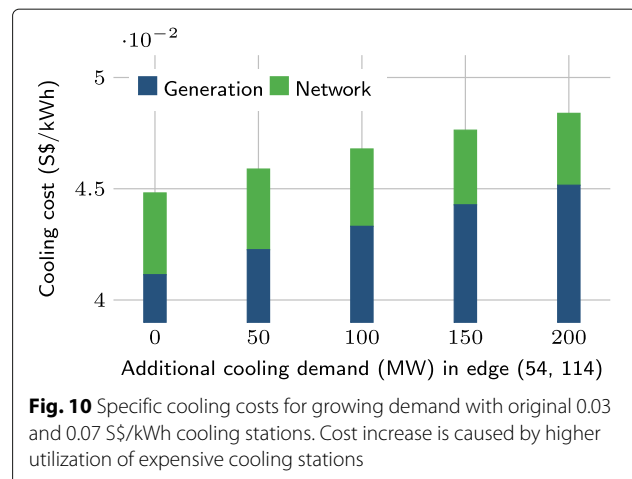
Discussion and future research

District cooling can be an attractive option for cities with constant high cooling load, compared to less efficient distributed cooling. The high demand density of Singapore's CBD makes it a very well suited candidate. Direct access to surface and seawater provides enough cooling potential to satisfy a significant fraction of the present cooling loads.

As Singapore is planning to establish further dense commercial areas similar to the CBD with many office blocks, e.g. in Jurong, more regions will become suitable candidates for district cooling. Moreover, the potential of district cooling could also be evaluated for densely populated residential areas, e.g. Bukit Panjang or Punggol.

The redundancy requirements on cooling stations could need refinement, possibly by relaxing the full (n-1) capability for the whole system to only certain areas. An extension could introduce the same requirement not only to cooling station, but also to crucial parts of the network.

Authors' contributions
JD developed and applied the optimization model to the case study. PK lead his expertise in planning district cooling networks to provide input data and scenario definitions. MD contributed the method for deriving the annual load duration curve. TM provided data for the case study region and vetted model results against local experience. All authors collaborated for writing the article. All authors have read and approved the final submitted manuscript.

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