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Integrated energy planning for historic city centres in the Netherlands

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Abstract

Purpose – The municipality of Amsterdam has ambitious goals to be natural gas-free by 2040. A major challenge is the heat transition of the historical centre, which dates to the early 17th century and is in parts listed as a UNESCO World Heritage site. The purpose of this paper is to introduce a design workflow that can aid in designing future scenarios for the transition of historic city centres. Inspired by the New Stepped Strategy, the workflow is based on Geographic Information System (GIS) data, bottom-up energy modelling and parametric tools and presents the results in a neighborhood of Amsterdam city centre.

Design/methodology/approach – The first step is the identification of conservation-compatible retrofit packages, allowing buildings to be heated at lower temperatures, while preserving historic values, improving indoor thermal comfort and minimising environmental impact. Best-balanced retrofitting scenarios are subsequently integrated within the broader urban context, considering opportunities for reusing energy waste streams and producing energy from local, low-temperature sources. In the end, optimal energy balance along with the strategic integration of thermal storage systems is assessed and used as input for the configuration of local heat and cold grids.

Findings – By combining expertise in architecture and energy planning, the workflow supports the exploration of scenarios that align heritage conservation with sustainable heat transition objectives.

Originality/value – The paper describes how this can provide essential information to local stakeholders and citizens groups, guiding them on the necessary steps to drive the collective transition to sustainable heating and cooling in historic urban areas.

Keywords Decarbonisation strategy, Built heritage, Decision-making, Local thermal grid, Local sources, Sustainable city

Paper type Research article

1. Introduction

1.1 Context

The majority of the built environment in the Netherlands continues to rely on high-exergy and carbon-emitting fuels, such as natural gas, for heating purposes (CE Delft, 2022). Although these fuels can reach temperatures as high as 1,500 °C, the requirements for heating domestic

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hot water (DHW) and living spaces are considerably lower, typically around 55 °C for DHW and 21 °C for living spaces. The use of high temperature (HT) or medium temperature (MT) heat from geothermal sources and industrial waste heat is a common strategy for promoting the decarbonisation of heating systems. Some newer districts on the outskirts of Amsterdam already make use of residual heat from industrial processes like waste incineration and electricity production but still use some additional natural gas. Insulated pipes with large diameters bring heat of 90° or more to the buildings.

Cities, such as Maastricht, Breda, and Utrecht, plan to expand their district heating networks towards their historic city centres (Gemeente Maastricht, 2021; Gemeente Breda, 2021; Gemeente Utrecht, 2021). However, city centres are not always within reach of these networks or there may not be available space underneath the small streets to have these pipes next to the other infrastructure. Municipalities may choose to keep these areas connected to the gas grid, with the expectation of significantly reducing demand and incorporating locally produced "green" gas. This strategy is seen in policy documents, also known as "Heat Transition Visions", for historic centres of cities like Amsterdam, Haarlem, Leiden or Delft (Gemeente Amsterdam, 2020; Gemeente Haarlem, 2023; Gemeente Leiden, 2022; Gemeente Delft, 2021). There is no clear roadmap on how to achieve these heating demand reductions, given the complexity of built heritage and the monumental restrictions. Additionally, recent research shows that hydrogen and biogas resources are limited, expensive and not as environmentally friendly as initially perceived (Korberg *et al*., 2023; Weidner and Guillén-Gosálbez, 2023; Miedema *et al*., 2018).

1.2 Energy planning in historic city centres in the Netherlands: challenges and opportunities

The preservation and revitalisation of old city centres present unique challenges and opportunities in urban planning, particularly in the context of transitioning towards carbon neutrality:

(1) *Retrofitting built heritage:* Historic city centres are characterised by a high density of protected built heritage, making large-scale deep energy retrofits difficult to implement due to the need for preservation of heritage values. Previous research highlights the importance of promoting the integrity of cultural heritage by ensuring that decisions about change involve an understanding of the values involved (Rosetti *et al*., 2022). This built heritage is often highly valuable for residents and stakeholders and may serve as a source of income through tourism. These buildings are essential in representing the cultural identity of the city and play an important role in the socio-cultural fabric of the city. However, building envelopes are typically moderately to poorly insulated and integrating air-source heat pump can be challenging because of noise pollution and potential conflicts of the outdoor unit with street view protection. When integrating energy-efficient measures, it is important to respect the integrity of the historic construction and to consider the high sensibility of the materials to condensation and mold growth. In this context, one opportunity is to revitalise traditional techniques and skills and explore the potential for contemporary applications such as for energy retrofitting (Council of Europe, 2009). Bio-based materials and products that can be reused should also be considered for renovation and transformation of the buildings.

(2) *Space and energy infrastructure:* In dense city centres, there is often a lack of space for new energy infrastructure. Infrastructure below the street level may be old and under pressure. Special attention must also be paid to the planning of seasonal storage systems, specifically Aquifer Thermal Energy Storage (ATES). The growing adoption of ATES in urban areas of the Netherlands has resulted in a high concentration of ATES systems in urban aquifers, often reaching levels of

congestion. For example, in densely populated area like Amsterdam area, the availability of subsurface space may become limited in the future due to the competing priorities of accommodating as many systems as possible while also maintaining sufficient distance between individual wells to prevent mutual interference (Bloemendal *et al.*, 2014).

(3) *Historic canals:* Initially designed for drainage and transportation purposes, canal networks were integrated into the urban planning of historic districts in Amsterdam, Utrecht, and Leiden. Streets were laid out in a grid pattern intersected by waterways. The municipality of Amsterdam has estimated that the potential for thermal energy from surface water is about 15 PJ, which is sufficient to supply 40–60% of the total heat demand of the city (Ruijs, 2019). Generating thermal energy from canal networks in historic city centres is an overlooked opportunity. Recently, Amsterdam has identified 200 kilometres of historic quay walls that need renovation or renewal. By thermally activating the new quay walls during the structural works of canal wall replacement, it would be possible to provide sustainable energy for nearby buildings. The heat can be collected in the summer, stored in the subsurface using ATES, and then used in the winter when the heating demand is at its peak. If desired, the opposite process can be applied for storing cold in winter and using it in summer, instead of relying on air conditioning systems to cool down buildings. By harnessing this heat, the inner city would heat up less, providing additional health benefits.

(4) *High-density and heterogeneous areas:* City centres are usually high-density, compact areas with limited greenery and high competition for space. Historical market squares and open inner-yards are other characteristics found in these areas, with streets generally being narrow. Land use typically consists of a mix of different functions with varying energy patterns, offering an opportunity for shared energy systems. There is potential to optimise energy efficiency by identifying opportunities for direct heat exchange, such as thermal load overlap (e.g. simultaneous heating and cooling) between buildings. The Green Light District research, conducted in the city centre of Amsterdam, shows that area has considerable potential for renewable energy from both natural and anthropogenic sources such as solar heat, heat from biomass, aquathermal energy from open water, or waste heat from cooling processes which is presently released into the air (Fremouw and Dobbelsteen, 2021). While it may be challenging to install new piping infrastructure in small streets with cobblestone pavement, making it approximately three times more expensive than outside the historic city (Henning, 2011), city centres could be well-suited due to high density of consumers. Further research is needed to explore the potential of source networks in historic city centres. This integration would involve exchanging heat and cold from local sources to local consumers, connecting them to local heat and cold storage, and relying as much as possible on low-temperature heating and high-temperature cooling with the help of heat pumps.

1.3 5th generation district heating and cooling networks

The recent development of Low-Temperature (LT) and small-scale networks, also known as 5th generation heating and cooling (5GDHC) networks, facilitates the integration and exchange of LT waste heat sources among different buildings (Gjoka *et al.*, 2023; Jansen *et al.*, 2021). Unlike previous generations of networks that supplied residual heat at HT, the 4th and 5th generations are characterised by LT (~60 °C) to Ultra LT (~45 °C) from sustainable energy sources, often combined with thermal energy storage. The lower supply temperature enables the use of multiple LT heat sources such as solar thermal energy, residual heat from cooling processes or aquathermal energy. Ideally, local heat and cold demands are balanced throughout the neighbourhood to reduce the need for additional supply. Centralised or decentralised heat pumps raise the supply temperature depending on the level of insulation of the buildings. These systems operate at significantly lower temperatures leading to lower distribution heat losses in transport and shorter distances.

Building heat losses can be mitigated through insulation and minimising ventilation losses, although this may not always be feasible for buildings of historical significance. Reusing energy by storing heat collected with photovoltaic-thermal (PVT) panels in a collective ATES during the cooling season is also an option. During the heating season, this stored heat can be used as a source for the heat pump, making it more efficient due to the higher source temperature. Simultaneously, the building can be passively cooled in the cooling season by using the cold source from the ATES, which is cooled by the heat pump during the heating season. Using the heat pump to heat a Domestic Hot Water (DHW) boiler and installing LT heat release equipment such as floor or wall heating, or low-temperature convector radiators allows for disconnection from the gas grid, resulting in annual savings on fixed delivery costs and network management costs. These systems offer the added benefit of passive cooling with minimal electricity usage.

One major advantage of 5GDHC network is the flexibility to an incremental approach (Boesten *et al*., 2019): houses in a neighbourhood can be gradually upgraded over many years. Connected buildings can have a post-heating facility – a heat pump, electric heater or green gas – which might gradually become redundant when building owners are able to thermally insulate their building better. The network can be conceived as modular and new connections can be added when budget is made available. Starting with small clusters, for example for a building block, the network can be expanded by connecting these local clusters to each other to exchange heat and cold.

5th generation heat grids require space for heat pumps, thermal storage systems, and grid infrastructure, and must be carefully integrated into the urban landscape. In the Netherlands, this type of networks is typically designed for new urban developments, and there is limited information available on historic districts, including their spatial integration.

1.4 Examples in the Netherlands

Although historic city centres are often compact and the buildings have large heat losses because of the lack of insulation, ventilation- and infiltration losses, there are still opportunities for 5GDHC networks based on the local potentials. Measures must be taken on several scales and integrated, from building till urban level. Due to the innovative nature of such networks, there are limited projects in the Netherlands. An example is the “Mijnwater” project in Heerlen, where residual heat of approximately 30 °C is extracted from a data centre and supermarket cooling systems. This heat is either used directly by heat pumps or stored in underground mineshafts and tunnels filled with groundwater, located 500 meters below ground level. The consistent “natural” temperature of 30 °C in this environment minimises heat loss throughout the year. The ATES systems serve as a collective source for multiple heat pumps. Another project, the “Zonnewarmte-project Ramplaankwartier” in Haarlem, involves connecting individual residences equipped with PVT panels to a low temperature grid that exchanges heat and cold. This grid is also linked to an ATES system for seasonal storage of heat and cold. The development of this project includes active engagement with residents to ensure successful implementation.

The local situation and potentials determine the network, its sources, components and spatial integration. Heerlen has coal mines for thermal energy storage and the buildings that are connected are offices and dwellings, mainly new build and well-insulated. Haarlem has a lot of dwellings built in the 20th century, often not well insulated, but a lot of roof surface for PVT panels and groundwater-aquifers for heat and cold storage.

1.5 Research objectives

The decision to become free of natural gas by 2040 raises questions about defining alternative heating systems for the existing built environment, the selection process, related decision criteria, responsible and relevant actors, and implementation timelines. This is especially challenging in a mixed, dynamic, multi-level urban environment such as historic city centres. Although similar transition processes have occurred in the past in different countries, the acceleration in the integration of climate-neutral heating systems is still lacking. With diverse ownership structures and perspectives of stakeholders, coupled with the freedom of choice granted to small and medium business owners and citizens, decision-making processes for new heating and cooling systems may not be optimal. Actors are currently not equipped with the information and knowledge to make effective decisions, and it is reported to be unlikely for the Netherlands to reach climate goals regarding the built environment in 2030. Reasons for this delay include factors such as a changing regulatory framework in the heating sector and public resistance to top-down pressure for expanding heat grids. There is a lack of basic understanding and information regarding: (1) the heat and cold demand of existing buildings per housing unit and function, (2) the available market solutions for energy retrofitting and sustainable heating and cooling systems, and (3) the dependencies involved in the delineation and performance of a collective solution.

Since 5th generation heating and cooling networks are designed to match specific local conditions, it is also not feasible to implement a "one-size-fits-all solution". The characteristics, level of insulation of the buildings, and spatial limitations of each neighbourhood dictate the configuration of the system. While open data offer a wealth of information for the initial exploration phase, there is a shortage of digital tools to guide the transition process towards optimal, collective infrastructures that can adapt over time. Finding optimal solutions is a time-consuming process that requires the development of tailored plans considering local potentials and limitations, thereby presenting a recurring challenge for local stakeholders.

Computational design methods could facilitate this process and parametrically analyse features of the area and define most efficient plans for clustering buildings. The purpose of this paper is to introduce a design workflow using Open geographic information system (GIS) data in QGIS, Rhinoceros 3D software tools, and Grasshopper, combined with multiple plugins, for the creation of algorithmic designs that can aid designing future scenarios for the transition of historic city centres. The present paper illustrates this design workflow with the preliminary results of the use case of Leliegracht, a neighbourhood located in Amsterdam city centre.

2. Materials and method

2.1 Design workflow and definition of the use case

The Amsterdam Guide to Energetic Urban Planning (in Dutch: Leidraad Energetische Stedenbouw LES), based on the Rotterdam Energy Approach & Planning (REAP) and the New Stepped Strategy (Kürschner *et al.*, 2011; Tillie *et al.*, 2009; Dobbelsteen, 2008), offers a step-by-step plan that indicates when, how, and to what extent specific measures can be applied on new and existing buildings. The steps are (1) "Research" the current energy demand, (2) "Reduce" the energy demand with post-insulation measures, windows replacement, or equipment upgrade, (3) "Reuse" waste energy streams by making optimal use of residual heat within and between buildings, and (4) "Produce" sustainably from local energy sources. Inspired by the New Stepped Strategy, the proposed design workflow, as depicted in Figure 1, begins with the simulation of energy retrofitting scenarios using Ladybug Tools (v. 1.6.0).

The selection of retrofitting packages is conducted via Design Explorer (v. 2). Demand data on the preferred retrofitting scenarios, along with additional datasets on potential sustainable heat and cold recovery or generation, open space, existing ATES systems, and building morphology, are pre-processed in QGIS before being sent to a clustering model. Using

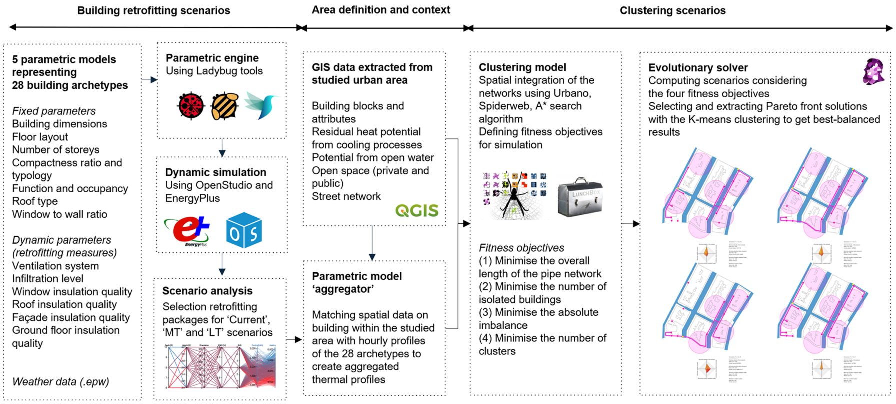

Figure 1. Overview of the design workflow (Dang, 2024)

evolutionary multi-objective optimisation methods, the model then provides the pareto front solutions for clustering buildings in the area based on an initial problem definition. For this paper, these objectives are set to minimise the overall length of the network, minimise the number of isolated buildings, minimise the absolute heat and cold imbalance within each cluster and minimise the number of clusters. Finally, users can compare scenarios and gain a better understanding of the trade-offs between different plans. This design workflow was tested on "Leliegracht", a neighbourhood located in Amsterdam Centrum. The area is situated on the western part of the "Grachtengordel", which was designated as a UNESCO World Heritage site in 2010 (Figure 2).

Figure 2. Location of Leliegracht neighbourhood in Amsterdam city centre (Dang, 2024)

Most buildings were constructed before 1900, with over 88% of the addresses having the highest level of protection, known as "orde" 1 (Gemeente Amsterdam, 2023). This densely populated and protected area consists of approximately 1,200 residential addresses and 285 non-residential addresses, including restaurants, cafes, shops, offices, hotels, and industrial functions. The neighbourhood is approximately 17.2 ha and counted about 1,870 inhabitants in 2024 (Amsterdam Onderzoek, 2024). In the following sections, the paper describes the materials, method and design considerations for each step of the workflow.

2.2 "Reduce" step or generating building retrofitting scenarios for heritage buildings

Bottom-up models are widely used to estimate and compare savings and the potential reduction of CO2 emissions of different energy retrofitting scenarios (Swan and Ugursal, 2009). In the case of the analysis of an area with multiple buildings, it is necessary to define a representative cross-section of the building stock. This consists of identifying the attributes of the selected buildings such as the function, construction year, typology, compactness ratio and determining a series of archetype buildings as reference objects for the simulation. Open GIS data provided by the Municipality of Amsterdam and the National register of addresses and buildings (in Dutch BAG "Basisregistratie Adressen en Gebouwen") were used to extract such statistical data. 28 different building archetypes were assigned with specific geometrical features and technical properties. The parametric models with housing function were calibrated and validated using reference values from available datasets of past research projects on sustainable housing heritage, "Collect Your Retrofits" and "Green Light District," within the Faculty of Architecture and Built Environment at Delft University of Technology (Dang *et al*., 2023). For the validation of non-residential building archetypes, existing model calculations from the Netherlands Enterprise Agency (in Dutch: Rijksdienst voor Ondernemend RVO) and Statistic Netherlands (in Dutch: Centraal Bureau voor de Statistiek CBS) were used (Agentschap, 2011; CBS, 2024).

Balancing conflicting design criteria of energy reduction versus conservation principles is essential to best evaluate retrofitting strategies. Using parametric engine Ladybug tools in Grasshopper, it is possible to compute of all possible retrofit scenarios for each building archetype as well as their associated impact on energy performance and thermal comfort as shown in earlier work described in (Dang *et al.*, 2024). From a very broad range of interventions, it is possible to filter out solutions according to the level of monumental protection, which specifies restrictions such as "measures must remain invisible from the protected street view" or "monumental windows cannot be altered". After narrowing down the number of options and thanks to this iterative approach, it is possible to get a better understanding on what insulation levels are excessive, what measures are most effective and what are the minimum requirements for achieving specific sustainability targets, while considering monumental restrictions. By assessing the minimum amount of insulation needed, it helps saving on materials and costs, which can have a significant effect on the building's embodied carbon footprint. Figure 3 illustrates that process of comparing the outputs of multiple retrofitting scenarios in Design Explorer.

For the performance indicators, the Municipality of Amsterdam estimates that buildings with a yearly heat demand below 80 kWh per square meters of floor area can be comfortably heated with a heat system which delivers heat at Medium Temperature (MT) and 50 kWh per square meters for LT systems (Gemeente Amsterdam, 2020). For each archetype, the hourly demand profile in heat and cold for "Current", "MT-ready" and "LT-ready" scenarios were refactored using the useable surface of each address from BAG dataset. The thermal profiles were subsequently used as input into the clustering parametric model to assess the heat and cold imbalance for each building cluster on the neighbourhood scale. Historic buildings are usually difficult to upgrade to a LT level, making hybrid solutions (e.g. a heat pump covers partly the heating demand) an interesting alternative. It is important to keep in mind that beyond the monumental status system and the date of construction of the building, other factors can potentially influence the range of options available for each building. Historic buildings may

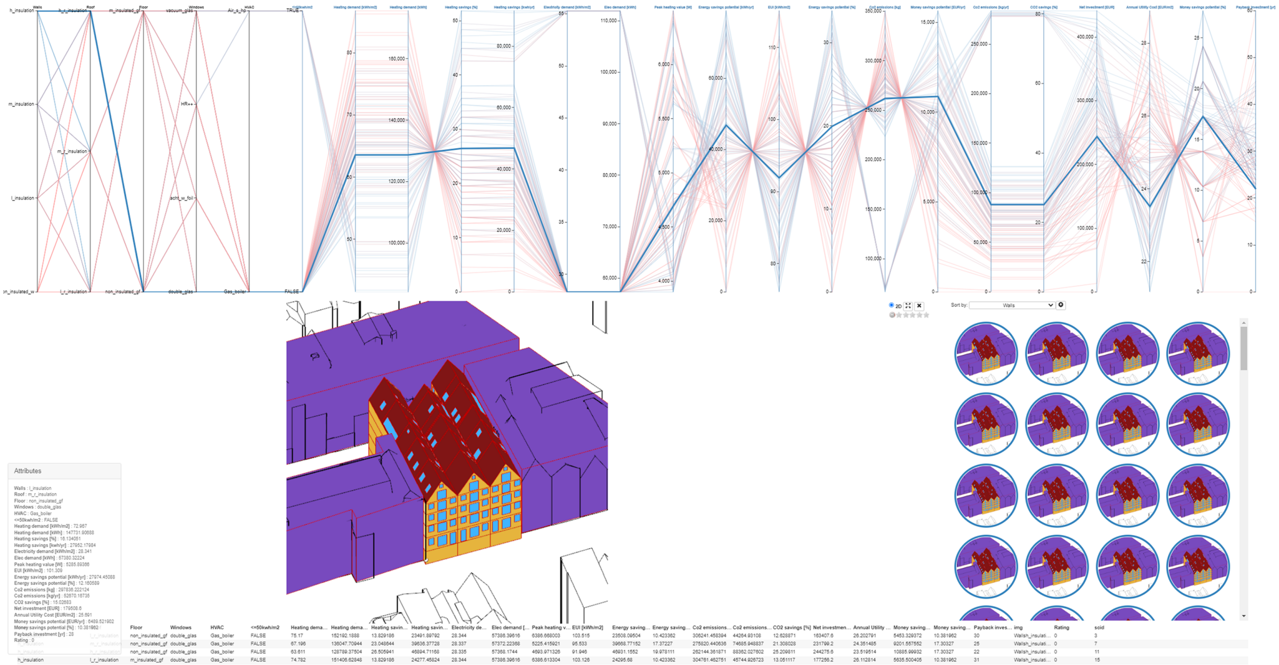

Figure 3. Visualisation of the different energy retrofit scenarios for an example heritage building of 23 residential units. Each line represents one scenario, or combination of measures, with impacts on energy savings, peak heating demand or reduction in operation CO2 emissions (Dang, 2024)

have been renovated several times and these transformations may concern the entire house or only parts. In this step, the worst scenario per building archetype was considered.

2.3 The "reuse" of waste heat from cooling processes and the "produce" potentials

Historic districts usually present a great diversity of building ages and functions with varying energy patterns (e.g. residential buildings that require heating versus offices or supermarkets that have cooling devices), making them interesting areas for the exchange of energy waste streams. By using information extracted from BAG data such as building location, size and function, it is possible to roughly estimate the capacity of these residual heat sources. The "PLANHEAT" research project provides information on the calculation method. formula (1) was used to estimate the residual heat potential from cooling process ($Q_{cooling}$) based on electricity demand used for the cooling process and the Coefficient of Performance (COP) of the cooling system (Fremouw and Gommans, 2018).

$$Q_{cooling} = Elec_{avg} \times Cooling_{\%} \times (COP + 1) \tag{1}$$

Residual heat is calculated at the district scale by correlating $Q_{cooling}$ with the floor area of non-residential buildings (e.g. retail shops, restaurants, offices, hotels, schools, and supermarkets). Additionally, we explore opportunities for using energy from local sources, such as aquathermal energy from open water or PVT panels. As shown in Figure 4, open data from the environmental map of Waternet was integrated into the clustering model. The results indicate that for Leliegracht, aquathermal energy from open water has the highest potential compared to residual heat from cooling processes and PVT potential (Waternet, 2023).

The geo-referenced data was then transferred as a shapefile to the clustering parametric model, using "Urbano" plugin. The purpose is to combine the supply potential with the demand profiles generated in the previous section. This matching process considers both time and space dimensions, including comparing energy patterns and the distance between the energy source and consumer.

2.4 Local source networks definition

Mini networks are most interesting where no large-scale heating networks are provided, with high urban density, requiring less load on electricity grid and less noise pollution. The research

Figure 4. Identification of local low temperature heat potential in GJ per year in Leliegracht neighbourhood (Dang, 2024)

focused on mini-networks of 2–200 homes, including seasonal storage and technical space (in private inner yards or public space). All addresses within the research area were clustered per building block using "Awap" plugin in QGIS and based on building morphology to allow for faster computation of the model (Pafka and Dovey, 2017). Data on the building blocks were then transferred to the clustering model using "Urbano". Figure 5 illustrates the steps for network creation in Grasshopper.

Inspired by the research of (Lumbreras *et al*., 2022), the method for generating the network follows the four main steps:

(1) *Graph creation using Delaunay triangulation*: the algorithm computes Euclidean distances between each centroid of the building clusters. The maximum Euclidean distance was set to 500 meters;

(2) *Routing*: search for the shortest paths from existing road segments for each previously defined pair of points using A* search algorithm. The shortest paths between each point were identified;

(3) *Minimise the overall length of the network*: Compute the minimum spanning tree using Kruskal's algorithm;

(4) *Define every clustering combination:* this includes every network combination within the optimised minimum spanning tree route (e.g. resulting in 4.082 network scenarios for Leliegracht)

The plugins "LunchBox" and "Spiderweb" provided the algorithms for performing calculations on graphs.

2.5 Open space and ATES systems integration

ATES systems present a promising solution in the Netherlands, potentially resulting in up to 11% primary energy savings in the built environment (Taskforce, 2009). The subsurface conditions in Amsterdam are highly suitable for storage, as the aquifer is 150 meters thick, of which 100 meters can be utilized for ATES (Bloemendal, 2018). Open data from the WKO tool were analysed to identify current ATES systems in Leliegracht (WKO tool, 2024). The purpose of this step was to assess the availability of open space required for drilling equipment. Using open data in QGIS, it is possible to analyse the size and shape of inner-yards within each building block, providing a better understanding of the boundary conditions for implementing ATES systems. In the present use case, a safety buffer of 2.4 meters from the façade of each building footprint was allocated for the drilling equipment. Open space area which are less than 2 square meters were also removed

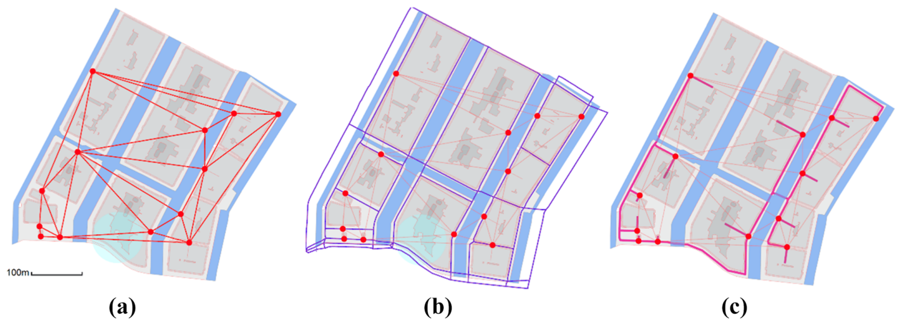

Figure 5. Network creation process in Leliegracht neighbourhood in Amsterdam Centrum: (a) Delaunay triangulation and Graph creation, (b) Input Street network, (c) Calculation of the minimum spanning tree (Dang, 2024)

from the resulting dataset. Based on the research by Beernink *et al*. (2022) on maximizing the use of ATES monowell systems in urban areas and using a circle packing algorithm, ATES monowell systems were positioned at a minimum distance of two times the thermal radius (Rth) from each other to prevent any mutual interferences that could result in decreased system efficiency. The volume of the monowells was calculated based on the imbalance within each building cluster, which determines the amount of energy that can be stored. The absolute imbalance for every cluster and isolated building was calculated based on two steps:

(1) *Hourly load matching*: the parametric model checks if load matching (simultaneous heating and cooling) is possible within the building clusters. It is assumed that if supply and demand occur within the same hour, these energy flows are exchanged within the nodes. This corresponds to the Demand Overlap Coefficient (DOC), first introduced by Wirtz *et al*. (2020). The DOC describes which share of heating and cooling demands can be fulfilled within the cluster. This is assessed based on the overlapping of demands to determine the balancing potential, which can exist within the building itself or between buildings.

(2) *Need for ATES monowell systems*: For the remaining hours when there is still demand to be fulfilled, the parametric model checks the amount of energy needed to be recovered from ATES seasonal storage within each cluster.

The dimensioning of ATES is conducted based on results of step (B). For each ATES, it is considered an optimal thermal radius ratio (L/Rth) of 0.5, with Rth representing the thermal radius and L representing the length of the well screen (Bloemendal, 2018).

2.6 Evolutionary strategy

When scoping an area of interest, one could optimize to include all consumers, or to minimize network length for energy exchange (e.g. due to reasons of network costs or lack of subsurface space for such a network), or to optimize the energy exchange within single clusters. This clustering exercise shows initial interdependencies when initiating and scoping new heating systems in the existing built environment. The parametric model used “Wallacei”, a plug-in integrated in Grasshopper, that runs evolutionary simulations and helps conduct the analysis and selection of optimised solutions. Table 1 describes the fitness objectives and the variables (or “genes”) used for the simulation.

Table 1. Overview of the fitness objectives and genes for the simulation (Dang, 2024)

Fitness objectives

#	Objective	Definition
1	Minimise the overall length of the pipe network	This objective is formulated for costs and efficiency reasons
2	Minimise the number of isolated buildings	The objective aims to find solutions that converge towards a fully integrated cluster, where all buildings can transition away from natural gas
3	Minimise the absolute heat/cold imbalance for every cluster and isolated building	This objective helps examining the absolute imbalance within each cluster and isolated node
4	Minimise the number of clusters	This objective aims to interconnect clusters

Genes

#	Definition	Domain
1	Clustering combination	0 to 4,082
2	Seed value defining the placement of ATES systems in public and private space	0 or 100

The evolutionary solver was used to generate a large number of solutions by varying the genes, considering the four fitness objectives. As a multi-objective problem, the four fitness objectives were not merged into one. The aim is to address each individual objective independently so that final optimal solutions may achieve high value for one criterion but may also perform very poorly on another criterion, allowing to extract multiple optimal solution in the final population (Deb *et al*., 2002).

3. Preliminary results of the use case

This study aimed to test the design workflow outlined in section 2.1 on the case study of Leliegracht, a neighbourhood in Amsterdam Centrum. After generating and selecting retrofitting scenarios for the different building archetypes in the area, the demand data was matched with the supply potential as calculated in section 2.3. The heat and cold imbalance, length of the network, and number of isolated nodes were used as indicators to evaluate the performance of the clusters. This process led to multiple network configurations with their respective design data. As shown in Figure 6, the clustering parametric model provided best-performing solutions based on the Pareto front analysis. This enables a quick comparison with a diamond chart that shows the performance of each objective for every solution.

Starting with more than 4,000 network scenarios, the simulation took about 5 h to converge to a set of best-performing solutions. This demonstrates that the proposed workflow can relatively quickly test a large number of network configurations. Breaking down the optimization problem into smaller-sized problems and solving them sequentially could also be tested in the future to optimize running time. The model displayed spatial variations in energy demand and supply within the neighbourhood. This highlighted that some clusters may be capable of providing excess energy, while most clusters need additional energy input to fulfil their demand. Using only the absolute imbalance as a fitness objective appears to be problematic since it does not distinguish between a shortage or excess of supply. It may be interesting in future steps to combine this objective with the shortage of supply to better weigh the energy performance of each cluster. Preliminary results of the optimisation process showed that no single solution is doing best in all the fitness objectives. For example, solutions that ranked well in minimizing the absolute heat imbalance and the shortage of heat supply ranked poorly in terms of the length of the network. Figure 7 displays one of these solutions and associated outputs.

The presented scenario proposes a network configuration where the Leliegracht neighbourhood could disconnect gradually from natural gas. To achieve this goal, the model shows that the buildings need to be retrofitting to a LT-level, and two networks need to be constructed, totalling an overall length of 1.52 kilometres. Interestingly, ATES monowells can be fitted in the private inner-yards of the buildings without interfering with each other so there is no need for claim for public space for storage. Two aquathermal energy systems (with 2 inlets and outlets) on two different channels feed in the two clusters and cover most of the demand. Only 5% of the supply comes from residual heat from cooling.

Overall, the test of the design workflow showed the power of using digital tools to narrow down the solutions and facilitate decision-making. Nevertheless, it remains the responsibility of the user to manually select from the array of generated network solutions.

4. Discussions and conclusions

To envision a future for monumental buildings, it is necessary to look at their past and to respect their monumental value, but also to find multi-scale solutions to make them future proof. When addressing issues of energy retrofits, it is essential to look at each individual situation (e.g. financial, organisational aspects) and understand the role and the ways to best engage citizens in that process. The heat transition of an historic area depends on many factors – energy prices, budget availability and subsidies, engagement of the building owners and technical feasibility. There is an urgent need for more citizen engagement and an integrative

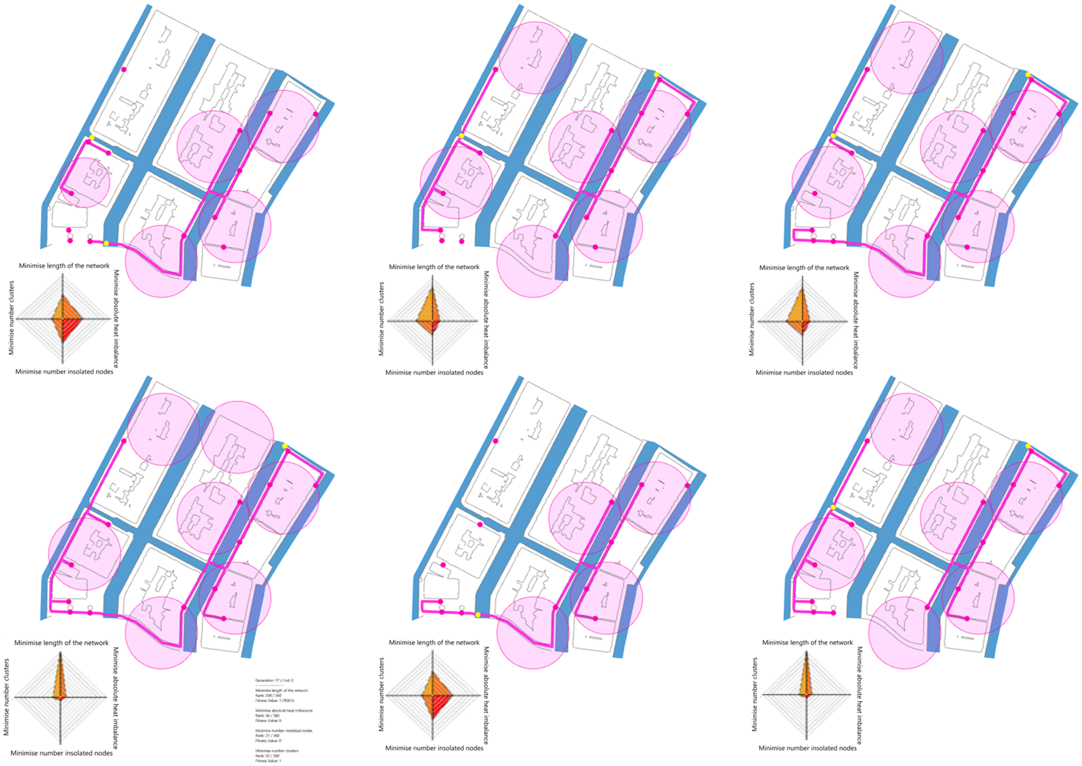

Figure 6. Example 6 solutions from the 20 Pareto front results generated by the parametric model using multi-objective evolutionary simulation. The filled circles represent the positions of the ATES systems combined with the associated networks. Each scenario is represented with a diamond chart, illustrating its performance against each of the four fitness objectives. Each axis corresponds to a fitness objective, with points nearer the centre indicating a fitter solution. The six scenarios perform well on three of the four objectives for the neighbourhood: “(2) minimise the number of isolated buildings”, “(3) minimise the absolute heat/cold imbalance for every cluster and isolated building” and “(4) minimise the number of clusters” (Dang, 2024)

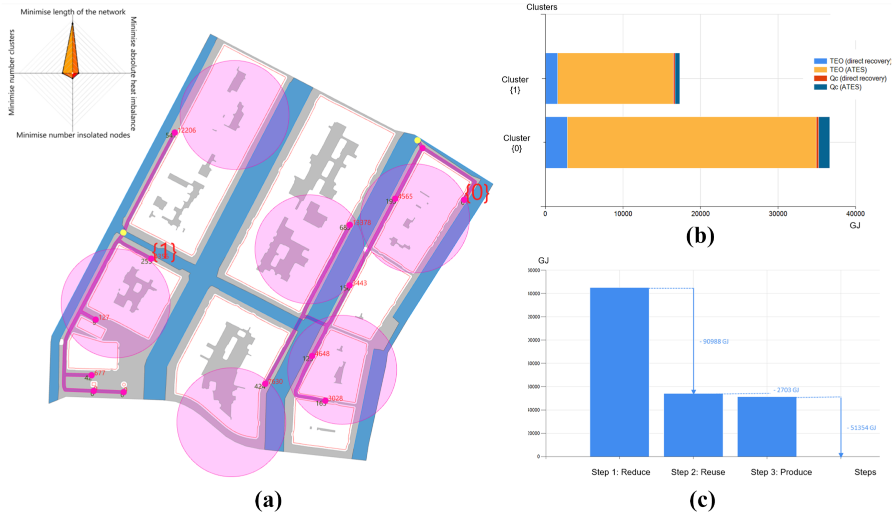

Figure 7. Example of generated outputs from the clustering parametric model for one of the scenarios comprising two clusters: (a) Mapping of the routes of the two clusters in Leliegracht, including the placement of ATES systems in private spaces and the performance for each of the four fitness objectives via a diamond chart; (b) Graph displaying the share of supply from hourly direct recovery (aquathermal energy from surface water and residual heat from cooling) and from seasonal storage for the two clusters; (c) Graph summarizing the gradual transition of the neighborhood following the three steps “Reduce”, “Reuse”, and “Produce” (Dang, 2024)

approach, including everyone in the energy transition, not just frontrunners. In dense, mixed urban regions such as the historic city centre of Amsterdam, regulations could guide and create more coordination. However, the transition towards a natural gas-free Amsterdam by 2040 will require a pace that is unprecedented and unlikely to be fully achievable solely by the municipal government of Amsterdam. Given the strong interest expressed by citizens and stakeholders to be involved in the redesign, redevelopment, and governance of urban energy systems, it is suggested that a proactive and well-informed engagement of individuals working towards collective action could significantly accelerate progress towards achieving climate objectives. Existing information is either fragmented, generic, or too technical for citizen groups, leading to information overload or limited opportunities for action. Groups of citizens who wish to disconnect from natural gas need expert guidance to retrofit their buildings and to develop transition plans.

The proposed workflow links the assessment of the existing building stock with the embedded energy flows of its surroundings, creating new opportunities and aiming to prevent future limitations for other actors transitioning in a later phase. It is crucial to evaluate future limitations as soon as possible, as the options for transitioning the building stock later may be hindered or even rendered impossible due to the scarcity of energy infrastructure capacity, limited potential for local source exploitation, permitting challenges, and the resulting economic challenges of alternative heating systems. This outcome is highly undesirable for the municipality, which has set the goal of transitioning the entire city away from natural gas rather than having just individual patches of change. One major added value of the design workflow is the possibility to connect small-scale solutions for historic buildings to existing opportunities of exchanging heat and cold on a neighbourhood scale. It shows that energy planning strategies for historic areas should not be only focused on the building level. Using quay renewal for the heat transition in Amsterdam is a good example of such logic: quays can operate as heat exchangers and play an essential role in connecting historic buildings to local, LT heat sources.

The design workflow serves as a potential starting point for effectively guiding local stakeholders, who wish to investigate dependencies in their integrated energy transition plans, in the early stages of the decision-making process. It allows for exploration and co-design of the local heating transition. Due to their versatility, the parametric engine can help quickly identify and prioritize impactful measures, creating stepped retrofitting plans. Citizen groups, as potential users, could have the opportunity to use the models to explore the mid and long-term impacts of options in their environment and collectively create visions for their neighbourhood. Ultimately, the goal is to assist in identifying trade-offs between different solution combinations. The comprehensive overview of best-performing solutions is also beneficial for municipalities, grid operators and other stakeholders, enabling them to be well-informed and thus guide their strategies accordingly. It allows for adjustments as the local context, regulations, business cases, and support schemes evolve in the ongoing dynamics.

5. Future work

As part of the EU-funded MultiCare project, future research steps will aim to define the robustness of the retrofit packages to future climate scenarios (such as risks of overheating and increasing cooling demand), the embodied carbon of insulation, and the associated trade-offs when using different insulation materials. A condensation check is also necessary to ensure that the selected retrofit packages will not cause deterioration of historic elements. Climate adaptive solutions, such as green roofs, walls, and trees, will also be explored in combination with building performance. The sizing of the ATES, the design logic for placing the inlets and outlets of the aquathermal energy systems, and the input of PVT potential would require some refinement.

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