Creating Clusters in a 5th Generation District Heating and Cooling Network

An alternative to a neighbourhood-based approach

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by

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Executive Summary

The recent earthquakes in Groningen, the impact of fossil fuels on climate change, and the Russian invasion in Ukraine underscore the urgency of finding an alternative to natural gas for heating purposes. In response, the Dutch government has set a goal to phase out the use of natural gas by 2050. As a result, municipalities are focusing on implementing alternative heating strategies in certain neighbourhoods. However, districts with older building stocks are often neglected, raising concerns that city centers with older, poorly insulated buildings and high heat demands may be left until later stages of the transition, despite the need for a clear heating strategy in these areas. Additionally, urban areas face the challenge of the urban heat island effect, which leads to trapped heat and elevated summer temperatures. This effect, coupled with the consequences of climate change, will increase the demand for cooling.

To initiate a new heat transition, it is crucial to adopt new sustainable and locally generated heat systems. A potential solution is the implementation of a 5th District Generation Heating and Cooling (5GDHC) network, which utilizes low-temperature heat and cold, potentially sourced from waste heat. However, the design and implementation of a 5GDHC network presents numerous challenges, including the absence of comprehensive guidelines and limited knowledge regarding the deployment of these systems on a larger scale or in an area with an older building stock. This research focuses on developing a tool that can identify potential clusters for a 5GDHC system in densely populated urban areas.

To achieve the research objective, a methodology is developed to identify clusters for a 5GDHC network. Clusters are essential for the implementation of a 5GDHC system in a larger area, as they mitigate investment risks and facilitate a clearer implementation process. The methodology in this study integrates the Single Linkage clustering algorithm and Geometric Graph Theory, which are extended into a model. This model generates clusters based on building locations and energy profiles, and assesses their performance using metrics such as the aggregated hourly lack of supply throughout the year and the total length of the pipe network.

A case study of the inner city of Amsterdam, part of the 'high hanging fruit' project by the AMS Institute, is utilized to test the model. The model requires data on potential waste heat and retrofitted buildings as input. Prior to running the model, a comprehensive data preparation process is undertaken to ensure the data are suitable for analysis. Three distinct approaches, calculated over different time periods, are employed to determine the allocation of clusters. These approaches are compared to the base case, based on single linkage clustering, the neighbourhood-based and the district-based approach. The latter two proved to be less scalable, and due to their too large and too small clusters, not suitable for the recommended bottom-up approach. From the other clustering approaches exhibits the approach based on the entire year the lowest hourly lack of supply, indicating a higher level of reliability. On the other hand, the base case approach yields the shortest total length of the network, implying potential cost savings. These two approaches are considered the most noteworthy outcomes in the case study.

Three distinct approaches were utilized to determine cluster allocation, namely the base case utilizing single linkage clustering, the neighbourhood-based approach, and the district-based approach. A comparison was conducted between these approaches and the base case. It was found that the neighbourhood-based and district-based approaches exhibited limitations in terms of scalability, resulting in clusters that were either too large or too small, which rendered them unsuitable for the recommended bottom-up approach. Among the alternative clustering approaches, the approach based on the entire year demonstrated the lowest hourly lack of supply, indicating a higher level of reliability. Conversely, the base case approach resulted in the shortest total network length, suggesting potential cost savings. These two approaches emerged as the most noteworthy outcomes in the case study.

The developed model effectively identifies clusters within a large urban area based on building locations and energy profiles. Trade-offs between pipe network length and energy efficiency must be considered when evaluating the model's results. These metrics have distinct implications, as the energy balance of a cluster may require different supply functions or render an area unsuitable for a 5GDHC system. The length of the pipe network influences implementation costs and social hinder. It is highly recommended to adopt a bottom-up approach and establish 5GDHC clusters incrementally within the city. The hourly disbalances, calculated by the model, can identify potential clusters ready for connection. Moreover, the performance metrics derived from the model can serve as valuable decision-making guides during the design phase of 5GDHC networks. To enhance the decision-making process further, it is crucial to integrate the model's information with urban planning considerations and engage relevant stakeholders. By combining these factors, a comprehensive and well-informed decision-making process can be facilitated, leading to more effective and efficient 5GDHC network designs and implementations.

The full model created within this research can be retrieved from:
https://github.com/svanburk/clustering5GDHC.git

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Introduction

1.1. Problem introduction

In 1959 the largest natural gas field in Europe was discovered in the Province of Groningen. The discovery of natural gas, a much cleaner fuel than coal, led to the decision to connect every household in the Netherlands to a natural gas grid. In only a decade the energy transition, from coal to natural gas, was completed (Ons Aardgas, 2021). Over the last decade, it became clear that the Netherlands must undergo another transition to replace natural gas-fired heating. Several reasons can be given in order to explain the need for this heat transition.

One of the events that contributed to the realisation was the earthquake that struck Groningen in 2012. The strongest earthquake so far in the Netherlands with a force of 3.6 on the Richter scale. Various earthquakes are measured in Groningen from 1991 until today. The earthquakes in Groningen have been linked directly to gas drilling in the region, causing damage to houses and safety issues for residents (Liefting, 2022). Consequently, the Dutch government aims to completely phase out the use of gas from Groningen by 2030 (Milieudefensie, 2018).

However, the need to import more natural gas in the absence of Groningen's extraction raises concerns about Europe's reliance on foreign gas. Particularly in light of the political tensions between Russia and other countries, the question of how much Europe wants to rely on foreign gas raises. The Russian invasion of Ukraine highlighted the European dependency on Russian natural gas and the risks that this dependency involves (Bump, 2022). In 2018, Dutch Prime Minister Rutte stated that Europe depends on Russian gas, which is not a problem when you make tight agreements (Cukier & Van Der Walle, 2018). But since the invasion of Ukraine, the relations between Russia and the West have been strained and economic sanctions have been imposed towards Russia. The closure of Nord Stream 1, the main Russian gas route to Europe, raises the suggestion that this may be the answer from Russia to the economic sanctions of the West (Beunderman, 2022). Tight agreements, as Rutte stated, can no longer be held with Russia, which means alternative supplies are needed.

Finally, the contribution to climate change of natural gas can be marked as a reason to move away from this fossil fuel. Whilst being the 'cleaner' fossil fuel, the combustion process of natural gas produces greenhouse gases that contribute to climate change. Heating accounts for 42% of the total energy demand in the Netherlands, more than electricity and mobility combined (Energie in Nederland, 2021). When the Netherlands want to conform to the Paris Agreement and reduce their emissions in 2030 by 55% and be climate neutral by 2050 (van Infrastructuur en Waterstaat, 2023), a heating transition is inevitable. The reasons described in this section all highlight the importance of a heat transition. It will be crucial to implement sustainable alternatives and energy-saving measures in order to reduce import dependency and contribute to a clean energy transition.

In line with the Paris Agreement, the Dutch government has set a target to phase out the use of natural gas by 2050. To this end, all Dutch municipalities are required to publish reports outlining their strategies for future heat supply (known as the ”Warmtevisie”) by 2021. These reports include plans for when each neighbourhood will be disconnected from the gas grid and what alternative strategies will be employed. Many municipalities are prioritizing new-build districts or districts where the solutions are the most obvious in the heat transition, assuming that new knowledge on heating strategies for older buildings will develop later. However, there is a concern that older, poorly insulated neighbourhoods with high heat demands may be left until later stages of the transition, despite the need for a clear heating strategy in these areas.

Most municipalities in the Netherlands with historic city centres, such as Leiden, Delft, Utrecht and Amsterdam, propose using sustainable gas in their historic city centres or have yet to develop a strategy for these areas (Delft, n.d.; Duin & Koelemij, 2020; Leiden, 2022; Utrecht, n.d.). Sustainable gas can take the form of green gas, which is produced by the breakdown of organic matter or carbon-free hydrogen (Leguijt et al., 2018). Both are viewed as crucial components of the energy transition, as they must replace natural gas in areas where other options are not feasible (van der Veen & Leguijt, 2021).

However, both of these gases come with many uncertainties. It is not yet clear how the supply of green gas, the demand for green gas in the built environment and in other sectors, and the costs of green gas will develop. Until at least 2030, it remains unclear what the most suitable areas are to deploy green gas in the built environment (van der Veen & Leguijt, 2021). Hydrogen is not expected to become available in the built environment before 2035, due to a lack of production and high costs. The large-scale use of hydrogen for heating in the built environment after 2035 will depend on the development of the costs and energy efficiency of the technology, the demand for hydrogen in other applications, and the conversion of the natural gas network into a hydrogen network (Jongsma et al., 2020).

Creating a new heating strategy is not the only challenge big cities face. The so-called urban heat-island effect occurs in bigger cities, where heat is trapped in buildings, roads, and stones. Temperature differences of 7 to 8 degrees Celsius can be measured between rural and urban areas (Atlasleefomgeving, n.d.). The effects of the trapped heat can cause heat-related illness, air pollution, and mortality, which can be even more dangerous with rising temperatures due to climate change (EPA-US, 2022). According to a report by the International Energy Agency (IEA), the number of air conditioners worldwide tripled between 1990 and 2016. The number of air conditioners is expected to grow to 5.6 billion by 2050, compared with 1.6 billion air conditioners in use in 2018. However, air conditioning systems have a high electricity demand and a high carbon footprint, posing a challenge to meet the total cooling demand in 2050. The amount of electricity needed to provide this cooling demand is as much as what China and India used together in 2018 (Basir, 2022).

It can be concluded that the heating and cooling of the built environment in urban dense areas require a new strategy. The current strategies have limited focus on districts with historic value, and the proposed alternatives may not be suitable, as the future of sustainable gases and their development is uncertain. Therefore, it is imperative to implement new sustainable and locally produced heat systems to initiate a new heat transition. Moreover, cooling is an essential concept that needs to be considered in urban dense areas, and a sustainable cooling supply needs to be developed.

Heat and cold networks can potentially provide a solution to the heating and cooling transition in urban dense areas. Traditional networks rely on a high-temperature source to supply heat to multiple buildings. However, such networks suffer from high thermal losses, which make transport and storage inefficient (Pass et al., 2018). To address these issues, newer generations of heating and cooling networks utilise lower-temperature heat, which could provide a local and sustainable solution by utilizing waste heat, aquathermal heat, or geothermal heat. This type of district heating and cooling network, which uses low-temperature heat, is referred to as the 5th generation district heating and cooling network (5GDHC). In this research, the 5GDHC network will be considered as an alternative heating strategy for urban dense areas with historic value.

The implementation of lower-temperature heating and cooling networks is still limited to small-scale cases. The largest 5th generation district heating and cooling (5GDHC) network has a length of 12.5

km (Wirtz et al., 2022). Designing 5GDHC networks for larger areas requires the area to split into different clusters, each with its own network. The sizes of the clusters must be large enough to create flexibility but not too large to maintain efficiency. Implementing clusters one by one creates a bottom-up approach that can lower investment risks (Expertise Centrum Warmte, 2022). Currently clusters of 5GDHC systems are often based on neighbourhood-based boundaries. in the Dutch Climate Agreement Nijpels (2018) suggests neighbourhood-based planning, but Boesten et al. (2019) stresses the need for more flexible planning of 5GDHC clusters. Integrating the demand profiles in the planning of new clusters create a more efficient 5GDHC system. This research aims to determine how clusters in a 5GDHC network can be designed efficiently.

1.2. Research approach

The objective of this study is to develop a tool that can partition an urban area into various clusters to enable a bottom-up approach to urban planning. A bottom-up approach facilitates the gradual connection of clusters to form a larger area, which is less complex than connecting a large area directly. The tool must consider both the location and energy consumption patterns of buildings to create these clusters. The geographical location of the buildings serves as the starting point for cluster creation, and the tool identifies street patterns. Energy profiles of buildings in a particular region are considered to develop energy-balanced clusters. The primary focus of the study is to distribute potential waste heat sources over the demand while maintaining geographically aligned clusters. In the end, all buildings in the selected area must be connected to the network.

This research contributes to the 'high-hanging fruit' project of the AMS Institute. With this project, the AMS Institute is exploring the possibilities for a sustainable and local heating method for the monumental buildings in the inner city of Amsterdam (Dang & Voskuilen, n.d.). The inner city of Amsterdam will be used as a case study in order to test the developed tool. With this research, the final goal is to create a tool that can be used in the design stage of a 5GDHC network in order to get more insights into potential clusters in an area. Although the tool is tested in the case study of the inner city of Amsterdam, the overall goal is to create a generally applicable tool, which can be used in other cities as well.

1.2.1. Research questions

The objective of this research can be described as follows: *The objective of this research is to develop a tool and find a method to divide a proposed area into clusters based on the geographical location and energy profiles of the buildings inside that area in order to create efficient 5GDHC systems. With the help of the created tool, users should be able to make choices upon the network topology design of 5GDHC networks.*

This objective is captured in the following research question:

What is a suitable approach to identify potential clusters, based on the geographical location and energy profiles of the buildings, for a 5GDHC network in an urban dense area?

In order to answer this main question, several sub-questions have been compiled:

1. *What is a 5GDHC network, and what are its key characteristics?*
2. *Which requirements and objectives can be derived from the actor analysis and the characteristics of an urban dense area?*
3. *How can a clustering approach incorporate both the geographical location and energy profiles of buildings?*
4. *Which metrics can be employed to evaluate the performance of the identified approach, based on the identified requirements and objectives?*

1.2.2. Thesis outline

Chapter 2 provides a comprehensive overview of various aspects of the 5GDHC (Fifth Generation District Heating and Cooling) system. It elaborates on the system's development, characteristics, relevant

Dutch regulations, the objectives of critical actors, and explores existing literature on the subject. The primary objective of this chapter is to gain a deep understanding of the 5GDHC system, and to provide an answer to the first and the second research sub-question. Chapter 3 focuses on reviewing academic theories related to clustering and energy infrastructure modeling. The aim is to identify and select appropriate methods that can be applied in this research. In Chapter 4, the selected methods are further elaborated upon to provide an answer to the third sub-question, and a model is constructed to address the main research question. The chapter provides detailed explanations of the chosen methods and presents the developed model. Additionally, the performance metrics used in the model are introduced to answer the fourth sub-question, evaluating the effectiveness of the model. Chapter 5 presents a case study centered around the inner city of Amsterdam. The model created in the previous chapter is applied to generate results specific to the case study. The chapter provides an analysis and discussion of the obtained results, offering insights into the application and performance of the model in a real-world scenario. Lastly, in Chapter 6 the conclusion of this research is provided and Chapter 7 presents the discussion.

2
System overview

In this chapter, a comprehensive overview of the 5th Generation District Heating and Cooling system, its characteristics, its application in an urban dense area, the actor objectives, and relevant literature will be presented. The section starts with introducing the emergence of heat networks. Subsequently, the definition and terminology of the 5GDHC system are discussed, providing clarity on its key concepts. This is followed by an exposition on the operational mechanisms and distinctive features of a 5GDHC network. Moreover, the role of 5GDHC within a Multi-energy system is elucidated, along with its significance in the context of urban dense areas, and the exploration of the limitations associated with its implementation. Additionally, a concise overview of the existing regulations in the Netherlands pertaining to 5GDHC is provided. Subsequently, an actor analysis is conducted, involving an extensive overview of the objectives of key actors involved in the system. Furthermore, the existing body of literature concerning the 5GDHC concept is reviewed, and several knowledge gaps are identified. The objectives of the present research and its contribution towards addressing these knowledge gaps will be outlined. Finally, a section is dedicated to enumerating all the requirements and objectives derived from this comprehensive system overview. This final section forms the foundation for the methodology and model that will be developed in the course of this research.

2.1. The 5GDHC network

2.1.1. Introduction to district heating generations

Heat networks have been utilised in society since 1880. In these first systems, steam was employed as a heat carrier at immediately useful temperatures. This first generation of heating networks (1GDH) is considered outdated today due to the high heat losses and the risk of accidents from steam explosions (Lund et al., 2014). Over the years, several changes have been introduced to improve the type of fluid, temperature levels, and heat source. The transition from steam to superheated water as a transport fluid marked the first significant improvement in district heating, resulting in the second-generation district heating (2GDH) system. From the 1930s till the 1970s 2GDH was the most dominant form of district heating (Lund et al., 2014).

In the third generation district heating (3GDH) system, supply temperatures were reduced to below 100°C, enabling greater flexibility in heat sources and more efficient transportation. This change marked the introduction of renewable sources and waste heat to the district heating sector. The third generation is still the most commonly used district heating system across Europe (Millar et al., 2020). The 3GDH system's popularity is largely due to its efficiency and lower costs in comparison to previous generations and oil-based heating systems (Lund et al., 2014). However, the 3GDH system still experiences distribution losses and high investment costs despite the more efficient production of heat (Buffa et al., 2019) (Abugabbara et al., 2020). Traditional heating systems generally rely on fossil fuels and high supply temperatures, which limit the feasibility of connecting low-temperature waste heat and the use and other sustainable sources (Gjoka et al., 2023).

The challenges facing district heating systems have resulted in the development of the 4th generation district heating (4GDH) network. This generation focuses on energy efficiency, smart integrated energy systems, and the utilisation of locally available renewable sources. By reducing the supply temperature to 50/70°C, performance and economic feasibility have increased (Lund et al., 2021). The 5th generation district heating and cooling (5GDHC) system was introduced to address the main limitations of 4GDH, namely the absence of a cooling system and the emphasis on centralised production (Abugabbara et al., 2020). This type of system was first discussed in literature around 2018 and introduces a lower supply temperature, with a maximum of 30°C (Revesz et al., 2020). Multiple sources can be used in a 5GDHC network, such as low-grade waste heat from nearby restaurants or offices. With these low operating temperatures, heat losses are minimised. Additionally, these systems can provide heating and cooling simultaneously and require the addition of a heat pump to supply the necessary thermal energy to the end user. Furthermore, energy can be exchanged between users and operational flexibility can be obtained from the coupling between electrical and thermal grids (Gjoka et al., 2023). The 5GDHC system is best suited for areas with similar heating and cooling demands (Lund et al., 2021). Due to its ability to incorporate multiple waste heat sources, combine heating and cooling, and offer high energy efficiency, the 5GDHC system will be used in this research.

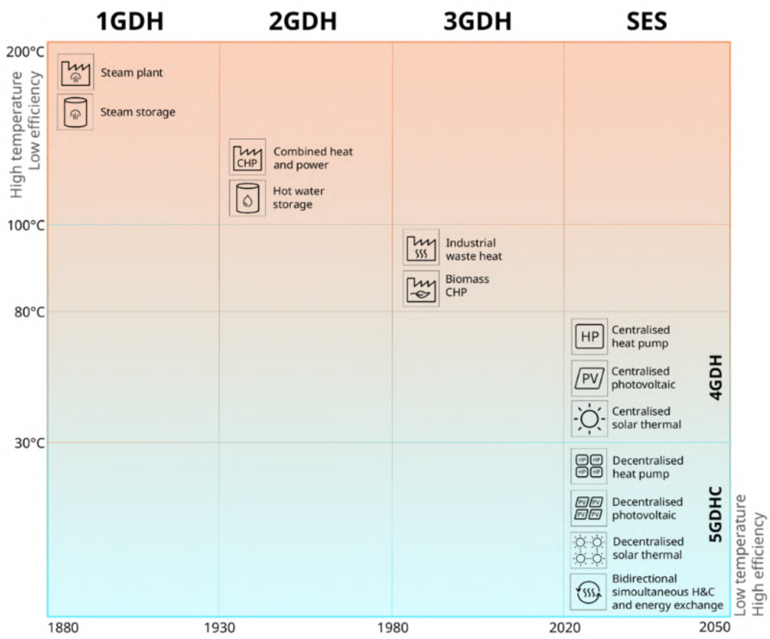
The introduction of the 5GDHC concept by Buffa et al. (2019) has generated debate. Lund et al. (2021) argues five abilities defined for 4th Generation District Heating (4GDH) systems, which include supplying low-temperature district heating, distributing heat in networks with low grid losses, recycling heat from low-temperature sources and integrating renewable heat sources, being an integrated part of smart energy systems, and ensuring suitable planning, cost and motivation structures, already cover the main ideas of 5GDHC but with some additional considerations (Lund et al., 2014). Lund et al. (2021) states that the new technologies presented in the 5GDHC are just a diversity of the fourth generation. Lund et al. (2021) suggests that 5GDHC should not be seen as a sequential or serial development of 4GDH in order to maintain transparency and clarity. Despite this, the term 5GDHC is increasingly being used in research to refer to low-temperature networks. Gjoka et al. (2023)'s study reflects to the 5GDHC and the 4GDH concepts as coevals rather than each other's successors. This research adopts this idea and reflects on the 5GDHC concept. This is also reflected in figure 2.1. The SES in figure 2.1 refers to the Multi-energy system which will be explained in 2.1.4. The definition of a 5GDHC system presented by Buffa et al. (2019) will be used in this thesis.

"A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substations with Water Source Heat Pumps (WSHP). It operates at temperatures so close to the ground that it is not suitable for direct heating purposes. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings. Through hybrid substations, 5GDHC technology enhances sector coupling of thermal, electrical and gas grids in a decentralised smart energy system."

2.1.2. The key characteristics of 5GDHC

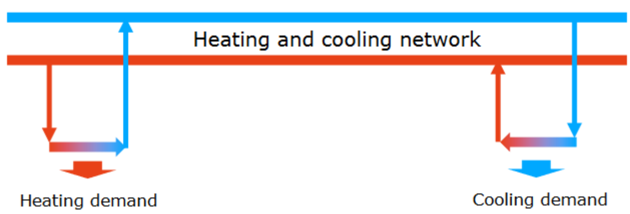
The 5GDHC systems possess several characteristics that distinguish them from other generations of heating networks. This subsection aims to elaborate on these characteristics. The first key characteristic is the low-temperature levels, which typically ranges from 5°C to 30°C in the network (Wirtz et al., 2020). The use of such low-temperature levels offers significant advantages. Firstly, the transportation losses are limited due to the low operational temperature, leading to a high system efficiency (Buffa et al., 2019). Secondly, traditional heat networks require insulated pipes to reduce heat losses. However, when operating temperatures are close to the ground, as is the case with 5GDHC, insulated pipes are no longer necessary. Consequently, the cost of the pipeline network is likely to decrease. Low-temperature levels also enable the connection to low-grade waste heat, low-temperature renewable energy sources, and geothermal and aquathermal energy, contributing to a circular energy economy where energy can be exchanged at the district level (Buffa et al., 2019). Since the low temperature is insufficient for direct heating, heat pumps are required in a 5GDHC system to deliver the required temperature (Gjoka et al., 2023).

Figure 2.1: Evolution of different generation district heating systems (Gjoka et al., 2023)



Another key characteristic of the 5GDHC concept is the bidirectional flows within the network, which include a hot and a cold pipe. Earlier generations, on the other hand, have a distribution network which consists of a supply and a return pipe with heat flowing from a centralised source to the suppliers (Gjoka et al., 2023). The bidirectionality of the 5GDHC network enables the possibility to connect multiple sources to the grid, with the opportunity to connect new suppliers over time. Additionally, this feature enables consumers to return their excess heat or cold back to the network, making them ”prosumers”. The two bidirectional pipes facilitate the system to provide simultaneous heating and cooling. When there is a demand for heating or cooling, the buildings extract heat or cold from the pipes and use a heat pump to attain the required temperature. The heat pump generates an excess flow with heat or cold, which can directly flow back to the network (Boesten et al., 2019). Figure 2.2 provides a simplified illustration of the interaction between the heating and cooling pipe.

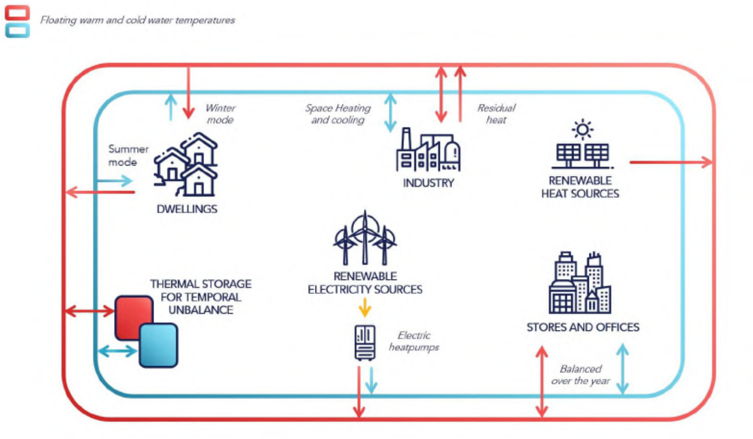
Figure 2.2: Two pipe system (Roossien et al., 2020)



2.1.3. Topology

Traditional heat networks usually adopt a tree structure, with a centralised energy source as the root supplying energy to numerous districts. However, the bidirectional flow, multiple energy sources, and prosumers connected to the 5GDHC system require a completely different network topology. A ring structure is suitable for sharing heating and cooling across the low-temperature network (Revesz et al., 2020). Laurberg Jensen et al. (2016) finds that a ring structure is a viable solution in urban dense areas. The direction of the flows inside the pipes is not fixed since the exchange of heat and cold is seasonally dependent. This could lead to capacity and pressure errors in a tree structure. However, in a ring structure, it is always possible to reach the targets through two routes, which improves the security of supply and minimises pressure drops. The ring network is a closed loop with a fixed diameter, dependent on the maximum required capacity in the selected area (Roossien et al., 2020). In figure 2.3 a simplified schematic overview of a 5GDHC system is shown.

Figure 2.3: Schematic overview 5GDHC system (Moors, n.d.)



Roossien et al. (2020) describes the design of a 5GDHC network as bottom-up. In which networks can be connected to each other to exchange thermal energy. Especially in districts with a high load diversity, connecting networks to each other has advantages. From the connection of multiple networks emerges a meshed network. This meshed network improves the balancing between heating and cooling loads, which increases the security of supply. Also, meshed networks can be easily extended.

A cluster in a 5GDHC network is a defined area with multiple buildings that are connected to each other through the distribution network. According to Roossien et al. (2020), the clusters are the building blocks of the 5GDHC network, and the network design is done on a bottom-up basis, starting with the building level, then moving to the cluster level, and eventually connecting the clusters to create a backbone network. Dividing a large area into clusters can lower the investment risk and increase flexibility in energy supply while reducing peak demand (Expertise Centrum Warmte, 2022). However, the clusters should be large enough to offer this flexibility and balance heating and cooling loads on both short and long time scales (Buffa et al., 2019). The backbone network connects the clusters and creates a meshed network that can improve the balancing between heating and cooling loads, increasing the security of supply. The meshed network can be easily extended, enabling the connection of multiple networks to exchange thermal energy. Expertise Centrum Warmte (2022) describes the 5GDHC network as a growth model, in which clusters can be developed individually at different times and can be connected in a later stage.

In an ideal scenario, the heat and cold demand among customers is balanced. In such cases, there is no need for additional heating or cooling supply (Roossien et al., 2020). However, if this balance between heating and cooling demand is not achieved within a given area, it becomes necessary to introduce supplementary sources to maintain the thermal balance. Consequently, it remains crucial to align these additional sources with the demand in order to achieve system balance. Failure to attain thermal equilibrium results in the inability to maintain the desired temperature levels within the fluid flows. In the absence of this thermal balance, the utilisation of an energy hub becomes necessary to rectify the system's imbalance (Npro Energy, 2023). To optimise the performance and operational costs of this energy hub, it becomes vital to establish clusters that exhibit a high degree of balance. When the energy balance within a cluster deviates significantly, it becomes increasingly challenging to harness the potential benefits of the 5GDHC system, such as the reuse of excess waste heat and the reduction of energy consumption. In conclusion, the most efficient cluster is one in which heating and cooling counterbalance each other, thus achieving a state of equilibrium.

Storage systems are used to offer flexibility to 5GDHC systems by balancing the temporal gaps between demand and supply (Boesten et al., 2019). Residual heat or cold won't always be available, so storage systems, like Thermal Energy Storage (TES), can act as a buffer. Two types of TES are interesting for district heating and cooling systems in densely populated areas (Guelpa & Verda, 2019). The first one is Aquifer Thermal Energy Storage (ATES). In ATES systems the naturally occurring self-containing underground layers trap ground (Schmidt et al., 2018). The second interesting storage method for district heating and cooling is Borehole Thermal Energy Storage (BTES). BTES charges the heat capacity of soil or rock with heat exchangers installed into boreholes of 30 to 100 metres deep (Schmidt et al., 2018). Despite the described benefits of energy storage, much is unclear about the co-operation with 5GDHC systems, since 5GDHC is a relatively novel concept Guelpa and Verda (2019). It however remains clear that seasonal heat storage can have a significant cost reduction for district heating and cooling systems (Schmidt et al., 2018). Energy storage gives the possibility to deal with the seasonal variations in 5GDHC systems. It is therefore an essential part of the network. Seasonal storage in combination with a 5GDHC system can cooperate in multi-energy systems (Gabrielli et al., 2020).

2.1.4. Multi-energy system

5GDHC systems can provide simultaneous heating and cooling, making them capable of addressing multiple thermal loads. Additionally, the use of near-ambient temperatures allows for the integration of low-grade waste heat and low-temperature renewable energy sources, positioning 5GDHC as a potential player in the Multi-energy system (MES) concept. The MES is a system designed to address the challenges associated with the large-scale integration of renewable energy systems (RES) into the energy grid. The intermittent character of RES, such as solar, wind, wave, and tidal power, due to natural element variability, poses a challenge to electricity grid operators to balance demand and supply in real time. It is found to be more efficient to integrate the electricity sector with other parts of the energy system than to utilise electricity storage to balance the fluctuating inflow of RES (Lund et al., 2016).

The framework of multi-energy systems allows various energy sources and technologies to interact with each other on different levels. This system aims to provide a more flexible, efficient, and resilient energy supply by optimizing energy use based on factors such as availability, cost, environmental impact, and unexpected events (Guelpa et al., 2019). Heat pumps play a vital role in 5GDHC networks, making the system dependent on the electricity infrastructure. The conversion of electricity to heat combined with thermal energy storage systems provides more flexibility for integrating RES (Lund et al., 2016).

5GDHC systems can provide benefits to MES due to fluctuating operating temperatures and the integration of electricity infrastructure. However, MES faces challenges due to its multi-disciplinary nature. Integrating multiple energy sources and technologies requires complex planning and coordination, with optimisation dependent on the chosen point of view of the system (Guelpa et al., 2019).

2.1.5. 5GDHC systems in an urban dense area

Urban dense areas, characterised by a high concentration of buildings and population, provide an ideal setting for the implementation of 5GDHC systems. These areas typically have a high heat density, meaning there is a significant demand for heating and cooling in a relatively small geographic area. This high concentration of heat demand enables efficient heat distribution and utilisation within the 5GDHC network, maximizing energy efficiency and reducing heat losses. In addition, buildings are typically in close proximity to each other, facilitating the establishment of a comprehensive heat network. The short distances between buildings make it feasible to connect multiple buildings efficiently, reducing the need for long heat distribution pipelines and associated energy losses. Urban dense areas often comprise diverse building types, such as residential, commercial, and institutional buildings, which have varying heat demand profiles. This diversity allows for energy synergies within the 5GDHC system, where waste heat from one building can be utilised to meet the heating and cooling needs of adjacent buildings, maximizing energy efficiency and resource utilisation.

When implementing a 5GDHC system in urban dense areas, several key requirements need to be considered. Firstly, urban dense areas require careful planning to ensure optimal system design, taking into account the existing building stock, future development plans, and infrastructure requirements. Comprehensive planning considers factors such as heat demand patterns, network layout, sizing, and connection strategies to maximise efficiency and meet the specific needs of the area. Secondly, retrofitting existing buildings to connect them to the 5GDHC system is a critical aspect of implementation in urban dense areas. Building retrofitting may involve adapting heating and cooling systems, ensuring compatibility with the district network, and improving energy efficiency measures within individual buildings to align with the goals of the 5GDHC system. Lastly, a successful implementation of 5GDHC systems in urban dense areas necessitates collaboration among various stakeholders, including city authorities, energy companies, building owners, and residents. Engaging stakeholders from the early stages of planning fosters cooperation, ensures alignment with local regulations and policies, and enhances acceptance and support for the system. By considering these requirements, urban dense areas can leverage the benefits of 5GDHC systems to enhance the energy efficiency, reduce environmental impact, and meet the heating and cooling needs of their communities effectively.

2.1.6. Limitations of 5GDHC

This section discusses the limitations and challenges that need to be considered in the implementation of 5GDHC systems, despite their potential benefits. Millar et al. (2020) identifies three technical challenges that require further research. The first challenge is the accurate sizing of the system, which is often oversimplified, resulting in inefficient heat networks. The lack of understanding during the design phase needs to be addressed to tackle the problem of incorrect system sizing.

The second challenge relates to the growth of Legionella bacteria, which occurs naturally in the ground and water. Low-temperature heat networks, between 25°C and 45°C, pose a challenge to the strong growth of this bacteria, which can cause several diseases, including fever and lung infections. Several control methods can be applied, but no method has been found to be conclusive. More research is necessary to develop efficient methods for controlling Legionella in 5GDHC networks.

The third challenge is related to low-energy buildings. 5GDHC networks are only viable when consumers' buildings have a sufficient energy label. Building standards need to be improved to minimise heat losses and create a higher system performance. Improving building standards is a difficult task that requires a skilled workforce and cost-effective measures.

Additionally to the challenges described by Millar et al. (2020), Gjoka et al. (2023) also identifies several drawbacks of 5GDHC systems, including substation complexity, thermal storage requirements, large pipe diameters, and higher pumping costs. These drawbacks also need to be carefully considered in the design stage.

While these technical challenges need to be addressed, the investments in technical talent, equipment sizing, energy performance metrics, and testing of realised projects create the biggest challenge for the implementation of 5GDHC systems (Millar et al., 2020).

2.2. Heating (and Cooling) networks in the Netherlands

The energy supply has become a prominent topic in recent years, with discussions revolving around the transition from fossil fuels and the exploration of alternative energy sources. Within this debate, the role of heat networks is also discussed. The implementation of heat networks is a contentious issue, with discussions about the social effects and the changes in the rules and markets. This section explores the involved actors, their objectives and the regulations related to this topic in the Netherlands.

In 2022, approximately 500,000 Dutch households were connected to heat networks, making them a significant contributor to the sustainability of the built environment (NOS, 2022). The Climate Agreement outlines the objective of transitioning 1.5 million households away from natural gas by 2030, with approximately half of these being supplied through a heat network. Consequently, heat networks constitute a vital component of the ongoing energy transition (Warmtenetwerk, 2022). Heat networks are a unique part of infrastructural projects. An important aspect of heat networks is the absence of a national network, which means that a consumer is not able to choose between producers. Well-defined market regulations are needed to cover this lack of competition and the monopolistic position of the owner of the network. In the Netherlands, the market regulations are covered under the 'Warmtewet', which outlines the duties of heat producers and the rights of consumers. (Rijksdienst voor Ondernemend Nederland, 2023).

2.2.1. New regulations

In October 2022 the Dutch government decided in the 'Wet Collectieve Warmtevoorziening' that heat networks should have public ownership (Jetten, 2022). This decision means that local governmental parties become more responsible for the development of heat networks. This umbrella organisation for Dutch municipalities states that public ownership could provide more clarity for citizens in the organisation structure and according to this organisation, municipalities want to play a role in the development of heat networks to guarantee affordability and energy security (van der Walle, 2022a). Opposing this governmental decision, the energy companies are saying that they don't want to invest in heat networks without having the majority of the control rights (Grootscholten, 2022). Another argument of the Dutch government in favour of their decision refers to the costs of these networks. Energy markets now sell their heat under the 'not more than usual' principle. This means that the tariffs of heat networks are directly related to gas prices. With high gas prices, companies can also raise their heat network tariffs. The new law should provide more transparency in the price mechanism. When the ownership of the network becomes public, possible revenues are easier to justify, since these revenues will flow back to society.

The responsible Minister Jetten promised that the following conditions should be satisfied before implementing the new law: the dominant role of municipalities should not delay the heat transition and municipalities should have enough capacity to handle the responsibility (van der Walle, 2022b). The government requested an advisory report in which the effects of the new law are analysed. This report concludes that implementing the law would delay the development of new heat networks. Without a majority of the shares, market parties are logically not investing their knowledge and money in new networks. The intended goal of connecting an additional amount of 500.000 buildings in 2030 buildings is likely to be unachievable with this new law (PwC, 2022).

Current laws and regulations are mainly focused on traditional heating networks. In the context of heating (and cooling) networks involving multiple suppliers, a comprehensive restructuring of the organisational framework is required, as an open network needs to be designed. It remains a question of which entity would be responsible to manage the network. A potential benefit of such an open network, characterised by a separation between grid operation and heat supply, is that various cost components become more transparent (Schilling & Schep, 2018). The novel technology of the 5GDHC system will change the role of heat suppliers since multiple suppliers will enter the network. This asks for new agreements and creates new interests. An incentive must be created to deliver to the network and more discussions must be held. Overall, it is essential to engage in discussions and collaborate with relevant parties to manage the trade-offs involved (Schilling et al., 2020).

2.2.2. Actor identification

The implementation of heat networks involves multiple stakeholders with varying perspectives and interests. This field is characterised by ongoing development, and many regulations are still in their early stages. This section introduces the most critical actors involved. In the next section, the objectives of these actors will be examined.

Heat suppliers

Heat suppliers are responsible for generating heat and delivering it to the heat grid. They can encompass various entities, including power plants that produce heat as a by-product, facilities that provide waste heat, geothermal sources, biomass plants, or renewable energy sources. These heat producers often operate as private parties. Typically, a single party serves as the heat supplier, and in some cases, they may also function as an energy company. However, the introduction of 5GDHC networks, which involve the integration of multiple energy sources and technologies, would alter the role of the heat supplier. In such networks, multiple parties would collaborate in the heat supply process, leading to a more diverse and decentralised heat provision system.

Energy companies
Energy companies play a crucial role in the implementation of heat networks. They are responsible for the planning, construction, operation and maintenance of the heat infrastructure. These companies supply heat to consumers and provide the necessary investments in the network. They ensure a reliable and safe supply of heat to end users. In the heat network, energy companies often function as network operators as well (Schilling et al., 2020). In many cases, energy companies in the heat network sector are private entities. Furthermore, the significant capital investment for an energy company limits the possibility of competition among multiple parties. Consequently, end-users generally do not have alternative energy companies available to select for their heat supply.

Electricity grid operators
Grid operators, responsible for managing the power grid, play a crucial role in the context of 5GDHC networks. As more homes transition to electric heat pumps on a large scale, the demand for electricity in residential areas increases significantly. To prevent power outages and ensure a reliable electricity supply, grid operators need to accommodate this increased demand by upgrading and expanding the power grid infrastructure in the respective neighbourhoods. However, addressing this increased electricity demand and grid expansion requires careful consideration and coordination among various stakeholders.

Governmental organs
The implementation of heat networks heavily relies on the involvement of local, regional, and national governments. These governmental entities play crucial roles in shaping the regulatory framework and providing support for the development and expansion of heat networks. At the local level, municipalities have a direct lead in determining the heat supply for each neighbourhood (Schilling et al., 2020). They have the authority to make decisions regarding the implementation of heat networks, considering factors such as local energy sources, infrastructure availability, and community needs. To ensure coordination and alignment, these plans formulated by municipalities must be coordinated at the regional level. Regional coordination allows for the harmonisation of heat network plans, utilisation of national heat sources, and establishment of necessary regional energy infrastructure (Vereniging van Toezichthouders in Woningcooperaties, n.d.). The national government plays a significant role in the overall planning and regulation of the heat transition. In the Dutch Climate Agreement, the national government presents comprehensive plans for the transition to sustainable heating systems, including the development and implementation of heat networks. The government is responsible for providing laws, regulations, and guidelines that support the growth of heat networks and ensure their compliance with national objectives and standards.

Housing corporations
Housing corporations provide rental housing for citizens with a lower income. Given that many of these buildings are situated in densely populated regions, they are well-suited for the establishment of district heat networks (Schilling et al., 2020). In line with the commitment to achieve carbon neutrality by 2050, housing corporations have agreed to develop plans to make their building stock more environmentally friendly. However, the initiation of new heat networks is primarily guided by the ”Regional Energy Strategy” and the ”Transitie Visie Warmte,” which are provided by governmental organisations (Schilling & Schep, 2018). This alignment with the plans set forth by Aedes, the branch organisation representing housing corporations, underscores the need for corporations to express their ambitions to the municipality. By communicating their aspirations, housing corporations can influence the municipality's planning process and ensure that their specific needs and goals are considered (Schilling et al., 2020).

End-users
End users play a crucial role as consumers and businesses that receive heat from the heat grid. As the recipients of heat, end users generate the demand that drives the operation of heat networks. End users are directly affected by the construction and maintenance activities associated with heat networks, such as roadworks, drilling, and the installation of heat pumps. Consequently, their experiences and feed-

back play a vital role in shaping the design, development, and operation of heat networks. Furthermore, the engagement and involvement of end users in decision-making processes are crucial for ensuring that their specific requirements and concerns are addressed. Their input can inform the development of policies, regulations, and practices that are responsive to their needs, promote energy efficiency, and enhance the overall effectiveness and sustainability of heat networks.

2.2.3. Actor objectives

The purpose of this section is to identify the objectives of the key actors involved in order to gain a deeper understanding of the system criteria. These objectives are presented in a table, as depicted in 2.4. The analysis of the actors' objectives reveals a considerable degree of overlap and the absence of conflicting objectives. Based on this analysis, four primary objectives can be derived. It becomes evident that ensuring an affordable, reliable, and sustainable heat supply represents the most crucial objectives arising from this analysis. Additionally, one of the listed objectives pertains to establishing connections with all potential consumers. The next part provides detailed explanations of these four objectives, along with the rationale behind their significance for each actor.

Figure 2.4: Table with the actors and their objectives

Actors	Objectives
Heat suppliers (in a 5GDHC network)	Low costs for heat consumption Reliable heat supply
Energy companies	Provide a reliable heat supply Provide sustainable heat supply Profitable business case Connect all possible consumers
Electricity grid operators	Maintain a reliable electricity network Enable the energy transition
Governmental organs	Phase-out the use of natural gas by 2050
Housing corporations	Phase-out the use of natural gas by 2050 Low costs for heat consumption Provide a connection to a reliable heat system
End-users	Low costs for heat consumption Reliable heat supply

Affordable heat supply

Within a 5th Generation District Heating and Cooling (5GDHC) network, stakeholders recognise the criticality of providing an affordable heat supply. The costs associated with such a heat network are multifaceted. Infrastructure costs entail the installation and maintenance of the network's essential components, including pipes, pumps, heat exchangers, and related equipment necessary for effective heat distribution. Connection costs encompass the expenditures associated with linking individual buildings or units to the network, which involve the installation of heat exchange units within the respective buildings. Operational costs, on the other hand, comprise ongoing expenses related to energy production, system monitoring, maintenance, and repairs. In the Netherlands, the "Niet Meer Dan Anders" (No More Than Otherwise) principle is an important aspect of heat networks. It implies that the costs of connecting to the network should not exceed the costs of using conventional heating systems. This principle ensures that end users do not face a financial burden when transitioning to a more sustainable energy solution. Nonetheless, to establish a financially viable system, it is crucial to incorporate affordability as a fundamental aspect in the development of 5GDHC networks. This can be achieved by accounting for both the upfront investment costs and the long-term operational costs involved.

Energy companies are responsible for the development and operation of the 5GDHC network. For them, a profitable business case is essential to ensure the sustainability and longevity of their operations. Heat suppliers play a crucial role in the 5GDHC network by providing the actual heat to the network. Connecting to a profitable network is important for them to ensure a return on their investment. An affordable heat supply in the network allows heat suppliers to offer competitive pricing, attract more customers, and establish long-term contracts, thereby creating a profitable business model. Housing corporations aim to provide affordable and sustainable housing solutions to their residents. By connecting to an affordable heat supply in a 5GDHC network, housing corporations can offer their residents affordable heating and cooling services, leading to satisfied residents. End users want affordable energy to manage their heating and cooling expenses. With an affordable heat supply in a 5GDHC network, end users can enjoy lower energy bills and have access to sustainable heating and cooling solutions, which positively impacts their financial well-being.

Reliable heat supply
Peak demand poses a significant challenge to the reliability of 5GDHC networks. The system must be designed to handle periods when the heat demand reaches its maximum levels. Robust infrastructure, efficient heat generation, and smart load management are essential components in managing peak demand effectively. By ensuring that the system can handle peak demand without compromising the heat supply, the reliability of the network is upheld. This can be provided with the implementation of cluster-based systems, where heating and cooling demands are relatively homogeneous within each cluster. Another critical aspect of a reliability system refers to the physical network infrastructure, which must ensure a reliable heat supply. The length of the network plays a role in determining the occurrence of failures. Generally, shorter networks have a lower probability of encountering failures compared to longer networks. This is because longer networks have a larger number of components, such as pipes, pumps, and heat exchangers, increasing the chances of potential points of failure. Therefore, network designers and operators should carefully consider the network's length to minimise the risk of failures and enhance overall system reliability. By considering these aspects, stakeholders can work towards developing and operating 5GDHC networks that meet the reliability requirements of all participants.

A reliable heat supply is crucial for various stakeholders involved in 5GDHC networks, including heat suppliers, energy companies, housing corporations, and end users. Ensuring a reliable supply is vital for heat suppliers as it allows them to maintain consistent service and meet the demands of their customers. Uninterrupted heat supply enhances their reputation and customer satisfaction and ultimately contributes to the profitability of their operations within the network. For energy companies, a reliable heat supply is equally important. Energy companies are responsible for the development, operation, and financial viability of the 5GDHC network. A reliable system enables them to establish long-term contracts and generate higher revenue. A robust and dependable heat supply is essential for energy companies to build a sustainable and profitable business case. Housing corporations aim to provide reliable heating and cooling services to their clients, in order to enhance customer satisfaction. By connecting to a reliable heat supply in the 5GDHC network, housing corporations can ensure that their residents have access to consistent and dependable heating and cooling solutions. End users, comprising residential and commercial consumers, rely on a stable heat supply for their day-to-day comfort and operations. A reliable heat supply ensures that end users can trust the system to meet their heating and cooling needs consistently. This reliability factor is crucial in minimizing disruptions, maintaining a comfortable living or working environment, and avoiding inconveniences caused by heat supply interruptions.

Sustainable heat supply
A sustainable heat supply in a 5GDHC network refers to the utilisation of energy sources and technologies that have minimal environmental impact, promote resource efficiency, and contribute to the reduction of greenhouse gas emissions. The integration of renewable energy sources, such as solar, wind, geothermal, and biomass, plays a pivotal role in ensuring a sustainable heat supply. Utilizing low-carbon energy sources helps to reduce the carbon footprint of the network and aligns with global climate goals. In addition, implementing energy-efficient technologies and practices within the network significantly reduces energy waste, resulting in a more sustainable operation. This can include efficient heat generation, heat recovery systems, and advanced control mechanisms to optimise energy use. A sustainable 5GDHC network takes an integrated approach, combining heating and cooling systems, optimizing energy flows, and utilizing waste heat. It is therefore important to create a heat network in which cluster can provide their own energy. This integration enhances overall system efficiency and

reduces reliance on conventional energy sources.

Energy companies benefit from a sustainable network by aligning their operations with environmental objectives, reducing their carbon footprint, and enhancing their reputation as environmentally responsible organisations. Sustainability also presents opportunities for new business models. Governmental organs have set targets to phase out natural gas by 2050, aiming to reduce greenhouse gas emissions and combat climate change. A sustainable 5GDHC network can play a crucial role in achieving these targets, providing a reliable alternative to natural gas for heating and cooling purposes. Housing corporations are committed to providing sustainable and affordable housing solutions. A sustainable heat supply allows housing corporations to offer environmentally friendly heating and cooling services to their residents, contributing to their sustainability goals and improving the overall quality of life for tenants.

Connect all users
Connecting all buildings in a city when developing a 5th Generation District Heating and Cooling (5GDHC) network holds significant importance for several reasons. Firstly, connecting all buildings in a city to the 5GDHC network allows for efficient heat distribution and utilisation. By integrating the entire building stock, waste heat from one building can be utilised to meet the heating demands of neighbouring buildings. This approach minimises heat losses, maximises energy efficiency, and reduces overall energy consumption, leading to significant energy savings. Secondly, it enables better demand flexibility and load balancing within the 5GDHC network. It allows for the optimisation of heat supply and demand across different buildings and neighbourhoods, ensuring a more stable and balanced distribution of heat. By spreading out the load, the network can handle peak demands more effectively, minimizing the risk of disruptions and ensuring a reliable heat supply.

For energy companies, this approach aligns with their objectives of expanding their customer base and creating a profitable business case. By integrating the entire building stock, a city-wide 5GDHC network can effectively meet the heating and cooling needs of the community while optimizing energy utilisation and minimizing environmental impact.

2.3. Related work

As discussed in 2.1.1 there is no consensus on the terminology of 5GDHC systems. This results in the presence of several terms in the literature. The term 5GDHC label started appearing in 2015 when Flexynets launched their projects (Lund et al., 2021). Although there is no consensus on the terminology, most researchers agree that the different system definitions can lead to misunderstandings and stress the need for a unifying name (Buffa et al., 2019; Lindhe et al., 2022; Lund et al., 2021; Sulzer et al., 2021). Due to the varying descriptions of the 5GDHC system available in the literature, it is important to also include other terminologies, such as bidirectional district heating cooling network, low-temperature district network and anergy network, in the literature research.

Several reviews on DH and 5GDHC systems have been published covering different aspects. DH systems have been implemented longer, but not all knowledge about those systems applies to 5GDHC systems. Traditional DH systems differ significantly from 5GDHC systems. The main difference is the connection of multiple sources, which makes the system even more complex and demands new technologies and topologies. Rezaie and Rosen (2012) reviewed traditional district energy systems from a technical, economical, and environmental perspective. Werner (2017) continues with a review of the traditional heating and 4GDH networks from the same perspectives and puts them in a global context. Both Buffa et al. (2019), Pellegrini and Bianchini (2018), and Wirtz et al. (2022) review existing cases of 5GDHC networks. Lindhe et al. (2022) presents a technical and functional review on 5GDHC and its place in shared energy systems (SES). García-Céspedes et al. (2023) reviews the integration of shallow geothermal energy technologies in 5GDHC networks from geopolitical, environmental and societal perspectives. Gjoka et al. (2023) focuses on the most recent developments of the 5GDHC technology and critically reviews the implementation barriers.

In these reviews, several challenges for 5GDHC networks have been addressed. The most commonly described challenge is the lack of guidelines for the design stage, caused by the relatively novel technology (Lindhe et al., 2022). The lack of guidelines limits a potential future researcher in relying on such guidelines to define the system (Gjoka et al., 2023). To overcome this challenge, Gjoka et al. (2023) suggests more research on reducing uncertainties in planning, design, and capital expenditure. Lindhe et al. (2022) states that more focus on the further development of design and simulation tools and business models is needed in order to tackle this challenge. Buffa et al. (2019) agrees with these statements and stresses the need for a change of mindset made by both network operators and potential excess heat providers, in order to stimulate the recovery of excess heat and to reduce the investment risks.

Two other challenges for 5GDHC networks are described by Wirtz et al. (2022). He finds that most current 5GDHC systems are designed for small to medium-sized districts. Wirtz et al. (2022) states that 5GDHC systems are feasible and suitable for large urban areas. Consequently, it is important to provide more research on implementing 5GDHC networks on a larger scale. Buffa et al. (2019) stresses the need for neighbourhood-based energy planning to create "self-balanced" independent clusters that can be connected to a backbone later. In this way, 5GDHC networks can evolve with modularity and in line with the development and planning of the urban area. This minimises the total investment costs. Boesten et al. (2019) argues against a neighbourhood-based design, since it can sometimes be beneficial to set other boundaries or include buildings from adjacent neighbourhoods. In order to create clusters with complementary demand profiles, it will be beneficial to take energy profiles into account while planning the design of 5GDHC clusters (Boesten et al., 2019).

The other challenge proposed by Wirtz et al. (2022) describes the dominance of new-build areas in research and currently developed 5GDHC networks. He concludes that 5GDHC has proven itself in newly built districts, and the next step would be to prove viability and profitability within an existing building stock. Additionally, Werner (2017) concludes that 5GDHC is a promising future solution in an urban energy system, but strong efforts are required to implement these systems on a large scale.

Next to the highlighted review articles, many theoretical studies on 5GDHC systems have been published as well. Several numerical evaluation studies have been performed to gain more insights into the development of 5GDHC systems. Wirtz et al. (2020) designed a linear optimisation model for the design and demand balancing in 5GDHC systems. Another optimisation study of Bünning et al. (2018) presents a concept for operational optimisation based on a temperature set point optimisation and agent-based control. von Rhein et al. (2019) developed a software tool that considers multiple network layouts to determine which buildings are feasible for a 5GDHC network. In a more integrated approach, Revesz et al. (2020) presents a model where 5GDHC is part of a smart energy system. The control of heat pumps, electric vehicles and storage systems proves to be both economically viable and carbon-saving within this model. Abugabbara et al. (2020) presents a bibliographic analysis of research on modelling and co-simulating of 5GDHC systems. Co-simulation is the coupling of different district energy models or building models, this produces a trade-off between simulation performance and model accuracy (Abugabbara et al., 2020). Many other articles focus on the techno-economical analysis or optimisation of a certain design parameter or element. Zeh et al. (2021) and García-Céspedes et al. (2023) focused in their studies on the integration of shallow geothermal potentials. Calise et al. (2022) introduces and analyses the concept of a solar-driven 5GDHC system. In the study of Quirosa et al. (2022), the CO_2 booster heat pump is analysed economically and energetically. Focused on a performance analysis Sommer et al. (2022) explored the hydrothermal challenges of 5GDHC systems and Pass et al. (2018) performed a thermodynamic analysis for modern individual and district thermal systems. All of these numerical studies focused on individual or small-scale cases or designs. The studies vary a lot in their focus areas, mostly based on optimisation or the performance of the system or certain system elements.

The topology of 5GDHC systems is an important subject in the literature. However, network topology is not included in many studies. 5GDHC differs significantly from the other generations when it comes to network topology. Traditional district heating networks often make use of a tree network with one central supplier. Due to the addition of multiple suppliers and the bidirectionality of the network, the network now must be ordered in a ring structure. The network topology in 5GDHC is discussed in the research of Jebamalai et al. (2022), in which a 3GDH and a 5GDHC network configuration are described and compared. This study finds that ring configurations are more expensive than tree configurations, but on the other hand more reliable and flexible. When making use of free excess waste heat, the network is economically viable (Jebamalai et al., 2022). In the study of Pass et al. (2018), further research on network topology optimisation is recommended to efficiently divide items over the network. Gjoka et al. (2023) argues that more research should focus on design parameters and system configurations in order to tackle the lack of guidelines in 5GDHC development. Several design tools are developed in order to create a planning approach for a selected area. Heat (2022) offers a GIS-based automated district energy network planning and design tool. WarmingUP (n.d.) developed a tool kit that connects a number of innovative tools for planning, design, hydraulic engineering and control of heat networks in one software package. However, the routing of the network is often drawn manually. A method to divide an area into clusters and provide a route for the pipe network is absent is most of these tools (F. Franchimon & E. Smulders, personal communication, April 26, 2023).

2.3.1. Knowledge gaps

In conclusion, the concept of 5GDHC is a relatively new technology, which may account for the lack of a clear and precise definition. Research emphasises the need for precise terminology to prevent misunderstandings. Additionally, the lack of technical standards, guidelines, and a common vision, limits researchers in defining and describing the system. Most of the research on 5GDHC has concentrated on small-scale or individual cases in new-built districts, while knowledge on implementing 5GDHC in larger areas with an existing building stock is lacking. However, developing 5GDHC networks in an existing district may be one of the biggest challenges. Furthermore, the design of 5GDHC systems and their network topology is inadequately reported in the literature. Research on traditional DH networks often cannot be extrapolated to 5GDHC networks, which have entirely different characteristics. Further research on network design is necessary to tackle the shortage of guidelines.

The aim of this research is to develop a planning approach that can be used in densely populated urban areas with older building stocks. Focusing on a large area, such as a city or a district, the research seeks to go beyond neighbourhood boundaries while creating physical arrangements of 5GDHC clusters. The research emphasises the inclusion of the energy balance and the geographical locations of buildings to identify appropriate clusters of a 5GDHC network in which every user can get connected.

2.4. Requirements and objectives of the system

This chapter has outlined a range of requirements and objectives associated with the implementation of a 5GDHC system. The objective of this section is to determine which specific requirements and objectives will be encompassed within the scope of this research. The analysis has focused on the topology of the system, the characteristics of an urban dense area, and the objectives of various stakeholders.

The topology section of this study has identified several fundamental requirements that serve as essential components of a 5GDHC network. Firstly, the pipe network within a cluster should be structured in a ring configuration. Secondly, the system must be divided into multiple clusters. Lastly, the energy balance of each cluster should approach equilibrium. It has been established that an urban dense area is an ideal environment for implementing a 5GDHC system. However, some requirements emerge from the implementation of a 5GDHC system within such an area. The development of 5GDHC systems must align with other present or future urban developments, infrastructure requirements, and system characteristics. In, addition, retrofitting buildings is crucial to facilitate their connection to a 5GDHC system. Finally, is vital to engage and collaborate with various actors. The four objectives that have been identified in the actor analysis are affordability, reliability, sustainability and connection to all buildings.

The items coming forth from these sections can be categorised into requirements and objectives. The items listed in the topology and urban dense area sections fall under the category of system requirements. However, due to their highly context-dependent nature, considerations related to other urban developments and stakeholder engagement will be excluded from the scope of this research. The objectives of connecting to all buildings will be treated as a requirement for this study, while the remaining objectives, identified in the actor analysis, will be retained as objectives. The requirement of the topology section to have an energy-balanced cluster can be categorised under both the reliability and the sustainability objective, and will therefore be left out of the requirements.

The objectives of affordability, reliability and sustainability will be converted to more concrete, measurable objectives. Affordability refers to the costs of the network. These can be split up into infrastructure, connection and operational costs of the network. The most variable part of these costs in this research will mostly depend on the length of the network. The longer the network, the more infrastructural and operational costs are spent. The reliability of the network also partly depends on the length of the network, due to the increasing potential risks. In addition, reliability also refers to the management of the demand and supply profiles within a cluster. Reliability can be provided with the implementation of cluster-based systems, where heating and cooling demands are relatively homogeneous within each cluster. This also encourages the sustainability objective. Therefore the two main objectives of the model will be:

1. The length of the network must be minimised
2. The energy balance of each cluster should approach equilibrium

3
Theoretical framework

This chapter offers a comprehensive review of the relevant academic literature pertaining to clustering and graph theory, aiming to identify appropriate methodologies for this research. Section 3.1 provides an overview of various clustering techniques and presents a problem formulation specific to the clustering aspect of this thesis. The suitability of the selected clustering methods for this research will be discussed in detail. In Section 3.2, the focus shifts to the network design of a 5GDHC (Fifth Generation District Heating and Cooling) system. Additionally, the introduction of geometric graph theory as an approach to designing the infrastructure network will be presented. Subsequently, the design of a ring structure within the 5GDHC system for this research will be examined and elaborated upon.

3.1. Clustering methodologies

The following part discusses various clustering approaches, their methods and applications. Clustering is the grouping together of similar data items, such that data points within a cluster are more similar to each other than to data points in other clusters (Fung, 2001). Clustering is a method that is used in many different problems and domains, from biology to crime analysis, making it a well-studied topic. There is a good amount of information on clustering out there and over 100 methods are available. Yet, finding the appropriate method is challenging and the performance of the algorithm can vary substantially depending on the data type (Rodriguez et al., 2019).

The aim of this thesis is to propose a methodology for categorizing urban buildings into distinct clusters in the context of a new 5GDHC network. The clustering process will take into account the buildings' geographical locations, as well as their energy demand and supply within a specific area. The desired outcome is to establish self-sufficient clusters, where the energy demand matches the energy supply and in which the length of the total network within the clusters is minimised.

While many clustering techniques are capable of handling multiple data variables, they typically create clusters based on similarities in the data. These clustering techniques are suitable for geographical features like latitude and longitude since it aims to cluster buildings that are in close proximity to each other. However, in the case of achieving an energy balance within a cluster, it is undesirable to have buildings with identical energy profiles grouped together. The objective is to form clusters in which buildings can mutually supply each other, thereby eliminating the need for similarities in energy data. A methodology is required that clusters buildings based on similar geographical attributes and distinct energy profiles, in order to achieve an energy balance close to zero for all clusters while the distance between the buildings is minimised.

Given that clustering based on location and energy balance necessitates different approaches, the decision has been made to first cluster buildings based on location. Subsequently, adjustments will be made to enhance the energy exchange within each cluster, thereby achieving a more balanced energy profile. This section elaborates on the optimal approach for clustering the data based on location. In the subsequent chapter 4, the adjustments made to the initial clustering approach, focusing on energy balance, will be elaborated.

The main objective of this chapter is to find a clustering method in which the length of the network inside each cluster can be minimised. Additionally, this method must be suitable for the data with locations of the buildings in an urban dense area. The following requirements for the cluster method are identified:

1. Clusters must be compact

   Creating compact clusters ensures that the buildings within each cluster are geographically close to each other. Compactness is important because it minimises the length of pipe network required to connect all the buildings within a cluster.

2. Clusters must not overlap each other

   It is important to ensure that the clusters do not overlap each other. Overlapping clusters could lead to redundant or overlapping pipe connections between buildings, which would result in inefficiencies in the 5GDHC network. Non-overlapping clusters help maintain clear boundaries between clusters, enabling efficient and independent control of heating and cooling within each cluster.

3. Clustering method must recognise non-convex shapes

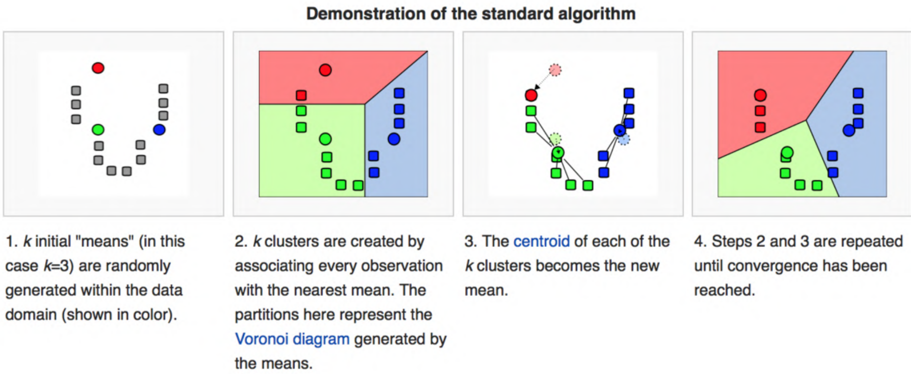
   Urban areas often contain irregularly shaped buildings and non-convex geometries. By using a clustering method that recognises non-convex shapes, you can accurately group buildings based on their geographical proximity, regardless of their shape. This is important because many clustering methods tend to produce convex clusters and may not capture the spatial relationships of buildings in complex urban environments.

The following subsection will provide an overview of available clustering methods. According to Han et al. (2012), the clustering methods can be categorised into four groups: partitioning clustering, density-based clustering, grid-based clustering and hierarchical clustering. These groups of clustering methods will be described in this section along with their applicability to this thesis.

Partitioning clustering

The first category of clustering methods is Partitioning clustering, which involves relocating instances by moving them from one cluster to another. This process begins with an initial partitioning, which can be pre-set by the user or can be chosen randomly (Rokach & Maimon, 2005). A well-known known partitioning heuristic is the K-means algorithm. This method partitions a dataset into K clusters (where K is a pre-specified number) based on the similarity between data points. The K-means algorithm selects K points from the dataset as initial centroids for the K clusters and then iteratively refines the cluster assignments and the positions of the centroids until a stable solution is found. The K-means algorithm is illustrated in Figure 3.1. Although extensive research has been conducted on K-means and the algorithm is computationally efficient, it has some limitations. K-means is not suitable for clustering datasets with non-spherical distributions or varying sizes, and it is also highly sensitive to the initial centroid positions and outliers of the dataset (Rodriguez et al., 2019; Rokach & Maimon, 2005). This clustering method assumes that the clusters have similar sizes and densities. In an urban dense area, buildings may have irregular shapes, and the desired clusters might not be compact or spherical. Partitioning methods may struggle to capture the non-convex and irregular shapes of the clusters which can be obtained in urban dense areas. Other Partitioning Methods have been developed to mitigate the impact of outliers or improve the robustness of the results, but they come at the cost of increased computation time (Rodriguez et al., 2019). The unsuitability of Partitioning Clustering for clustering non-convex shapes makes it unsuitable for the clustering problem defined in this research.

Figure 3.1: Linkage methods (contributors, 2023)



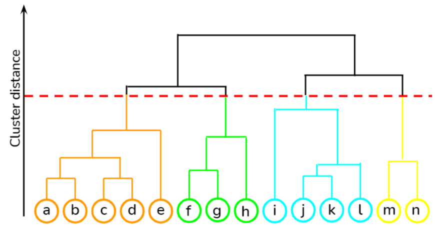
Density-based clustering
Another clustering category is Density-based methods. This method offers the ability to identify arbitrary shapes and detect noise or outliers. The identification of arbitrary shapes is beneficial since spatial data rarely contains regular-shaped clusters (Chaoji, 2009). Despite its advantages, density-based clustering has several limitations that make it unsuitable for this research. Density-based clustering assumes that clusters exhibit different density levels, where high-density regions represent clusters and low-density regions represent noise or outliers. If the density of buildings in the urban dense area is relatively homogeneous throughout, it might be challenging for density-based clustering algorithms to differentiate meaningful clusters from noise and to accurately separate and distinguish individual clusters. In addition, if the density of the data is uneven, the clustering results will be of poor quality (Xu & Tian, 2015). Moreover, density-based clustering requires relatively large amounts of memory and computation time compared to other clustering methods, making it impractical for large datasets or real-time applications. As a result, density-based clustering is not a suitable method for this research.

Grid-based clustering
Grid-based clustering is a clustering method that partitions data points into rectangular or square grid cells. The basic idea is to create a grid over the data space and assign data points to the grid cells based on their location. Grid-based clustering is often employed in spatial data analysis to identify clusters of data points that are close together in space. One of the primary advantages of grid-based clustering methods is their computational efficiency, which is not dependent on the dataset size, but rather on the number of cells in each dimension in the quantised data space (Han et al., 2012). However, grid-based clustering methods can be sensitive to the choice of grid size and cell shape, and may not perform well on datasets with complex structures or high-dimensional data. Moreover, grid-based clustering methods partition the data space into grid cells and assign data points to these cells. This approach assumes that clusters align well with the grid structure and that they exhibit similar sizes and shapes. In an urban dense area, buildings can have irregular shapes and may not conform to the grid structure. Grid-based clustering may struggle to capture the arbitrary shapes of the potential clusters inside an urban dense area. (Madhulatha, 2012). Thus, Grid-based clustering is not appropriate for addressing the problem formulation in this research.

Hierarchical Methods
Finally, the application of Hierarchical Methods for clustering data will be introduced. This approach groups similar data points by recursively dividing or adding the data into subgroups to form clusters. The resulting structure is a dendrogram, which is a tree-like diagram that shows the relationships between clusters at different levels of the hierarchy. By cutting the dendrogram at a specific height, a desired number of clusters can be obtained (Han et al., 2012). An example of a dendrogram is provided in figure 3.2. The y-axis of the dendrogram represents the distance between the clusters and points.

Hierarchical clustering does not require the number of clusters to be predetermined. It allows for the exploration of the data structure at different levels of granularity, as the clustering hierarchy can be cut at any desired threshold derived from the dendrogram. This flexibility is useful when the optimal number of clusters is unknown or when multiple levels of detail are of interest. Furthermore, hierarchical

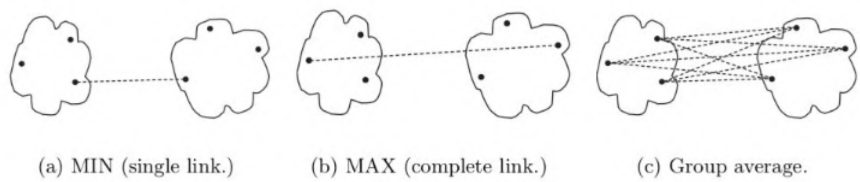
Figure 3.2: Dendrogram (Elbasheer, 2021)



clustering does not impose any specific shape constraints on the clusters. It can capture complex relationships and identify non-convex clusters by considering the overall similarity between data points. However, the effectiveness of hierarchical clustering in recognizing non-convex shapes depends on the distance metric used and the linkage criteria employed during the merging process. In addition, hierarchical clustering can be sensitive to the choice of distance metric and linkage method used to calculate the distance between clusters (Xu & Tian, 2015).

Since the suitability of hierarchical clustering can depend on the type of distance metric, these metrics will be explained first. In Hierarchical clustering, different distance metrics can be used to measure the distance between clusters. The distance metrics most frequently utilised in Hierarchical clustering are single, complete, and average linkage. The single linkage metric measures the distance between two clusters by computing the shortest distance between any two data points in the respective clusters. In contrast, complete linkage determines the distance between two clusters by calculating the maximum distance between any two data points in the respective clusters. Finally, with average linkage, the distance between two clusters is computed as the group average of all pairs of data points in the two clusters. The linkage or distance metrics are illustrated in Figure 3.3.

Figure 3.3: Linkage metrics (Jarman, 2020)



Single linkage clustering is suitable for handling non-spherical clusters. In addition, the connection of the nearest data points suits very well to the objective to minimise the total length of the pipe network. However, single linkage clustering can cause the "chaining" effect, where clusters can be linked together through a series of single-link connections. This can lead to the formation of long, elongated clusters that may not accurately represent the underlying structure of the data.

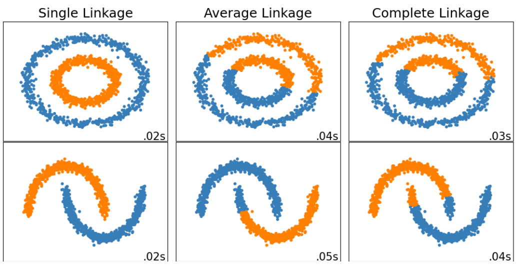
In contrast, complete linkage tends to produce more compact clusters with distinct boundaries. It is suitable for datasets with well-separated clusters, where clusters are relatively spherical or globular in shape. Nevertheless, it can struggle to accurately detect non-convex clusters since it only considers the maximum distance between points from different clusters. It may result in merging clusters that have non-convex or complex shapes, leading to suboptimal clustering results.

Lastly, average linkage strikes a balance between single and complete linkage by considering the average distance between points from different clusters. It can produce non-convex clusters that are relatively compact while maintaining a moderate level of connectivity between points. However, it can also produce clusters that are too compact or too dispersed. Also, Average linkage requires calculating the average distance between points from different clusters, which results in a computationally more demanding method than the other linkage methods (Jarman, 2020).

In figure 3.4 the different outcomes of implementing the different linkage methods on two different datasets are shown. In this figure, the single linkage method succeeds in effectively dividing the datapoints into compact clusters in a non-convex shape. The single linkage method is not dividing direct neighbours into different clusters, whilst the other clusters are doing this. Therefore, single linkage clustering is best suitable to recognise the non-convex shapes of the street patterns in an urban dense area. Therefore, this method will be used in this research. The next section will discuss in more detail how single linkage clustering works and how the limitations of this approach will be handled in this research.

Figure 3.4 illustrates the outcomes of applying various linkage methods to two distinct datasets (see Figure 1). In this depiction, it can be observed that the single linkage method effectively partitions the data points into compact clusters, exhibiting non-convex shapes. Unlike the other methods, single linkage clustering ensures that neighbouring data points are not assigned to separate clusters. Consequently, it is deemed most suitable for recognizing the non-convex patterns inherent in the street layout of densely populated urban areas. Therefore, the current research adopts the single linkage clustering method. The subsequent section presents a short introduction to single linkage clustering and addresses the associated limitation of the chaining effect, while proposing a strategy to mitigate this issue.

Figure 3.4: Linkage methods on different datasets (Pedregosa et al., 2011)



3.1.1. Single linkage clustering

Single linkage clustering, also referred to as the nearest-neighbour method, is an iterative process that merges the two closest clusters into a larger cluster until all data points are part of the same cluster. The distance between two clusters is determined as the minimum distance between any two data points, with one point from each cluster.

It is worth noting that the Single Linkage Clustering algorithm shares similarities with the Minimum Spanning Tree (MST) algorithm, commonly employed in Graph Theory. The MST algorithm aims to identify a subset of edges in a weighted, undirected graph that connects all nodes with the lowest total weight or length possible. The MST algorithm is referred to as a tree since it contains no cycles and spans all nodes within the graph. A brief introduction to Graph Theory is available in Section 3.2.1. The clusters created by selecting a distance in Single Linkage Clustering can be obtained by applying the MST algorithm on the graph and removing edges that exceed that distance, as explained by Gower and Ross (1969).

The chaining effect, which may arise in single linkage clustering, occurs when new data points are repeatedly added based on their shortest distance, leading to the merging of clusters that are not very similar. This effect is a consequence of merging clusters just because one of their data points is the closest to another point in another cluster, while most other points in the two clusters have a significantly larger distance (Jarman, 2020). This issue can be problematic when the dataset contains noise or outliers. In single linkage clustering, these outliers form separate clusters while other data points are merged into the same cluster, resulting in the formation of elongated clusters.

In urban dense areas, the occurrence of outliers in building locations is often minimised. However, some buildings may still be isolated compared to others. In such cases, these isolated buildings can form small clusters, while buildings located in denser parts of the area may form large clusters that are susceptible to the chaining effect. To create more compact clusters, slight adjustments can be made to the single linkage clustering process. Clusters with a low number of buildings can be merged with another cluster that has the closest distance to one of its data points. In this scenario, the single distance metric is employed again, but only to merge a small cluster with another. If a cluster becomes too large or wide, it can be split by identifying the largest distance between two data points and dividing the clusters accordingly. These principles align with the concept of the minimum spanning tree, where an additional edge is added from one cluster to another or the longest edge is removed within a cluster.

3.2. Network design of a ring structure

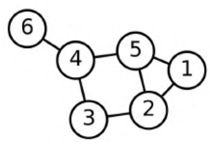
Now that the chosen clustering method for this research has been determined, it is crucial to explore how the ring structure within each cluster can be established. This aspect requires an effective method that can design an infrastructure network. Network optimisation modelling approaches are commonly employed to optimise the design of network topology. Network infrastructures serve as the fundamental framework of society, facilitating essential services, utilities, and connections between suppliers and consumers (Heijnen et al., 2014). Extensive scientific research has been dedicated to network infrastructures, spanning various domains such as road networks and power grids. Based on the requirements outlined in Section 2.4, it has become evident that the ring network should interconnect all buildings, while simultaneously aiming to minimise the total length of the network.

The literature offers multiple methods for network design. Heijnen et al. (2019) distinguish three distinct approaches for network system design, namely Mixed Integer (Non-)Linear Programming, Agent-Based Modeling, and Geometric Graph Theory (GGT). Geometric Graph Theory is an understandable method particularly suited for infrastructure planning design involving diverse actors Heijnen et al. (2019). Given its merits of speed, reliability, and comprehensibility, this approach will be adopted in the present research. The subsequent subsection will provide a concise overview of GGT, followed by a discussion on the implementation of the ring network.

3.2.1. Introduction to graph theory

GGT is a branch of mathematics in which graphs are used to study the pairwise relations between objects (Dye, 2021). Graph Theory is as old as the famous bridges problem of Euler (1953) (original from 1736). In a graph, *nodes* are connected with *edges*. Each edge forms a connection between two nodes. A graph is represented in a 2D plane in which edges form straight lines between nodes. Graph theory is used in a wide range of fields, including computer science, social network analysis, transportation planning, and biology. A very simple example of a graph is given in figure 3.5.

Figure 3.5: Simple graph (Dye, 2021)



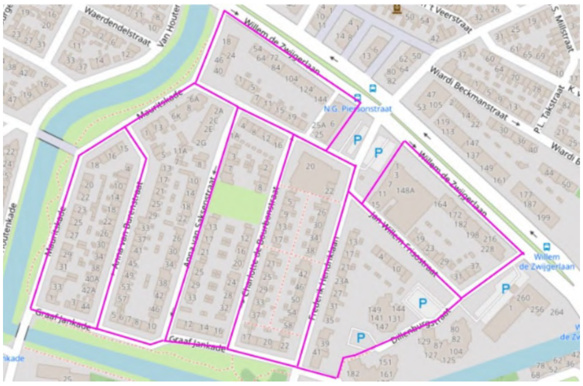
An important concept in graph theory is the *path* in a graph. This is a sequence of edges that connects a sequence of nodes in a graph. In other words, a path is a way of moving from one node to another by following a sequence of edges that connect them. The graph in the example of 3.5 is a *connected graph*. This means that there is a path between every pair of nodes of the Graph. In other words, for any two nodes in a connected graph, there exists at least one path (a sequence of edges) that starts from one node and ends at the other node. When the edge between nodes 4 and 6 is removed in the graph in figure 3.5, this graph becomes *disconnected*, since there exists no path from node 6 to any other node. The *degree* of a node in graph theory is defined as the number of edges that connect to a particular node. In the example of figure 3.5 node 1 has a degree of 2, node 2 a degree of 3 and node 6 a degree of 1. In a *weighted* graph all edges are associated with a weight. The weight of an edge represents some measure of distance, cost, time, or any other quantity that is relevant to the problem being modelled by the graph. A *tree* is a graph that is connected but contains no cycles. This means that between any two nodes, there is exactly one path.

3.2.2. Ring structure

A 5GDHC network is generally connected in a ring structure, which calls for a different approach since most network infrastructures are designed in a tree structure. A typical configuration for a 5GDHC network is a ring structure. More detailed information on this topic can be found in section 2.1.3. This ring network should connect every building to connect all users while aiming to minimise the overall length of the network, as described in Section 2.4.

Two methods to design a ring network for a 5GDHC system can be found in design frameworks. Laurberg Jensen et al. (2016) proposes a ring network that loops through multiple supply points, making them the starting points for the network structure. This structure is extended with branches reaching all buildings. On the other hand, Jansen et al. (2021) presents a design where all nodes, no matter if it is a supply or demand node, are connected to a main ring structure. In this approach each building can be reached from two different directions, utilizing multiple smaller closed circuits instead of a single large loop with branches. This concept is illustrated in Figure 3.6.

Figure 3.6: Ring structure 5GDHC (Jansen et al., 2021)



The method proposed by Laurberg Jensen et al. (2016) demonstrates a notable dependence on the specific location of the supply nodes. In cases where the supply nodes are not evenly distributed across the area, the resulting branches of the network can become considerably long. This can have adverse effects on the overall network length and may lead to reduced redundancy and reliability. Conversely, the utilisation of multiple smaller closed circuits, as exemplified in the approach presented by Jansen et al. (2021), offers distinct advantages in terms of enhanced redundancy and reliability within the network. This design allows for each building to be approached from two different directions, thereby fortifying the network against potential failures or disruptions. Furthermore, the approach proposed by Jansen et al. (2021) demonstrates a more straightforward and automated design process for establishing the ring structure. By connecting all nodes to a main ring structure, the design task is simplified as it obviates the need for extensive branching emanating from the supply nodes. Consequently, this approach aligns more closely with the objectives of this research, which makes it the preferred method for creating the ring network.

4

Methodology

This chapter explores the methodologies for the main steps in this thesis, namely clustering and routing of the pipe network. Within the theoretical framework, single linkage clustering and graph theory have been selected to achieve the objectives of this study. In this chapter, the link between these methods and their application will be discussed. The final method must contribute to the primary aim of this research, namely finding a suitable approach to identify potential clusters in an urban dense area. To assess the performance of the selected approach, several metrics will be introduced in Section 4.1. Subsequently, the model and its sequential steps will be described in detail in Section 4.2. Lastly, various assumptions underlying the model will be discussed in Section 4.3.

4.1. Performance metrics

In order to define and evaluate the results of the model, it is imperative to identify the performance metrics. These metrics can be derived from the objectives identified in Section 2.4. The first objective is to minimise the total length of the pipe network. The second objective is to approach an equilibrium of the energy balance in each cluster. This section translates these objectives into measurable metrics.

The first objective, namely the minimisation of network length, can be operationalised by considering the overall length of the pipe route within each cluster. To quantify this measure, all the streets within a cluster are transformed into a graph representation, and a ring network is constructed using the methodology outlined in Section 3.2. This methodology involves identifying the streets located within each cluster and establishing closed circuits exclusively within that cluster. In order to establish closed loops within the network, it is imperative to ensure that every node in the network has a degree greater than 1, indicating that each node is connected to at least two other nodes. This condition guarantees the formation of closed loops within the network. Consequently, the total length of the ring network corresponds to the aggregate pipe length of the cluster under consideration. For the purpose of this study, this metric will be referred to as **the total length**.

The energy balance of a cluster can be characterised by its heating and cooling demand and supply. Since heating demand can serve as cooling supply and vice versa (Jansen et al., 2021), heating demand is evaluated as a negative number, while cooling demand is considered a positive number. Similarly, heating supply is represented by a positive value. The energy balance of a cluster can be computed by summing these numbers. A positive value indicates that there is a surplus of supply, while a negative number denotes a deficit. The secondary objective of this research is to achieve an energy balance in each cluster that approaches zero. It is essential to consider multiple time steps in the evaluation of the model's performance, as heating and cooling demands are heavily influenced by weather conditions and can exhibit substantial variations throughout the year. Assessing the overall imbalance across all clusters fails to provide an indication of clustering performance, as the summation over all clusters consistently yields the same value. Conversely, examining the absolute imbalance may not offer a clear understanding as it does not distinguish between a shortage of supply and an excess of supply. Therefore, this research has shifted its focus towards analysing the hourly shortage of supply to obtain a more detailed assessment of cluster performance. However, it still can be valuable to examine the overall imbalance to understand how clusters perform over the span of months and to identify seasonal patterns. In conclusion, the sum of the hourly lack of supply per year will be used as the second performance metric. This measure will be referred to as **the energy balance**. For cluster specific performance, it is recommended to look into the disbalance or lack of supply per month.

4.2. The model

The model is designed to provide a tool for identifying suitable clusters for a 5GDHC system in urban dense areas. To achieve this aim, the model incorporates both graph theory and single linkage clustering to identify clusters that connect all the buildings within a selected area. The model calculates the two performance metrics. The model is implemented using the Python programming language within the JupyterLab environment and can be used in other environments as well. A short explanation of the model is provided in the following paragraph. The next sections will reflect on these steps in more detail.

Firstly, the single linkage clustering method is applied to the selected area to identify clusters based on building location. Although single linkage clustering is able to meet this objective, it is imperative to also take the energy profiles of the buildings into consideration as well. Therefore, another method will need to be developed to modify the clusters generated by the single linkage clustering approach. Hence, the size of the clusters is adjusted to create more compact clusters. Then, the energy balance of the clusters is adjusted by switching buildings with identical ZIP codes to create more energy-balanced clusters. Finally, the tool calculates the performance of the metrics.

4.2.1. Input data

To set up the model, several input data files are required. However, this data may not be readily available for all areas, and obtaining data on potential waste heat sources may require extensive research. The following data are necessary for the model to proceed with the subsequent steps:

1. Geographic coordinates of the buildings
2. ZIP code of the buildings
3. Demand of the buildings (in kWh per hour)
4. Geographic coordinates of the potential waste heat sources
5. ZIP code of potential waste heat sources
6. Supply of potential waste heat sources (in kWh per hour)

The specific type of geographic coordinates utilised in the model is not of significance, as long as a consistent reference system is consistently applied across all data.

4.2.2. Single linkage

The process of single linkage clustering is explained in Section 3.1.1. In this initial stage of the model, the geographic area is partitioned into clusters based on their respective locations. To accomplish this, comprehensive data pertaining to the spatial coordinates of all buildings within the area is required. The implementation of this step leverages the SciPy package specifically designed for Python programming language.

To establish the clusters, a maximum distance parameter is employed. This parameter sets the threshold for the maximum allowable distance between two points in order for them to be assigned to the same cluster. Consequently, it also determines the number of initial clusters generated. As explained in section 3.1, this distance parameter determines the point at which the dendrogram will be cut. Alternatively, instead of using a distance value as an input variable, the number of desired clusters could be utilised. However, given the variability in input data, employing a fixed parameter proves more convenient. It should be noted that the precise value selected for the distance parameter does not exert a decisive influence on the final outcome, as the clusters will undergo subsequent modifications based on both a minimum and maximum value criterion. However, it is important to note that the selection of the maximum distance parameter may have an impact on the resulting outcome. Nonetheless, considering that the subsequent adjustments in cluster size are based on the single linkage distances between or within clusters, it is anticipated that any potential effect stemming from the choice of the maximum distance parameter will be relatively constrained.

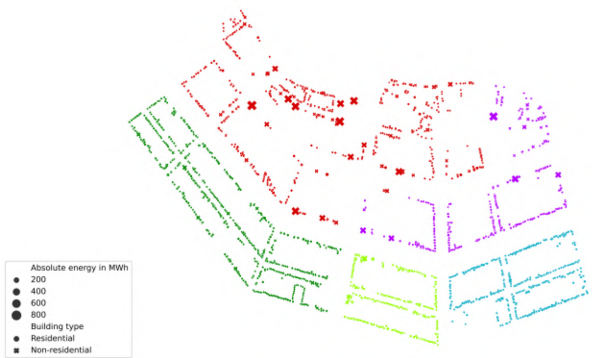
4.2.3. Adjusting the cluster sizes

As explained in Section 3.1.1, the initial clusters obtained through single linkage clustering can exhibit significant variation in size. To create more similar clusters, modifications are made to the cluster sizes by applying a minimum and maximum limit. The cluster size refers to the number of buildings contained within each cluster. In the first step of the modification process, clusters larger than the specified maximum value are identified. These oversized clusters are then split into smaller parts until no part exceeds the maximum value. This ensures that the resulting clusters adhere to the desired size limit. Next, clusters that are smaller than the designated minimum value are assessed. These undersized clusters are merged with the closest neighbouring cluster to increase their size. This merging process aims to create more balanced and representative clusters.

It is important to note that the maximum size of a cluster is not a strict limit since subsequent modifications prioritise achieving the minimum cluster size. Consequently, there may be instances where some clusters exceed the maximum size. This flexibility is assumed to be accepted since this sizing mainly serves to facilitate the creation of similar and compact clusters. An example illustrating the effect with and without these modifications is provided in Figures 4.1 and 4.2.

Figure 4.1: Without any modification of the cluster sizes

Figure 4.2: With modification of the cluster sizes



While this research adopts a minimum and maximum number of buildings as criteria for cluster size, it is worth mentioning that in the development of 5GDHC clusters, the size of a cluster often depends on the potential capacity of the pumping system within an area (F. Franchimon & E. Smulders, personal communication, April 26, 2023). However, to simplify the model, the current approach utilises a predefined range of buildings for each cluster.

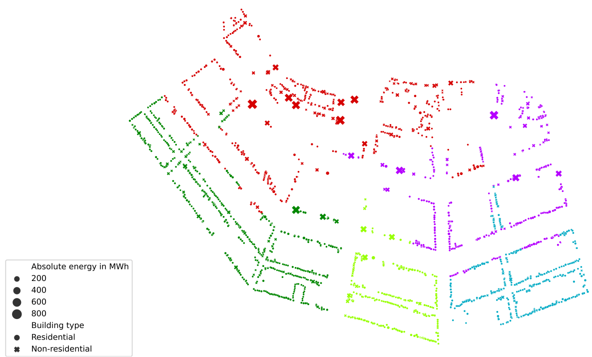
4.2.4. Adjusting the energy balance

Single linkage hierarchical clustering is initially used to divide buildings in the selected area into different clusters based on their location. However, considering the energy profiles of buildings is also crucial in creating clusters for a 5GDHC system. To optimise the clustering process, an additional algorithm has been proposed. This step aims to create clusters that can independently meet their own heating and cooling demands, utilizing the clusters obtained from single linkage clustering as a starting point.

While the first step considers each building individually, this optimisation step groups buildings with the same ZIP code together. Single linkage clustering is preferred in the initial step because it allocates neighbouring buildings to the same cluster. In the optimisation process, parts of clusters are adopted from other clusters or given away to other clusters. To maintain compact clusters, individual building switches between clusters are not allowed. Instead, adjustments are made by switching buildings with the same ZIP code between clusters. Furthermore, the possibility of switching streets has also been tested to optimise the clustering. The distinction between switching streets and ZIP codes is depicted in Figures 4.3 and 4.4. However, it has been decided to perform adjustments based on ZIP codes since streets can be lengthy, and using ZIP codes helps maintain more compact clusters. The distance between the ZIP code and the cluster is calculated between the two closest points of both.

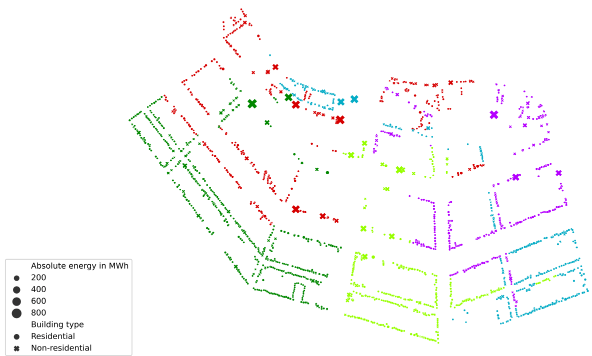
Figure 4.3: Cluster adjustments based on streets

Figure 4.4: Cluster adjustments based on ZIP codes



The algorithm operates as follows: Initially, it examines whether any clusters are encountering a deficit in their energy supply. If all clusters have an adequate supply, the algorithm terminates. However, if there are still clusters experiencing an insufficiency in energy supply, the algorithm evaluates potential improvements within the given parameters. For each cluster with an insufficient supply, the algorithm investigates whether a nearby cluster possesses a surplus supply. In such cases, a comparison is made between the sizes of the two clusters. If the cluster with the energy shortage is larger, it transfers buildings sharing the same ZIP code and exhibiting a higher demand than supply, to the other cluster that has a sufficient supply. Conversely, if the cluster with the energy shortage is smaller, it receives buildings from the cluster with an energy surplus, where these buildings belong to the same ZIP code and have an adequate supply. The clusters involved in this transfer are selected based on their closest proximity to one another. The algorithm iterates until no further improvements can be made. It is important to note that in order to maintain compact clusters and ensure the connectivity of streets within a cluster, a rule is applied where new parts are not linked with other new parts. Consequently, only the initial cluster is allowed to establish connections with sections of other clusters. The impact of not implementing such a rule is demonstrated in Figure 4.5.

Figure 4.5: Cluster modifications with chaining effect



4.2.5. Calculation of the energy efficiency

In this part of the model the metric of the energy balance will be calculated. As described in Section 4.1, this will be achieved by calculating the hourly energy disbalance for each cluster over the course of a year. To perform this analysis, a dataframe containing the hourly demand and supply data for all buildings is required. This data will be utilised to calculate the hourly energy disbalance for each cluster. The total energy disbalance is obtained by summing the disbalances across all hours in a year for each cluster and each month.

4.2.6. Routing methodology

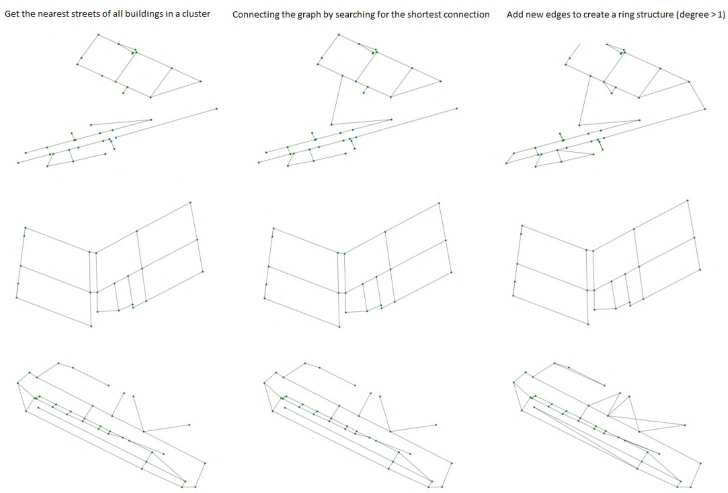
The other performance metric, the total length of the network, aims to calculate the total length of the ring structure inside each cluster. For this purpose, another algorithm is designed to measure the performance of this metric. This part makes use of the OSMnx and NetworkX packages for Python. OSMnx is a package that enables the user to model, project and visualise geospatial data (Boeing, 2016). NetworkX is software facilitating the creation, manipulation, and study of the structure, dynamics, and functions of complex networks (Hagberg et al., 2008). The algorithm for determining the total length of the ring structure within each cluster can be summarised in the following steps:

1. Get the OSMnx street graph of the polygon of the selected area
2. Select a cluster and find for all buildings the closest street in the OSMnx street graph
3. Add all these streets to a subgraph
4. If the subgraph is not connected, add the shortest path via the streets to connect the graph
5. Add an extra link to nodes with a degree of 1

6. Calculate the sum of the length of all edges in this graph
7. Apply steps 2 to 5 for all identified clusters
8. Sum the total length of all clusters, this is the total length of the pipelines in the clusters

The OSMnx street graph can be obtained by providing a polygon representing the selected area. This graph comprises all the streets within the polygon, where streets are represented as edges and junctions, beginnings, and ends of streets are represented as nodes within the graph. The OSMnx street graph can be based on different network types, but the model selects the ”walk” network type. This network type includes all streets that can be traversed on foot, providing the most detailed results in most cases. However, it is not guaranteed that the nearest streets of buildings in a specific cluster form a connected graph. To ensure the connectivity of the network, which is crucial for connecting the pipes, the algorithm employs Dijkstra's shortest path algorithm to find the shortest route for connecting the graph. The details of Dijkstra's algorithm can be found in 3.2. In cases where the graph is disconnected at multiple points, the process is repeated until the graph becomes connected. The identified route(s) are then added to the graph. In order to form closed circuits, all nodes must have a degree greater than 1. Therefore, nodes with a degree of 1 are connected to the nearest node through a new connection. In Figure 4.6 the process of creating connected clusters with closed circuits is illustrated for three different clusters. Finally, the total length of the graph is calculated for each cluster, representing the total length of the pipe structure within that cluster.

Figure 4.6: Adjustments to create a connected clusters with closed circuits



4.3. Assumptions

The model incorporates several assumptions in its algorithm. One such assumption is the calculation of distances between data points. The calculation of the distance in the model between data points is based on Euclidean distance, this is the length of a straight line segment that would connect two points (Gregersen, 2023). This simplification disregards the street network and calculates distances based on a direct path. Incorporating the street network into the distance calculation would be more realistic, but it would significantly increase computational complexity, especially when dealing with a large number of data points, such as the selected case with over 50,000 data points. Therefore, for efficiency reasons, Euclidean distance 'as the crow flies' is used. It should be noted that when using Euclidean distance with latitude, longitude, or spherical data, a conversion is required for distance calculations.

The algorithm is initially designed under the assumption of an overall lack of supply to accommodate the case study requirements. Although 5GDHC networks encompass both heating and cooling, the current model prioritises heating demand, which is currently typically higher in urban areas. The heating capacity is often the limiting factor in 5GDHC networks, which is why the model starts with areas experiencing a lack of supply. However, as the proportion of heating and cooling demands becomes more balanced, the model can shift its focus to achieving a closer-to-zero energy balance instead of solely addressing the supply deficit in the cluster. Therefore, in order to adapt the model for an area with a balanced profile, minor adjustments need to be made to the algorithm.

5

The case study: a 5GDHC network in the inner city of Amsterdam

This chapter presents a detailed case study utilizing the model introduced in the previous chapter to generate results. The chapter starts with an introduction to the case, which involves the development of a 5GDHC network in the inner city of Amsterdam. Subsequently, the input data utilised in the case study is listed, and the process of data preparation is discussed. Furthermore, the chosen parameters employed in the analysis are explained. Finally, in Section 5.4, the outcomes of the case study and the assessment of its performance are presented. The full model created within this research and all datafiles can be retrieved from https://github.com/svanburk/clustering5GDHC.git

5.1. Introduction to the case study

As explained in section 1.2, this thesis will use the inner city of Amsterdam as the case study. This thesis contributes to the high-hanging fruit project of AMS. This project focuses on how the heat transition can be shaped for the inner city of Amsterdam. The plans of the municipality in terms of heat transition are not yet properly defined, while especially this area could gain a lot of profit by changing the heat supply, because of the high demand. Some individual or commercial projects are initialised to make a transition to a more sustainable and local heat supply. These projects are a good effort towards a heat transition, but a collective approach is needed to allocate the resources more efficiently. Especially in an area where open space is limited, careful considerations should be made on the use of open space. AMS is researching an alternative heating strategy in the inner city. The high-hanging fruit project has three main objectives, namely (Dang et al., 2023):

1. Develop an innovative and generic approach for energy retrofitting for historical buildings
2. Investigate low-temperature heat sources
3. Develop an integrated vision of the gradual energy transition of the inner city

Some research in the high-hanging fruit project is already finished. Dang et al. (2021) conducted research on the reduction of heat demand in monumental buildings by designing retrofitting approaches for these buildings. The inner city of Amsterdam has many monumental and old buildings, most of them poorly insulated, which causes a high heat demand and makes them unsuitable for a 5GDHC network, therefore retrofitting the buildings is essential in the heat transition of the inner city. In a not yet published research by Hung-Chu Chen, the potential waste heat sources of non-residential buildings in the inner city of Amsterdam are studied. Both of these researches provide data that are used in this thesis. This thesis will contribute to the last objective listed above. By identifying potential clusters in the inner city a start can be made to develop an integrated vision for the heat transition.

5.2. Data

Multiple data sources have been used in this research. Most of the data is provided by AMS Institute. The following list contains the main sources of the data used in this research, including the purpose and the source.

1. The shapefiles containing all addresses and buildings in the inner city with their location and properties, originating from BAG Kadaster. These shapefiles were provided by AMS. With the use of this shapefile, the location, ZIP code, construction year, surface, function and type of the buildings have been retrieved.
2. The shapefiles with the polygons of different neighbourhoods and areas in the inner city have been retrieved from de Haan (n.d.). The polygons are used for extracting data from a certain area in the inner city in the testing phase.
3. The datafiles containing the retrofitted residual demand per hour. This is provided and created by Maéva Dang from AMS Institute. This data contains the hourly demand of different residential building types. Retrofitted means that the data has been changed according to the possibilities for improving the energy label of the building. The building types have been divided into several groups. The groups reflect on the building type, year of construction, type of protection and if cavity wall insulation is possible. This data has been used to find the retrofitted demand for each residential building in the inner city of Amsterdam.
4. The shapefiles containing the potential waste heat in the inner city of Amsterdam are created by Hung-Chu Chen and are provided by AMS Institute. This shapefile is used to add the potential waste heat to the model and contains the yearly potential waste heat, location, and function of each building.
5. With the data set of Voulis (2019) the potential waste heat per hour has been calculated. This data contains the electricity demand per hour for each building function. This hourly distribution is used to make a distribution for the hourly waste heat potential.

5.2.1. Data preperation

Before this data could be used, it was prepared into multiple dataframes. Containing the demand or supply of all residential buildings and the buildings containing potential residual heat. The dataframes differ in the time period in which the supply or demand is calculated. These preparation files can be found in the code map. During the data preparation, some assumptions have been made. These assumptions are listed below.

1. Only buildings with a residential function are included. 3268 buildings have no specified function. These buildings are assumed to have other, not specified functions, than a residential function, and are therefore not included in the data.
2. There are 17624 buildings of which the year of construction is 1005. Amsterdam (n.d.) reports that 1005 is used as the default value for buildings in the city centre. The reason behind this value is that the original year of construction is not known for a large number of properties. It is assumed that these buildings are built before 1945.
3. When the building data is merged with the address data, 3 values got lost (from 54870 to 54787 data points). This is ignored, due to the probably low impact of this loss.
4. Apartments, semi-detached and terraced houses are included in the residential data. 25 detached houses and 16 two-under-one-roof houses are excluded because they are not very common.
5. A distinction is made between buildings that are protected and those that are not for the buildings with a construction year before 1945. Retrofitting gets a better result when the buildings are not protected. Some buildings newer than 1945 are also protected. However, for these buildings, no distinctions have been made.

6. The presence of a cavity wall has been considered when matching the retrofitting scenarios with the buildings. Here some assumptions have been made based on the construction year. Based on the research of Kaandorp et al. (2022) the data assumes to have no cavity wall when the building is built before 1975. After this year it is assumed that all buildings have a cavity wall.

7. The coordinate reference system used in the data is EPSG:28992 (Amersfoort / RD New – Netherlands), which is used as the basis for geographical indications for European Netherlands at the national level (Wikipedia-bijdragers, 2023).

8. The energy balance is calculated in the data by taking the negative heating demand and subtracting the hot water demand, followed by adding the positive number of the cooling demand. As explained in 4.1 heating demand can provide cooling supply and the other way around.

9. In order to retrieve the retrofitted demand, the retrofitted data in kWh per m^2 metre belonging to the category of the building, is multiplied by the surface of the building.

10. The waste heat data is provided on a yearly base. However, hourly data is needed to calculate the hourly disbalance. Therefore the waste heat data is converted to hourly data. The distribution of the waste heat over the hours is taken from a dataset in which the distribution of electricity demand is given (Voulis, 2019). The distribution differs per building function. A distinction is made between offices, retail, schools, supermarkets, restaurants and hotels. However, the dataset of Voulis (2019) provides even more details on the function, such as a distinction between primary and secondary schools, while this information about the difference is not available in this case study. Since this information only refers to the hourly distribution, choices have been made to just pick one category for each function.

11. The retrofitting scenarios are based on a sample of multiple years, so no specific year is considered. The hourly waste heat potential based on the electricity demand from Voulis (2019) is based on data from 2019.

5.3. Chosen parameters

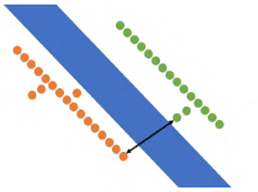
In order to create results, the model needs several input parameters. These input parameters can be optimised for the input data. The input parameters are the minimum and maximum size of a cluster and the distance in which clusters can switch parts with other clusters. For the data of the inner city of Amsterdam, the parameters are set as follows:

1. Minimum size of a cluster: 1000 buildings
2. Maximum size of a cluster: 3000 buildings
3. Distance between ZIP codes in which potential adjustments are allowed: 100 metres

As explained in 4.2.3 the minimum and maximum values of the cluster size are purely created to create more compact clusters. The maximum size is also no hard boundary since it is followed by the step to create clusters larger than the minimum value. The initial clusters created in the case study vary in size between 1066 and 5850. Boesten et al. (2019) argues that a 5GDHC system can be developed in an area starting from approximately 75.000 m². The inner city of Amsterdam is 8,04 km² and 57.453 buildings are included in this case. This would mean that the absolute minimum of buildings inside a cluster is 536. No hard maximum boundaries can be found in the literature for the size of a 5GDHC cluster. However, it is important to consider practical and operational considerations when determining the size of a cluster. Managing and operating a large cluster can present challenges in terms of control, monitoring, and maintenance. As the cluster size increases, the complexity of managing the network and balancing the supply and demand within the cluster may also increase. This is also the reason why a bottom-up approach with multiple clusters is chosen within this research. As also explained in 4.2.3 the actual cluster sizes mainly depend on the capacity of balancing stations in a selected area.

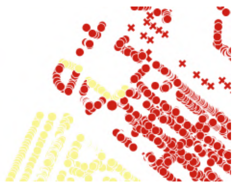
The maximum minimum distance between ZIP codes that determines whether they are allowed to switch is set to 100 meters. This parameter refers to the distance between two points of two different clusters. If the distance between the ZIP code and another cluster is below 100 meters, the algorithm is permitted to switch them. The measurement of the distance between two clusters is illustrated in Figure 5.1.

Figure 5.1: Minimum distance calculation



The value of 100 meters for the maximum minimum distance between ZIP codes is determined through a trial-and-error process and visual inspection of the results. By testing different values, the impact of each value on the clustering outcome is evaluated. If a value is too large, it may result in switching parts of clusters that are not in close proximity to the other cluster. Choosing a too large distance is illustrated in Figure 5.2. It can be observed that the light yellow cluster has expanded, but that streets of the red cluster are now in between the initial light yellow cluster and the expansion of this cluster. The objective is to only switch parts of clusters that are immediate neighbours. Conversely, if the value is too small, no adjustments will be made between clusters. The chosen value of 100 meters ensures that adjustments are made between clusters that are direct neighbours within this distance range.

Figure 5.2: Minimum maximum distance of 120 meters between clusters illustrated



5.4. Results

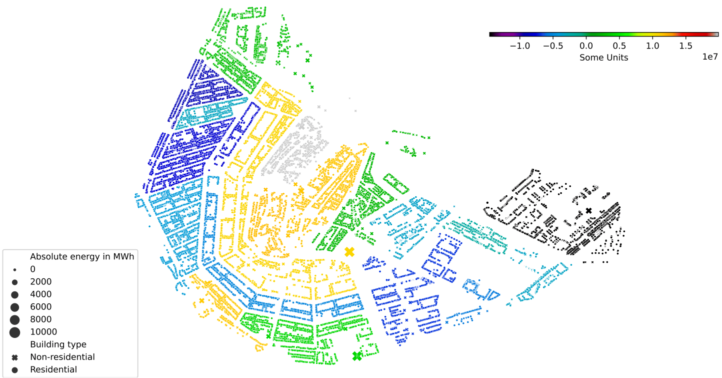
The model utilises all imported data to generate its results. Its objective is to propose an alternative approach to the neighbourhood-based design of 5GDHC networks. Figure 5.8 illustrates the neighbourhoods present in the city centre. The model's outcomes for the inner city of Amsterdam will be presented in this section. Initially, the model establishes a base case solely relying on Single linkage clustering, as depicted in Figure 5.3.

Figure 5.3: Clustering the inner city of Amsterdam, base case

Figure 5.3 displays the base case clustering results, where suppliers are depicted as crosses. The size of the dots or crosses in the figure represents the order of magnitude of the energy balance. Notably, two significant suppliers stand out due to their size. The purple cross located in the centre corresponds to the city hall, while the darker green cross represents the central bank of the Netherlands, which is undergoing renovation until the end of 2023. The energy balance per cluster is given in the legend on the right of the figure.

The clusters formed initially using the single linkage algorithm serve as the foundation for the clusters before being adjusted according to their energy balance. Figure 5.4 illustrates the energy balance of all initial clusters in the city throughout the year. A notable observation is that the clusters located in the central areas of the map have generated more supply than demand. On the other hand, clusters situated at the borders of the map exhibit a higher demand for energy supply. This analysis highlights the spatial variations in energy generation and consumption within the city. It indicates that certain clusters have the potential to contribute surplus energy, while others require additional energy supply to meet their demands.

Figure 5.4: Energy balance per cluster



In order to enhance the performance of the clusters, the algorithm focuses on improving the initial clustering by switching parts of clusters with other clusters. To evaluate the performance of the adjusted clusters, a specific time period needs to be selected for calculating the energy balance. Three different time periods have been chosen to compare the clustering results and their performance based on the selected metrics. These time periods include the whole year, the coldest day and the coldest month, which are determined based on the average coldest conditions since the available data does not correspond to a specific year. The case study data has an overall lack of heating supply. This means that the coldest periods of the year will be the most crucial in terms of shortages. Therefore, selecting the coldest periods to compare the clustering have been chosen. By considering different time periods, a comprehensive assessment of the cluster performance can be obtained.

1. The whole year
2. The coldest day, 14th of February (de Vries, 2023)
3. The coldest month, January (Wikipedia-bijdragers, 2022)

Figures 5.5, 5.6 and 5.7 depict the adjusted clusters obtained by modifying the initial clusters for different time periods. The variation in the time periods leads to differences in the number of adjustments made to the initial clusters. It is noteworthy that clustering over a longer time period results in more significant changes compared to the base case in 5.3. This can be explained by considering that when the clusters are based on, for instance, the coldest day all clusters exhibit a negative energy balance. This explanation can also be used to describe why some clusters are more affected by the adjustments than others. This can be attributed to the fact that in certain areas all initial clusters have a lack of supply. In such cases, interchanging parts between clusters does not contribute to an absolute improvement in the total energy balance. Moreover, clusters with sufficient supply surrounded by other clusters with sufficient supply will also remain unchanged as in the initial clustering. Hence, adjustments to the initial clusters are not advantageous in these approaches.

Figure 5.5: Clustering the inner city of Amsterdam, coldest day

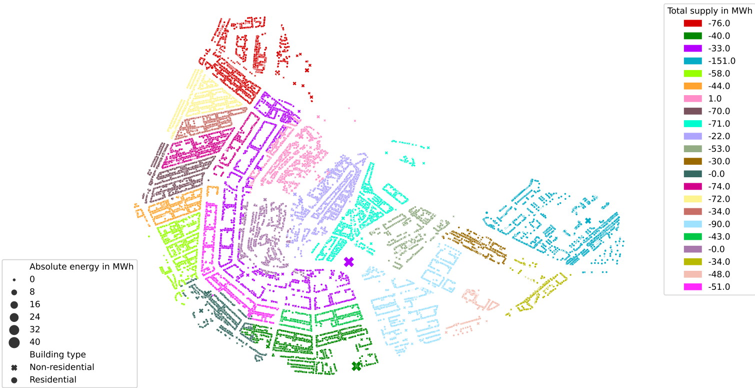


Figure 5.6: Clustering the inner city of Amsterdam, coldest month

Figure 5.6 illustrates an observation of interest regarding the clustering results. Specifically, in the upper right portion of the figure, the purple cluster extends into the red clusters. This situation is not in accordance with the model's constraints, as a cluster is not permitted to span a large area with such a large distance in between. The presence of this anomaly can be explained by the fact that in this particular area, the ZIP code 1013GM is divided by another street. It is crucial to be vigilant and address such anomalies during the analysis and interpretation of the clustering results.

The proposed approaches try to form an alternative to a neighbourhood-based design. In Figures 5.8 and 5.3 certain similarities can be observed. However, it is important to note that the approach in this research creates 24 clusters, while there are 69 neighbourhoods and 10 districts in the inner city of Amsterdam. As a result, direct one-to-one comparisons between these approaches are not possible. Observations reveal that the clusters in the Jordaan neighbourhood (located on the west side of the city) demonstrate a considerable similarity to the neighbourhood-based approach. Other clusters either connect multiple neighbourhoods together or form entirely new boundaries. Ultimately, a notable difference between the two figures becomes apparent.

5.4.1. Performance of the energy balance

In this subsection, the results of clustering under various approaches will be discussed, focusing on the performance metrics described in section 4.1. Starting with the energy balance of the clusters, the evaluation is based on the hourly lack of supply of the clusters. The results of hourly lack of supply per approach are presented in Figure 5.9, together with the other performance metric, the total length. A

Figure 5.7: Clustering the inner city of Amsterdam, whole year

Figure 5.8: Neighbourhoods in the inner city

notable difference of 6,6 GWh is observed between the base case and the best-performing approach, which is the clustering over the entire year. This improvement could replace the average gas demand of 380 households (ENGIE, n.d.). Although the improvement of 5,6% compared to the base case may seem relatively small, it represents a significant amount of energy. On the contrary, it can be observed that a neighbourhood-based approach performs significantly worse on the energy balance metric compared to other approaches. This phenomenon can be attributed to the presence of a larger number of clusters in this particular approach. The increased number of clusters leads to the formation of smaller clusters, which encounter greater challenges in handling peak demand and providing flexibility. The district-based approach outperforms the base case in terms of energy balance but does not perform better than the whole-year approach. Nevertheless, it is important to acknowledge that the district-based approach only identifies 9 clusters. While larger clusters may excel in managing peak demand and providing flexibility, they may pose difficulties for the bottom-up approach and elevate investment risks.

Furthermore, it is insightful to examine the hourly disbalance of the clusters throughout the month, as shown in the graph in Figure 5.10. This graph allows us to assess the performance of individual clusters over time. Moreover, it helps in identifying clusters that can be prioritised for development in a bottom-up approach to 5GDHC. Additionally, this information is valuable for planning storage systems, as it provides insights into the fluctuations and patterns of energy supply and demand within the clusters. In conclusion, Figure 5.9 offers valuable insights into the differences between the approaches, allowing for a comparison of their overall performance based on the hourly lack of supply metric. On the other hand, Figure 5.10 provides more detailed information regarding the performance of individual clusters within each approach. This allows for a closer examination of how each cluster performs in terms of its hourly disbalance, offering a better understanding of their energy profiles.

Figure 5.9: Total hourly lack of supply per year in GWh

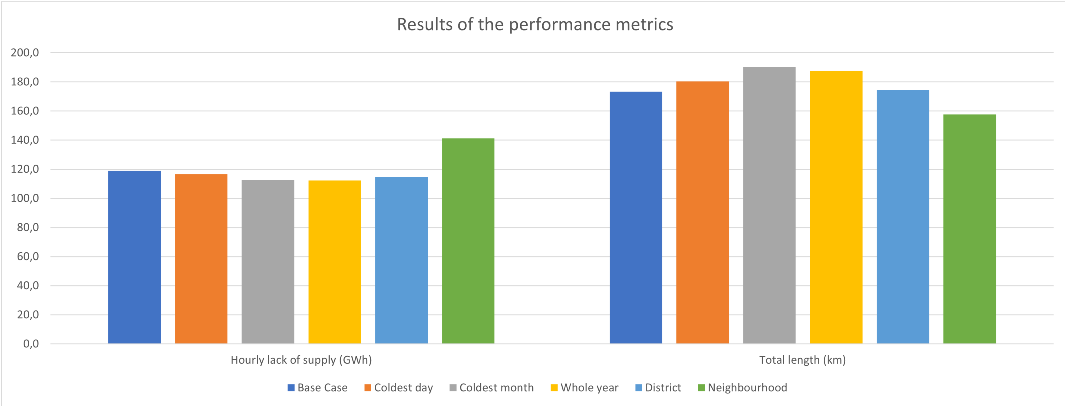
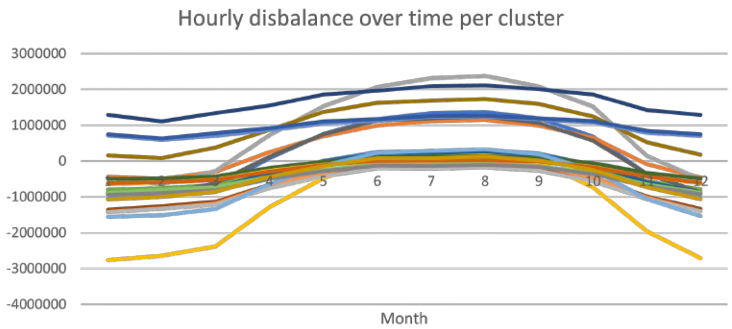


Figure 5.10: Total hourly disbalance per cluster in GWh



5.4.2. Performance of the total length

The total length of the network is the other metric used to compare the different approaches. This metric has various implications, such as the increase in costs and greater social impact when the length of the network increases. Figure 5.9 presents a comparison of the total lengths and the shortage of supply across the various approaches. It is worth noting that the network created during the coldest month is longer than the network calculated over the entire year, while more adjustments can be observed in the whole year approach. A portion of this deviation can be attributed to the error associated with the ZIP code, as explained in Section 5.4. However, the major part of the 2.7 km difference observed in the coldest day approach compared to the whole year approach is likely caused by the coincidentally of more unfavourable adjustments in the coldest day approach. When examining the performance metrics, it is most reasonable to focus on the base case approach calculated over the entire year. The pipe network in the whole year approach is 14,3 km longer than the base case approach, which is an addition of 8,4%. The total length grows more than the decrease in energy balance, specifically by 5.6%.

It is noteworthy to observe that the neighbourhood-based approach exhibits a reduction in length by 15.7 km compared to the base case. Despite its bad performance in terms of energy balance, it raises curiosity as to why this approach, consisting of 69 clusters, surpasses the other approaches significantly in the total length metric. One possible explanation for this phenomenon could be the reduced necessity for interconnections among disjointed sections of clusters, given the smaller area covered by each cluster. The total length of the district-based approach, consisting of 10 clusters, is comparable to that of the base case, with the latter displaying only marginal improvement.

5.4.3. Case conclusions

This case study introduces an alternative approach to address the heat transition in Amsterdam's inner city. Among the clustering approaches considered, the whole year approach performs the best in terms of energy balance, while the neighbourhood-based approach excels in minimizing the total length. However, it should be noted that the neighbourhood-based approach performs significantly worse on energy balance compared to all other approaches, primarily due to its larger number of clusters. The base case approach ranks second in terms of total length. Consequently, the selection of either the whole year or base case approach for clustering is advised, depending on which metric is considered more important.

The cluster approaches based on single linkage demonstrate a preference over the district- and neighbourhood-based approaches due to the scalability of single linkage clusters. The district-based approach, comprising only 9 clusters, proves inconvenient for the recommended bottom-up approach. Implementing such a small number of clusters would lead to increased investment costs and risks, while also posing significant challenges in operational planning for such a large area. The neighbourhood-based approach, consisting of 69 clusters, faces difficulties in managing peak demand and providing flexibility, which also becomes evident when observing its performance in the energy balance metric.

For the bottom-up approach, careful selection of clusters suitable for development is crucial. Preferably, clusters with low supply deficiencies should be chosen to enable self-sufficiency in energy supply. While for clusters experiencing substantial supply deficiencies, alternative supply sources should be explored before a 5GDHC network can be developed. It is important to note that the formed clusters are based solely on residential demand. Figure 5.4 illustrates that central clusters possess adequate supply, making them suitable for the development of a 5GDHC system. Nevertheless, these clusters also contain a relatively high number of non-residential buildings. Therefore, it is essential to calculate the energy balance including the demand of the non-residential buildings in order to identify clusters that can be prioritised for development.

Furthermore, incorporating urban planning knowledge into the decision-making process is crucial. This can involve synergizing other construction projects with digging activities or exploring renovation opportunities within the inner city. For instance, the AMS Institute's project focuses on renovating quay walls and includes heat exchangers within canal walls, reducing the required space for a 5GDHC project and enabling the incorporation of aquathermal energy as an additional heat source (BK, 2021). This can enhance the supply capabilities of specific clusters. By integrating the outcomes of this study into the decision-making process, a more inclusive and effective implementation of the 5GDHC system can be achieved.

6
Conclusion

To achieve the target set by the Dutch government to phase out the use of natural gas by 2050, a transition in heating systems is imperative. However, current planning approaches primarily prioritise districts that can easily adopt alternative heating solutions, often overlooking districts with older building stocks. This study addresses the challenges associated with implementing a 5th Generation District Heating and Cooling (5GDHC) system in a dense urban area. Since 5GDHC is a relatively new technology, several drawbacks can be identified. The lack of guidelines, clear terminology, and planning tools present obstacles for researchers and practitioners. Additionally, existing literature primarily focuses on small-scale cases and newly developed areas, with limited attention given to network topology. To address these knowledge gaps, this research concentrates on creating clusters within a 5GDHC network. The research question guiding this study is:

What is a suitable approach to identify potential clusters, based on the geographical location and energy profiles of the buildings, for a 5GDHC network in an urban dense area?

Creating clusters within a 5GDHC system allows for the coupling of waste heat sources to meet the heating demand of residential buildings. Furthermore, larger clusters facilitate better management of peak demand. However, larger clusters may introduce complexities in network management and cluster balancing. It is therefore crucial to form clusters to enable a bottom-up implementation of the system. The creation of clusters in this research serves as an alternative to the neighbourhood-based approach recommended in the Dutch Climate Agreement (Nijpels, 2018), offering more flexibility in planning and optimizing the efficiency of the 5GDHC system.

A comprehensive model has been developed as a tool to create clusters within a 5GDHC system in an urban dense area. The model's objective is to establish connections among all buildings in the selected area while minimizing the network length and creating clusters that are energy balanced. To achieve this, the model takes into account both the geographical location and energy consumption patterns of the buildings, employing a combination of methodologies. The initial step of the model involves using single linkage clustering to create clusters based on geographical location. These clusters serve as the starting point for further adjustments based on cluster size and energy balance. This process ensures that clusters are optimised in terms of their physical distribution and energy requirements. The model proceeds by evaluating the performance metrics of the newly created clusters. The first metric focuses on the hourly lack of supply, which provides an indication of how well a cluster or approach performs in terms of energy balance. This metric assesses the adequacy of the energy supply within the clusters. The second metric measures the length of the pipe network required for each cluster. To calculate this, graph theory is applied, enabling the determination of the total length of the pipe network necessary to serve all buildings within each cluster. By considering both the location and energy profiles of the buildings, the model effectively creates clusters within the 5GDHC system, optimizing their spatial distribution, energy balance, and network connectivity. This holistic approach aims for an efficient and sustainable development of heating and cooling solutions within urban dense areas.

The model has been tested in the case study on the implementation of a 5GDHC system in the inner city of Amsterdam. The AMS Institute has supplied the necessary data for this study, including information on potential sources of excess waste heat supply and data on the energy demand of buildings in retrofitting scenarios. These data inputs were utilised to assess the performance and effectiveness of the model in the specific context of the inner city of Amsterdam. The clustering approaches in the model are based on a certain time period. For the inner city, the clustering has been calculated for three different approaches: the coldest day, the coldest month and the whole year and can be compared to a base case, based on single linkage clustering, and the current neighbourhoods and districts in the inner city of Amsterdam. These approaches have been tested on their performance on the identified metrics.

When evaluating the performance of the case study in the model, it can be observed that clustering over a longer time period allows for more significant adjustments. Clustering based on colder time periods often leads to an overall lack of energy supply, limiting potential improvements. The algorithm only provides adjustments to the initial clusters when neighbouring clusters exhibit different energy profiles. Assessing the hourly lack of supply metric over the course of a year, the neighbourhood-based approach performs the poorest. This can probably be devoted to the small clusters in this approach, which struggle to provide flexibility. On the other hand, the whole year approach achieves the best performance in this metric, improving by 6.6 GWh or 5.6% compared to the base case approach. However, it should be noted that the total length of the network increases the most in the whole year approach, with a 14.3 km extension or 8.4% increase compared to the base case approach. The cluster approaches based on single linkage exhibit a preference over the district- and neighbourhood-based approaches due to the ability to scale the clusters based on single linkage.

The tool generates multiple outputs, with the base case and whole year approaches identified as particularly interesting in the case study. The choice between approaches involves a tradeoff between energy balance and network length, each with distinct consequences. The energy balance of a cluster may require different supply functions or even render an area unsuitable for a 5GDHC system. The length of the pipe network relates to implementation costs, as well as logistical and social implications due to the necessary underground drilling. Given the diverse consequences, selecting a definitive approach remains challenging and is ultimately left to the interpretation of policymakers. The recommended bottom-up approach in this research requires the selection of potential clusters ready for development. The developed tool can provide recommendations on approaching bottom-up development based on the performance metrics.

6.1. Scientific contribution

This research makes several scientific contributions to the field of 5th Generation District Heating and Cooling (5GDHC) systems and urban energy planning. Firstly, it addresses a significant knowledge gap by focusing on the design phase of 5GDHC systems in densely populated urban areas with older building stocks. While previous research primarily concentrated on small-scale cases and new-built districts, this study expands the understanding of implementing 5GDHC in larger areas with existing building stocks.

Moreover, the research develops a comprehensive model that integrates geographical location and energy consumption patterns to create clusters within a 5GDHC system. With the designed methodology and performance metrics, the model presents an alternative to a neighbourhood-based approach. This model fills a gap in the literature by providing a practical planning tool for optimizing the energy balance, and network topology of 5GDHC clusters. The model enables researchers and practitioners to design efficient and sustainable heating and cooling solutions in urban dense areas.

6.2. Societal contribution

The societal contribution of this research lies in its potential to support the transition towards more sustainable and energy-efficient heating and cooling systems, aligning with the goals set by international agreements. The research directly responds to the Dutch government's target to phase out the use of natural gas by 2050 by addressing the challenges associated with implementing 5GDHC systems in dense urban areas with older building stocks. By focusing on the areas that are often overlooked in current planning approaches, this research presents an alternative in which the urban dense areas with a historic character can also contribute to the heating transition Furthermore, the developed planning approach and model offer practical tools for urban energy planners, policymakers, and stakeholders involved in the transition to sustainable heating and cooling systems. The model's ability to identify potential clusters based on geographical location and energy profiles of buildings allows for better decision-making in the design phase of 5GDHC systems. By considering both energy balance and network length, the model enables planners to optimise the efficiency, cost-effectiveness, and environmental impact of 5GDHC networks.

Ultimately, the societal impact of this research lies in its contribution to the reduction of greenhouse gas emissions, the improvement of energy efficiency, and the enhancement of energy resilience in urban areas. By facilitating the adoption of 5GDHC systems in densely populated areas with existing building stocks, the research supports the creation of sustainable and livable cities, improving the quality of life for residents while mitigating the environmental impact of heating and cooling systems.

6.3. Policy recommendations

The successful planning and design of a 5GDHC network require the active involvement and cooperation of all critical actors. By fostering collaboration and engagement among these stakeholders from an early stage, policymakers can ensure a more inclusive, effective, and socially accepted implementation of 5GDHC systems. This tool can also be used in order to demonstrate to urban residents and other actors in which areas the implementation of a 5GDHC network would be most advantageous. Active cooperation with actors in the planning and design of a 5GDHC network promotes a sense of ownership, increases social acceptance, and enhances the overall effectiveness of the implementation process. By actively involving stakeholders, policymakers can harness local knowledge, build trust, and create a more sustainable and resilient 5GDHC network that meets the unique needs and characteristics of the local community.

When designing a 5GDHC system, it is essential to consider long-term planning and future city developments. The incorporation of these factors ensures that the 5GDHC system is not only suitable for current needs but also capable of adapting to future requirements and challenges. By considering future city developments, policymakers can strategically plan the location and layout of the network infrastructure, minimizing construction disruptions. In addition, future city developments often can also involve the integration of renewable energy generation. By taking these developments into account, policymakers can design the 5GDHC system to be compatible and synergistic with these types of energy. This integration allows for improved energy efficiency and enhanced overall urban sustainability as in Multi-energy systems. This forward-thinking approach ensures cost-effectiveness and maximises the efficiency of the 5GDHC system.

Several tools have been developed to facilitate the design of 5GDHC networks. The approach proposed in this study can complement these existing tools by effectively identifying potential clusters and establishing a path for the pipe network. While current tools primarily concentrate on hydraulic engineering and network control aspects, the incorporation of a clustering method enhances the overall efficiency of the 5GDHC system design process. Consequently, the integration of these tools can yield benefits in terms of improving the efficiency of the design process and enhancing the performance of the final 5GDHC system.

6.4. Future research

This research designed an approach to create clusters for a 5GDHC network in a selected area. While this study provides some guidelines for the design of a 5GDHC network, further research on this topic remains highly important. The relatively novel technology has not been studied for a long time, which makes new research even more relevant. Some topics for future research have been identified in this study. Firstly it is important to provide more research on large-scale implementation and design of 5GDHC systems, also in areas with historical value. Research on the implementation of 5GDHC in these types of areas is uncommon. Secondly, it would be interesting to gain more insights into the combination of different energy systems that can be combined with a 5GDHC system, such as storage systems or the extraction of aquathermal energy. Combining multiple systems provide multi-energy systems which can provide a more flexible and resilient energy supply, making them a crucial component in the transition to a more sustainable and low-carbon energy future.

More specifically, with respect to this research, the incorporation of diverse energy systems alongside waste heat presents an opportunity to enhance supply capacity and promote a more flexible system, enabling the developed tool to be utilised within the framework of Multi-Energy systems. Additionally, it is recommended to investigate the role of heat pumps in the process of dividing an area into clusters. It should be noted that heat pumps occupy significant space and necessitate additional electrical capacity.

Moreover, the integration of the tool developed in this research with existing tools would contribute to the development of more efficient design tools. Furthermore, exploring the implications of climate change on future demand and supply patterns would be a valuable aspect to incorporate into this research. Incorporating future demand and supply projections would assist in designing a 5GDHC system that is resilient and adaptable to future changes. Lastly, it is worth mentioning that this research primarily focuses on the demand from residential buildings. Incorporating non-residential demand would offer additional insights into the energy balance of clusters, facilitating the selection of clusters that are well-suited for development.

7 Discussion

The method developed in this research demonstrates both strengths and weaknesses. On one hand, it effectively partitions a district and achieves the proposed objectives. On the other hand, certain simplifications were made to enhance the model's manageability. A notable limitation is the exclusion of technical details such as pipe network diameter, heat losses, pressure drops, and the role of heat pumps. Incorporating these factors would improve the accuracy of the calculations. Especially the role of heat pumps is very important in a 5GDHC system. The size of a cluster, which is now assumed to fall within a minimum and maximum number of buildings, relies on the available heat pump capacity in the area. Understanding the role of heat pumps and their capacity in determining cluster sizes is crucial for effectively designing and optimizing the system.

The clustering process employed in the model utilises crow's fly distance instead of street length, primarily due to the vast amount of data, which would lead to computational inefficiency. However, on a smaller scale, the inclusion of street length distances in clustering could be feasible. Exploring the potential benefits and challenges of including street length distances could contribute to a more comprehensive understanding of the clustering process. Another limitation of the model is its reliance on the initial clusters identified in the base case, with minimal changes occurring after adjustments. Introducing an algorithm that incorporates energy balance from the outset may yield clusters with more balanced energy profiles, but it may also result in longer network lengths. The model currently includes only excess waste heat, but additional sources could be incorporated, such as aquathermal energy, although not in the clustering process, since these sources are often not located inside a neighbourhood. Evaluating and determining suitable areas for such sources can be done afterwards. In areas with other potential sources, only the base case may be relevant.

Some practical implications of the study's findings can be identified. While the model performs well with Amsterdam's data and objectives, its applicability to other densely populated urban areas remains uncertain. The model relies on current climate data, but future climate changes will affect demand and supply, potentially leading to more balanced heating and cooling requirements. Adjustments to the model would be necessary to accommodate such changes. The research overlooks the exploration of available underground and open space, which can pose constraints during the implementation of a 5GDHC network. Limited space is a critical factor in urban dense areas, restricting the placement of heat pumps and the development of the pipe network. Therefore, it is crucial to investigate the required space allocation for heat pumps within a district or cluster.

The current version of this tool is built upon the insights gained from the data obtained from Amsterdam. Although the initial development of the model is intended for application in various urban dense areas, it should be acknowledged that certain design decisions may have been influenced by the available data specific to Amsterdam. As a result of limited data availability for other urban areas, the tool has not been tested on alternative cases thus far. However, it is anticipated that the tool will be applicable to other urban dense areas, given that the cluster requirements have been defined based on the characteristics commonly observed in such areas. Still, it remains valuable to test the performance of this model on other cases for further research, taking into account variations in climate, demand, and available infrastructure.

This study presents the development of a model aimed at addressing the specified requirements. To ensure the model's adherence to these requirements, a thorough verification process is necessary. Throughout the development of the model, the design specifications and corresponding output have been extensively examined. Visual representations depicting the clustering procedure offer valuable insights into the model's functionality. Detailed observations and documentation have been undertaken to capture the adjustments made to the clusters. Chapters 4 and 5 provide a comprehensive account of the methodology and model construction, supplemented with visualisations. However, to guarantee the accuracy and reliability of the model, it is recommended to conduct more extensive verification tests.

Although it may be challenging to compare the model's outputs with real-world data, given the limited application of 5GDHC systems on a large scale and the absence of calculated performance metrics, validation remains a crucial step in ensuring the credibility and dependability of the model's results. To assess the alignment between the model outcomes and the research objective, a visual inspection of the results can be performed. It is worth noting that, similar to the verification process, conducting more comprehensive tests for validation would enhance the reliability of the model.

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