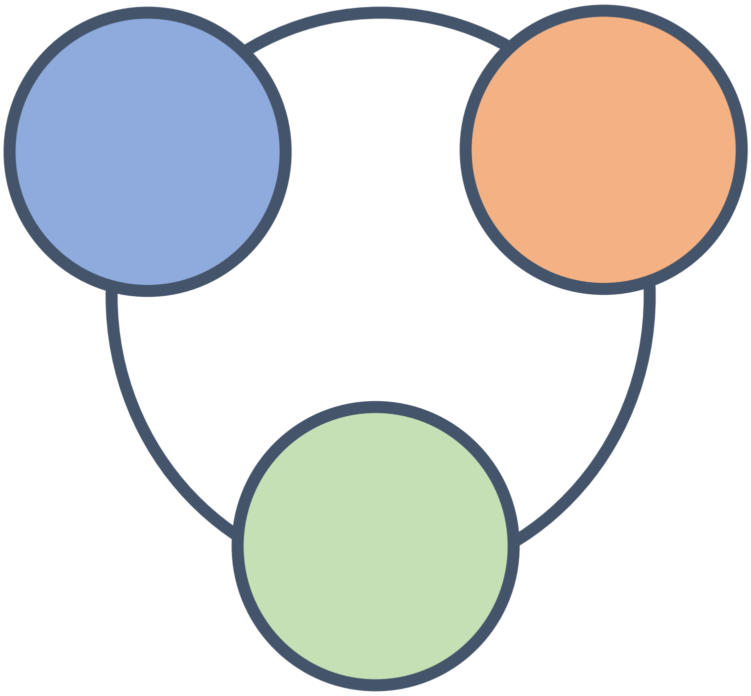
Crowded Urban Underground

Amke Koek

Analysing space demand of transitioning urban underground infrastructures

3/6/2020



This is the thesis of Amke Koek as part of the MSc. Urban Environmental Management with the specialization in System Engineering. The thesis supervisor is **Dr. Ir. Wei-Shan Chen**. Also, a case study provided by the Municipality of Amsterdam, will be included in this research.

WAGENINGEN UNIVERSITY AND RESEARCH | MUNICIPALITY OF AMSTERDAM

Crowded Urban Underground

An exploratory research into space demand of transitioning urban underground infrastructures

Author
Amke Koek BSc | 951129451090

Supervisor WUR
Dr. Ir. Wei-Shan Chen

Case study provided by the Municipality of Amsterdam

Course Information
MSc Urban Environmental Management
MSc Thesis Urban Systems Engineering | ETE-81836
Wageningen University Research | The Netherlands

Year
2019/2020

Disclaimer: All data from personal communication has been interpreted by the Author

Note: Urban Underground Infrastructures (UUI) in this thesis, refers to the underground cables and pipes in cities and not to underground mobility infrastructures.

Acknowledgements

During this thesis I have done a couple of interviews with different professionals from Waternet, Deltares, the municipality of Amsterdam, the municipality of Rotterdam and the municipality of Almere. I would like to thank all participants of the interviews for giving me valuable input for this thesis. Thereby, I want to give thanks to everyone who helped me to get in contact with potential interviewees. Also, I would like to thank my contact persons at the municipality of Amsterdam very much for letting me join the planning process of Haaksbergweg and inviting me for other interesting meetings and sessions. Not to forget, the ETE department. Thanks a lot for the good time I have had at ETE, including some nice events, a good working place/environment and the feedback a got from several of you. Also my student colleges I want to thank for their presence and feedback. Then, I would like to thank my thesis supervisor, Momo. Thank you very much for your input, feedback and encouragement during the whole process, from the proposal to the final thesis.

A special thanks as well to my boyfriend, family and friends who were a great support to me.

Abstract

The densification of urban area together with climate adaptation and mitigation measures are increasing the amount and capacity of UUI's and putting pressure on the available underground space. Thereby, the current underground spatial planning is often unstructured and lacking holistic approaches. If the current planning methods continue to be used, the is a risk of having no space left for future need.

This thesis investigated if there is enough underground space to meet the space demand for future UUI. In order to find out, a qualitative research has been performed. Therefore, interviews have been conducted with infrastructure providers and planners of underground space at different companies and municipalities in the Netherlands. This was supported by a literature study. Also, the planning process of a specific road in Amsterdam, Haaksbergweg, has been observed. To find out if there is enough underground space, first of all, an evaluation was done of the existing tools and protocols used for integral planning of UUI. This was followed by an investigation of the technical opportunities and constraints of the UUI transitions and the challenges for asset management. At last, the spatial and temporal challenges of the planning process were analysed.

Although it became clear that no tools or models were being used for an integral planning of UUI, there was one protocol used for this purpose. However, the protocol had some main implications. A tool set-up was created within this thesis for future quantitative analysis. For the technical constraints and opportunities, a table was made. Also, an additional table was made for possible synergies between infrastructures. Technically, there is enough underground space if deeper layers are being used. However, the costs constrain the feasibility of accessing those deeper layers and using this space. Thereby reservations of space for future use is an important factor that is often not considered during the planning process. Also, the pressure from infrastructures on the space inside buildings seems to become higher.

Regarding those upcoming challenges for UUI planners, multiple recommendations are given. First of all, planners/designers of underground space could try to include contractors/project developers more in the planning process. Also, they could take more note of the possible synergies between infrastructures. Infrastructure providers could relook at their role as an infrastructure provider. To see where a shift can be made towards more decentralized systems, which will require a more service-oriented way of providing. Policy makers are improving the currently used protocol for an integral planning of UUI. Thereby they should think of negative mutual influences, but also take into account the site-specific conditions. When it is difficult to include this in a protocol, policy makers could contribute to the realization of a model/tool, as suggested with the tool set-up given in this thesis.

Table of contents

List of figures and tables

List of acronyms

COB	Nederlands kennis **C**entrum voor Ondergronds Bouwen en ondergronds ruimte gebruik
DWF	Dry Weather Flow
MUT	Multi Utility Tunnel (Dutch: ILT)
RCM	Reliability Centred Maintenance
RWD	Rain Water Drain
UUI	Urban underground infrastructure(s)
UVWC	Underground Vacuum Waste Collection (Dutch: OAT)

1 Introduction

The densification of urban areas together with climate adaptation and mitigation measures, are leading to multiple urban underground infrastructure (UUI) transitions. More and larger UUI are required due to the increased need for housing, especially in the bigger cities e.g. Amsterdam (Municipality of Amsterdam, 2018), which causes expansions and densification of the build area (Korthals Altes, 2019). Moreover, climate change forces many politicians and decision makers to implement climate adaptation and mitigation measures which will also increase the amount and capacity of UUI.

First of all, the energy transition is putting forward several new UUI e.g. heat and cold storage and replacement of gas (Ministerie van Infrastructuur en Waterstaat & Ministerie van Economische Zaken en Klimaat, 2018). Also, potentially aditional infrastructures are needed for district heating, making use of residual heat to support the energy transition (Ministerie van Economische Zaken, 2016, pp. 53-54). Together with the development of other relatively new energy transition technologies that demand underground space, this results in an uncertain need for more underground space in the future (Bartel & Janssen, 2016).

Second, climate adaptation measures, such as increasing water retention by implementing more green areas, water buffering zones, improved separated sewer systems etc., will increase the amount and capacity of UUI (e.g. Maring & Blaauw, 2018). Also, the need for urban green is likely to increase even more due to the increased public awareness of the functions that green spaces offer within the urban environment (Belmeziti et al., 2018).

At last, the infrastructure for municipal solid waste is changing. The Netherlands is in transition to a circular economy with the aim to be fully circular by 2050 (Ministerie van Infrastructuur en Waterstaat, 2016). Meaning that all waste streams should be used as new resources. For this, separation for improved quality of waste streams is required. Thereby, increasingly more Underground Vacuum Waste Collection (UVWC) appear to transport and collect waste in cities (Delmastro et al., 2016). UVWC in crowded urban areas can reduce the solid waste collection traffic and the amount of containers and bins in the streets (Hidalgo et al., 2018), though at a cost of increasing occupation of the urban underground. Multiple researches have been carried out to compare the commonly used truck-based collection system and the UVWC system (e.g. Chàfer et al., 2019; Punkkinen et al., 2012; Teerioja et al., 2012). However, those were done for economic and environmental (i.e. emissions) comparison of the systems and not for a spatial analysis. Altogether, UUI transitions are putting extra pressure on the demand for underground space and therefore ask for a good holistic planning approach.

However, currently underground spatial planning is often unstructured and lacking holistic approaches. Around the globe, UUI planning has always been planned on a 'first come, first served' basis (Stones & Heng, 2016). Also, the planning of the public space is often being led by the planning and development of buildings and other constructions above ground level (e.g. Municipality of Amsterdam, 2018). Which leads to risks or failures for the UUI planning. Furthermore, the planning cycles employ mainly the common trench or open-cut method, which is based on digging out soil, putting in cables and pipes and finally covering it up again with soil. The current methods used for UUI planning are often short-term and based on lowest initial construction costs at the decision-making moment (Hunt et al., 2014). Which is a problem, especially while in several cities, urban population densities are growing faster than their supporting infrastructure due to the speed of the urbanization process (Delmastro et al., 2016). If the current planning methods continue to be used, the risk of having no space left for future need will increase (Bosch & Broere, 2011). Adding extra infrastructures to cope with the population growth is more and more demanded nowadays. To conclude, there is an emerging need to improve the UUI planning process to tackle the challenges of climate change and urbanisation.

1.1 Problem statement

The current planning of UUI follows certain protocols. New infrastructure techniques and designs are however often not included in those protocols, which makes the planning process more difficult. Also, due to the current and upcoming transitions, new UUI may not be suited to be implemented with the same protocols as currently used.

Another issue is the lack of comprehensive technical understanding of interdependencies among UUI. This technical understanding is still in an initial phase, even though it is critical to understand risks related to infrastructure interdependencies (Chang, 2009). Although few examples of research on combining two underground infrastructures do exist (e.g. Abbas et al., 2019), no research could be found about an effective arrangement of multiple infrastructures (i.e. more than two). Sterling et al. (2012) also points out that there is a general lack of wide-ranging planning measures to regulate UUI planning.

Asset management is increasingly being used to improve the integral UUI planning. One of the main problems with asset management is the lack of high quality data of the existing UUI and different functions of the underground (Hao et al., 2012; Maring & Blauw, 2018). Asset management is currently looking at all separate infrastructures individually while the whole underground can be seen as one system (Maring & Blauw, 2018). Therefore, asset management should be applied for the underground with its elements as a whole.

One technique for UUI arrangement is to make use of Multi Utility Tunnels (MUT's). These are underground tunnels where multiple infrastructures can be placed inside together. The MUT's are being adopted in several cities (e.g. Wang et al., 2018; Vähäaho, 2014) and can serve as a long-term solution for infrastructure arrangement. The infrastructures will be more easily accessible; depending on the type of MUT, sometimes surface openings for maintenance are no longer necessary. Because of the relatively high investment costs of MUT's, research has been carried out on the economic viability and the economic tipping point of three different types of MUT's (Hunt et al., 2014). Also, research can been found about decision making for MUT planning based on other criteria such as urban environment and maintenance requirement (Curiel-Esparza & Canto-Perello, 2013). However, the question remains how MUT's can be of help for infrastructures that are in transition and how they would contribute to manage the demand of urban underground space.

At last, von der Tann et al. (2019) mention that the prioritization of underground functions above each other and the prioritization of underground compared to surface interventions has still to be solved. They also point out another issue, that the geological settings are often not considered as main importance and basis for UUI planning and decision making.

1.2 Research aim and questions

The aim of this research is to **help finding out if there is enough urban underground space to meet the demand of space for transitioning UUI for redevelopment projects in dense cities such as Amsterdam.** To do so, a qualitative analysis of the spatial challenges for transitioning UUI is carried out. Although this thesis will not create a tool/model to quantify the spatial challenges, it does provide a tool set-up (Appendix IV) for future quantitative analysis.

The focus of this thesis will lay on the following UUI, since those can be seen as the main underground space demanding infrastructural transitions: urban drainage systems (rain and sanitary sewers), municipal solid waste, and district heating systems. Other UUI will however also be mentioned whenever relevant.

Research questions

The general research question that has been formulated is:

Is there enough underground space to meet the space demand for future UUI?

To answer the main question, the following sub-questions have been formulated:

1. How do the currently available UUI planning tools and protocols incorporate underground space demand for the transitioning infrastructures?
2. What are the technical constraints and opportunities for the UUI transitions that will affect the planning?
3. What are the main upcoming changes in asset management due to the ongoing or upcoming infrastructural transitions and how do they influence the demand for urban underground space?
4. How could the planning process for underground infrastructures be improved to incorporate and be more prepared towards current and future UUI transition?

2 Methodology

2.1 Research design

To help answering the main question "is there enough underground space to meet the space demand for future UUI", an explorative research is performed, making use of expert interviews, input from a case study and a literature study.

Von der Tann et al. (2019), who are looking into system approaches for urban underground space planning, recognize a typical process-loop for system approaches (Figure 1). This thesis will dive into the system analysis and problem specification part, with a look ahead to the design and implementation phase. The purpose definition and evaluation and monitoring are not the focus of this thesis but should not be forgotten.

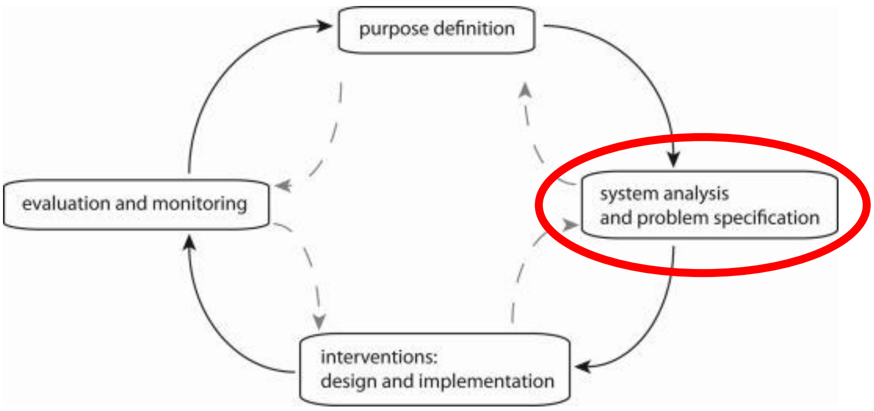


Figure 1: An example of a typical process-loop for system approaches (von der Tann et al., 2019)

Figure 2 shows the approach that is used to perform this study, starting with an evaluation of the currently used tools and protocols for planning and design of UUI. This is followed by the identification of upcoming UUI transitions. Then the technical and practical demand of space are investigated. For the technical demand of space, two parts can be distinguished; 1) the demand of space for the required capacity and the demand of space for design criteria, including material thickness, slope, expansion loops, valves, insulation etc.; 2) the demand of space for arrangement restrictions of the infrastructures. The practical demand of space is based on the accessibility to the UUI e.g. a standard space around the infrastructure for easy maintenance, but also manholes. At last, the spatial and temporal challenges in the planning process are evaluated, leading to a stepwise approach for UUI planning.

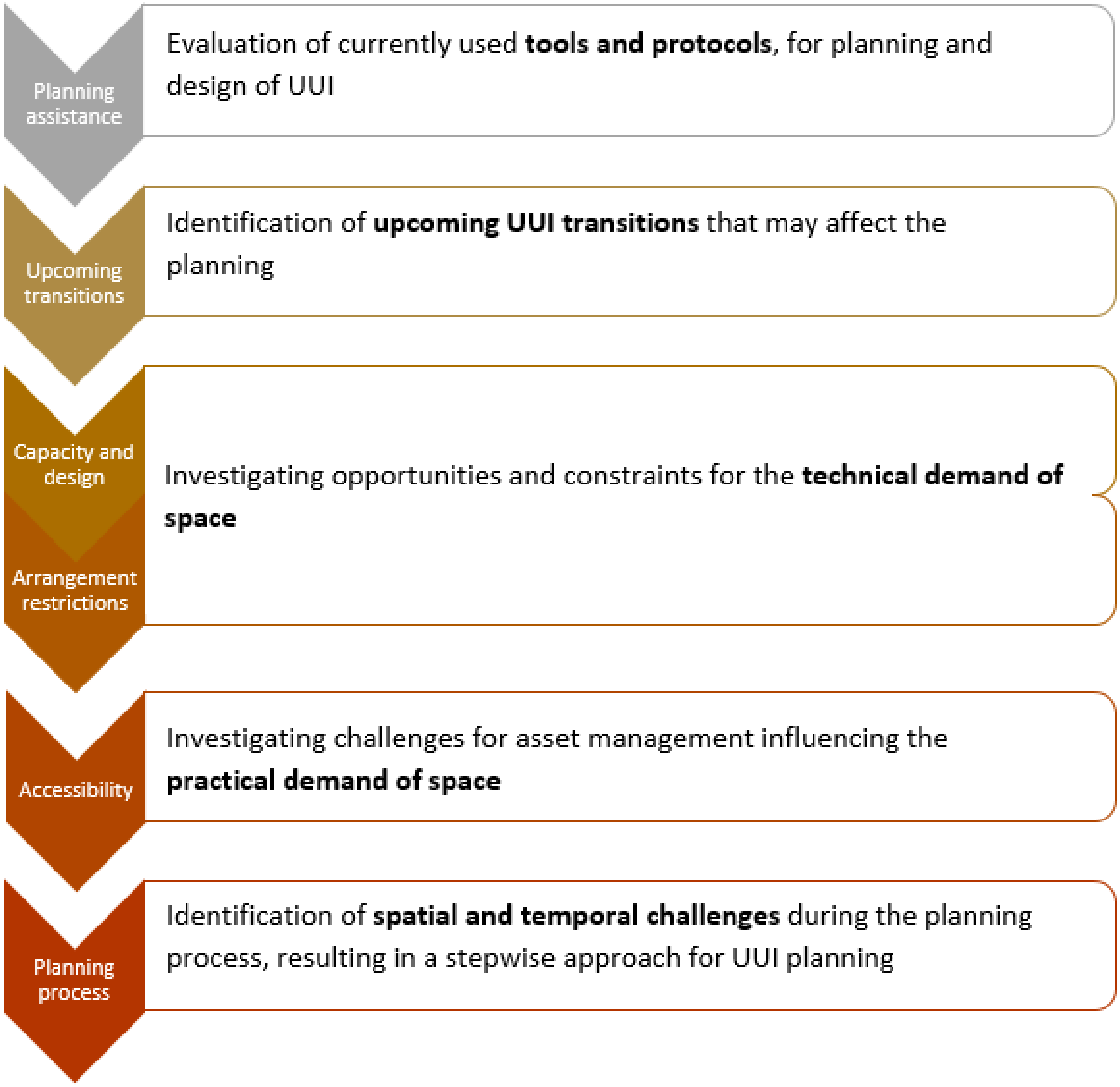


Figure 2: Study approach in several steps

2.1.1 Evaluation of existing tools and protocols

Urban underground planners and infrastructure providers are using tools and/or protocols to guide them through planning processes. It is therefore relevant to identify what is missing in those tools and protocols and if they take the infrastructural transitions into account.

Together with literature research, the technique of snowball sampling (Kumar, 2014) is used on the experts/interviewees in order to find relevant tools and protocols that are being used. The expert, who is expert in his/her field, probably knows best what tools and protocols do exist and who are using them. The technique of snowball sampling is useful when there is little known about the group of study (Kumar, 2014). Potential biases caused by this technique are diminished by verifying the results with literature.

2.1.2 Technical constraints and opportunities

The technical demand of space consists of a demand for the required capacity, a demand for several design criteria, and an arrangement demand (Paragraph 3.2.1). To get a good overview of the constraints and opportunities for the technical demand of space, different infrastructures are being investigated with regard to their transitions. The results are given in a table which gives an overview of the different constraints and opportunities per infrastructure. Also, a table is created showing some of the possible synergies between infrastructures.

At last, other emerging topics with regards to the technical demand of space are being discussed, such as reservation of space, abandoned infrastructures, reuse of infrastructures and the emerging technologies or ideas to improve the underground arrangement of infrastructures.

2.1.3 Challenges for asset management

The space demand for accessibility is part of the practical demand of underground space, and is mainly based on demand by asset management. Asset management includes the frequency of condition assessment and maintenance which depends on the deterioration rate of a specific infrastructure, upcoming infrastructure additions, the average life time and also available inspection technologies.

There are different types of asset management. Schneider et al. (2006) describe a common way to classify maintenance strategies based on the condition and importance of the functioning of the asset (Figure 3). For this thesis, the type of maintenance strategy that is used per infrastructure provider is examined. Also, the underground space used for asset management is explored and discussed.

MUT's are implemented increasingly more common as a solution for infrastructure arrangement in dense urban areas. Besides the advantages and disadvantages of the MUT's themselves, the use of MUT's might increase or decrease the use of underground space. To evaluate whether a certain type of MUT is relevant to use or has the preference, the answers/opinions from different planners and engineers, designers and infrastructure providers are discussed. Also, the overall opinion about the use of MUT's is investigated.

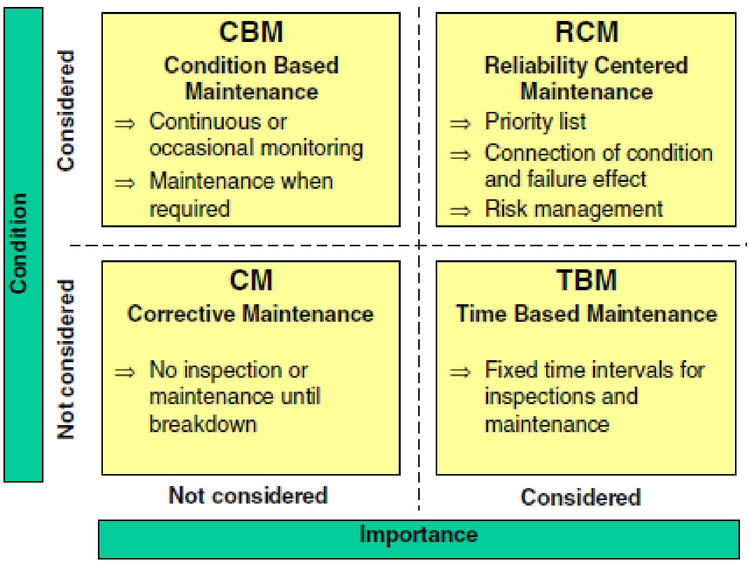


Figure 3: Classification of maintenance strategies (Schneider et al., 2006)

2.2 Case study: Haaksbergweg, Amsterdam

This thesis focuses on a specific area to retrieve information from experts and to contextualize the actual problems. This area is a part of the redevelopment project of ArenAPoort: Haaksbergweg in Amsterdam (Figure 4). The ArenAPoort area currently mainly consists of businesses, but the aim is to construct about 1200 residences in addition (Municipality of Amsterdam, 2017). Within the department Space and Sustainability of the municipality of Amsterdam, a project team is working on a design for the underground infrastructures. Meetings of the planners and designers together with engineers and infrastructure providers are held roughly every other week under the name "Connecting Opportunities" (CO1,2,3,4, Appendix II).

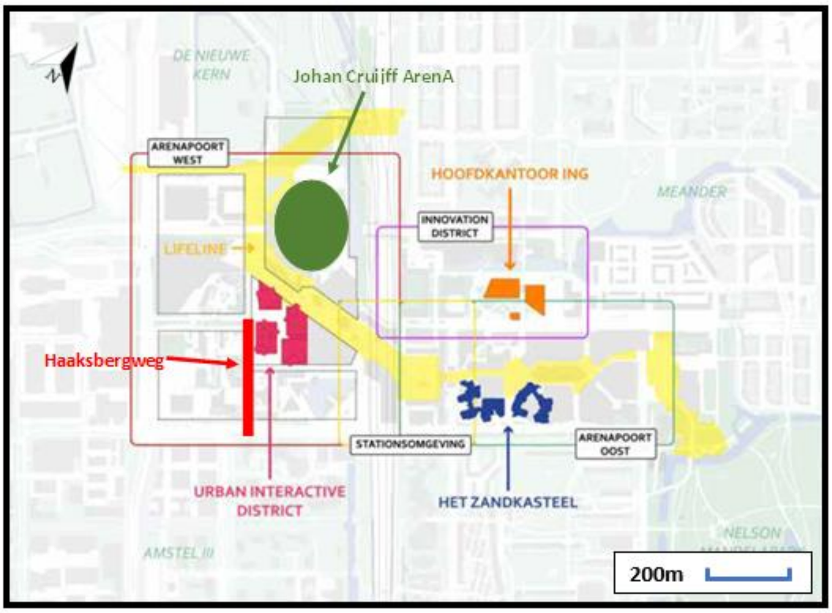


Figure 4: Haaksbergweg, red line and Johan Cruijff ArenA, green oval as part of the project area of ArenAPoort, adapted from (Project group Arenapoort, 2019, p. 6).

Another part of the ArenAPoort area is the Johan Cruiff ArenA (Figure 4), where national as well as international soccer matches are being held, complemented with large scale dance events (Johan Cruijff ArenA, n.d.) . Altogether, this causes a lot of waste and is one of the main reasons that an UVWC system (e.g. Chàfer et al., 2019; Hidalgo et al., 2018) is considered for the redevelopment of residential and commercial areas of ArenAPoort (UD, UD/A, personal communication, September 18, 2019). The scale for this thesis is the street level, excluding the connections from the street to the residences and focusing on the challenges in the street itself where all infrastructures have to be combined and arranged.

Haaksbergweg (Figure 4) is the case study that is used to give more context and depth for answering the research questions. Case study designs are often used when little is known about the topic or when a more holistic understanding of the situation is required. The advantage of a case study design, is that the research can be carried out with more detail. Though, a disadvantage of a case study design is that it will be more difficult or even impossible to generalize the ultimate findings (Kumar, 2014). For this reason, the case study will only serve as a way to contextualize the theoretical problems in a real case situation.

2.3 Data collection

Data collection was done through literature review, interviews and the observation of meetings between infrastructure providers, and planners and engineers. Literature review started before the observations and interviews, which led to an increased understanding of the context before setting up the interview questions. Interviews and observations were however not planned after the literature review but more or less at the same time. This choice was necessary in order to cope with the time schedules of the experts.

2.3.1 Literature study

Literature review

Science Direct has been used as a main database to find relevant, scientific literature. In addition, the online library of Wageningen University and Research and Research Gate were used. At the start of the thesis, the following search terms were used: "planning underground infrastructure constraints", "urban underground planning", "UUI planning", "multi utility tunnels (MUT)". Scientific literature on those topics was however found to be limited. Therefore, other search terms were added such as: "infrastructure transitions", "new sanitation", "automated vacuum piping systems", "climate adaptation" and "first flush sewer". When relevant articles were found, literature was also collected via references from inside those articles (snowballing).

Besides published scientific articles, national published documents from "het Nederlands kennis centrum voor ondergronds bouwen en ondergronds ruimtegebruik" (COB) were retrieved. COB is translated as "the Dutch knowledge centre for underground construction and underground use of space". As stated on their website and pamphlet: "The COB is a network organization focussing on collecting, developing and providing access to knowledge about and related to underground use of space" (COB, 2019b). Besides documents from the COB, practical and internal reports and protocols were retrieved from the municipalities of Amsterdam and Rotterdam. In the Netherlands, NEN protocols are often used by policy makers as practical guidelines. One relevant NEN-protocol for integral planning of UUI is analysed, namely the NEN 7171-1.

For the literature review, scientific articles were analysed as well as practical documents such as reports from engineering bureaus or knowledge institutions. Those reports were analysed to get a more in depth understanding of the technical and practical constraints faced during planning of underground infrastructure.

2.3.2 Interviews

2.3.2.1 Experts

The experts are divided into three main groups: 1) underground planners and engineers, 2) infrastructure providers and 3) urban designers of public space (Appendix I). This is done to get a clearer view from different perspectives on the challenges regarding the planning of underground infrastructure. Every group has its own specific field of expertise. Infrastructure providers might know more about the technical and maintenance challenges of their own infrastructures, where the planners and the engineers might have a better understanding of the integral planning process with its challenges (e.g. mutual influences). The designers of the public space may in turn be more familiar with the integral planning process from an even larger scale, especially regarding the interrelation between the surface and underground space.

Besides gaining information from experts during the interviews, more in depth information was retrieved during observations of meetings (Appendix II). Those meetings were between infrastructure providers, planners and engineers and sometimes urban designers of public space. The meetings also served as a way of verifying the relevance of the research and thereby improving the external validity. Unfortunately, no specific contact persons/experts could be reached for the topics district heating and green space. Information about those topics was however partly given by other experts or during various interviews, meetings and congresses.

2.3.2.2 Interview questions

The interviews were held in a semi-structured way. This provided a guideline throughout the conversation and a structure to cover all topics, but also allowed for a more flexible conversation and the opportunity for follow-up questions to retrieve more in-depth information. The questions were systematically set-up beforehand, but were slightly adapted per expert based on the type of infrastructure and the difference between infrastructure providers and planners/engineers of the underground space. Sometimes an open additional question was added to allow the expert to give some insight on a topic which might have been missed. The format of the interview questions can be found in Appendix (III).

2.3.2.3 Reliability of the questions

In order to have reliable questions for the interviews, the questions were carefully selected and revised where required. In particular attention was payed to the possibility of different interpretations of certain words. The advantage of an oral, person-to-person interview, is that the interviewer can always ask questions in a different way when a question has not been understood or the answer could use some elaboration. The answers retrieved from interviews might be unintendedly biased. Therefore, answers are verified with literature. Conversely, also literature might have its flaws due to the theoretical level and the lack of practical knowledge applied in the field of research. Therefore, the answers of the experts are expected to be a very helpful contribution. Hereby, the different data sources of primary and secondary data can strengthen each other.

2.4 Validity of the research

Internal validity

To improve the internal validity, a triangulation of data was applied. Triangulation is used to make the retrieved data more valid and grounded. Kumar (2014) describes triangulation as a method that makes use of the same set of data, collected through different approaches and examined from different perspectives, which will provide a better understanding of the problem. For this thesis, the same questions have been asked to different experts. For the infrastructure providers, two persons were interviewed about the same infrastructure. The municipality of Rotterdam has been interviewed to prevent a limited view on the topic by only observing the process in Amsterdam.

External validity

Since this thesis is meant to be applicable for dense cities/city centres such as Amsterdam in the Netherlands, more input and experience from different cities would increase the external validity. Nevertheless, since Amsterdam and Rotterdam are already belonging to the largest and most compact cities of the Netherlands, the assumption has been made that those cities are dealing with the largest problems regarding underground space. It is expected that other cities can learn from this when they are becoming bigger and more compact.

3 Results and Discussions

The results of the interviews and observations are discussed in this chapter. First, the evaluation of the currently used tools and protocols is given (paragraph 3.1). Followed by paragraph 3.2 about the technical constraints and opportunities of UUI transitions. Then, the challenges for asset management are being discussed (paragraph 3.3). At last, the planning process with regard to the arrangement of transitioning UUI is explained (paragraph 3.4). To refer to the interviews, abbreviations have been used, which contain information on the function of the expert and their category (Appendix I). Abbreviations have been used for the meetings as well (Appendix II).

3.1 Integral planning

During the interviews, providers were asked which methods they used for the planning and design of their infrastructure and planners were asked which methods they used for the planning of the infrastructures all together. From this, the currently used tools and protocols or other ways of working with infrastructure planning and design were retrieved (Appendix V). The Dutch norm, NEN 7171-1, appeared to be the main protocol with technical criteria for integral UUI planning. Therefore, this NEN norm will be discussed in this chapter.

3.1.1 NEN 7171-1: a Dutch norm for technical criteria concerning integral planning of UUI

The NEN 7171-1 is a Dutch norm which gives the requirements for the arrangement of underground infrastructures for new construction areas, both for public and private properties. Thereby, three main themes are being addressed: 1) influence on infrastructures from the underground itself, 2) accessibility of the infrastructures, 3) influence of infrastructures on each other (mutual influences). The requirements are given in the form of minimum distances: the space required for maintenance and space required between infrastructures of the same theme (e.g. between two heat pipes). In the appendixes of the norm, two tables are given for possible mutual influences. One table contains information for normal conditions and the other contains information for failure conditions. Also, a table is given with most usual capacity, coverage, and number of cable and pipes per type of road.

The norm works well for places where there is enough room underneath the street. It gives a clear and standard overview of how infrastructures should be planned. This standardization prevents excavation damage, since not all infrastructures are digitalized as they should be (UE, CCP, personal interview, November 18, 2019).

3.1.2 Implications of the NEN 7171-1

Multiple implications can be found for this norm. First of all, no minimum distances are being given between infrastructures of different themes. According to the norm, there might be an influence of heat infrastructure on drinking water. No specific numbers are however given. Right now, the minimum distance that drinking water pipes should have kept from heat sources is being researched by KWR (I, SAM, Water, personal interview, November 14, 2019; Agudelo-Vera & Blokker, 2019). According to another research carried out by KWR together with Evides (Agudelo-Vera et al., 2017), underground heat stress can be indicated by a combination of exposure to solar radiation, anthropogenic heat sources and the type of top layer.

Internal documents from municipalities which are being used for integral planning of infrastructures seem to be based on this norm or not based on any kind of integral planning. Because no recommendations are being given in the norm regarding standard distances to prevent negative influences, distances that are being used seem to be solely based on preventing excavation damage for each infrastructure separately.

The NEN protocol is meant for new construction areas. Redevelopment areas, such as Haaksbergweg, are no target group. This stresses the lack of protocols for integral UUI planning for redevelopment areas. While horizontal planning of infrastructures is standard in the current NEN protocol, for densely populated streets horizontal planning will not provide sufficient room for all infrastructures. Therefore, deviations from the norm have to be made.

Infrastructure providers may worry about the increasing strictness of regulations, increasing costs, the accessibility to their own infrastructure and increasing risks for damage to other utility companies (I, SAM, Water, personal interview, November 14, 2019). It is therefore likely to come across resistance from infrastructure providers when deviations from the norm are required. The norm provides standardizations for the planning of UUI. Infrastructure providers like to use those standardized profiles since they then know what to expect and thereby prevent excavation damage (CO1, September 18, 2019). According to the infrastructure providers during one of the CO meetings in Amsterdam, the costs are rising for all deviations from standards and will be settled nationally (CO2, October 9, 2019). Which means that taxes for residences will rise. This may be the reason that infrastructure providers want to be cost neutral (BS, November 21, 2019).

3.1.3 Revision of the NEN 7171-1

The NEN 7171-1, which exists in its current form since 2009, is currently being revised. This takes more time than expected, possibly due to all the relatively sudden changes regarding the energy transition (UE, CCP, personal interview, November 18, 2019).

The revision of the NEN 7171-1 can be seen as an opportunity to improve the currently used criteria and include more criteria based on the long-term planning for the transitioning infrastructures. With the large-scale infrastructure transitions that are currently coming up, changes from the standards are expected to be unavoidable. The question here is whether new norms should be made to cover less common circumstances and if more research is required to see what infrastructure providers need in order to become more flexible in less common circumstances.

The findings of the currently carried out research about the influence of heat infrastructure seem to be suggesting that local conditions and local context are influencing the heating of drinking water infrastructure (Agudelo-Vera et al., 2017). With the new NEN 7171-1, part of the new criteria for the long-term planning could be based on the results of the abovementioned research and indicate minimum distances to specific types of anthropogenic heat sources, taking into account:

- Top layer of the soil
- Size and temperature of anthropogenic heat sources (e.g. district heating)
- Changing climate (hours and intensity of sun)

It is expected that those factors will make a standard distance very hard or even impossible. In this case, a model is required to calculate those more site-specific minimum distances.

3.2 Technical opportunities and constraints

In this paragraph the main technical constraints and opportunities for transitioning UUI that will affect the planning are described.

3.2.1 Capacity, design and arrangement

3.2.1.1 Municipal Solid Waste

In Amsterdam increasingly more waste containers are needed, which is a result of an increasing population in combination with the decision for an improved waste separation at-source (I, SC, Waste, personal interview, November 4, 2019). Waste containers in Amsterdam are also increasingly more often placed inside buildings to free space underneath the road (I, SC, Waste, personal interview, November 4, 2019). Other reasons contributing to this shift, are aesthetic value, such as more green, fewer cars and less static objects (such as waste containers) in the street. Once the inlet of a solid waste collection system is inside a building, the municipality of Amsterdam wants to have all separation possibilities (i.e. organic, glass, paper etc.) there as well (I, SC, Waste, personal interview, November 4, 2019). In practice this means that all buildings (that might have had shared containers together) will have their own containers or inlets inside the buildings.

The aim of reducing the number of static objects in the street and to reduce car/truck traffic can partly be met by the implementation of an UVWC system. This system is an upcoming technology that requires more underground space than the commonly used containers. First of all, horizontally, the piping structure has a diameter of about 600 mm. Also vertically space is required; the buffer space for the waste at the inlets will take up 500 liters per inlet and at each bend in the system a manhole has to be placed (Paragraph 3.3). According to Ruben Verbaan, director of CentralNed[1], the diameter of the system would be smaller when the system would be constructed again (COB, 2017a). A smaller diameter can save energy and costs, but the vertical space for the manholes and buffer space for the waste is not likely to be diminished. In the Netherlands, the cities Almere and Arnhem already have an UVWC system in place. Also, in Amsterdam there are serious plans to implement UVWC systems for certain locations. The head of the executive team waste from the municipality of Almere thinks that the UVWC system in Almere will not disappear in Almere, despite of the financial setbacks (I, HEW, Waste, personal interview, December 2, 2019). The amount of waste is still increasing, which is logical since the population growth in the city of Almere is the fastest of the Netherlands (CBS, 2018). Although nationally, another trend is emerging (Figure 5): people start to have less overall waste to dispose (CBS, 2019). Another advantage of the UVWC system is that it is easily adaptable to changing situations. For example, less waste means that the system has to operate less often which will save energy and costs. Even if there will be no waste left, the system is expected to be relatively easily adapted to another type of system such as transporting resources (highly separated waste streams) or packages (I, HEW, Waste, personal interview, December 2, 2019).

[1] CentralNed is the only company in the Netherlands that is permitted to construct UVWC systems (COB, 2017)

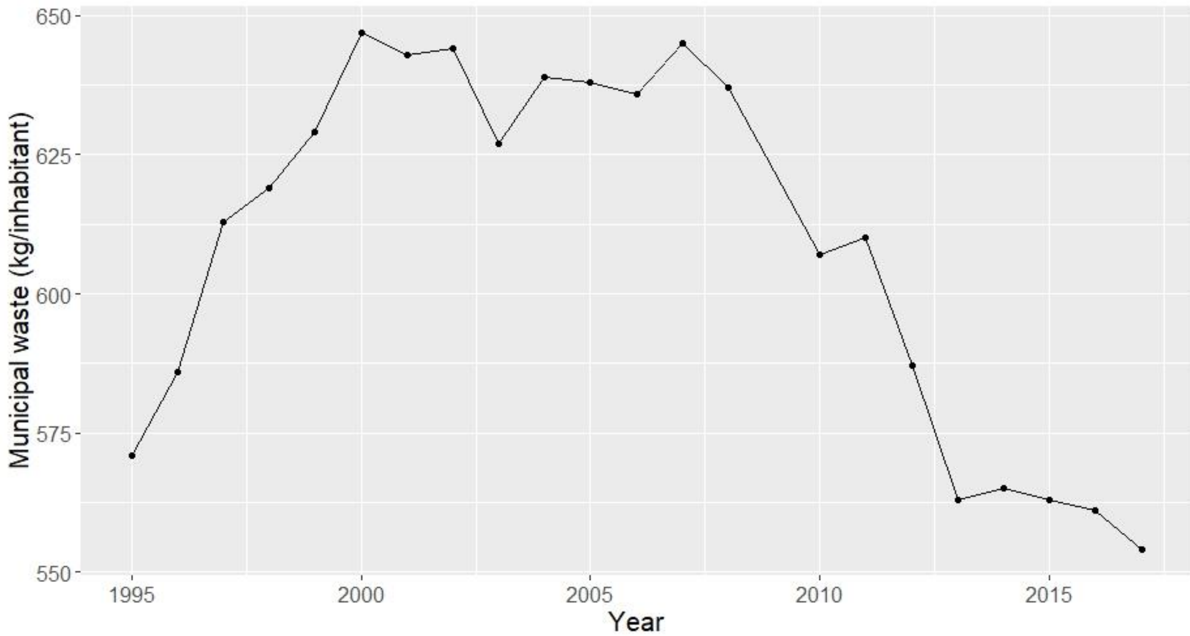


Figure 5: Municipal solid waste average in the Netherlands in kg/residence, from 1995 to 2017 with data from CBS (2019)

3.2.1.2 Sewer system

The main transition for the sanitary sewer used to be the separated system, dividing rain water and sanitary water, mainly to protect the environment and human health by preventing combined sewer overflows. Currently, also other transitions are appearing and leading to more diverted streams (Figure 6). With an increased awareness of the need for resource recovery, a paradigm “new sanitation” is emerging. New sanitation is based on the separation of black water and grey water (Zeeman, 2012). Therefore, a vacuum pipe system is used to collect the more concentrated black water, consisting of feces and urine with a limited amount of water and sometimes supplemented with organic waste. The grey water stream, with water from the shower, washing machine and kitchen, still has its normal volume when no measures are being taken. The transition towards new sanitation will require new infrastructures (Zeeman, 2012). More pipes are required underneath the street but also, according to the senior consultant water, soil and climate, inside buildings more space will be taken up. Which is often not preferred by project developers/contractors (UE, CWSC, personal interview, November 18, 2019).

Besides the extra infrastructure for new sanitation, there is also a need for discharge of the first rainfall which takes along the dirt from the roads. Therefore, an extra infrastructure may be required. During a meeting at Waternet, it was said that this so called “first flush” infrastructure could be prevented if all the rainwater could be infiltrated in green areas such as wadies (BIW, 30 Oktober, 2019).

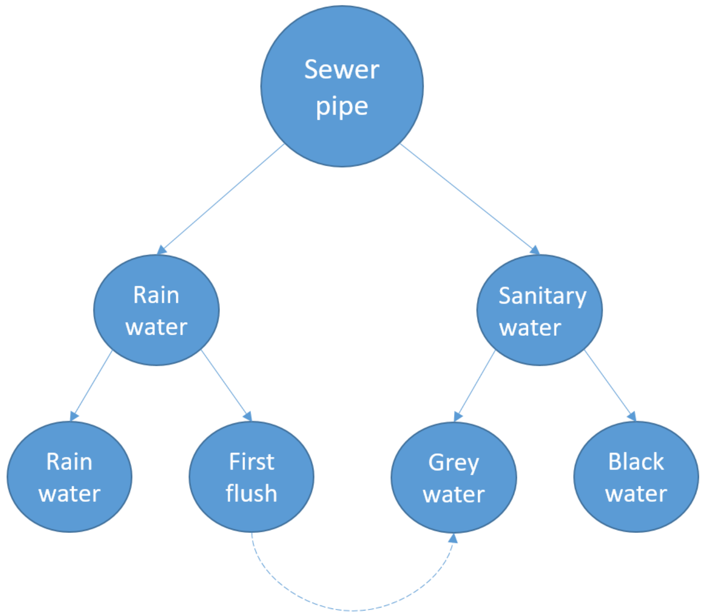


Figure 6: Increase in sewer infrastructures through separation of streams

In some countries, the grey water stream could also be reused e.g. as water to flush the toilet or water the garden (Yoonus & Al-Ghamdi, 2020). Less water usage is likely to result in less underground space required for infrastructure water supply and discharge. However, Dutch legislation around safety and health protection is currently making reuse of grey water in the Netherlands in the near future quite unlikely. Thereby, new sanitation has not been applied (yet) on a larger scale. In the development plans for Strandeiland in Amsterdam, there is an idea to implement new sanitation for 8000 residences (Waternet, 2019; I, SAM, Water, personal interview, November 14, 2019). Therefore, a large-scale vacuum system has to be constructed and it is not known how many pumps are required for a well-functioning system (I, SAM, Water, personal interview, November 14, 2019; NS, November 28, 2019).

The way sewer systems occupy underground space due to their structure, is depending on certain (internal) standards. Those standards exist for the maximum distance that house connections need to be from the main sewer (CO2, October 9, 2019). This also indicates how many main sewers a street should have. When the distance from the house to the main sewer becomes too large, for example with very broad roads, two main sewers might be needed: one at each side. Therefore, in a larger street like Haaksbergweg (case study) there are multiple sanitary sewers present, with in the middle of the street, often a transport sewer. This sewer has a piled supporting structure and a slope which starts at 1.8 meters below surface.

The collection sewers from smaller streets all come together in the transport sewer that transports the sanitary wastewater to the treatment plant or pumping station. A main technical problem is the settling of the collection sewer. Because of the piled supporting structure of the transport sewer, this sewer will not settle. Therefore, a flexible connection needs to be created between the collection and the transport sewer (I, SAM, Water, personal interview, November 14, 2019). Right now, in Amsterdam there is an increase in the replacement of collection sewers, due to a faster settlement that is leading to a decrease in the runoff potential (Waternet, 2016).

3.2.1.3 Climate adaptation

The municipality of Amsterdam requested a higher sewer pipe capacity to cope with heavy rainfall. The problem is, that the RWD infrastructure lasts on average for 60 to 80 years, which makes it an economic as well as environmental burden to replace them a long time before the “expiring date” (I, SAM, Water, personal interview, November 14, 2019). Therefore, the aim is to infiltrate and retain as much water as possible instead of using the RWD infrastructures, or in order to keep those infrastructures small in sizes. This is a challenge due to (1) the increasing intensive rainfall events and (2) the relatively high groundwater level in many parts of the Netherlands. For the Haaksbergweg case in Amsterdam, it is more difficult to infiltrate and retain rainwater due to the high groundwater level (CO2, October 9, 2019).

Rainproof interventions to cope with the heavy rainfall events should preferably be retaining water with use of green and Wadi's. A crates infiltration system is not preferable, since the costs are high and it requires quite an intensive maintenance (I, SAM, Water, personal interview, November 14, 2019).

The increase of trees and green causes several constraints and opportunities. First of all, trees can cause harm to infrastructures. For example, when their roots are infiltrating the sewer system and expand. This is mainly a problem in older city parts (U, USWM, personal interview, December 9, 2019). Municipalities often have a standard for the distances between trees and infrastructures, depending on the size of the tree (Internal document Municipality of Amsterdam). With respect to the surface space, the locations for trees in a street are already limited since there are regulations and guidelines for the placement of trees to assure accessibility of certain locations and safety (D, DPS/LA, personal interview, January 15, 2020).

On the contrary, urban green spaces are becoming increasingly popular, not only due to their climate adaptation characteristics, but also due to other functions: from ecosystem services to human well-being services (Belmeziti et al., 2018). Eventually, more green areas capable of retaining rain water will reduce the amount of rainwater that needs to be discharged (Belmeziti et al., 2018), and thereby the capacity for drainage pipes.

3.2.1.4 Energy transition

The main underground space demand for the energy transition mentioned by the experts is the district heating. It is expected that this will require the largest amount of space for the energy transition. Even though, according to the NEN 7171-1 protocol, the diameters of current district heating infrastructures in the Netherlands are on average about 225 and 450 mm for a main road, it is expected that the diameters of heating infrastructures will increase in number and capacity with the increasing demand for district heating. Larger pipe diameters are already being used; for example, in Amsterdam a pipeline with a diameter of 1020 mm is in use (Internal Document Municipality of Amsterdam). Also in other parts of the world, for example in Tallinn, capital city of Estonia, pipe diameters of 1200 mm are being used (Volkova et al., 2018). Although, a change in type of gas consumption might slow down the district heating transition. Vattenfall and Stedin are companies that each provide energy to about 2 million households in the Netherlands (Vattenfall, n.d.; Stedin, n.d.). Those companies would like to keep the gas infrastructures because they see a potential in the use of hydrogen gas in the future (UE, PM/TA, personal interview, December 6, 2019; UE, CCP, personal interview, November 18, 2019).

An increase of electricity cables is also expected. In a scenario with district heating and without gas, the space needed for electricity cables has to be doubled or even tripled as more electricity is demanded to drive heat exchangers and pumps (BS, November 21, 2019). On the other hand, the efficiency of electricity cables is being improved which may decrease the space demand of the increasing electricity demand (BS, November 21, 2019).

With the increase of district heating systems and electricity cables, more heat will be produced in the underground. There is little known about the effects of heat production on other infrastructures e.g. drinking water pipe and on the soil life, ecosystems and green (U, USWM, personal interview, December 9, 2019).

3.2.1.5 Drinking water

To keep the risks of legionella bacteria in the drinking water low, the drinking water should not exceed a temperature of 25°C (Agudelo-Vera et al., 2017; Blokker et al., 2019). This aim will become increasingly more difficult to reach with the increase of temperature in summertime, heating up the asphalt and the increase of district heating systems and electricity cables. Not only should the drinking water pipes be covered with enough soil and preferably green, also the pipes should be placed as far from the heating infrastructures and electricity cables as possible (BS, November 21, 2019). Even when this is doable in a street, problems may occur at the crossroads where drinking water pipes are forced to cross the heating infrastructures and the electricity cables (I, SAM, Water, personal interview, November 14, 2019). Thereby, the drinking water pipes will be dimensioned with a smaller diameter where possible to save water, which makes them more vulnerable for heat as well (I, SAM, Water, personal interview, November 14, 2019; Blokker et al., p156, 2019). Also, a smaller diameter means that the limit of the amount of residences the infrastructure can serve will be reached sooner.

3.2.2 Mutual influences

The current NEN 7171-1 already possesses a table with the possible negative influences from infrastructures upon each other in normal conditions and under failure conditions. However, a table giving an overview of the possible synergies between infrastructures could not be found. Also, during the connecting opportunities sessions about Haaksbergweg in Amsterdam, the possible positive influences of infrastructures upon each other were barely discussed (CO1,2,3 and 4). Therefore, a table showing where infrastructures may benefit from each other has been constructed in this research (Table 1) based on the information given in this paragraph (3.2.1) and some additional information given below the table.

Table 1: The way UUI might be positively influenced by, or having synergies with other UUI

Influence of / Influence on	Sanitary sewer (SS)	Drinking water	Rain water	Solid waste (pipe)	Green	Heat or cold
Sanitary sewer (SS)				+ Organic waste increases value of black water		+ Lower temperature of the SS water
Drinking water			+ Multi sourced drinking water		+ Cooling effect on drinking water	
Rain water		+ Less rainwater drainage			+ Provides space for infiltration	
Solid waste	+ Separation and collection of organic waste					
Green		0	+ Water for green to grow		+ Increase biodiversity	
Heat or cold	+ Collect heat from SS water					

Legend

Synergies: +/+	One side benefit: +/0	Trade-offs: +/-	Still unknown

\+ = positive influence
0 = no influence
\- = negative influence

Solid waste and Sanitary water

By collecting the organic waste and the blackwater using the same infrastructure, i.e. the blackwater sewer of the new sanitation, the solid waste collection and the sanitary sewer infrastructure can both benefit. The UVWC system has to collect the waste one type of waste less, saving energy and costs (or could collect another type of waste instead) and the black water will get a higher value, i.e. a higher potential to create biogas (STOWA, 2011).

Heat and Sanitary water

A special synergy can be found for sanitary water and heat recovery. More often, ways to recover heat from waste water are being investigated (e.g. Erhorn et al., 2018; I, SAM, Water, personal interview, November 14, 2019). Besides the energy that can be recovered from the waste heat of the sanitary sewer, the sanitary water itself will be cooled, which will decrease the production of sewer gasses that can be harmful for the concrete sewer pipes and ultimately may extend the lifetime of the sewer pipe (Gray, 2010, p414-415; Joseph et al., 2012).

Rainwater and drinking water

An opportunity to deal with the rainwater can be to find use for it, with a certain degree of treatment depending on the type of end use (Gray, 2010, p32); for example, toilet flushing or laundry. This can reduce the pressure of rainwater on the sewer system and, when stored properly, provide water in times of water scarcity. However, larger storage tanks or open pools will be required to do so. The other advantage is that less drinking water will be required when a larger share of the drinking water demand can be fulfilled with rainwater.

Even drinking water quality can be reached with a certain degree of rainwater treatment. Currently this is mainly done in remote areas with a freshwater shortage (e.g. Alim et al., 2020; Senevirathna et al., 2019). Still, in the future multi-sourcing of drinking water may also become more common in urban areas and eventually even in the Netherlands, especially with the increase of dry summers.

3.2.3 Reuse of infrastructures

The reuse of old infrastructures for new purposes is not common. During a congress from the COB several new technologies and ideas for the planning of UUI were presented by professionals (FUS, November 1, 2019). One of them was the usage of old infrastructures as casing for new infrastructures. There were, however, barely any professionals that supported this idea. Though, the Senior Asset Manager Water Chain did have an experience of using an old drinking water pipe as casing for a pressurized sanitary sewer pipe (I, SAM, Water, personal interview, November 14, 2019). This was done because of the limited amount of space.

During the interviews, there were not many positive reactions either about the reuse of old infrastructure. The project manager and technical advisor for the municipality of Amsterdam explained that the existing infrastructure had to be removed because it was old and contaminated (UE, PM/TA, personal interview, December 6, 2019). At Waternet it was said that the reuse is very difficult due to the quality of the infrastructure materials. Yet, some of the old pipes are being used as bypass pipes during maintenance work (I, SAM, Water, personal interview, November 14, 2019).

The UVWC system in Almere is not expected to become outdated. Even if we are directing towards a fully circular economy and there will be no waste anymore in the future, the system can still be used. For example, for the transport of raw materials (I, HEW, Waste, personal interview, December 2, 2019), but you could also think of packages.

In the Netherlands, part of the energy transition is to get rid of natural gas. New developed areas are not connected to the gas network any more. In old areas, gas infrastructure might be kept in place to examine possibilities to use the gas infrastructure in the future for hydrogen gas (UE, CCP, personal interview, November 18, 2019; UE, PM/TA, personal interview, December 6, 2019).

Table 2: Main technical constraints and opportunities for different infrastructures

Infrastructure transition	**Constraints**	**Opportunities**
Heat	- The district heating is expected to be one of the largest space demanding transitions (almost all interviewed experts) - Heat has effect on other infrastructures and the effect on the soil life itself and the green is unknown (U, USWM, personal interview, December 9, 2019)	- Usage of the old gas infrastructure for hydrogen gas (UE, PM/TA, personal interview, December 6, 2019; UE, CCP, personal interview, November 18, 2019)
Rain water and green	- For delta cities such as Amsterdam: relatively high groundwater level, making it more difficult to retain water (CO2, October 9, 2019) - Tree roots can be a threat to infrastructures (U, USWM, personal interview, December 9, 2019)	- More green for rainwater retention will reduce the amount of rainwater that needs to be discharged (Belmeziti et al., 2018) and therefore the capacity of drainage pipes
Sanitary water	- Settling of collection sewers (Waternet, 2016) - Increased need for pipes due to separation of wastewater streams (Zeeman, 2012; UE, CWSC, personal interview, November 18, 2019)	- New sanitation likely causes a decrease in pipe diameter - Heat can be recovered from the sanitary sewer (e.g. Erhorn et al., 2018; I, SAM, Water, personal interview, November 14, 2019)
Drinking water	- Heating up of the drinking water (Agudelo-Vera et al., 2017; Blokker et al., 2019) - Smaller diameter will make the water more vulnerable for heat (I, SAM, Water, personal interview, November 14, 2019; Blokker et al., p156, 2019)	- The trend of creating more urban green for climate adaptation measures will also provide a more relatively cool top layer of the underground, to protect the drinking water from heating up (BS, November 21, 2019)
Solid waste	- More containers are needed for improved separation at source (I, SC, Waste, personal interview, November 4, 2019)	- Containers are more often placed indoors, which saves some space underneath the road and creates more aesthetic value at the road sides (I, SC, Waste, personal interview, November 4, 2019)
UVWC system	- UVWC systems takes up significantly more underground space then containers (I, SC, Waste, personal interview, November 4, 2019; I, HEW, Waste, personal interview, December 2, 2019)	- UVWC systems can be easily adapted for changing future needs (I, HEW, Waste, personal interview, December 2, 2019)

3.2.4 Upcoming challenges for underground planners

3.2.4.1 Reservations of space

Due to the lack of easily accessible underground space, the debate about reservations of underground space is coming up. Currently, no underground space is being reserved for future use at new constructed areas (UE, PM/TA, personal interview, December 6, 2019; BS, November 21, 2019). The underground is already full and with reserving space, costs are being made for uncertain future needs. The trend towards more self-sufficient buildings with decentralized systems might even decrease the need for underground space.

The project leader urban soil and water management from Deltares thinks more rules are needed for the arrangement of the underground space (U, USWM, personal interview, December 9, 2019). Which was also mentioned by an advisor management underground from the municipality of Rotterdam, during his speech in a congress (SS, October 3, 2019). He would like to see new regulations that allow the municipality to refuse new cables and also allow the municipality to demand space for reservations. In Rotterdam, they are already trying to reserve space for district heating systems but also for tree roots and solid waste containers (UE, CCP, personal interview, November 18, 2019).

The question arises where space should be reserved. Reservations of space are mainly considered when there is already a shortage of underground space. Generally, this means that certain infrastructures have to be put deeper into the soil to save space above for future infrastructures. The other way around is not preferable or even impossible since the old infrastructures would be affected when other infrastructures would be placed underneath (UE, CWSC, personal interview, November 18, 2019). Digging deeper is however more expensive and it is not clear who should cover the extra costs.

Not only underground space can be considered for reservations, also buildings should be constructed in a way that later they can be easily adjusted to the additional or transitioned infrastructures. For example, with a certain construction project in Amsterdam the designers tried to reserve space in the building for the implementation of an UVWC system (D, DPS/LA, personal interview, January 15, 2020). This happened however too late in the process and could therefore not be included in the construction anymore. This implies how important a condition or demand like this is to be proposed and included at an early stage in the process (D, DPS/LA, personal interview, January 15, 2020).

3.2.4.2 Abandoned infrastructures

Most municipalities in the Netherlands are struggling with abandoned infrastructures. Those are infrastructures that are not registered in the online database for cables and pipes (Kadaster) and therefore unknown who owns them and if they are still in use.

In Amsterdam, the problem of abandoned infrastructures is quite present. Especially at locations that used to be private property. Here, cables and pipes did not have to be registered and therefore it is often unknown what will be found and if certain cables or pipes are still in use. In the planning process, this takes time and causes delay. Procedures have to be carried out to find the owners of the cable/pipe in question. Once those procedures are carried out, but no owners could be found, still the cable or pipe may only be removed at own risk of the municipality (UE, PM/TA, personal interview, December 6, 2019). In practice this means that when the municipality removes the cable/pipe and damage or nuisance occurs, the municipality is also responsible and has to solve it. This, possibly in combination with the removal costs, is why planners sometimes leave abandoned cables and pipes where they are. Especially in business areas where the risks are high. While those areas are likely to be the areas where the lack of underground space is most urgent.

A project leader urban soil and water management from Deltares suggests that a removal obligation might be a good solution to get rid of the abandoned cables and pipes (U, USWM, personal interview, December 9, 2019). Some kind of removal obligation already exists. At Waternet, all pipes from Waternet itself until a depth of 1,5 meter below surface, have to be removed immediately when they are out of function (I, SAM, Water, personal interview, November 14, 2019). Thereby, all pipes that are not removed immediately, should come back on drawings.

In the solid waste sector, abandoned infrastructures are not such a problem (yet). Waste containers in Amsterdam are all in use and there is even a shortage of containers. In Almere, an UVWC system has been implemented for solid waste instead of the regular container – truck-based collection system. This system is in use as a whole; however, according to the head of the executive team waste, in the worst case, the whole system will be filled up and a new pipe will be placed next to the old one (I, HEW, Waste, personal interview, December 2, 2019).

In Rotterdam, the problem of abandoned infrastructures is less common. Mainly because of the way the city was rebuild after the Second World War, when large parts of the city were demolished. During the rebuilding of the city, maps were made to register all new cables and pipes (UE, CCP, personal interview, November 18, 2019). Those maps became a valuable tool for the planning of UUI preventing excavation damage and also preventing the frequency of surprises from abandoned infrastructures.

According to the designer of public space, one of the most important steps in the underground infrastructure problem is the registration of data (D, DPS/LA, personal interview, January 15, 2020). A well-functioning data management system is required.

3.2.4.3 Uncertainty of transitions

The degree in which UUI transitions will proceed is uncertain. To start with the new sanitation. This system is currently only being applied at small scales. Large scale implementations are mainly being stagnated due to acceptance from end users (Poortvliet et al., 2018; NS, November 28, 2019). At the congress about new sanitation, where experts from the Netherlands and Belgium came together to discuss transitions in the waste water treatment field, it became clear that most experts expected a large-scale implementation of new sanitation, although, not within 15 years from now (NS, November 28, 2019). This result can be strengthened by Poortvliet et al. (2018) who found out that 64% of the 338 survey participants indicated that they would be likely to use new sanitation if they were owner/user. Thereby, they found that personal pro-environmental norms together with risk and benefit perception influenced the acceptance of new sanitation. On the contrary, some of the experts at the congress of new sanitation were less positive about the new sanitation transition. In their experience, a lot of improvements were also being done within the current waste water treatment systems and new sanitation could be a misleading terminology, suggesting that only new sanitation is innovative and future proof (NS, November 28, 2019).

Also, some critical notes can be given about the UVWC system. For example, about the quality of the separated waste streams. Organic waste seems to be of less quality (I, HEW, Waste, personal interview, December 2, 2019) and the exact cause for this has not been researched yet. Also, water intrusion sometimes occurs, making the paper less suitable for recycling (I, HEW, Waste, personal interview, December 2, 2019). The strategic consultant waste chain does not think an UVWC system is a better solution than the current truck-based collection system (I, SC, Waste, personal interview, November 4, 2019). Although it will save some truck rides, they will still be needed for the fractions that are not suitable for transport with the UVWC system. Thereby, the UVWC system might be less fitting for the trend to place more containers or inlets inside buildings. When inlets are placed in the cellar, inside a building, more height differences are expected which will lead to a higher energy demand and higher costs (I, SC, Waste, personal interview, November 4, 2019).

3.3 Challenges for asset management

Asset management is something relatively new for the urban underground (SS, October 3, 2019) and the asset management approach is increasingly applied on the planning of underground infrastructures (COB, 2019a).

3.3.1 Condition assessment

For condition assessment, different topics will be addressed including the materials that are being used, the average life time of the infrastructures, the frequency of condition assessment and the type of inspection technologies. At the end of this paragraph, Table 4 presents the main findings.

3.3.1.1 Material usage

The solid waste containers are made of steel. The steel layer of the containers used to be more robust. Due to need for cheaper containers however, they became thinner and less robust. The pits are made of concreate and used to accommodate the steel containers. This concrete is not yet circular, but this will be a logical next step in the process from the municipality of Amsterdam of becoming a circular city (I, SC, Waste, personal interview, November 4, 2019). Also, the pipes of the UVWC system are made of steel (I, HEW, Waste, personal interview, December 2, 2019).

For the water infrastructures, mainly PVC is being used. Depending on the type of wastewater sometimes also HDPE is used, for example for industrial waste water. PVC is not only strong and impermeable; it is also lighter than for example concrete. This is important to minimize the settlement of the infrastructures (I, SAM, Water, personal interview, November 14, 2019).

Transport pipes are usually made of concrete. Sanitary collection sewers made of PVC at street level. Rainwater sewers are also made of PVC at street level and possibly of concrete at higher scale. Drinking water pipes are currently mostly made of PVC.

3.3.1.2 Average life time

A solid waste container has a life span of about 10 years. The concrete pit may reach the 25 to 30 years (I, SC, Waste, personal interview, November 4, 2019). For the UVWC system the average life time is more complicated. First of all, since the system is relatively new, not many estimations of lifetimes are known. For the straight pipes this could be 30 to 70 years. For the bends, the life time is significantly shorter due to the pressure that is being put on the bends because of the collision of the waste on the bends. Also, the bends closest to the common collection point are the ones that have the most waste collisions and therefore the fastest deterioration rate. Depending on the distance of the bend to the common collection point, the lifetime can be 2 to 6 years. On average this will be 5-6 years for most of the bends (I, HEW, Waste, personal interview, December 2, 2019).

The average lifetimes of the water infrastructures mainly depend on the type of material. Currently the lifetime of transport pipes is been estimated at 60-80 years, sanitary sewers on average have a lifetime of 45-55 years, rainwater sewers also have a lifetime of 60-80 years and drinking water pipes have an average lifetime of 80 years and distribution pipes may even survive for 100 years (I, SAM, Water, personal interview, November 14, 2019).

3.3.1.3 Frequency condition assessment

Solid waste containers have a condition assessment once every year. Before the assessment, they will be cleaned entirely (I, SC, Waste, personal interview, November 4, 2019). For the UVWC system the frequency of condition assessment is again more complicated. Therefore, the bends have a condition assessment every month while the straight pipes probably only have a condition assessment once every year (I, HEW, Waste, personal interview, December 2, 2019). According to Schneider et al. (2006), this type of condition assessment can be classified as time based maintenance (TBM).

The condition assessment of the sanitary sewer pipes in Amsterdam however, shifted from a time-based maintenance (TBM) to a reliability centered maintenance (RCM). This means that the condition assessment is been done more goal-oriented to reduce the costs and will be assessed based on the life time of the system, the usage and the amount of failures (Schneider et al., 2006). The transport sewer, for example, is on average inspected every 5 years, but the first 20 years this may not even be necessary (I, SAM, Water, personal interview, November 14, 2019).

3.3.1.4 Replacement

For replacement and/or for repair of infrastructures, roads have to be opened. One of the main problems with this is the disruption of the public space (D, DPS/LA, personal interview, January 15, 2020). In Rotterdam a covenant has been made with the infrastructure providers, saying that the sewer system is leading for opening the road. Other infrastructure providers may choose to replace their infrastructure at the same time without costs for opening the road, or wait and pay the costs for opening the road themselves at the moment their infrastructure needs to be replaced (UE, CCP, personal interview, November 18, 2019; COB, 2018). Also, the municipality can demand from the infrastructure providers that they do not open the road for the next couple of years.

Since the rules and regulations are becoming stricter and the underground is getting crowded, infrastructure providers are becoming more worried about the accessibility to their own infrastructure without damaging other infrastructures. Also, they become worried about the financial feasibility of their current maintenance strategies (I, SAM, Water, personal interview, November 14, 2019). Replacement of infrastructures can be quite difficult. With a good asset management system, as many infrastructures as possible should be replaced at the same time. Though this is a complicated task due to the differences in lifetimes.

The UVWC system in Almere is laying quite deep and underneath other infrastructures. Therefore, the head of the executive team waste from the municipality of Almere says that it will be difficult to replace it (I, HEW, Waste, personal interview, December 2, 2019). There are few options to deal with a deteriorated UVWC infrastructure: 1) possibly a coating can be applied on the inside of the pipe, 2) new pipes with a smaller diameter could be put inside the old pipes or 3) in the worst case, everything will be filled up and a new pipe will be placed next to the old one (I, HEW, Waste, personal interview, December 2, 2019).

The project leader urban soil and water management from Deltares mentions the idea to create a fund to prevent opening the road for each cable/pipe that is not in use anymore (U, USWM, personal interview, December 9, 2019). When a provider notices that a cable/pipe has reached the end of its lifetime, he should contribute to the fund. In the end there should be enough money to remove all the old cables and pipes at once.

3.3.1.5 Inspection technologies

For solid waste, the technologies used for condition check-up depends on the infrastructure. Containers will be inspected visually when the container is lifted out of the pit with a truck (I, SC, Waste, personal interview, November 4, 2019). Also, the concrete pit will then be assessed from the inside, not from the outside. The condition of the UVWC system is mainly being checked with sensors. At each bend, on the outside a sensor is placed that measures the thickness of the material (I, HEW, Waste, personal interview, December 2, 2019). Thereby, at every bend a manhole is placed to have access to the sensor.

For the water infrastructure smart bolts are being used as well as other sensors and technologies that can measure amongst others the coordinates of its location, the reinforcement of the concrete pipe at that location and the leak detection (I, SAM, Water, personal interview, November 14, 2019). For drinking water no specific technologies were mentioned, though possibly non-revenue measures are indicating where leaks occur (Open, 2017).

Table 3: Type of material, average life time, frequency condition assessment (check), type of technology used for inspections for different UUI, and at last the way to excess the infrastructure for condition assessment

Infra	**Material**	**Life time**	**Frequency check**	**Technologies**	**Access to technology**
Container SW	Concrete pit, containers of steel	Pit: 25-30 years Container: 10 years	Once a year after cleaning	Visual inspection	Container lifted by truck
UVWC	Steel	Bends: 5-6 years Straight pipes: 30-70 years	Bends: once a month Straight pipes: once a year	Sensors	Manholes
Sanitary sewer	PVC, HDPE, Concrete	45-55 years	RCM: about every 5-20 years	Smart bolts and robots	Manholes
Drinking water	PVC	80 years	RCM	Non-revenue water	Not required
Rain water	PVC, concrete	60-80 years	RCM	n.a.	n.a.

3.3.2 Space demand for accessibility

3.3.2.1 Infrastructure-specific demand of space

For the UVWC system, at every bend in the system a manhole is placed to have easy access to the most vulnerable points of the system (I, HEW, Waste, personal interview, December 2, 2019). For the sewer system also manholes are required to act during calamities. Thereby, a funnel shape above the pipe is needed as space for accessibility. This shape starts with 0.5 meters of space besides the pipe and going out in a 45 to 60 degree angle depending on the softness of the soil (Figure 7). The more solid the soil is, the higher the angle can be. For transport pipes often a sheet pile is being used for maintenance instead of an angle (I, SAM, Water, personal interview, November 14, 2019). The space above an infrastructure (orange space in Figure 7) can be used for infrastructures of the same provider, but is never used for infrastructures from other providers (UE, PM/TA, personal interview, December 6, 2019). The less providers there are, the easier it would be to arrange the infrastructures.

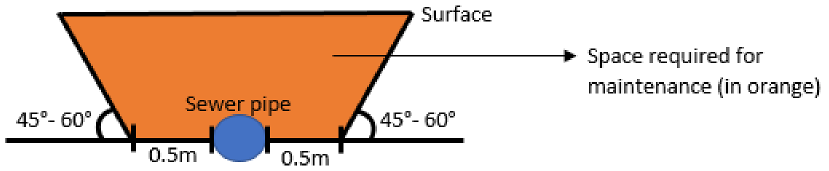


Figure 7: Space for maintenance sewer pipe (based on: I, SAM, Water, personal interview, November 14, 2019)

At the municipality of Rotterdam the exact amount of space required for maintenance is given by certain internal standards.

3.3.2.2 Pipe casing – pit construction

Another technique used for UUI planning is the pipe casing – pit construction (Figure 8). Especially for data and electricity cables this is a good solution. Hollow casings are put through the soil, connecting different pits. Through the hollow casings, cables can be moved on. This is easier for maintenance since most of the time no excavation is required.

Figure 8: An example of pipe casing - pit construction (COB, 2017b)

3.3.2.3 MUT

About the use of MUT's (Figure 9) the experts were often a bit reserved with their answers. Most of them liked the idea and possibilities of a MUT, but were not really familiar with the field of MUT's. The use of MUT's for main roads is a relatively new technique that has been applied in few places in the Netherlands.

The project leader urban soil and water management from Deltares thinks MUT's have to be implemented (U, USWM, personal interview, December 9, 2019). They can prohibit the ongoing opening of the road for maintenance, which is seen as an urgent need (U, USWM, personal interview, December 9, 2019; Bosch & Broere, 2011). Also, by using MUT's there comes more space for trees and their roots.

Currently, one of the main technical issues is the water intrusion in the MUT (CO3, November 21, 2019). The MUT of the Mahlerlaan in Amsterdam seemed to be a nice solution for multiple problems, however, there were problems with the water intrusion. Pressurized pipes were used to pump the water out of the tunnel. The risk of water is one of the reasons why Liander, the electricity provider, does not want to join a MUT with their cables. Water and electricity can cause risks together (CO3, November 21, 2019).

The main concern of the planners, engineers and designer seems to be the costs of the MUT. It is well known that the investment costs are high for MUT's. Although the full advantages and cost reductions regarding for example the maintenance of the infrastructures are not yet fully known. It is confirmed by multiple people that from the MUT at the Mahlerlaan in Amsterdam, more can be gained than expected according to the project manager and technical advisor for the municipality of Amsterdam (BS, November 21, 2019).

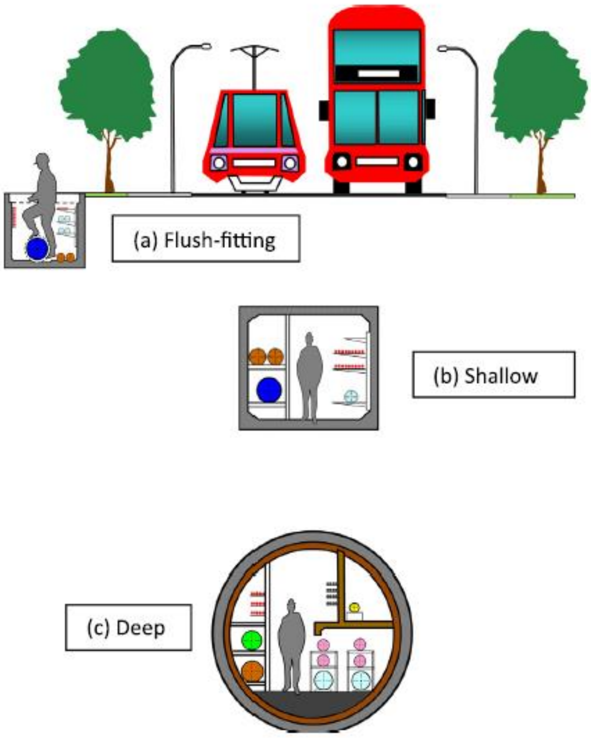


Figure 9: Different types of MUT construction (Hunt et al., 2014)

3.3.3 Shift in type of condition assessment

The type of condition assessment (paragraph 2.1.3) may also affect the planning of the UUI, depending on the way the maintenance is being done. With TBM, a clear frequency can be seen and also be incorporated in the planning process; however, with RCM there is no regularity. The regularity of maintenance is not a problem when the inspection is being done by means of sensors or robots. Only during the inspection, the road has to be opened or at least partly blocked. This will cause an unwanted disturbance and should be carefully involved in the planning process beforehand. Therefore, RCM should either be done in a way that is not disruptive, or the frequency of condition assessment should be estimated in such a way that a pattern can be included in the planning process.

RCM will be more difficult with new types of infrastructures. For new sanitation, more pipes with a smaller diameter will replace the old larger pipe. A smaller diameter, together with higher concentrated waste water, will have influence on the speed of clogging and therefore on the maintenance frequency. RCM can then only be carried out when the clogging process is well understood and researched.

It is unknown whether the TBM and RCM for UUI is typical for the Netherlands as a whole or only for specific cities or situations. According to Costello et al. (2007), in the UK, corrective maintenance (CM) is commonly used, which is a reactive form of condition assessment with all related consequences. Also, scientists from Hong Kong found that mainly CM or TBM were being used, based on surveys (Wang et al., 2019).

3.3.4 Role of infrastructure providers

Another point of discussion is to what extend it is needed for the representative infrastructure provider, who takes part in the planning process, to be updated about the maintenance process. Since the condition assessment and maintenance of infrastructures are part of the underground space demand. According to the Senior Asset Manager, he is working at a strategic level which is the link between the higher management layer and the more executive team (I, SAM, Water, personal interview, November 14, 2019). Even though this strategic level already appeared to be implemented to help filling up the gap between the management layer and the more executive teams, the inspection techniques were not really known on the strategic level. The inspection and maintenance were done by a special team. Some maintenance or inspection techniques will have influence on the amount of underground space that is required for maintenance. Especially now increasingly more inspection robots are becoming available, maybe infrastructure providers should be educated about the opportunities to decrease space demand with upcoming maintenance and condition assessment strategies for their infrastructure.

The change towards more decentralized systems, with fewer large-scale UUI, will also ask a change in focus from infrastructure providers: from infrastructure oriented, towards more service oriented. Since the knowledge is already possessed by the infrastructure providers, it seems a logical step to help them improving their knowledge and slightly shifting their focus.

3.4 Planning process

Based on interviews with multiple infrastructure providers conducted in recent **previous research**, it was concluded that more guidance or coordination from the municipality on the planning process was required (SS, October 3, 2019). Mainly because utility companies are acting from the present, risk avoiding with a reserved attitude and not as much with an eye on the future. Thereby, the coordinating framework is not always working or up to date, which complicates the aligning process among the infrastructure providers (usually companies) (SS, October 3, 2019). To improve the alignment of underground space utilization, the following three elements were considered to be necessary for facilitating the planning process: (1) a common language, (2) a comprehensive understanding of the tensions and (3) understanding about each other's requirement (BS, November 21, 2019).

There may be uncertainties about the division in responsibilities among different stakeholders. For example, between infrastructure providers of drinking water and electricity (BS, November 21, 2019). Both claimed that the other should provide insulation for their infrastructure in order to prevent the drinking water from heating up. The drinking water provider argued that the polluter should pay, while the electricity provider argued that they had to get rid of the heat and therefore should not insulate their infrastructure.

Usually an urban designer came with a design to each of the infrastructure providers respectively; the master planning and design can therefore be sent back and forth between the designer and each infrastructure provider multiple times to suffice the overall demands. This is a time-consuming process and often ignorance on certain synergies or trade-offs occur due to the lack of collaboration and integral view. Currently, a shift towards a better collaboration has been initiated by the municipality of Amsterdam to improve this process (BS, November 21, 2019).

3.4.1 Haaksbergweg planning process

Haaksbergweg is one of the experimental initiatives to improve the integral planning process. For Haaksbergweg the first steps are being taken to come to a more integral approach for UUI planning in Amsterdam, by a regular participation of the different infrastructure providers in the planning process to discuss the realization of the redevelopment of Haaksbergweg (CO1,2,3 and 4). This paragraph will shortly give some of the problems that are being faced for this specific case study.

First of all, during the CO meetings it was noticed that there was a need to have more focus on the underground during the planning phase (CO1, September 18, 2019). With the current way of planning, the ideas for the surface (above ground) are leading the entire planning, followed by the possibilities of the underground. Secondly, the data that was available about the infrastructures of Haaksbergweg in the Kadaster, was missing important facts that had to be retrieved during additional meetings. Multiple pipes could be seen in the Kadaster, but the function of the pipes and if they were still in use could not be seen (IB, September 30, 2019). Also, the question whether, and in what form to make use of a MUT arose each meeting.

Every session, the (updated) design of a cross section of Haaksbergweg was discussed and eventually three different designs were presented as the final options (CO4, January 15, 2020). Each design presented cross sections of Haaksbergweg at three different locations. This was needed due to the complicated sections for example with a tunnel underneath the road. Together with many other components, the main differences between the designs were:

1. Making use of a technique to bundle cables
2. Making use of a casing pipe pit construction
3. Making use of a MUT

During this session the preferences of people were being discussed to make a choice between the three designs. Because only the infrastructure provider from Waternet was present, the designs would afterwards be sent to the other infrastructure providers for feedback.

3.4.2 Spatial planning

Instead of planning per street, the aim to plan the UUI for a vaster area at once is being adopted in Amsterdam. For example, for the sewer system, the replacement or maintenance of infrastructures was often planned and done per street. This made it difficult or even impossible to make an integral design for a larger area. Currently this is changing to a more integral planning for the longer term. Amsterdam has been divided into certain blocks and per block infrastructure providers have to give a plan for the next 5 years for their infrastructure. During those 5 years the road may only be opened for calamities (I, SAM, Water, personal interview, November 14, 2019).

Another point is that there may be less space under the road in the future since the amount of space for roads might decrease with the aim to have less cars in the city. Houses are being built closer together as part of the compact city but also economically driven and the surface space will be giving more priority to cycling lanes and green. This may lead to more infrastructures that have to be put underneath the green or (partly) inside buildings.

At the feedback session from the engineering bureau, a reminder was given to the planners/designers to look at the bigger picture and not only the street itself (IB, September 30, 2019). Also, during the broader session with infrastructure providers and urban underground planners (BS, November 21, 2019), where the aim was to come with a common plan for infrastructure arrangement of a street intersection, it became clear that infrastructure providers constantly wanted to look at the bigger picture, a larger scale.

Another threat to the optimal use of underground space is the defined division of money between different construction projects that each have their own budget to spend. This budget is solely for that specific project and therefore no projects that are close by or future projects can be taken into account (U, USWM, personal interview, December 9, 2019). This may lead to a loss of opportunities.

3.4.3 Temporal planning

The project leader urban soil and water management from Deltares (U, USWM, personal interview, December 9, 2019) advocates for a smarter asset management system. An opportunity of the energy transition may be that the whole underground will be opened and consequently give room for a thorough revise of the way the underground infrastructures are arranged. Therefore, a long-term planning can be made. At the same time, smart sensors and monitoring systems can be applied to thoroughly collect data about the assets.

To the question, how to act pro-actively with an uncertain future, the idea of scenario planning came up. Where, overlap between scenarios could guide the directions of the first steps that should be taken (BS, November 21, 2019).

Project developers are often more focused on the short term. Demands could be made to make developers act in a certain way, e.g. certain demands to focus more on the long term. Although this does not always have the desired effect since it is difficult to check whether the demands have been met (UE, CWSC, personal interview, November 18, 2019). The senior consultant water, soil and climate herself likes to work more with encouragement of intrinsic motivation (UE, CWSC, personal interview, November 18, 2019).

3.4.4 Management framework for UUI planning

Eventually, when zooming out to see the "bigger picture", a priority and arrangement of steps for the planning process can be made. Figures 8A, B and C visualize how those potential steps could look like in the future within their context. The figures in Appendix VI show how the planning is currently done.

First of all, the **collaboration** between designers of public space and planners and designers of underground space can be improved by sharing ideas at an earlier stage (Figure 8A) to decrease the gap between surface- and underground planning. For the case study Haaksbergweg, this process was started by appointing two designers of public space the task of underground planners. The advantages can be that the previous designers of public space may know more about the designing process of the public space and may be able to see certain related pitfalls in time. Although it should be continuously kept in mind to collaborate with the other designers of public space who are working on the design for the public space to prevent the upkeep of the gap between surface and underground planning. Thereby, the planning task was previously done by engineers from the engineering bureau of Amsterdam (IB) and those engineers were, after the shift, less involved with the planning process. It should also be considered that this might make the bridge larger between the underground planners and the more technically focused infrastructure providers. The same counts for the designer of public space and the contractor/project developer. Building on a **shared overall vision** at an early stage in the process is likely to result in an improved alignment and saving time and effort at a later stage. This is especially important as infrastructures seem to take up more space inside buildings in the future (e.g. waste containers inside building, more infrastructure for new sanitation, heat infrastructures through cellars etc.). To make the shared overall vision more specific and practical, **boundary conditions** can be made. For example, 30% of the total surface area should be green or space should be reserved for an UVWC system. Since reserving space for UVWC has to be done in the underground as well as inside a building. Those boundary conditions should count for all of them together and not just for the one of the participants. Thereby, it is important to make a clear division in tasks and responsibilities.

To reach this shared vision, several steps should be taken. Some steps can be taken jointly (1 and 2, Figure 8A), others are more bound to be the expertise of the separate teams (3,4 and 5, Figures 8B and C). For this framework, 5 steps have been chosen. Either to show the importance of the order of steps, or because the step did not seem to be commonly considered.

Although the **site-specific conditions** might be mainly important for the underground planners and designers, it is needed to make decisions about the second step: what can be **arranged locally**. For this second step, the importance of collaboration between all fields/participants is expected to be highest. Also, the involvement of future residents is recommended for this step, to create a certain commitment for the longer term.

Within the team for planning and designing underground space (Figure 8B), there seemed to be blockage in exchanging information. Therefore, it is suggested to create some kind of **communication platform**, where:

1) Exact information about capacity, design, arrangement but also asset management from infrastructure providers (illustrated as Water, Electricity and Waste in Figure 8B) can easily be shared with the planners and designers of underground space
2) This same information shared between infrastructure providers may create more understanding of each other's needs
3) Information about the shared overall vision with its boundary conditions can be shared with the infrastructure providers, in order to stimulate thinking in creative solutions and better understand the reason behind the requests from the planners and designers of public space

Then, in order to make a design for the underground space, three steps should be considered. First of all, step 3 suggests that the **opportunities for mutual influences** (synergies and trade-offs) between different infrastructures should be investigated (Table 2). Besides the benefits for one or multiple infrastructures, this may also save underground space. Second, step 4 suggests to look into the **reservation of underground space**. Since the reservations of space are not (yet?) really included in the norms (NEN 7171-1), it is important to come to a joint decision about this topic; including a clear division of possible related costs. At last, since as explained in paragraph 3.4.2, planning with different scales is a challenge, step 5 suggests a way of planning that involves planning for **different scales at the same time** (Figure 7C). Then, preferably jointly for all scales, the so called 'alert system' could be used to see where the plan does not fit. This 'alert system' can be part of the tool set-up as presented in appendix IV.

In the end, when a few different possible designs have been made and presented, a decision should be made to select the best design (Figure 8B). In Amsterdam, this final selection process seemed to be based on personal preferences of participants (CO4, 15 January, 2020). To come to a more validated decision however, an **assessment framework** based on carefully selected and weighted criteria may help. This selection of criteria could be done by the team of underground planning and design. While the assessment framework itself could be made by a consultancy company.

3.4.4.1 New vs Redevelopment

Figures 7A, B and C, are not specified to redevelopment- or new to be developed areas. This does however, have an influence on the process. Since at a redevelopment area, the underground is often already full of old, either in use or abandoned, UUI. Therefore, on average, the steps will be more difficult for a redevelopment area (Table 5).

Step 1: For existing infrastructure, when not registered (in the Kadaster), risks for removal are higher for redevelopment areas than for new to be developed areas.

Step 2: Technically, it will be easier to plan what services can be arranged locally for a new area. For this step however, it is very important to involve all stakeholders. This is more difficult for a new area since many stakeholders are often only known in a later stage. For a redevelopment area it will be easier to involve the already known infrastructure providers and users of the public space, possibly even the future residences may be known at an earlier stage.

Step 3: Opportunities for mutual influences may be more difficult to find/implement in areas for redevelopment, since part of the UUI is already in place and should not be removed or replaced.

Step 4: Reservations for future infrastructures will be harder for redevelopment areas as well, since the underground is already full and many infrastructures have not reached their end-of-life time.

Step 5: At last, also the design on different scales will be harder for redevelopment areas. Some infrastructures may need to be replaced, which may not be possible with large scale.

Table 4: Implementation of steps in New area vs Redevelopment area

	New area	Redevelopment area
Step 1		
Step 2		
Step 3		
Step 4		
Step 5		
Legend		
More difficult		Easier

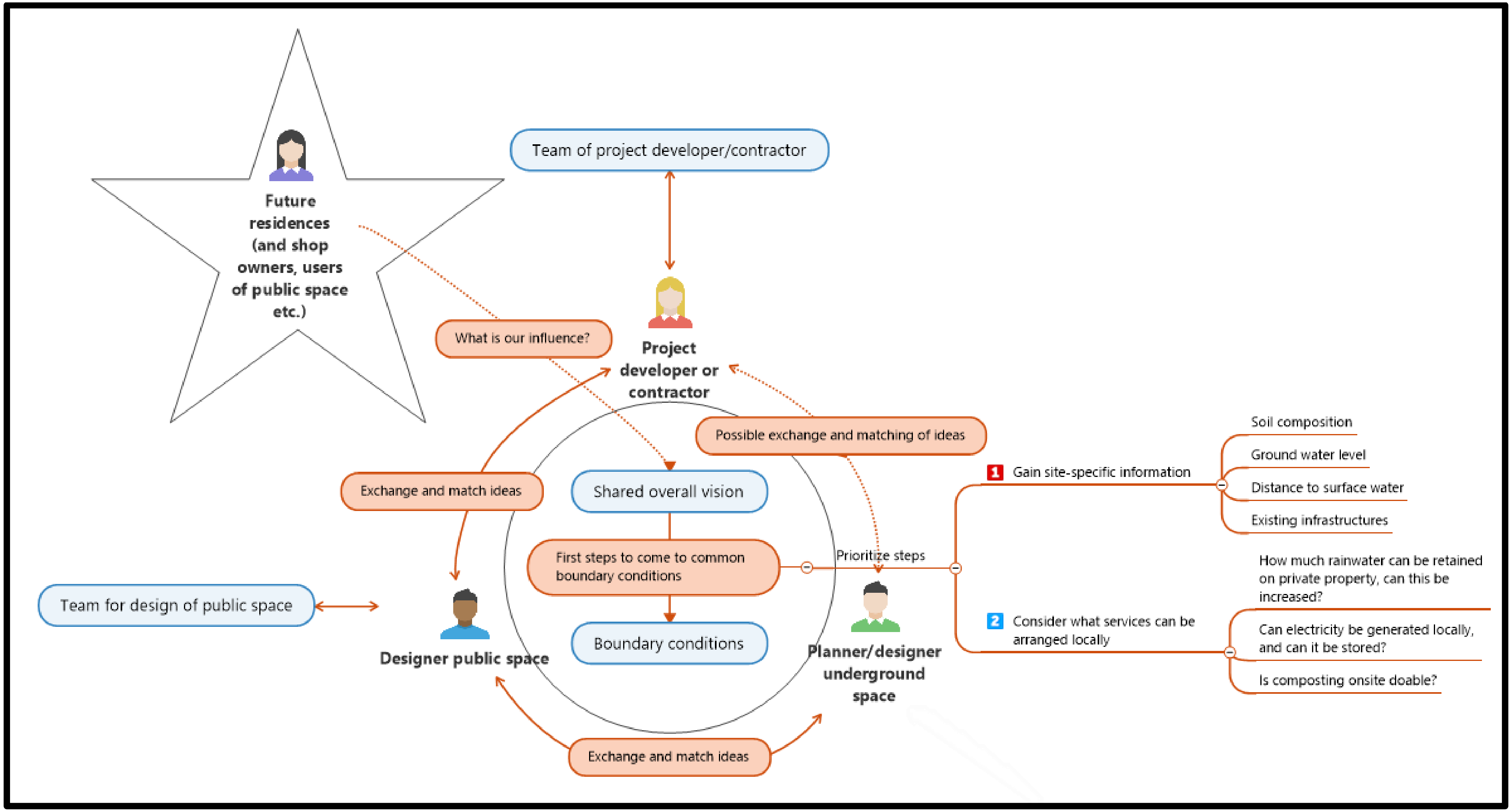


Figure 10: An improved collaboration between different stakeholders: planners/designers of underground space, designers of public space and project developers/contractors. Including the first two steps for the planning process of UUI: 1) gaining site-specific information and 2) considering what services can be arranged locally.

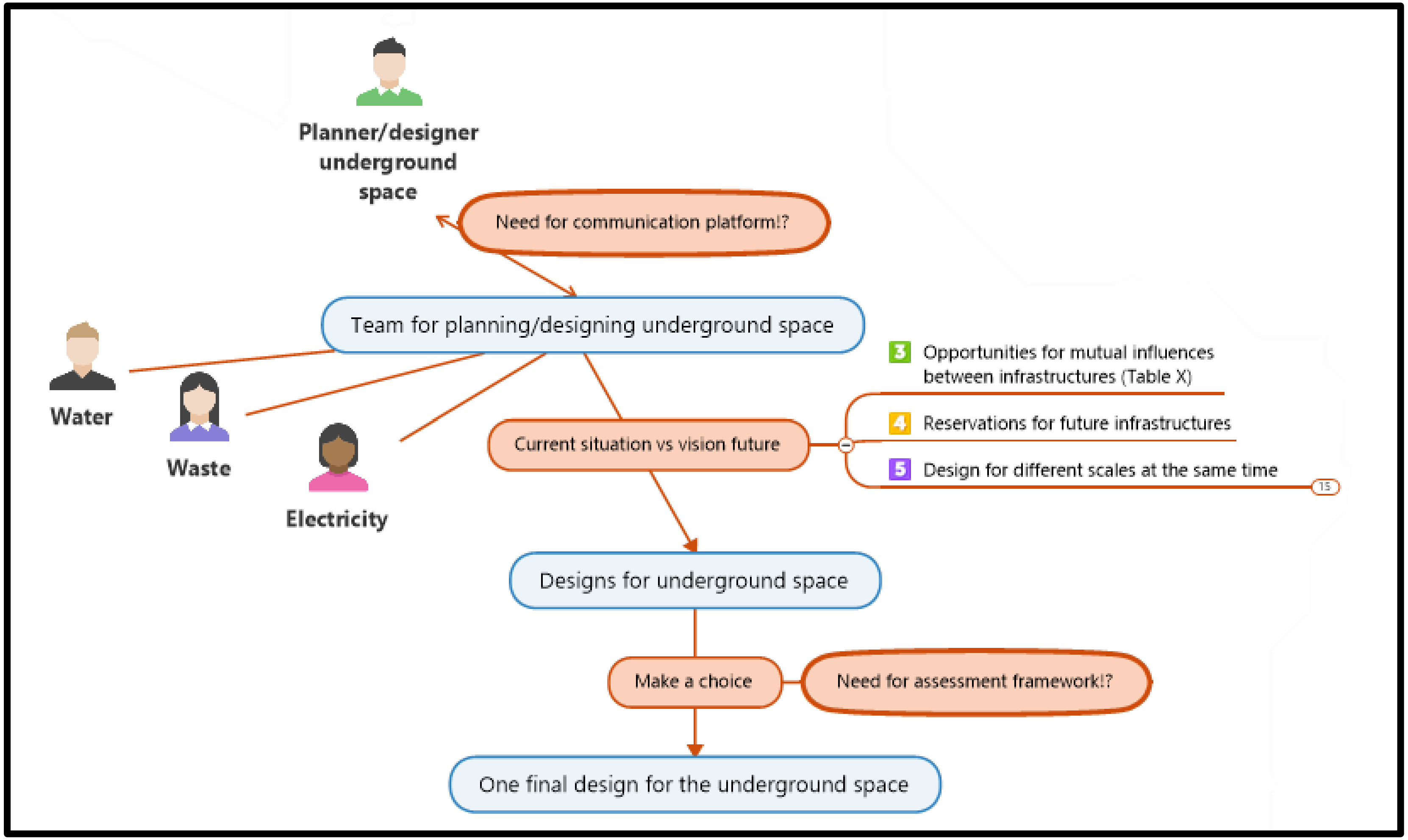


Figure 11: Team for planning/designing of underground space coming to a final design for the underground space, by 3) finding opportunities for mutual influences between infrastructures (Table 2), 4) considering reservations of underground space for future infrastructures and 5) making designs based on different scales analyzed at the same time.

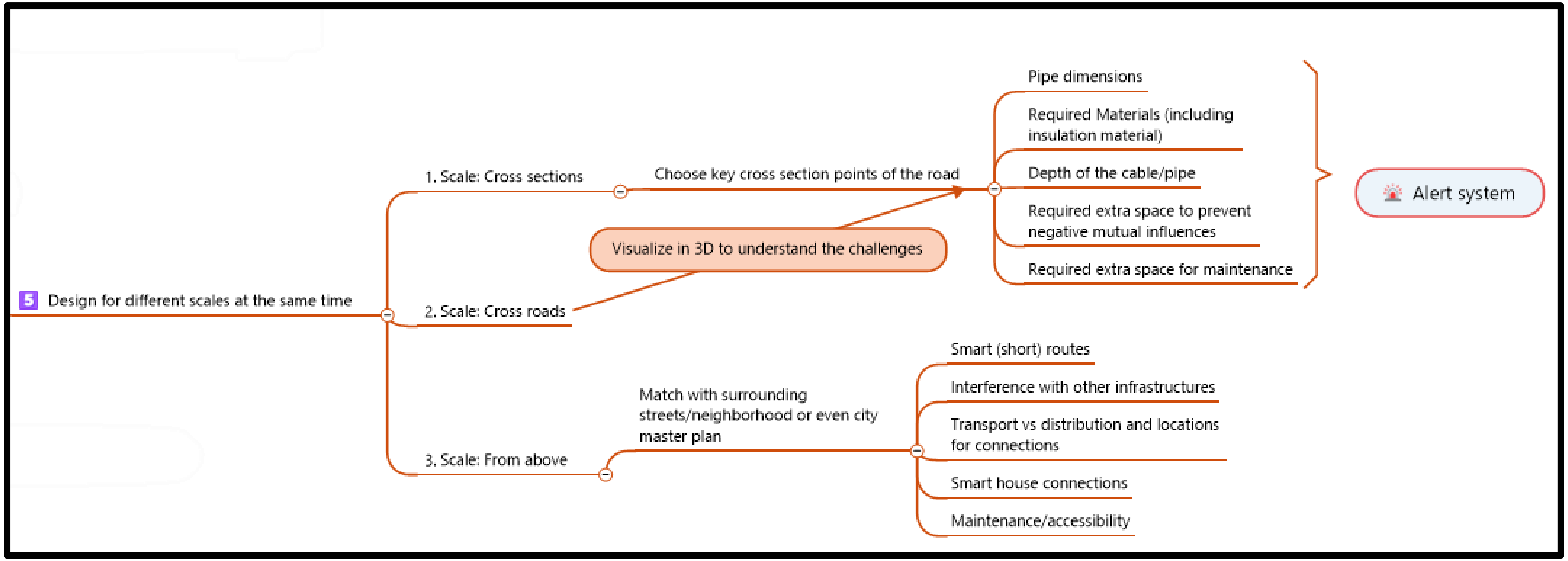


Figure 12: Zooming in on step 5, three different scales can be identified: 1) cross sections of the road, 2) cross roads and 3) from above.

4 Conclusion

No tools or models are being used for an integrated planning of UUI. There is one protocol though: the Dutch NEN 7171-1 norm, used for the integrated planning of UUI. Implications with this protocol are: 1) it is solely based on a horizontal planning of UUI, 2) no recommended distances are given between infrastructures of different themes 3) not all UUI are mentioned and 4) influence from heat infrastructures on drinking water is mentioned, but not specified.

Table 2 presents an overview of the main technical constraints and opportunities for different infrastructures with regard to their space demand or location in the underground. The main upcoming underground space demanding transition, mentioned by experts, is the district heating system. Although it is uncertain to what extend it will replace or supplement the gas infrastructures since hydrogen gas is an emerging heat carrier that is thought of as capable of replacing natural gas. Thereby, the effect of heat on green and other infrastructures such as drinking water is unknown, which is an important and yet uncertain factor for the planning process. Then, new sanitation will ask for a new kind of infrastructure. More different pipes for the separation of sanitary water streams, with smaller diameters are expected. Also, the UVWC system will take up underground space. Not only horizontally, based on the diameter of the system, but also vertically, due to the required manholes at each bend in the system.

Space demand for arrangement, including finding synergies, and maintenance are easily overlooked during the planning process. This is a missed opportunity, since some of those synergies may even save underground space. Table 2 presents some of the possible synergies between UUI.

Besides the technical characteristics of infrastructures, also space is required for accessibility to the infrastructure. Due to emerging and advancing inspection technologies, opening of roads for condition assessment is increasingly less needed. Although it is not yet known what type of condition assessment is being used or will be used for areas where new sanitation has been implemented, the trend for the water infrastructure from TBM to RCM, likely does not have a large effect on the planning of UUI. The repair and replacement of infrastructures on the contrary does often have an influence on the planning of UUI. High replacement costs, e.g. due to a deeper position of the UUI, will sometimes even lead to old infrastructures that will not be removed due to costs, making the underground even more crowded.

UUI transitions have influence on the demand for underground space. Technically, there is enough underground space to provide, if deeper layers are being used. However, mainly the costs seem to be limiting the feasibility of accessing those deeper layers and using this space. Thereby, other factors that may play a bigger role in the future besides costs can be the ecological value of underground space and the need for green. In order to keep the economic as well as the environmental costs low, steps should be taken to make the planning of UUI significantly more efficient.

Reservations of space for future infrastructures are often not included during the planning process. While not only reservations in the underground, but also inside buildings are of importance due to the increasing pressure on space demand emerging with the upcoming UUI transitions.

5 Recommendations

Due to the explorative character of this thesis, multiple recommendations have been established. The recommendations are divided and directed to the different actors and are summarized in Figure 9.

5.1 Planners/designers of underground space

First of all, a well-organized communication platform for infrastructure providers and planners of underground space may help to save time and effort. Also, it may increase the understanding of the needs and tensions from infrastructure providers between themselves and between the planners and the providers. The synergy table as presented in paragraph 3.2.2 could very well be part of this communication platform, encouraging to incorporate all the opportunities where different infrastructures can benefit from each other.

Then, it is recommended to consider reservations for future infrastructures. Although the actual demand of space is not yet clear, the opportunity to reconsider the integral planning of infrastructures together with the energy transition is there right now. When more space appeared to be reserved than required, this space can very well be used for water retention and biodiversity goals. Until there is more certainty about the influence of district heating on drinking water, green and other infrastructures, it is recommended to reserve extra buffer space where possible.

At last, it is recommended to think of criteria, on which different planning scenarios could be assessed. A consultancy company could be asked to create an assessment framework based on those criteria. With an assessment framework, decisions made about the final planning of the UUI can be made with better consideration behind.

5.2 Infrastructure providers

For infrastructure providers it is recommended to relook at their own role in the current system and how it might change with the upcoming UUI transitions. First of all, with the increase of more decentralized systems more focus should come on the infrastructures within buildings and the house connections to the street.

Also, using standard planning methods is not feasible for each street. The communication platform may be a good way to show the upcoming concerns and the influences of certain measures for the utility companies. At last, an improved system for data management for UUI is recommended. When all data available about UUI is precise and reliable, the risks for excavation damage are also expected to decrease.

5.3 Policy makers

Policy makers are already working on improving the current NEN 7171-1 protocol, used for integral planning of UUI. This thesis provides some recommendations that may contribute to this process. First of all, include more vertical planning in the new protocol. Though also look into ways to really include reservations of space and the obligation to remove old infrastructures when they become out of use. This should be included in such a way that costs are evenly shared. Another recommendation is to look ahead and incorporate the infrastructures that are currently emerging, such as the UVWC system, and their influence on other infrastructures.

It should also be emphasized that improving the NEN 7171-1 protocol will very likely not solve all the problems related to the integral planning of UUI. Therefore, policy makers could contribute to the realization of the model to quantify the space demand and supply and also to the communication platform. Since the policy makers are expected to know what steps are missing in the protocols and should be arranged elsewhere.

At last, an opportunity for the data management of UUI could be the Madaster. Madaster is an online platform that serves as a library for materials of the build environment and would like to expend to underground infrastructures including cables and pipes (Madaster, 2019). By combining the Madaster with the currently used Kadaster which registers the locations of UUI, a valuable tool may emerge.

5.4 Research institutions

For research institutions multiple recommendations are suggested. First of all, a model or tool could be established to quantify space supply and demand. A set-up for such a tool can be found in appendix IV. The tool could screen out certain unrealistic planning scenarios at the start. For example, if horizontal planning of infrastructures is possible or if alternative solutions should be investigated.

Second, there seems to be a need for an integrated planning method to find an optimal planning for UUI for different scales at the same time. It used to be enough to do this for infrastructures separately, but the upcoming transitions, the lack of underground space and the increased awareness of mutual influences take this challenge to a whole new level of complicatedness.

Thirdly, the sustainability of the UVWC systems is not yet clear. The few researches that have been done about this upcoming system and the comparison to the truck-based collection system, are sometimes contradicting each other and findings about improved separation seem to be questionable. Research on the economic, as well as social and environmental impact of the system and the influence on the quality of the waste streams is therefore recommended.

Also, a recommendation is given about the need to find more synergies between UUI. For example, finding out where synergies occur between (soil) biodiversity and UUI. Since increased biodiversity may lead to more resilient green areas. Possibly synergies can be found with help of bio-mimicry.

At last, it is recommended to collaborate with the COB for researches about UUI. A lot of knowledge and practical experience is gathered at this network organization, which can be valuable as basis for new researches.

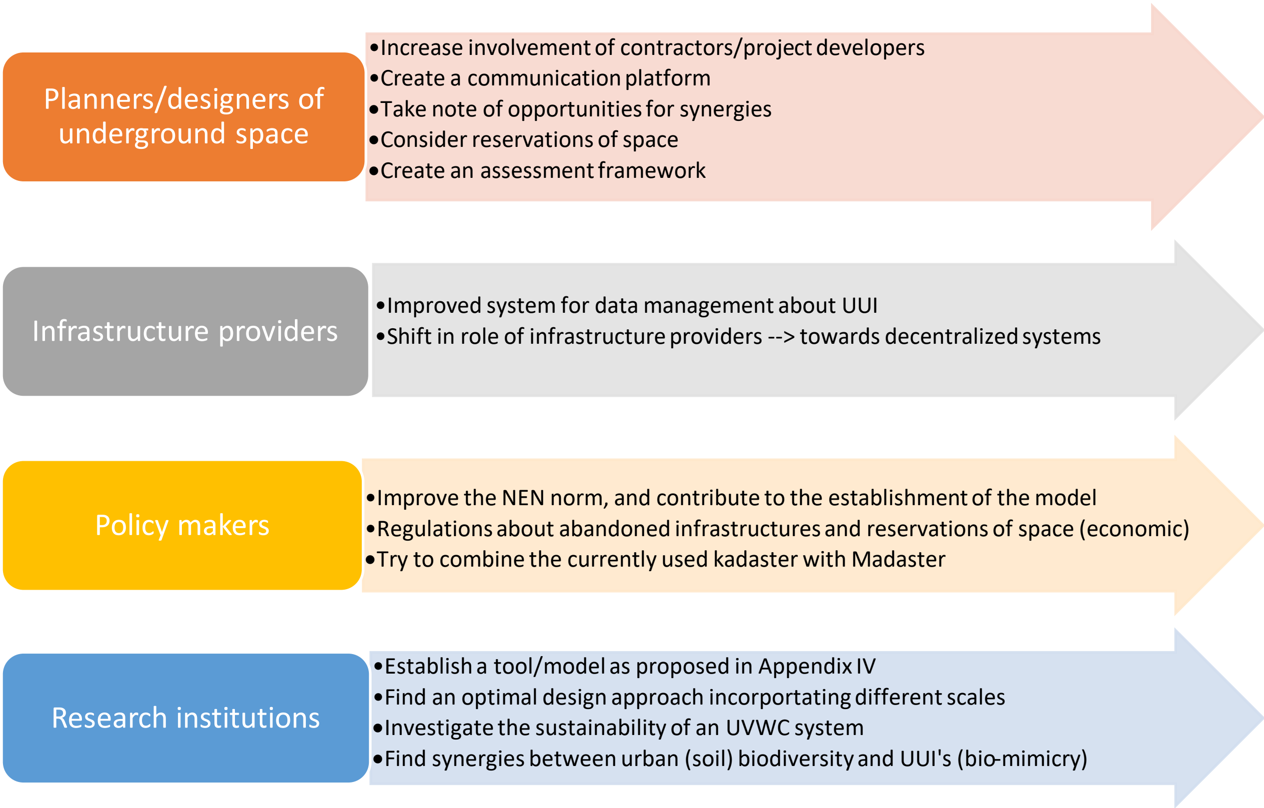


Figure 13: Recommendations based on the findings of this thesis

Bibliography

Abbas, A., Ruddock, F., Alkhaddar, R., Rothwell, G., Carnacina, I., & Andoh, R. (2019). Investigation of the structural performance of two flexible pipes set in one trench with a new placement method for separate sewer systems. *Tunnelling and Underground Space Technology, 92*. doi:10.1016/j.tust.2019.103019

Agudelo-Vera, C., & Blokker, M. (2019). Drinkwater en temperatuur: niet te koud, niet te warm, maar precies goed. Retrieved from https://www.kwrwater.nl/projecten/drinkwater-klimaatbestendig-nu-en-in-de-toekomst/

Agudelo-Vera, C. M., Blokker, M., de Kater, H., & Lafort, R. (2017). Identifying (subsurface) anthropogenic heat sources that influence temperature in the drinking water distribution system. *Drinking Water Engineering and Science, 10*(2), 83-91. doi:10.5194/dwes-10-83-2017

Akpan, P. U., Jones, S., Eke, M. N., & Yeung, H. (2017). Modelling and transient simulation of water flow in pipelines using WANDA Transient software. *Ain Shams Engineering Journal, 8*(3), 457-466. doi:10.1016/j.asej.2015.09.006

Alim, M. A., Rahman, A., Tao, Z., Samali, B., Khan, M. M., & Shirin, S. (2020). Suitability of roof harvested rainwater for potential potable water production: A scoping review. *Journal of Cleaner Production, 248*. doi:10.1016/j.jclepro.2019.119226

Bartel, S., & Janssen, G. (2016). Underground spatial planning – Perspectives and current research in Germany. *Tunnelling and Underground Space Technology, 55*, 112-117. doi:10.1016/j.tust.2015.11.023

Belmeziti, A., Cherqui, F., & Kaufmann, B. (2018). Improving the multi-functionality of urban green spaces: Relations between components of green spaces and urban services. *Sustainable Cities and Society, 43*, 1-10. doi:10.1016/j.scs.2018.07.014

Bosch, J., & Broere, W. (2011). *The urgent need for physical planning of the Underground in the Netherlands*. Paper presented at the World Tunnel Congress and 37th General Assembly, Helsinki.

CBS. (2018). *Groeiers buiten de Randstad*. Retrieved from Den Haag:

CBS. (2019). Gemeentelijke afvalstoffen; hoeveelheden. Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83558NED/line?dl=FB58&ts=1578410921388

Chàfer, M., Sole-Mauri, F., Solé, A., Boer, D., & Cabeza, L. F. (2019). Life cycle assessment (LCA) of a pneumatic municipal waste collection system compared to traditional truck collection. Sensitivity study of the influence of the energy source. *Journal of Cleaner Production, 231*, 1122-1135. doi:10.1016/j.jclepro.2019.05.304

Chang, S. E. (2009). *Infrastructure Resilience to Disasters*. Retrieved from

COB. (2017a). Buizenpost voor Almeers afval. Retrieved from https://www.cob.nl/magazines-brochures-en-nieuws/verdieping/verdieping-sept2017/ondergronds-verblijven/buizenpost-voor-almeers-afval/

COB. (2017b). *COB Evaluatie mantelbuizenputconstructie*. Retrieved from

COB. (2018). Convenant Rotterdam: graafrust, kostenreductie en minder hinder. Retrieved from https://www.cob.nl/magazines-brochures-en-nieuws/verdieping/september-2018/kabels-en-leidingen/convenant-rotterdam/

COB. (2019a). *COB_Common-ground-ondergrondse-infra_Cahier-12april2019*. Retrieved from Delft:

COB. (2019b). Zo werkt het COB. In COB (Ed.).

Curiel-Esparza, J., & Canto-Perello, J. (2013). Selecting utilities placement techniques in urban underground engineering. *Archives of Civil and Mechanical Engineering, 13*(2), 276-285. doi:10.1016/j.acme.2013.02.001

Delmastro, C., Lavagno, E., & Schranz, L. (2016). Underground urbanism: Master Plans and Sectorial Plans. *Tunnelling and Underground Space Technology, 55*, 103-111. doi:10.1016/j.tust.2016.01.001

Erhorn, H., Görres, J., Illner, M., Bruhn, J.-P., & Bergmann, A. (2018). NeckarPark Stuttgart, District heat from wastewater. *Energy Procedia, 149*, 465-472.
Gray, N. F. (2010). *Water Technology*: Elsevier.
Hao, T., Rogers, C. D. F., Metje, N., Chapman, D. N., Muggleton, J. M., Foo, K. Y., . . . Saul, A. J. (2012). Condition assessment of the buried utility service infrastructure. *Tunnelling and Underground Space Technology, 28*, 331-344. doi:10.1016/j.tust.2011.10.011
Hidalgo, D., Martín-Marroquín, J. M., Corona, F., & Juaristi, J. L. (2018). Sustainable vacuum waste collection systems in areas of difficult access. *Tunnelling and Underground Space Technology, 81*, 221-227. doi:10.1016/j.tust.2018.07.026
Hunt, D. V. L., Nash, D., & Rogers, C. D. F. (2014). Sustainable utility placement via Multi-Utility Tunnels. *Tunnelling and Underground Space Technology, 39*, 15-26. doi:10.1016/j.tust.2012.02.001
Johan Cruijff ArenA. Mission Statement Johan Cruijff ArenA. Retrieved from https://www.johancruijffarena.nl/organisatie/organisatie.htm
Joseph, A. P., Keller, J., Bustamante, H., & Bond, P. L. (2012). Surface neutralization and H(2)S oxidation at early stages of sewer corrosion: influence of temperature, relative humidity and H(2)S concentration. *Water Res, 46*(13), 4235-4245. doi:10.1016/j.watres.2012.05.011
Kennisportaal Ruimtelijke Adaptatie. Infoworks ICM. Retrieved from https://ruimtelijkeadaptatie.nl/hulpmiddelen/infoworks-icm/
Korthals Altes, W. K. (2019). Planning initiative: Promoting development by the use of options in Amsterdam. *Land Use Policy, 83*, 13-21. doi:10.1016/j.landusepol.2019.01.025
Kumar, R. (2014). *Research methodology*. London: SAGE.
Madaster. (2019). ONTWIKKELING VAN MADASTER. Retrieved from https://www.madaster.com/nl/ons-aanbod/roadmap
Maring, L., & Blauw, M. (2018). Asset management to support urban land and subsurface management. *Sci Total Environ, 615*, 390-397. doi:10.1016/j.scitotenv.2017.09.109
Ministerie van Economische Zaken. (2016). *Energieagenda-2016*. Retrieved from Den Haag:
Ministerie van Infrastructuur en Waterstaat. (2016). Rijksbrede programma 'Nederland circulair in 2050'. Retrieved from https://www.afvalcirculair.nl/onderwerpen/beleid-circulaire/rijksbreed-programma/
Ministerie van Infrastructuur en Waterstaat & Ministerie van Economische Zaken en Klimaat. (2018). *Structuurvisie-ondergrond*. Retrieved from Den Haag:
Municipality of Amsterdam. (2017). ArenAPoort & Amstel III. In. Amsterdam: Municipality of Amsterdam.
Municipality of Amsterdam. (2018). *Methode integrale aanpak openbare ruimte*. Retrieved from Amsterdam:
Open. (2017). Non-revenue water management, the challenge facing water and sewage companies. Retrieved from https://www.openintl.com/non-revenue-water-management-the-challenge-facing-water-and-sewage-companies/
Poortvliet, P. M., Sanders, L., Weijma, J., & De Vries, J. R. (2018). Acceptance of new sanitation: The role of end-users' pro-environmental personal norms and risk and benefit perceptions. *Water Res, 131*, 90-99. doi:10.1016/j.watres.2017.12.032
Project group Arenapoort. (2019). *Startnotitie_ontwikkelstrategie_arenapoort_mei_2019_lr_1*. Retrieved from Amsterdam:
Punkkinen, H., Merta, E., Teerioja, N., Moliis, K., & Kuvaja, E. (2012). Environmental sustainability comparison of a hypothetical pneumatic waste collection system and a door-to-door system. *Waste Manag, 32*(10), 1775-1781. doi:10.1016/j.wasman.2012.05.003
Schneider, J., Gaul, A. J., Neumann, C., Hogräfer, J., Wellßow, W., Schwan, M., & Schnettler, A. (2006). Asset management techniques. *International Journal of Electrical Power & Energy Systems, 28*(9), 643-654. doi:10.1016/j.ijepes.2006.03.007

Senevirathna, S., Ramzan, S., & Morgan, J. (2019). A sustainable and fully automated process to treat stored rainwater to meet drinking water quality guidelines. *Process Safety and Environmental Protection, 130*, 190-196. doi:10.1016/j.psep.2019.08.005

Stedin. SAMEN WERK MAKEN VAN EEN LEEFWERELD VOL NIEUWE ENERGIE. Retrieved from https://www.stedin.net/over-stedin

Sterling, R., Admiraal, H., Bobylev, N., Parker, H., Godard, J.-P., Vähäaho, I., . . . Hanamura, T. (2012). Sustainability issues for underground space in urban areas. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning, 165*(4), 241-254. doi:10.1680/udap.10.00020

Stones, P., & Heng, T. Y. (2016). Underground Space Development Key Planning Factors. *Procedia Engineering, 165*, 343-354. doi:10.1016/j.proeng.2016.11.709

STOWA. (2011). *Deugd_duurzame_energie_uit_geconcentreerde_strome-hydrotheek_(stowa)*. Retrieved from Amersfoort: https://edepot.wur.nl/189780

Teerioja, N., Moliis, K., Kuvaja, E., Ollikainen, M., Punkkinen, H., & Merta, E. (2012). Pneumatic vs. door-to-door waste collection systems in existing urban areas: a comparison of economic performance. *Waste Manag, 32*(10), 1782-1791. doi:10.1016/j.wasman.2012.05.027

Vähäaho, I. (2014). Underground space planning in Helsinki. *Journal of Rock Mechanics and Geotechnical Engineering, 6*(5), 387-398. doi:10.1016/j.jrmge.2014.05.005

van den Hurk, B., Tank, A. K., Lenderink, G., Ulden, A., Oldenborgh, G. J., Katsman, C., . . . Drijfhout, S. (2007). New climate change scenarios for the Netherlands. *Water Sci Technol, 56*(4), 27-33. doi:10.2166/wst.2007.533

Volkova, A., Mašatin, V., & Siirde, A. (2018). Methodology for evaluating the transition process dynamics towards 4th generation district heating networks. *Energy, 150*, 253-261. doi:10.1016/j.energy.2018.02.123

von der Tann, L., Sterling, R., Zhou, Y., & Metje, N. (2019). Systems approaches to urban underground space planning and management – A review. *Underground Space*. doi:10.1016/j.undsp.2019.03.003

Wang, M., Deng, Y., Won, J., & Cheng, J. C. P. (2019). An integrated underground utility management and decision support based on BIM and GIS. *Automation in Construction, 107*. doi:10.1016/j.autcon.2019.102931

Wang, T., Tan, L., Xie, S., & Ma, B. (2018). Development and applications of common utility tunnels in China. *Tunnelling and Underground Space Technology, 76*, 92-106. doi:10.1016/j.tust.2018.03.006

Waternet. (2016). *Gemeentelijk-rioleringsplan-amsterdam-2016-2021*. Retrieved from Amsterdam:

Waternet. (2019). Nieuwe sanitatie. Retrieved from https://www.waternet.nl/innovatie/co2-reductie/nieuwe-sanitatie/

Yoonus, H., & Al-Ghamdi, S. G. (2020). *Environmental performance of building integrated grey water reuse systems based on Life-Cycle Assessment: A systematic and bibliographic analysis*. Sci Total Environ. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/31931201

Zeeman, G. (2012). *New sanitation bridging cities and agriculture*. Retrieved from Wageningen:

Appendix I: Experts per category with abbreviation

Table 5: The experts per institution divided into three groups

Function and company	Category	Interview or meeting	Abbreviation (Abr.)
Senior Asset Manager (SAM) Water Chain at Waternet	**Infrastructure provider (I)** Urban underground planner/designer (U) Engineer (E) Designer of public space (D)	Personal interview on November 14, 2019	I, SAM, Water
Hydraulic Analyst (HA) at Waternet	**Infrastructure provider (I)** Urban underground planner/designer (U) Engineer (E) Designer of public space (D)	Personal interview on November 14, 2019	I, HA, Water
Strategic consultant (SC) waste chain at Municipality of Amsterdam, department: Waste & Resources	**Infrastructure provider (I)** Urban underground planner/designer (U) Engineer (E) Designer of public space (D)	Personal interview on November 4, 2019	I, SC, Waste
Head of executive team waste (HEW) at Municipality of Almere	**Infrastructure provider (I)** Urban underground planner/designer (U) Engineer (E) Designer of public space (D)	Personal interview on December 2, 2019	I, HEW, Waste
Consultant cables and pipes (CCP), management underground at Municipality of Rotterdam Engineering Bureau	Infrastructure provider (I) **Urban underground planner/designer (U)** **Engineer (E)** Designer of public space (D)	Personal interview on November 18, 2019	UE, CCP
Senior Consultant Water, Soil and Climate (CWSC) at Municipality of Rotterdam Engineering Bureau	Infrastructure provider (I) **Urban underground planner/designer (U)** **Engineer (E)** Designer of public space (D)	Personal interview on November 18, 2019	UE, CWSC
Project manager (PM) and Technical advisor	Infrastructure provider (I)	Personal interview on December 6, 2019	UE, PM/TA

(TA) at Municipality of Amsterdam Engineering Bureau	**Urban underground planner/designer (U)** **Engineer (E)** Designer of public space (D)		
Project Leader Urban Soil and Water Management (USWM) at Deltares	Infrastructure provider (I) **Urban underground planner/designer (U)** Engineer (E) Designer of public space (D)	Personal interview on December 9, 2019	U, USWM
Senior designer of public space (DPS) and landscape architect (LA) at Municipality of Amsterdam	Infrastructure provider (I) Urban underground planner/designer (U) Engineer (E) **Designer of public space (D)**	Personal interview on January 15, 2020	D, DPS/LA
Landscape architect (LA) at Municipality of Amsterdam	Infrastructure provider (I) **Urban underground planner/designer (U)** Engineer (E) **Designer of public space (D)**		UD, LA
Urban designer (UD) and architect (A) at Municipality of Amsterdam	Infrastructure provider (I) **Urban underground planner/designer (U)** Engineer (E) **Designer of public space (D)**		UD, UD/A

Appendix II: Observations of meetings

Table 6: Meetings attended by the author

Name	Abr.	Date	Location	Content
Connect Opportunities (Koppel kansen) Haaksbergweg	CO1	18-09-19	Municipality of Amsterdam	Meeting between the infrastructure planners of the municipality and the infrastructure providers. Electricity and water infrastructure providers were there. Planners explained the situation/ideas and the providers reacted on the plans and explained the obstacles. Focus: the way underground is included in the planning process, how will it fit the space: which infra can be merged or removed, what increase is expected?
Integral session with IB	IB	30-09-19	Municipality of Amsterdam	The plans for Haaksbergweg were shown to people from the engineering bureau (IB) of Amsterdam. A discussion was formed about the practicability of the design.
Shift, surface/subsurface as prerequisite for designing and ambitions	SS	03-10-19	Central Library of Rotterdam	Organized by platform bodembeheer (soil managment). The session was meant to connect people from all different fields of work connected to the underground use of space: policy makers, consultants but also infrastructure providers. The focus was the required shift, to work in a fundamentally different way with the underground space.
Koppel kansen Haaksbergweg	CO2	09-10-19	Municipality of Amsterdam	Meeting between the infrastructure planners of the municipality and the infrastructure providers. Electricity and water infrastructure providers were there. Planners explained the situation/ideas and the providers reacted on the plans and explained the obstacles. Different themes were discussed this time. Focus: discussion about location infra and use of utility boxes.
Background information from water infra providers	BIW	30-10-19	Head Office of Waternet	Insight in the pipes from Waternet, where are they located and what can change?
Full under surface (Vol onder maaiveld)	FUS	01-11-19	Delft	Organized by the COB. A meeting with about 120 professionals from the work field. About 20 people presented their idea/solution to the lack of underground space. After this there was a poster market where the different professionals could talk to the idea pitchers. People were divided into 6-8 groups and small sessions were held to deepen out the initial ideas.
Broader Session about planning of underground	BS	21-11-19	Municipality of Amsterdam	Municpality and infrastructure providers from almost all infrastructures (water, data, electricity, heat). The results of two different

infrastructure in Amsterdam (PVO)				sets of interviews were discussed: technical and governance. Afterwards one group made an underground profile for a street which led to new questions and discussion points. The other group discussed the governance part in more detail.
Koppel kansen Haaksbergweg	CO3	21-11-19	Municipality of Amsterdam	Only Liander was represented of the infrastructure providers. Therefor the discussion went about the electricity and the use of MUT or smaller utility boxes.
New Sanitation	NS	28-11-19	Hoeve	Meeting with many people from the water/sanitation field of work. At the border of the Netherlands and Belgium. Many different topics were discussed about new sanitation and also the future of new sanitation was discussed.
Koppel kansen Haaksbergweg	CO4	15-01-20	Municipality of Amsterdam	Three draft designs of the street intersection of Haaksbergweg were presented. Only Waternet was present from the infrastructure providers and a public space designer.
Bio-mimicry, Sweco	BM	17-01-20	Sweco, de Bilt	Brainstorm day with people from different municipalities, and companies/engineering bureaus about the application of bio-mimicry in the field of underground infrastructures.

Appendix III: Interview questions format

Introduction

Thank you very much for participating in this research.
I am a master student from Wageningen University, and specializing in the direction of urban systems engineering. For the department of Environmental Technology, I am investigating the space demand of underground infrastructures in dense urban areas. During this interview some questions will be asked concerning the planning of underground infrastructures from your expert point of view. The answers of this interview will be processed in the thesis report and will be handled with strict confidentiality. The final report will be shared with the department R&D of the Municipality of Amsterdam, with third parties that also gave input by means of interviews (Deltares, Waternet, Municipality of Almere, Municipality of Rotterdam) and with Wageningen University.

Aim of this research

The aim of this research is to **see if there is enough urban underground space for transitioning infrastructures of redevelopment projects in dense cities such as Amsterdam**. This will be done by looking at three elements that might influence the demand of space either directly or via planning requirements: the capacity of the infrastructure, the arrangement constraints and the type and frequency of the asset management.

Questions per category:

Green: question for planners and providers
Yellow: question for planners
Blue: question for providers

Table: interview questions with desired outcome and justification of the question

Question	Desired outcome and justification of the question
Currently used tools and standards for urban underground planning of infrastructures	
1. What tools/guidelines/standards/norms do you use to support the infrastructure planning?	Number and names of tools and or standards to get insight in the range of tools and standards
2. What are the main limitations of these tools and standards? • Are infrastructure transitions incorporated?	Variety of limitations of the tools and standards and knowledge about the integration of infrastructure transitions, to assess where knowledge gabs and practical gabs lay in the current tools and standards.
Technical constraints	
3. What is the current situation of your infrastructure in your city (street level e.g. Haaksbergweg)? Infrastructure capacity/diameters, give room for other aspects.	Overview of the current underground space which is in use.
4. What infrastructure is in use? • Does it fulfill its purpose?	From this overview, highlighted the infrastructures that are not in use/ abandoned
5. What infrastructure can be re-used for other services?	From the highlighted infrastructure, an estimation of what can be re-used for which purpose.

6. What are the expected developments of (your) underground infrastructures?	Changed capacities of infrastructures or additional infrastructures that have to be implemented.
7. What arrangement constraints (buffer zones) are you working with? • Will this change?	Overview of buffer zones between certain infrastructures to see how this might influence the demand of space.
8. What other infrastructures might influence your infrastructure?	Additional information for logic of buffer zones and mutual influences
Challenges for asset management and use of MUT	
9. Is there a change in materials/design criteria's (slope, pipe capacity, etc.) that are being used for the infrastructures?	Current and possibly future use of different design criteria that might influence the demand of space, to see if the space demand changes.
10. What methods and technologies do you use for the condition assessment of the infrastructure? • Do you foresee a change in this in the (near) future?	Methods and technologies used for condition assessment and possible changes are relevant information to get more insight in the space demand for accessibility and in decision making about the applicability of MUT's.
11. What is the frequency of the condition assessment? Also, will this change?	Frequency of condition assessment to help assess whether a MUT is applicable.
12. What is the average life time of the infrastructure(s)?	Life time of infrastructure, also to help assess whether a MUT is applicable.
13. When and how is the maintenance requirement incorporated in the planning process? • Does the maintenance require more space and if so can you give an indication?	Insight in the planning process and in the possible extra space demand for maintenance of the infrastructure.
14. How do you incorporate developments throughout time with the planning of (your) infrastructures?	Insight in dimensioning of infrastructures and possible reservations of space.
15. Under what conditions would you recommend to implement (or would you like to join) a MUT?	Insight in the requirements for joining a MUT from different (infrastructure) perspectives
16. What type of MUT would you prefer and why?	Insight in the different types of MUT's linked to the different infrastructures
Planning support tool set-up	
17. What do you think of this tool set-up? • Relevance? • Content?	Feedback on tool set-up to adapt the current tool set-up and make it more useful/valuable

Finishing words
Thank you very much for participating in this research, you will receive a version of the final thesis.

Appendix IV: Underground infrastructure planning support tool set-up

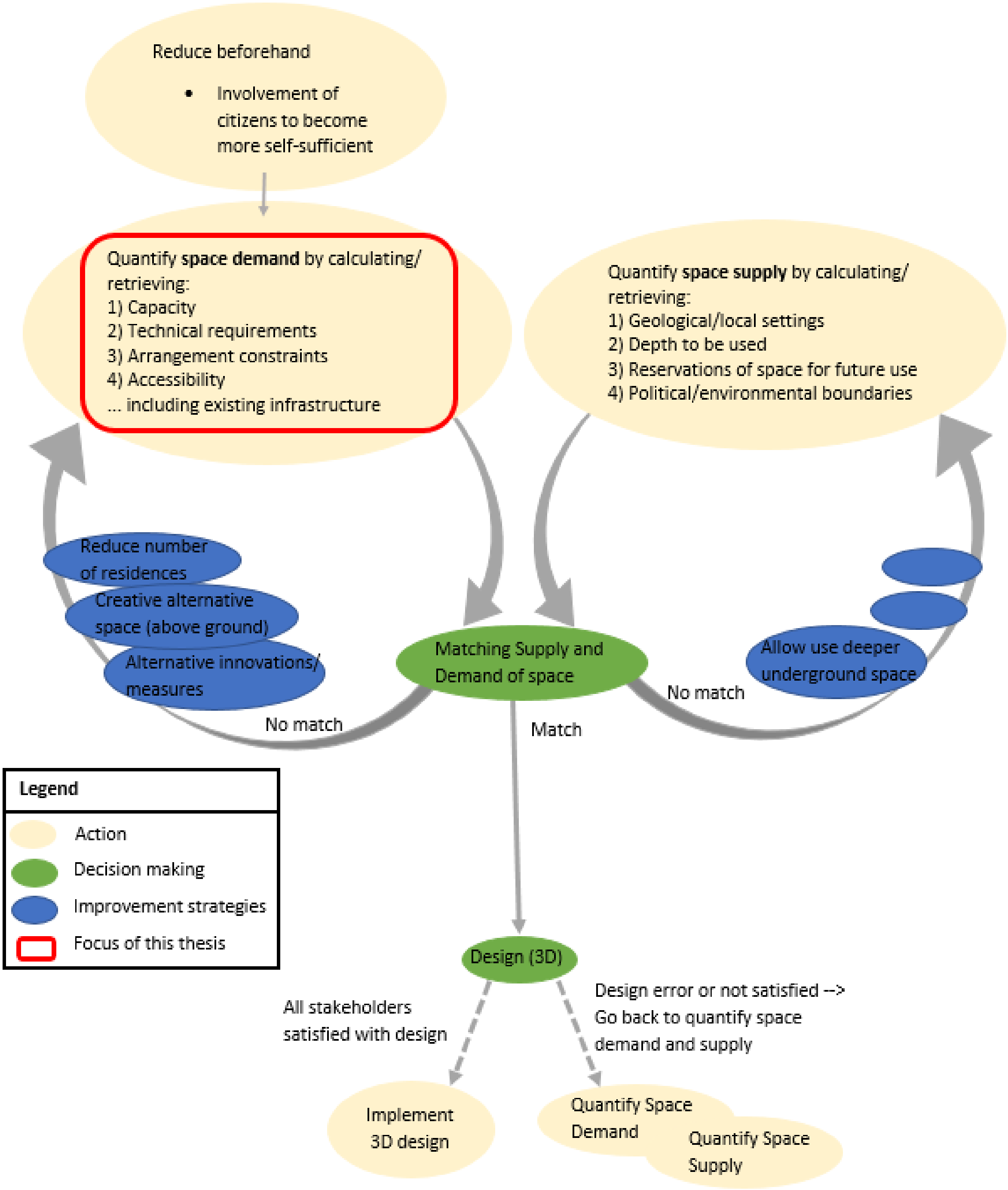


Figure 14: Tool set-up. In yellow the actions that should be taken: four steps for the demand of space, four steps for the supply of space and eventually the implementation of the 3D design. In green the decision making about the outcome of the match between supply and demand of space and about the outcome of the 3D design. In blue the improvement strategies that can be applied when no match between space supply and demand can be made. Also, the focus of this thesis is shown with the red box.

To tackle the spatial challenges for the integral planning of UUI, a tool can be made which helps with the planning and decision making of UUI. Figure X shows a possible set-up for such a tool. In here, the space supply is defined as the space available for accommodating UUI, while space demand refers to the space occupied by the UUI. For the quantification of space demand as well as space supply, multiple steps can be taken. To start with space supply, first of all, the planning of UUI is depending on the geological settings and local context (von der Tann et all., 2019). Those include the groundwater level, soil composition, slopes, local governance etc. and will mainly influence the **space supply** part. Also space reservations for future use and the depth that may be used will decrease the supply of space. At last, political and environmental boundaries may also influence the space supply.

The quantification of the **demand of space** also requires multiple steps to be taken. First of all, existing infrastructures demand space if they cannot be reused, replaced or removed. Second, new infrastructures or transitioning infrastructures will demand space on top of that. Not only the capacity of the cables and pipes that are needed to meet the maximum flowrate will demand underground space, also technical requirements, arrangement restrictions and accessibility can influence the space demand. With arrangement constraints, the space needed between certain infrastructures to prevent them from negatively influencing each other is meant. For example, drinking water pipes should not be placed in a certain range from a heat infrastructure to prevent health risks caused by increased microbial activity within drinking water due to the increased temperature (Agudelo-Vera et al., 2017).

However, before quantifying the demand of space, it would be best to prevent the demand of space where possible. This can be done by involving citizens and requesting their help for example, by retaining water in their own gardens or by reducing their waste production. Also without the help of citizens themselves, agreements can be made with contractors/project developers about the degree to which more decentralized systems can be applied.

The tool should be able to match the supply and demand of space and thereby incorporating all the above-mentioned space influencing elements. When enough space can be supplied to meet the demand, a design (3D) can be made. However, when there is not enough space to meet the demand, improvement strategies can be taken in order to either decrease the demand of space or, on the other side, increase the supply (Figure 1).

With improvement strategies on the space demand site, three potential strategies are included in this set-up (Figure 1). First of all, alternative measures and innovations can be applied e.g. pipe in pipe techniques. Another improvement strategy is to look for creative space above ground to release pressure from the underground, e.g. camouflage cables by putting them through hedges/trees. Eventually, the service demand could be revised too. Meaning, that the planned number of residences or other buildings should be decreased, leading to a decreased space demand for UUI.

At last, when a 3D design has been made and all stakeholders are satisfied with the design, the 3D design can be implemented gradually. However, if a design error occurred or not all stakeholders are satisfied with the design, the cycle of the tool should be repeated, starting with the quantification of space demand and supply.

The full lined red box shows the focus area of this thesis (Figure 1), for the qualitative investigation of space demand for transitioning infrastructures. This tool can eventually be used by planning practitioners to easily screen out certain site-specific scenario's.

Appendix V: Tools and protocols

Table 7: Evaluated tools and protocols, describing the aim of the tool/protocol, the extent to which space demand is being incorporated and the user as found by this study. Abbreviations: DWF: dry weather flow. RWD: Rain water drainage.

Tool/protocol	Aim	Space demand incorporation	User	Sources
Infoworks ICM	Predicting bottlenecks for the DWF and RWD infrastructure	Barely. The diameters are altered to see when bottlenecks occur. The diameter is therefore a variable and not an outcome.	Waternet	(Kennisportaal Ruimtelijke Adaptatie, n.d.; I, HA, Water, personal interview, November 14, 2019)
Wanda	E.g. pump and line sizing, flow distribution and operational control.	The software is able to make a hydraulic design for the water infrastructure.	Waternet	(Akpan et al., 2017; I, HA, Water, personal interview, November 14, 2019)
NEN 7171-1	Providing criteria for arrangement of infrastructures	Standard distances and guidelines for dimensions and buffer zones based on horizontal planning.	Municipality of Rotterdam	(NEN 7171-1; UE, CCP, personal interview, November 18, 2019)
Internal documents	Providing a standard for arrangement of infrastructures	Standard distances and guidelines for dimensions and buffer zones.	Waternet, Municipality of Rotterdam, Municipality of Amsterdam	(I, SC, Waste, personal interview, November 4, 2019; I, SAM, Water, personal interview, November 14, 2019)
Asset management system	Looking for optimal timing of infrastructure maintenance and replacement	Based on costs and lifetime of infrastructures, space demand often not included.	Probably all municipalities in the Netherlands use something like this	(U, USWM, personal interview, December 9, 2019)

Infoworks ICM

Infoworks ICM is hydraulic software which is being used by professionals at Waternet, a company that plans almost the whole sewer network in Amsterdam for the Municipality of Amsterdam. The software can be used for design and management of the water infrastructures (Kennisprotaal Ruimtelijke Adaptatie, n.d.). Both the dry weather flow (DWF) and the rainwater drain (RWD) are incorporated in Inforworks ICM. The database of the company itself is being used as input data for the software. When giving a certain input to the system and playing with the pipe diameters, bottlenecks can be found. Those bottlenecks are for example places where the water will exceed the ground level and cause flooding's (I, HA, Water, personal interview, November 14, 2019).

Currently, the sewer system should be able to deal with the standard curve**.** This curve represents a rain shower of 20 mm in one hour. The standard curve is needed to compare data between different cities. However, it is questionable if this curve is still suitable (I, HA, Water, personal interview, November 14, 2019). Since due to climate change, the intensity of rainfall events will increase (van den Hurk et al., 2007).

To see where the bottlenecks will occur with the standard curve, the diameters of the pipes are altered in Infoworks ICM. This way, the problems which occur at different pipe diameters will be found. This consideration, together with other considerations such as the water demand of the households results in the selection of a certain pipe diameter.

WANDA

At Waternet, WANDA is being used for pressurized water infrastructures (I, HA, Water, personal interview, November 14, 2019). The software is developed by Deltares, an independent institute for applied research for water and underground in the Netherlands. WANDA can be used for multiple purposes in different fields of work. Also, it can make an optimized hydraulic design for the infrastructure (Akpan et al., 2017), which is required since the exact dimensions of pressurized water infrastructure is more important for optimal use compared to a non-pressurized system.

Guidelines intern

For the waste sector in Amsterdam, guidelines are being followed. Guidelines are used instead of a framework to be more flexible in the planning since it is possible to deviate from a guideline. Many things are being decided quite subjective. This is needed because many things are being decided quite subjective and based on esthetic values. Furthermore, an assessment framework is being used, based on sustainability aims, costs, service, ambition for the public space, risks and flexibility (I, SC, Waste, personal interview, November 4, 2019).

Waternet also uses intern guidelines which are based on requirements set up by Rioned and Dutch norms (I, SAM, Water, personal interview, November 14, 2019). Rioned is a foundation and an umbrella organization in the Netherlands, focusing on sanitary water, rainwater and groundwater.

Other tools

For the waste sector in Amsterdam, simple tools and excel are being used to calculate the number of containers that are needed for a certain area and the locations (I, SC, Waste, personal interview, November 4, 2019, personal interview, November 4, 2019).

At Waternet in Amsterdam, next to Infoworks ICM and WANDA, also geographic information system (GIS) is sometimes used for the planning of infrastructures (I, HA, Water, personal interview, November 14, 2019).

Asset management system

Most municipalities use some kind of asset management system to plan their infrastructures for certain areas (U, USWM, personal interview, December 9, 2019). This asset management system is often based on criteria such as the lifetime of the infrastructures and the costs. For example, in Rotterdam there is a covenant between the municipality and the infrastructure providers. The idea is now that, ideally, only once in the 50 years the road has to be opened to replace most of the infrastructures. Then, the municipality can demand “excavation rest” for a certain period of time (UE, CCP, personal interview, November 18, 2019). With an asset management system however, the local conditions might be overlooked. For example, the type of soil might influence the life time, with a stronger soil type, the infrastructure network might have a longer lifetime then in a softer soil type (U, USWM, personal interview, December 9, 2019).

Appendix VI: Prior situation as basis for the management framework

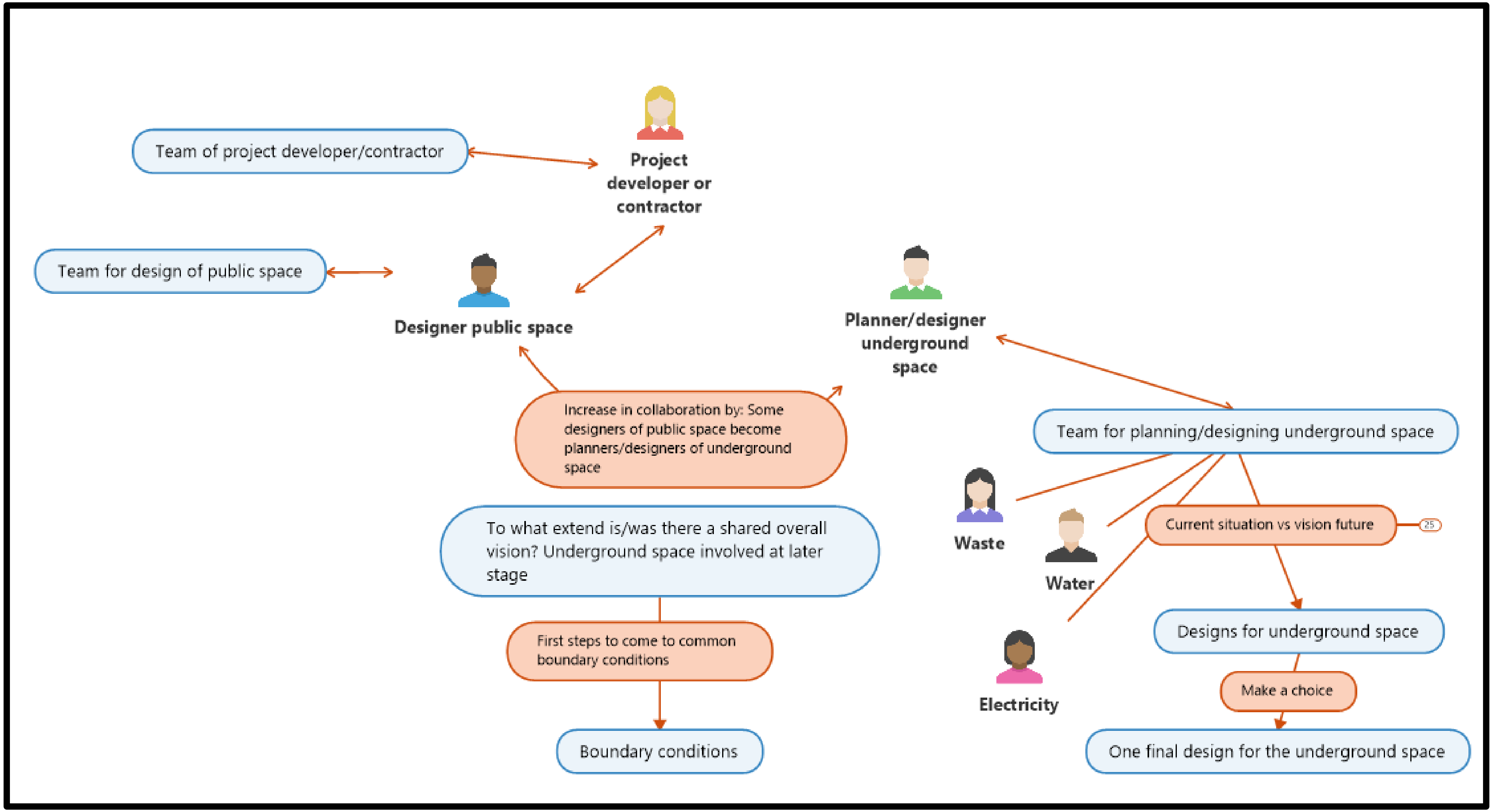


Figure 15: Prior collaboration of actors during the planning process of UUI

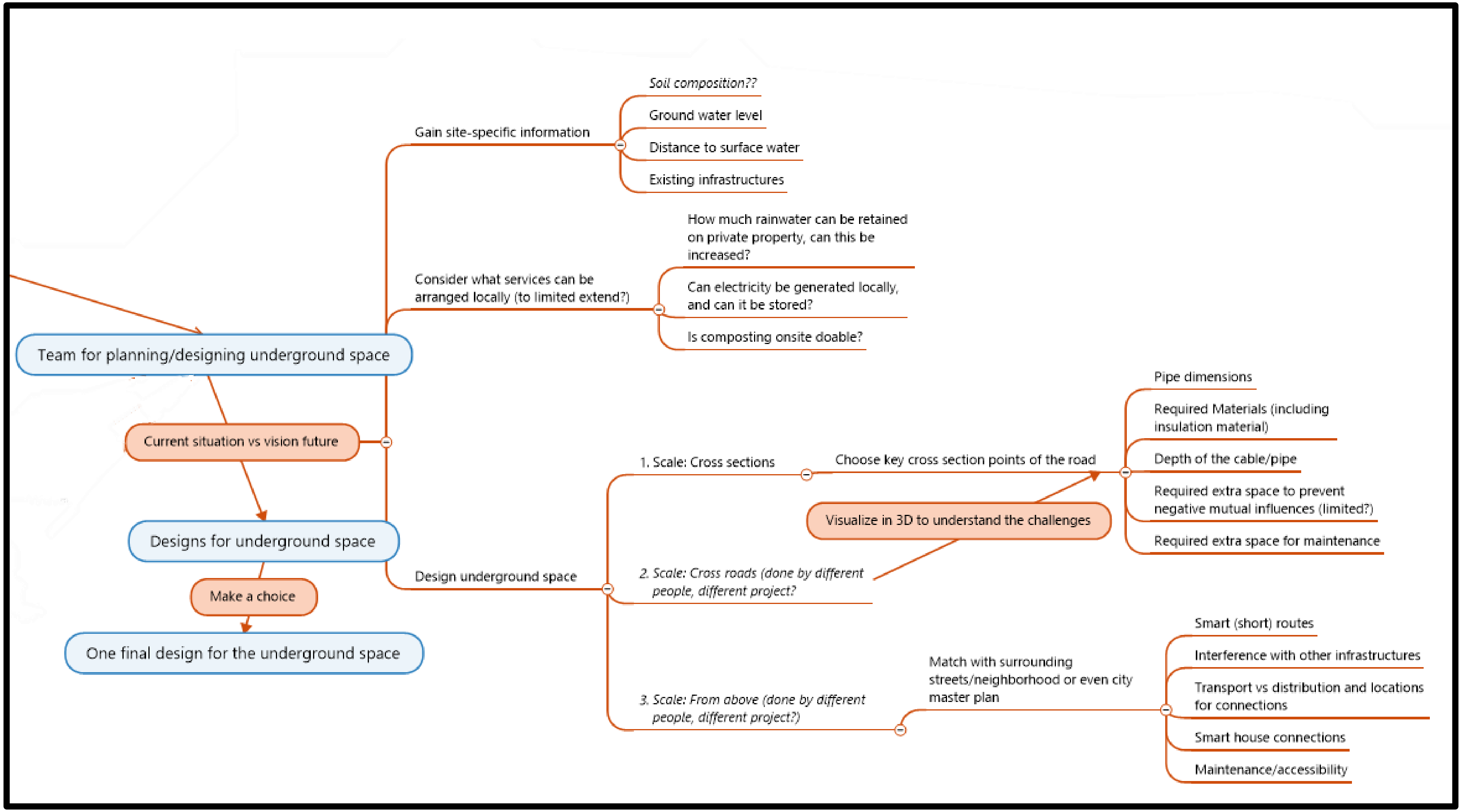


Figure 16: Prior steps taken during planning process of UUI