IMPROVED STRATEGIES, LOGIC AND DECISION SUPPORT FOR SELECTING TEST TRENCH LOCATIONS

PDEng Candidate: Paulina Racz
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PDEng Candidate
Author Paulina Racz
Organisation
University University of Twente
Faculty Engineering Technology (ET)
Department Construction Management & Engineering (CME)

Trajectory
Professional Doctorate in Engineering (PDEng)
Civil Engineering

Case study organisation
Agentschap Telecom

Information support companies
Kadaster, Enexis, WittevenBos, Baas bv, Van Gelder, Terra Carta, Heijmans, Liander

Examination Committee
Director PDEng programme Dr. drs. J.T. (Hans) Voordijk
Professor responsible chair Prof. dr. ir. A.G. (André) Dorée
Supervisor at University of Twente Dr. ir. M. (Marc) van Buiten
Supervisor at Agentschap Telecom RJ. (Robert-Jan) Looijmans
Expert from other research chair Dr. C. (Carl) Schultz

Report
Status Final

Date November, 2017
Preface

This project could not have been accomplished without the support of wonderful people who God put in my life. First of all, I would like to thank my supervisors at University of Twente, Prof.dr.ir André G. Dorée and dr.ir Marc van Buiten, as well as my company supervisors, Frank van Bree and Robert-Jan Looijmans at Agentschap Telecom for their thoughtful advices and recommendations. I would like to also express my gratitude to the experts who were the part of my Support Group and who shared with me their impressive knowledge and experience: Ad van Houtum (Kadaster), Roland Bakker and Rene Gerrits (Enexis), Bram van der Linde (Witteveen+Bos), Hans Lauwen (Baas bv), Harry Niland and Peter Hamersma (Agentschap Telecom), Harald Neimeijer (Van Gelder), Karel Meinen (Terra Carta), Peter Gerwen, Floris Konings and Maartijn Rademakers (Heijmans). I would like to also say a special thanks to all the companies that agreed to take part in the interviews and workshops. Without them it would not be possible to define the strategies currently used to locate test trenches and to identify the problems.

I am also grateful to all my colleagues and friends from the Construction Management and Engineering department. Some days were hard for me due to the amount of work, but, thanks to you, a smile always appeared on my face. Moreover, your work, projects and tasks were an incredible inspiration for me.

Mom, Dad and Grandma - without you, I would not achieve anything of that what I have done. You have always supported me, given me your encouragement and not let me give up. Thank you for that!

Especially, I would like to say thank you to my amazing boyfriend Pablo. He supported me in both the bad and good moments of my project. He wiped sorrow from my face when I was really stressed and was near me when I needed him. Thank you, my love!

The last, but not least, I would like to thank God for the power He gave me; power that did not let me give up and which encouraged me to look for solutions.
Management summary

Test trenches are the shallow trenches, which are dug to confirm the exact location of underground utilities (cables and pipes). Before breaking the surface, contractors and crews need to do a “KLIC request for information”. The relevant utility owners provide information about the existing underground networks for the specific location(s). Since several of these networks were buried a long time ago, the actual location may not match with the provided location data. To check the accuracy of the provided information, and to inspect the actual conditions, often require that test trenches are dug. While test trenches provide vital information, the digging and inspection of these test trenches takes time and effort and may even introduce added hindrances and risks. The selection of number and location(s), therefore, always requires trade-offs and compromises. Although digging of test trenches is a common practice, the reasoning regarding location(s) is mostly implicit, unclear and not well documented.

Interviews and workshops uncovered that companies follow a general path of locating test trenches such as analysing project’s and excavation site’s data, using ground scanning devises and computer support, applying best practices, such as locating test trenches at the end and beginning of excavation polygon, locating test trenches on utilities intersections and path changes, or checking the area up to 1.5m from excavation site. Nevertheless, behind of all of those strategies, there is the decision-makers’ experience, which plays a significant role in the test trench decision-process. The new situations they face on construction sites raised their awareness and increase their knowledge. As a result, they locate test trenches in places in ways that less experienced decision-makers would not.

Construction projects are becoming more and more complex. Thus, it is challenging for engineers to deal with large amounts of data; especially when many contractors are involved. Furthermore, time pressure often leads to inattentive risk assessment, which results later in many damages.

This report describes the steps I took to identify improving strategies, logic and decision support for selecting test trench location. For the final product, I evolved a functional specification of Decision Support System (DSS) and developed a prototype. The developed DSS is a self-learning tool. This means that users can feedback and influence calculations. The tool is based on careful risk assessment. It aims to assist and support decision-makers to locate test trenches, rather than to automate this location.

The system consists of four main elements: (1) Information database: this aims to support decision-makers in data selection, collection and aggregation, (2) Experience database: this aim to support knowledge and experience sharing between the decision-makers, influence risk calculation by improving an algorithm on users’ experience, (3) Problem-solving system: this conducts risk calculations, to generate a risk map and gather users’ feedback on proposed test trenches, (4) Project internal information sharing database: this supports information sharing between contractors involved in project, supports progress tracking and gathers information about test trench findings, damages and the situation facing users, which are subsequently sent to the experience database. The DSS is designed, not only for decision-makers (designers and contractors), but also for all other users involved in test trenches execution process, such
as job planners, machines operators or the network operators. The designed prototype does not include all elements described in the functional specification. However, it demonstrates an innovative way of test trench locations support and marks a direction towards the final product development.

The idea for a DSS have not appeared immediately in my head. During last two years I have studied many scientific literature, performed workshops, conducted interviews and followed many courses which helped me to improve both my knowledge and skills. Meanwhile, I had also participate in several conferences and took part in organizing symposia. All those activities allowed me to meet interesting and smart people, learn a lot from another projects and increase my level of professional maturity. The overview of the performed educational activities is attached to this report in appendix 1 whereas the steps I followed towards Decision Support System development and complementary activities are visualised in Figure 1 and described in Table 1.

Table 1. The description of the performed activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Short description</th>
<th>Lesson Learned</th>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject and Procedures studies</td>
<td>Includes studies of the legislation, guidelines and norms.</td>
<td>Increasing the procedural and legislation knowledge.</td>
<td>Chapter 1</td>
</tr>
<tr>
<td>DSS and literature studies</td>
<td>Includes studies of DSS, decision-making, excavation and excavation damages prevention, visualization techniques and analysis methods.</td>
<td>Increasing knowledge about the excavation, the decision-making, analysis methods and visualization.</td>
<td>Chapter 2</td>
</tr>
<tr>
<td>Interviews</td>
<td>Interviews were conducted in several construction and design companies. Includes also construction site visits.</td>
<td>Understanding the excavation procedures, uncovering the test trench location strategies and experiencing in practice how the test trenches are planned and dug. In addition, several problems were discovered and users’ needs were gathered.</td>
<td>Chapter 2.2</td>
</tr>
<tr>
<td><strong>Workshops with designers and contractors</strong></td>
<td>Two workshops were conducted in order to uncover strategies and define the logic behind made decisions.</td>
<td>Helped to uncovered logic behind test trench decision-making. In addition, understanding decision-makers’ mindset and gathering their requirements.</td>
<td>Chapter 2.2</td>
</tr>
<tr>
<td><strong>Collaboration with Lars Syfuss</strong></td>
<td>Collaboration with the student from the Muenster University. Based on provided data he developed first prototype of DSS.</td>
<td>Lars showed that it is possible to build automatized Decision Making System to locate test trenches. Lars work taught me a lot about using computer support.</td>
<td>Chapters 2.2 and 3.1</td>
</tr>
<tr>
<td><strong>Meetings with the Support Group</strong></td>
<td>Meetings with the group of experts: designers, contractors, job planners, network operators, data specialist and inspectors.</td>
<td>Members of the group supported me with their knowledge and experience during the design by providing me with their feedback and opinions. Finally, they participated in product verification and validation.</td>
<td>Chapters 1 and 4</td>
</tr>
<tr>
<td><strong>Design and Decision Support Systems Conference (DDSS)</strong></td>
<td>Conference took place in Eindhoven (The Netherlands). Conference paper: <em>To dig or not to dig: How to determine the number and location of test trenches.</em></td>
<td>While writing a paper I had learned a lot about analytical ways of analysing the decision-making process. I came also with major conclusions about currently used strategies. In addition I have learned about other projects.</td>
<td>Chapter 7: Appendix 5</td>
</tr>
<tr>
<td><strong>Naturalistic Decision Making (NDM) conference</strong></td>
<td>Conference took place in Bath (United Kingdom). Conference paper: <em>Naturalistic decision-making perspective on uncertainty reduction by civil engineers about location of underground utilities.</em></td>
<td>The conference helped me to better understand decision-makers behaviour. The studies of NDM directed me towards the idea of the tool which will assist and support users and make use of their knowledge and experience.</td>
<td></td>
</tr>
<tr>
<td><strong>International Workshop on Computing in civil Engineering (IWCCE) conference</strong></td>
<td>Conference took place in Seattle. Conference paper: <em>Decision Support System for Test Trench Location Selection with 3D Semantic Utility Model</em>”. It was a paper written together with Muenster University.</td>
<td>The papers summarized worked we made together with Lars Syfuss. Work done with Lars taught me a lot about computing in Civil Engineering and using new technologies to support decision-makers in taking important decisions.</td>
<td></td>
</tr>
<tr>
<td><strong>Blog innovatiemagazine Pioneering contribution</strong></td>
<td>Article: <em>To dig or not to dig? Improved strategies, logic and decision support for selecting test trench locations</em> was written for the Pioneering blog.</td>
<td>Writing the article helped me to summarized gathered information and gave an overview on made work. Moreover, it resulted in interesting comments from the practitioners.</td>
<td></td>
</tr>
<tr>
<td><strong>National Cable and Piping Conference (KLO)</strong></td>
<td>Presentation of my project. Representing ZoARG programme. Participating in workshops.</td>
<td>The conference helped to summarized made work. In addition, I had many interesting discussions with practitioners. I have also learned a lot, during workshops, about excavation damages prevention</td>
<td></td>
</tr>
<tr>
<td><strong>2nd ZoARG Symposium</strong></td>
<td>Participating in organizing the Symposium. Performing workshop with practitioners.</td>
<td>The symposium increased my confidence about made designed as it received many positive comments from practitioners. Moreover, using serious gaming techniques the designed was validated.</td>
<td></td>
</tr>
</tbody>
</table>
Product Summary

This chapter provides answers for the key questions related to the Decision Support System (DSS) for selecting test trench locations. The questions correspond to four aspects of the products, which will be recommended in PDEng study guide: (1) Artefact’s functionality, (2) Artefacts’ construction, (3) Artefacts’ realisation, and (4) Artefacts’ impact.

I. Artefact’s functionality aspects:
   - How will the artefact improve test trench locations decision-making?
   - Will proposed solutions satisfy the users’ requirements?
   - Will different users, with different level of education, be able to use the tool?
   - What is the goal of the tool? Can it also support other decision problems?

The designed prototype of the Decision Support System helps decision-makers in many aspects. First, it assists them in data collection by highlighting important factors that must be analysed, given their impact on increasing the risk of damage. Second, it supports data aggregation, so that decision-makers do not store data in multiple files, as has happened before. Thanks to this function, information is not missed and users can easily access the data. Third, the DSS supports experience sharing through the accumulation of users’ feedback and information about new situations, test trench findings and damage experienced recorded in the database. Last, but not least, the designed prototype performs risk calculation using the data and generates a risk map of excavation site, which can be further used to select test trench location.

Furthermore, future developers of the final tool might improve the system in its functioning via the Functional Specification of the system. The algorithm could be changed according to location of the project test trenches (design or construction). It could be improved to self-learn elements experienced by users. In addition, test trenches could be mapped so users have a clearer view on problems. Finally, the DSS could support information sharing with specific projects. This could eliminate miscommunication on the construction site, particularly when many contractors are involved.

The meetings with the experts who joined the Support Group to support me during the product development, as well as discussions with other experts during the ZoARG Symposium 2017, verified that design DSS meets their requirements. The following stakeholders’ requirements were fulfilled:

- **Updatable**: One core idea of the tool is that it will learn from users’ experience and, thus, it can easily be updated with new information. In addition, risk maps give the possibility, not only to support users in test trench location, but also in construction projects in general. In cases where ground-scanning techniques reduce the need for digging test trenches, the DSS could still be used to support ground scanning device users in developing the area checking strategy.

- **Innovative**: It is an innovative tool as it allows users to conduct all decision operations within one system compare to the situation earlier which needed several software systems. Moreover, it can
support, not only decision-makers, but also workers on construction site by increasing their risk awareness.

- **Affordable:** Most construction companies use ArcGIS. Thus, they would not have additional costs to implement the DSS.

- **Reliable:** Results of the workshops where the prototype was presented show that users mostly agreed the tool was reliable and they indicated only a few places in which they disagree with the system. These can be easily improved by introducing a self-learning algorithm in the DSS.

- **Fast:** As all decision steps take place within one system, the test trenches are located much faster than previously.

- **Accurate and precise:** ArcGIS warns user in case added data has different geographical coordinates. In addition excavation site tessellation ensure detailed risk assessment.

- **User-friendly:** As all decision-steps take place on a map with risk represented using a colour scale, DSS can be used across different education levels.

- **Compatible:** ArcGIS is compatible with other engineering programmes, such as AutoCAD, Infraworks, Excel, FME and many others.

- **Supportive:** The designed DSS support data collection, data aggregation, experience sharing, data sharing, visualisation and knowledge development.

- **User involvement:** Users are not excluded from the decision-process and can actively take part it.

Discussion with experts showed that the developed DSS has broader application than just locating test trenches. It can visualise risk situations and can be used by workers whilst performing the tasks. Workers aware of risk will perform their work more carefully and reduce the damage caused during construction. In addition, the system could be used to build strategies for the use of ground scanning devices and reduce the number of dug test trenches. Last, but not least, it can be combined with risk assessment modes used by network operators and help them with better control of projects on or near their utilities.

II. **Artefacts' construction:**

- How does the design process looked like?
- What are the major components and subcomponents of the artefact?
- How can the artefact be validated?

To design the product to improve test trench locations decision-process first needs the currently used strategies and problems related to them to be recognised. This was a challenging task, as there was little literature knowledge about locating test trenches. Hence, interviews and workshops were conducted. They indicated significant problems relating to: (1) data collection, (2) data aggregation, (3) risk assessment, (4) communication, (5) experience sharing, (6) information sharing, (7) differences in knowledge and skills of the users, (8) use of new technologies, (9) users motivation, and (10) reporting. Thus, DSS consists of the following components designed to solve the problems: (1) information database (assists in data collection and support data aggregation), (2) experience database (supports experience sharing), (3) problem processing system (supports risk assessment and decision-process control), and (4) project Internal Information sharing database (supports information sharing between involved
contractors and gather information). The important function of this DSS is to assist and support decision-makers, rather than replacing them with an automatic test trench decision-making process. The artefact was tested with experts using serious gaming techniques. They had to locate test trenches on the map without risk and, afterwards, on maps with risk for works to replace an old sewage system. Subsequently, they were asked to provide feedback on assessed risk and indicate places where they disagreed with the calculated risk. The results showed that they mostly agreed with the suggestions of the tool. They admitted that adding functionalities as described in system architecture would definitely increase the value of the prototype. Nevertheless, the developed DSS needed more testing and, involve the experts to engage real experience in the database to improve the implementation process.

III. Artefact’s realisability:
• How can the artefact be realised?

The Decision Support System was based on the ArcGIS software, as it supports spatial data analysis, data aggregation and data visualisation. Construction and design companies often use this software. Thus, the implementation of DSS by companies would not require much investment cost. The system architecture was discussed with IT developers and prototype presented to them. Their feedback showed the proposed system components could be developed using currently available techniques. Some components, such as data aggregation and data sharing, are already used as part of other support systems.

IV. Artefact’s impact:
• What were the risks during the artefact development stage and what are possible risks during its implementation?

There is evidence to believe that the designed DSS, if implemented, will influence societal values, as better decisions on test trench location will limit unnecessary damage that, depending on utility concerned, can significantly impact the environment and the health and safety (H&S) of workers and residents leaving in the neighbourhood.

Nevertheless, before full implementation there are some significant threats that may cause implementation failure and must be considered, including:

• **Technical risk:** A developer for the final tool will not be found and the prototype will not be improved.
• **Customer risk:** Users might not want to share information with other. Thus, an experience database will not develop new information and risk scores will not be improved.
• **Business risk:** Bigger companies might be interested in using the tool. However, smaller companies might not want to spend their time on implementing the system.

In addition, I also identified other threats when developing the model as follows:

• **Time pressure:** The PDEng trajectory required one year of education activities and one year of product development. The risk was of not developing my product on time.
• **Schedule problems:** During my PDEng trajectory, I had to combine both study and work. Moreover, I had to meet the schedule of the experts in my support group, as they could not meet often due to their work activities.

• **Budget problems:** The challenge of choosing software given user’s ability to cover the high implementation costs.

• **Requirements fulfilling risk:** Many requirements gathered during workshops and interviews highlighted trade-offs. The risk is that the final tool will not meet all requirements adequately.
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Racz P., van Buiten M., Doree A., “Naturalistic decision-making perspective on uncertainty reduction by civil engineers about the location of underground utilities”, 13th International Conference on Naturalistic Decision Making 2017, Bath, Uk


1. Introduction on project development

Modern engineers must perform their work carefully to avoid damaging buried underground utilities. The exact location of pipes and cables must be confirmed before starting ground works. Current detection equipment still cannot provide complete certainty and requires extensive training in order to obtain the correct data. Digging test trenches remains an important practical tool to interpret subsurface conditions. However, deciding on the number and location of test trenches is problematic. Nevertheless, decisions about their location seem to be taken randomly and are based mostly on intuitive judgments.

Test trenches (Dutch: *proefseuven*) are shallow trenches used to visually identify the location of the underground utilities. Their maximum length is 1.0 m and the depth depends on soil condition and underground water levels (CROW, 2016).

The project examined the Dutch excavation context where clarity of test trenches location strategy is one major goal of the Dutch Government. Test Trenches location is required by law in the Netherlands. Thus, the strategies used should be clearly defined to avoid further excavation damage. Nevertheless, practitioners in other countries are also familiar with the test trenches location problem as described in such programmes as: PAS 128:2014 in United Kingdom (UK) or “Call before you dig” in United States (US).

The goal of the project was to uncover current strategies of test trenches location in the Netherlands, describe the logic behind decisions and, finally, to improve them by creating a Decision Support System (DSS).

To achieve the project’s goal involved several steps before proposing a solution. First, it was necessary to understand the excavation process and related legislation. Thus, the first two months of the project were dedicated towards literature, legislation and guidelines studies, as well as meetings with practitioners. Interviews were conducted to define stakeholders and scope some test trenches location problems. Second, in order to understand decision-makers’ behaviour, I deepened my knowledge about decision-making methods and behavioural psychology. Nevertheless, literature studies were not sufficient to fully describe the strategies used. Inspired by colleagues, I developed decision games to help with the data gathered during workshops. Third, with support of my company supervisor, I invited practitioners to take part in workshops to understand the role of experience in test trenches decisions and to visualise the current decision-making strategy. Finally, together with my supervisors, we decided to conscript a support group consisting of designers, contractors, job planners and network operators to assist the design of the Decision Support System. The feedback, suggestions and opinions helped me to design Decision Support System and shape a risk map of an excavation area to support users to extract the maximum information from the minimum number of test trenches.

The report describes the steps taken to develop the DSS and specify the functions of the proposed system and its prototype.
1.1. ZoARG (ReDUCE) Network

University of Twente, Reggefiber and other partners created the ReDUCE programme (Reduction of Damage to Utilities and Careful Excavation (Dutch: ZoARG, which is an acronym of Zorgvuldige Aanleg en Reductie Graafschade). This programme is realised to promote careful approaches in construction and maintenance of the underground infrastructure by investing in the development of new methods and technologies that prevent excavation damages (Reggefiber & University of Twente, 2015). The project described in this report is the part of the ReDUCE programme. The major contributors to the project are Ministry of Economic Affairs, Agentschap Telecom and KPN (previously Reggefiber). In addition, several companies were interviewed and took part in workshops with some representatives participating in support group meetings.

1.2. Project description and its objectives

Excavation work demands modern engineers to take many precautions. They must schedule their works in such a way that existing underground utilities will not be disturbed. This is a challenge, given that underground spaces have become increasingly busy. Many types of cables and pipes, underground infrastructures, precious fauna and flora, as well as archaeological findings, can make excavation work difficult. Underground utilities can cause many problems. Damages to high-risk pipes and cables (e.g. gas pipelines, the sewage system, industry pipelines and/or high-voltage electricity cables) can have profound impacts on the environment and the health of workers and people living and working in the area neighbouring the excavation area.

Engineers to improve the safety of excavation procedures use Ground Penetrating Radars (GPRs) and Augmented Reality (AR) technologies. However, these technologies are costly and still do not provide complete certainty. Furthermore, even if maps and plans of underground utilities are available, the information contained by these sources might be incorrect. Therefore, test trenches are often dug to confirm the exact locations. These trenches are variously described as test holes (Canada), trial holes (UK and US), potholing (Australia) and proefsleuven (the Netherlands). They all have the same goal: to establish precisely what is underground before excavation starts.

There is always doubt as to where to locate test trenches. Utilities’ maps, GPRs and AR support those decisions. Nevertheless, it is the responsible decision-makers (designers, contractors) who make the final choice. The process of selecting the test trench location appears to be random and mostly based on the personal judgment of an individual. This exerts considerable pressure on these decision-makers faced with meeting deadlines and faced with the nagging uncertainty about the actual location of subsurface utilities and the risk of excavation damage to the utilities (Racz, Van Buiten, & Dorée, 2017c).

There are four main motivations that made the topic of test trenches location worth of investigation.

The first motivation is related to differences between maps of underground space and the actual location of utilities. Dutch mapping agency, Cadastre, provides maps with utilities’ location and associated documentation. However, there can be a difference between current and primary location of utilities
since many were buried a long time ago. Changes may appear due to human errors and due to differences of reference points’ position and additional soil levels. Moreover, any obstruction can change the straight alignment of underground utilities (Electrical and Mechanical Services Department, 2005). Uncertainty of a utilities’ location requires careful risk assessment. Test trenches can help in uncertainty reductions. However, first, it is necessary to point places that indicate possible deviation from the maps.

Second, every excavation carries a risk of damage, even hand-digging. Thus, because of both economic and safety reasons, the number of test trenches should be preceded by careful analysis of project, excavation area and available data.

The third motivation is related to information exchange between all units involved in excavation process. Experience of decision-makers plays important role in test trenches location decisions. Unshared experience results in missing important data that should be taken into consideration while situation analyses. Digging test trenches is common practice, but the process of their location is mostly implicit, unclear and not documented. In addition, many damages happened because of problems with information exchange between excavators, network operators and other units involved in excavation work. To relieve the communication problem, in 2008, the Underground Network Information Exchange Act was established. The act defines excavation procedures and specifies the information exchange flow between excavation units. However, decisions about the number and location of necessary test trenches still depend on responsible decision-maker.

Last, but not least, digging test trenches is time-consuming and takes lots of effort. Thus, the location process cannot be random and must be based on solid information of the involved units, safe digging procedures and careful risk assessment.

Various design questions were raised at the beginning of the project and afterwards investigated, as follows:

- What are currently used strategies of selecting test trenches location?
- What are pros and cons of current system?
- What is the role of decision-makers in current decision process? Is there any logic behind their decisions?
- What must be improved in the current system in order to reduce the number of excavation damages?
- How to get maximum amount of information from the minimum number of test trenches?
- What are the needs and requirements of decision-makers for support system?
- Will the proposed system fulfil users’ requirements?

From these questions seven project objectives were defined:

I. To define the currently used strategy for selecting test trenches location.
II. To find the pros and cons of current strategy.
III. To describe the logic behind test trenches location decisions.
IV. To propose and develop a Decision Support System for selecting test trench location.
V. To test if the solutions effectively supported decision-makers.
VI. To develop solutions that could meet users’ requirements.
VII. To evaluate the implementation of the design solution in the real world.

1.3. Current test trenches location system

Knowledge about the excavation process in an area of investigation is a major step towards understanding decision-makers behaviour. Thus, in this first section, the excavation procedures in the Netherlands will be explained. Next, the role of test trenches will be emphasised. Finally, the current decision-making system will be presented. This system will be later elaborated in Chapter 2- Problem investigation and analysis.

1.3.1. Excavation procedure in the Netherlands

The information from this chapter were included in my conference paper (Racz et al., 2017c).

The Netherlands has a national digital mapping system (referred to as “KLIC”, which is an abbreviation for Kabels en Leidingen Informatie Centrum). This system was developed by the Cables and Pipes Information Agency (Cadastre) and provides the excavator with maps of utilities in the area of interest, together with any necessary documentation. In spite of this, damage to underground utilities persists. According to the data provided by Cadastre, almost 33,000 cases of damage were recorded involving Dutch utilities in 2015 at a cost of their repairs mounted to €30 million per year (Kabel en leiding overleg KLO, 2016). The Underground Networks Information Exchange Act (WION), together with KLIC, provides a solid foundation for making decisions. The WION describes the steps that excavators must follow before breaking the surface, and the KLIC system supports them with the relevant maps. In Figure 2 the KLIC system is presented. It is important to send a notification on time at least three, but not earlier than 20, working days before the excavation work starts. Cadastre will send data back to excavator within two days. Moreover, network operator may suggest in documentation that some precautions are needed, for instance, because of dangerous utility’s content. When attention is required, the start of excavation must be notified to the network operators who has to ensure precautions within three working days from that time. They might decide to send a supervisor on excavation site (WION, 2008).

Excavators, using programme called KLIC-viewer, can read the utilities’ maps, together with all added documentation.

Figure 2. The KLIC system in the Netherlands (Groot, 2008)
New European regulations, such as Infrastructure for Spatial Information in the European Community (INSPIRE), as well as feedback from KLIC users, allow Cadastre to receive feedback to improve the system. As a result, the KLIC-win system was developed and is slowly being implemented to provide users with location data in vector format to create data sets with added value, such as 3D visualisations (Kadaster, 2016). It is expected that KLIC win will replace the current KLIC system at the beginning of year 2018.

Furthermore, guidelines were developed in order to support excavators before, during and after digging. In the brochure written by CROW (national infrastructure knowledge platform) excavators can find brief explanation of all the steps that cannot be omitted during the excavation procedure. By following a simple flowchart, excavators can check if all steps were accomplished in the following project stages: (1) KLIC notification, (2) Job planning, (3) Excavation site searching and (4) Excavation proceeding. The translation of CROW’s brochure (CROW, 2013) is presented in Figure 3 and Figure 4.
At excavation place

- Are the conditions approved by municipality?
- Did you receive the acknowledgment from Cadastre with the contact details to present network operators?
- Are the cables and pipes placed on received drawings?
- Are precautions required because of danger or high value?
  - Min. 3 days before digging contact a network operator
  - No extra care required.
- Is the information actual (not older than 20 working days)?

- Have the instruction been received in advance?
- Is it clear which effect may have a job for cables and pipes?
- Are the additional precautions required and planned?
- Is it determined how many test trenches must be done?
- Is the information complete and clear?

- Are there data from drawings plotted at the working area?
- Is the exact location of test trenches cleared?
- Are the test trenches possible to do (no limitations such as hard surface, foundation, underground water)?
  - It is necessary to determine the way of checking with the operator
- Have the test trenches been already dug?
- Is the actual situation compatible with received KLIC data?
- Are there detected only the cables and pipes known from KLIC data?
- Have the deviation, with the range of 1 meter, been kept?
- Have the notified cables and pipes been found?

Consult with manager/FAGM adviser/Publication LTD "Gratisschade vorkomende labels en leidingen-flichtijn aangrijpend grafkaders."

Instruction:
- Close to the cables and pipes only manual digging;
- Knowing and following the safety instruction received from network operator;
- Careful repairing of cables and/or pipes;
- Do not push yourself, strike or repair;
- Report damages to network operator.
Cables and pipes searching and localizing

- Note changes of soil (such as color and density);
- Watch the surrounding (e.g., surface differences);
- Surveying the situation and/or take a picture to supplement the test trenches;
- To complete the information about test trenches mark the location on the ground level;
- Be careful in case of house connections, they are sometimes not marked in KUIC data base;
- Set the location area (using detection devices)

Possible anomalies during excavation

- Care about you work and work area;
- Be aware of sudden alerted situations;
- Be aware of changing in length direction. Cables/pipes are not always straight between 2 dug test trenches;
- Ground cover along ditches is often less than expected;

Care while digging

- Keep the bucket stretched to disturbed ground;
- The bucket only turn in order to create loose soil;
- Use the flat bucket without teeth;
- Pay attention during shifting to crushing and demolition;
- Avoid collapsing of surrounding pavements and soil;

Initiative, consultation and communication

- In case of calamity indicate that to operator;
- Imagine yourself as responsible excavation team and take initiative;
- Consult if you are not sure;
- You are never obligated to proceed in uncertain situations;
- First safety for everybody;
- In case of damaged trenches and pits are not fill up;
- Report even small damages to the network;

Other

- Work properly and safely for your environment;
- Provide adequate coverage and deposit;
- The strange smell or color may indicate a contaminations. Do not dig further as there is evidence of contaminations and/or asbestos;
- Report the archaeological tracks.
Crow guidelines from 2008 (CROW, 2008) and 2016 (CROW, 2016) contain best practices to apply during project preparation, execution and maintenance. Both guidelines emphasised the necessity of checking the location of utilities up to 1.5 m from the excavation profile. Furthermore, the newest CROW guideline distinguished two kinds of safety buffers: horizontal (1.5m) and vertical (0.2m).

Both guidelines obligate excavators to plan and dig test trenches before starting excavation. Old guidelines (CROW, 2008) pointed to test trenches as the most effective way of localising utilities and distinguished situations for when test trenches were necessary and when they were not necessary. By contrast, new guidelines (CROW, 2016) allow a variety of methods to be used in addition to test trenches, including ground scanning techniques (radio detection, ground penetrating radars (GPR), acoustic, navigation systems and sub-bottom profiling) and check holes (small holes which allow controlled searches to see if a utility exists in certain location after checking area with ground radar). Test trench location, according to the new guideline (CROW, 2016), should be preceded with careful risk assessment. The length of test trench should not exceed 1.0 m on both sides of the theoretical location of cables and pipes. In turn, their depth may differ depends on soil condition and ground water level. The example of test trench (Dutch: *proefsluif*), check hole (Dutch: *proefgat*) and ground scanning technique (GPR) are illustrated in Figure 5.

Dutch norm NEN 7171 “Underground utility networks planning” (Nederlands Normalisatie-instituut, 2009) provides decision-makers with information about minimum depth of utilities. It is especially important in case there is no information about the depth of utilities on excavation site and thus, excavators need to assume how many meters under the ground the utilities are. The depth of utilities depends on the area they are located as presented in Table 2.
<table>
<thead>
<tr>
<th>Table 2. Depth of utilities according to Nederlands Normalisatie-instituut (2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CAI</strong></td>
</tr>
<tr>
<td><strong>Number</strong></td>
</tr>
<tr>
<td><strong>Residential area</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Main Road</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Road in industry zone</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Road outside urban area</strong></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

1.3.2. *Role of test trenches*

Test Trenches are criticised by some practitioners. They say that it is enough to use current levels of ground scanning radars to locate utilities. Fortunately, most of interviewees emphasised the necessity of using both techniques - uncovering utilities using test trenches and confirming the location of utilities using ground scanning devices. Research studies (Health and Safety Authority, 2010) have shown that scanning devices have several limitations. Thus, before choosing a device, the excavation situation has to
be carefully analysed and other techniques, such as test trenches, have to be used before excavation
starts. In addition, using scanning devices requires sufficient knowledge and strategy development in
order to use them effectively. Some examples of detection devices with their advantages and limitations
are described in Table 3.

<table>
<thead>
<tr>
<th>Type of device</th>
<th>Short description</th>
<th>Advantages</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hum detectors</td>
<td>Instruments that detect the electromagnetic field by live electricity cables, which have a current flowing through them.</td>
<td>• Will detect the electricity cables if the flow is going through them. • Will not detect service if there will be little or no current flowing by cable at that time; • May not detect some well-balanced high-voltage cables that generate little magnetic field.</td>
<td></td>
</tr>
<tr>
<td>Radio Frequency detectors</td>
<td>Device which responds to low-frequency radio signals.</td>
<td>• Signal will be re-emitted by cables and metallic pipes; • If the ultra-high Radio Frequencies are emitted the plastic pipes can be detected.</td>
<td>• Other metallic object can re-radiate the signal.</td>
</tr>
<tr>
<td>Electromagnetic radio location</td>
<td>Small portable transmitter or signal generator is connected to a cable or pipe, or close to them so the signal is induced into it.</td>
<td>• Indicate the system because it is being traced from a known point.</td>
<td>• Transmitter may be not located correctly; • Has no capacity for locating non-conductive service as HDPE Pipes or Fiber Optic cables.</td>
</tr>
<tr>
<td>Ground-Penetrating radar</td>
<td>It is transmitting a radio frequency signal into the ground and measuring the variations in the reflected signal receive back (anomalies in the ground)</td>
<td>• Can detect nonconductive materials; • Nowadays the 3D GPR can give more clear information.</td>
<td>• Some kind of soil, water may disrupt the signal.</td>
</tr>
</tbody>
</table>

Excavation damages prevention programmes in other countries also emphasise the need to use test
 trenches. The American programme, “Call before you dig”, advises excavators to expose utilities before
starting excavation in order to support scanning techniques. Similarly, British PAS 128:2014 describes the
need to combine test trenches with scanning techniques. There is always an uncertainty about location
of underground utilities, the location and depth may vary from the one presented on maps. Furthermore,
obstacles, soil condition, water level and utility material may decrease the effectiveness of scanning
devices. Thus, utilities’ exposure before excavation may reduce the risk of damage. Test trenches help not
only to inform the excavator about type of utilities, their location and depth, but also about their number
(i.e. number of cables in one duct) and intersections with other utilities. However, it is necessary to
carefully plan the location of test trenches in order to place them in points where data and experience
suggest damage is possible.
1.3.3. Current test trenches location system

This section describes briefly the current strategy for selecting test trenches location and its logic. The analytical and naturalistic perspectives will be presented in detail in chapter 2- Problem investigation and analysis. The brief description aims to help the reader to understand further problem analysis and solution investigations.

The current decision-making system is based on a combination of data analysis with users’ experience application, which is subsequently supported by use of visualisation tools. The strategy is not precise because, behind the explicit decision-making steps, such as checking the utility location at the beginning and end of excavation polygon, there is an implicit decision-making process based on an experts’ experience. I identified the following steps taken by decision makers:

- Data analysis (i.e. utilities’ maps);
- Site analysis (i.e. ground conditions and obstacles);
- Detection (GPRs and other detection equipment);
- Use of best practices (i.e. applying a 1.5 m spatial buffer region);
- Computer support (i.e. visualisation and data sharing software);
- Decision about test trench location;
- Reporting about decision results.

Depending on the company, one or more combinations of steps are used by decision-makers to locate test trenches. The main influence is the size of the company, its budget and interest in new technology application. Their interests focus on the most efficient techniques to minimise excavation damages. Moreover, each step is influenced by knowledge and skills of decision-makers. The current test trenches location decision-making strategy is visualised in Figure 6 and elaborated in chapter 2.3 - Analysis of existing decision-making process.
1.4. Design Methodology

In my design, I used a design cycle in order to organise my work. This is a part of the engineering cycle which consists of the following five steps (Wieringa, 2014):

- Problem investigation: What is the problem to be solved and what is its effect?
- Treatment design: What solution can be applied in order to solve the problem?
- Treatment validation: Will solution solve the problem?
- Treatment implementation: Implementation of the solution.
- Implementation evaluation: How successfully the solution treated the problem?

The design cycle covers first three mentioned above steps. The next sections briefly describe methods used to accomplish each of the design steps.

1.4.1. Problem investigation

Improving strategies and logic requires clear understanding of problems that exist in currently used decision system. Thus, several questions must be answered:

I. Who are the stakeholders?
II. How the currently used strategy looks like?
III. What is the logic behind made decisions?  
IV. What are the problems in current strategy?

The problem investigation was conducted in four phases. First, literature and legislations studies were performed to understand national procedures. Second, I investigated if there is a problem in currently used strategies that arrives from statistical data. Third, I looked at strategies from point of view of the stakeholders. And last, I examined the behaviour of the stakeholders when they faced new situations.

Data collection

The literature studies included Dutch and international books and articles about excavation process. Furthermore, I investigated the American and British methods to compare them with Dutch procedures. Studies of Dutch excavation legislation and guidelines helped me understand the role of units involved in the construction projects. Next, I have searched for connections between test trenches location and damage occurrence using databases of damages in the years 2015 and 2016. Agentschap Telecom and the one of the Network Operators provided those data. In order to see the test trenches location process through the eyes of the decision-makers I conducted interviews in the several companies. Finally, I invited some stakeholders’ representatives to join workshops and I challenged them to locate test trenches for unfamiliar and uncertain projects. Moreover, workshops gave a great opportunity for strategies comparisons that resulted in interesting discussions between experts. All techniques used and their results are elaborated in detail in chapter 2 - Problem investigation and analysis.

Data analysis

Data were analysed from two types of perspectives: (1) analytical, and (2) naturalistic. The analytical analyses of data were performed using Simon decision-making model (Simon, 1977). The model helped me to describe the current strategies used to locate test trenches. In turn, workshops showed that the experience of the decision-makers plays an important role in the test trenches location process. The Naturalistic Decision Making researchers (Klein & Crandall, 1996; Klein & Klinger, 1991; Rasmussen, 1983) developed the models that support psychological analysis of people’s behaviour. The use of these models in my project resulted in explanation of logic behind the decisions. The detailed description of methods and their results are presented in chapter 2 - Problem investigation and analysis.

1.4.2. Treatment design

The identification of the currently used strategies together with understanding of the logic behind those decisions directed me towards solution development. Identified problems needed a solution that will improve the test trenches location process and, consequently, reduce the number of excavation damages. I chose V-model (see Figure 7) to guide me through design development.
V-model, when compared to other system engineering models, has more advantages at the beginning stage of a design. Compared to the “waterfall” model, it allows the verification and validation that are important in case of designing the Decision Support System. What is more, it also allows for feedback from later design stages while providing more design freedom compared to the “spiral” model (Blanchard & Fabrycky, 2011).

In order to make my design process effective, I invited representatives of several companies to join the Support Group meetings including designers, contractors, network operators, job planners, Cadastre specialist and WION (WION, 2008) inspectors. They supported me with their knowledge and experience and provided valuable feedback to improve my work and test if the design met with users’ requirements. Considering how busy the members of the team were, we scheduled four meetings, which corresponded to the design stages:

- **Meeting 1 (25.01.2017).** During the first meeting, I presented my findings and conducted partial value management workshop. The goal of the first part was to discuss the currently used strategy that I have defined. During the second part of the meeting, the value management (VM) workshop
was performed. The purpose of the VM was to optimise decision strategy by defining users’ needs and consequently increase the value of the Decision Support System (DSS). During this workshop several alternatives were mentioned and the best was chosen. After the meeting, needs were transformed to requirements and the DSS development started. The requirements were shared among the team members for an approval.

- **Meeting 2 (14.06.2017).** The system mock-up (see appendix 4) was presented and evaluated by the group’s members. The idea for a DSS was to use risk-assessment as the main component. Hence, the aim of the meeting was to gather the risk-assessment scores for elements that can increase the risk of damage and its level of consequence. Nevertheless, the data gathering techniques appeared to be too complicated. Therefore, it was decided that users should define the scores using digital form and the meeting focus on ideas and missing elements. After the meetings, risk scores were defined and I started to develop the system components.

- **Meeting 3 (21.09.2017).** The goal of the meeting was to present designed DSS, check its effectiveness and gather feedback about its functions. After the meeting, the final system improvements were made.

- **Meeting 4 (30.10.2017).** The final meeting aimed to summarise the entire project and present the final tool.

All meetings, their design, performance and results are elaborated in chapter 2 - *Problem investigation and analysis* and chapter 3 - *System Requirements*. The designed artefact is described in chapter 4 - *Functional Specification of the Decision Support System*.

### 1.4.3. Treatment verification, validation and implementation

Treatment validation is the last stage of the design cycle. The difference between validation and verification is always confusing. So, to avoid misunderstanding I started with definitions of these processes. Validation helps to determine if design meets customer needs; whereas verification focuses on checking if a system is well-designed (Blanchard & Fabrycky, 2011).

**Validation and verification methods**

Designed Decision Support System (DSS) was validated during meeting 3. To check system usefulness, users were asked to mark test trenches, first without, and later, with the system and to signal in each case whether they disagreed with system’s suggestions. At the end of the meeting, participant were asked whether the system met their needs so we could verify their requirements. The same procedure was repeated during ZoARG Symposium. This took place on 19th October 2017. The system validation is described in detail in chapter 4.6 - System validation and its verification in chapter 4.7 - System verification.

**Implementation**

The DSS will need to be also tested in real-world condition for several months before it could be regarded as ready for implementation. Furthermore, the system needs improving by a professional IT developer to remove bugs and errors and to add additional functions as described later. Both these aspects were
omitted during the prototype design due to the limited time and information technology background. Recommendations for implementation are described in chapter 5.2-Recommendation for future implementation of the DSS.

Following the approach described in chapter 1.4- Design Methodology, the development process is visualised in Figure 8.

![Figure 8. Report Overview Visualization](image)

The description of each phase, together with related activities and their results are described in Table 4.
<table>
<thead>
<tr>
<th>Design phase</th>
<th>Activities</th>
<th>Fulfilled objectives (chapter 1.2)</th>
</tr>
</thead>
</table>
| **Chapter 1. Problem Definition** | - Legislation and guidelines studies;  
|                                  | - Project description;  
|                                  | - Project objectives;  
|                                  | - Problem statement.                                                       | I. To define currently used strategy for selecting test trenches location.                     |
| **Chapter 2. Problem investigation and analysis** | - Data gathering methods;  
|                                  | - Data analysis;  
|                                  | - Analytical analysis;  
|                                  | - Naturalistic analysis.                                                   | I. To define currently used strategy for selecting test trenches location.  
|                                  |                                                                       | II. To find the pros and cons of current strategy.                                         |
|                                  |                                                                       | III. To describe the logic behind test trenches location decisions.                        |
| **Chapter 3. Requirements analysis** | - Requirement Engineering;  
|                                  | - Value management;                                                       | V. To develop solutions that meet users’ requirements.                                       |
| **Chapter 4. Test Trenches Decision Support System Design** | - Overview of proposed solution;  
|                                  | - Functional Specification of proposed DSS;  
|                                  | - Preliminary Design: system prototype.                                    | VI. To propose and develop Decision Support System for selecting test trench location.  
|                                  |                                                                       | V. To develop solutions that meet users’ requirements.                                       |
|                                  |                                                                       | VI. To test if solutions effectively support decision-makers.                          |
| **Chapter 5. Conclusions and Recommendations** | - Overview of proposed solution;  
|                                  | - Functional Specification of proposed DSS;                               | VII. To evaluate the implementation of the design solution in real world.                  |
2. Problem investigation and analysis

In this chapter the stakeholders are defined and the methods used to collect data elaborated. Subsequently, the analysis will be conducted using two kinds of perspectives: (1) analytical and (2) naturalistic. The uncovered problems will be summarised in the conclusions.

2.1. Definition of stakeholders

The problem investigation started with stakeholders’ identification to actually understand who the decision-makers are. It was done by the literature, guidelines and legislation studies.

During my analysis, I followed the Ian F. Alexander’s Onion Model (Alexander, 2005). The onion model was initially used as the model of the universe, however Alexander used it to build the stakeholders’ taxonomy. In his model the stakeholders are the people, with their roles, on whom the system depends. The Onion Model for my project is shown in Figure 9.

![Figure 9. The Onion Model](image)

The Onion Model consists of four or more circles. The circle draw in the middle-‘The Product’- contains the product of design. In my case, the product is Decision Support System for selecting test trench location. The circles around ‘The Product’ contain the stakeholders that have an impact on product design and whose opinion is needed to build an effective and reliable tool. Further, those stakeholders will be the users of that product and, because of that, their requirements are necessary to take into account while the tool is designed. In “The System” circles locate the direct users of the system: (1) Designers, (2) Contractors. Both of these groups I will refer to as “decision-makers”. The Beneficiaries of the product, the investors, government and network operators, belong to the set called ‘The containing System’. The
last circle of the model covers the other beneficiaries of the product and all the other kinds of stakeholders. The last orbit is defined as ‘The Wider Environment’ circle. In my project, the other Stakeholder that benefit from the Decision Support Tool are utility customers. Customers do not want to be disconnected from sources. Decreasing the number of damages using Decision Support System (DSS) for Selecting Test Trench location can do this.

2.2. Problem investigation

As explained in the design methodology, in order to gather data four methods were used: (1) Statistical data analysis, (2) Interviews, (3) Projects’ observations and (4) Workshops. This section gives detailed information about these methods’ design and, subsequently, their performance and obtained results. These results are further elaborated from analytical a naturalistic perspective.

2.2.1. Statistic of excavation damages

**Goal**

The goal of statistical investigation was to find:

- the connection between presence of test trenches and number of strikes;
- the reasons why test trenches were omitted;
- the reasons of damages which occurred despite of presence of test trenches;
- to which utilities damages happened frequently.

**Source**

Two databases were analysed. The database from Agentschap Telecom contained data for 34135 damages in 2015 as notified to Cadastre. The second database from Network Operators presents data for 11423 damages in 2016.

**Calculations and results**

The Cadastre’s database from 2015 shows the main damages were caused to the data-transport cables and to the low-voltage electricity cables. The whole overview of strikes caused to each type of utilities is shown in Figure 10.
Furthermore, it was noticed that utilities of some network operators were damaged more often than the others.

In order to understand to which utilities decision-makers may pay more attention I calculated total cost of damages and mean cost for the each utility type. The total cost of damages was 26 496 710 euros and means are presented in Table 5 calculated using programme SPSS.
Table 5. Cost of damages in 2015

<table>
<thead>
<tr>
<th>Underground system</th>
<th>Mean</th>
<th>N</th>
<th>Std Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>814,70</td>
<td>2872</td>
<td>6707,073</td>
</tr>
<tr>
<td>Gravitational sewage</td>
<td>2661,34</td>
<td>85</td>
<td>6383,360</td>
</tr>
<tr>
<td>Delivery Sewage</td>
<td>6118,44</td>
<td>57</td>
<td>18526,427</td>
</tr>
<tr>
<td>Telecommunication cables</td>
<td>675,06</td>
<td>14509</td>
<td>1702,967</td>
</tr>
<tr>
<td>High voltage line</td>
<td>57979,84</td>
<td>14</td>
<td>66339,800</td>
</tr>
<tr>
<td>Medium voltage line</td>
<td>4926,87</td>
<td>544</td>
<td>14932,320</td>
</tr>
<tr>
<td>Low voltage line</td>
<td>603,79</td>
<td>10065</td>
<td>1278,433</td>
</tr>
<tr>
<td>Low pressure gas pipeline</td>
<td>601,74</td>
<td>4516</td>
<td>916,244</td>
</tr>
<tr>
<td>High pressure gas pipelines</td>
<td>2250,21</td>
<td>120</td>
<td>6147,252</td>
</tr>
<tr>
<td>Heat</td>
<td>9437,08</td>
<td>25</td>
<td>19743,027</td>
</tr>
<tr>
<td>Petro-chemical pipeline</td>
<td>300000,00</td>
<td>1</td>
<td>12345</td>
</tr>
<tr>
<td>Dangerous content</td>
<td>7049,33</td>
<td>6</td>
<td>4002,734</td>
</tr>
<tr>
<td>Other</td>
<td>1409,01</td>
<td>115</td>
<td>4432,373</td>
</tr>
<tr>
<td>Total</td>
<td>778,26</td>
<td>34134</td>
<td>3561,252</td>
</tr>
</tbody>
</table>

The most costly were the damages made to the high-voltage lines and petro-chemical pipelines. The number of damages was low - fourteen for high-voltage cables and only one for petro-chemical pipelines. However, the cost of repair was high. There were 2872 damaged water pipes that resulted in 814 euro repair costs; a relatively low amount compare to the networks mentioned above. The same example can be presented for pipeline with dangerous content. This damage last year cost approximately 7650 euros. This data highlights the scale of problem and the urgent need to avoid the damage to the underground systems, to reduce costs and impacts on the environment and safety.

The presence of test trenches was not mentioned in Cadastre database. This information I obtained from an internal database of one of the Network Operators. This database was much more extended and provided information about test trenches and explanations why damages occurred. According to this data, for 11422 damages registered, 4256 where caused where there were test trenches and 4488 of them occurred in places were test trenches were not dug. Moreover, 2678 damages had no information about presence of test trenches. The reasons for damage happening in spite of the presence of test trenches is visualised in Figure 11.
The most frequent damage to the utility services were: (1) mechanical damages, (2) damages to house connection, (3) damages while fibre cables were connected to the houses, (4) damages to data-transport cables, (5) damages due to lack of information on utilities maps, (6) damages to disconnected utilities, (7) damages when tree was pulled together with utilities, (8) damages due to absence of Network Operator supervisor, (9) damages due to ground conditions (soil type, reduce visibility), and (10) damages while digging test trenches.

2.2.2. Interviews

Goal

The interviews were conducted in order to:

- Understand excavation procedures in the Netherlands;
- Learn whether there was one strategy for selecting test trench location or if it differed between companies;
- Learn how decision-makers gathered the maximum information from the minimum number of test trenches;
- Learn users’ opinion about the necessity of digging test trenches and current excavation procedures;
- Collect users’ needs for future support system.

Design

The Design Process Unit (DPU) approach (Becker Jaruregui & Wessel, 2013) was used to structure questions for the interviews (see Figure 13). DPU is a part of another design method, DfX (Design for eXcellence), as presented in Figure 12. DPU can be defined as the knowledge that is compulsory to design.
The design parameters are properties of the artefact that can be manipulated to achieve the performance. The scenario parameters describe the properties that cannot be changed and have to be considered in the design. The performance uses both the design and scenario and it assesses the quality of the analysis (Becker Jauregui & Wessel, 2013). There are five categories of DfX methods: (1) Guidelines, (2) Checklists, (3) Metrics, (4) Mathematical models, and (5) Overall methods (Becker Jauregui & Wessel, 2011).

Figure 12. Taxonomy of the DfX template (Becker Jauregui & Wessel, 2011).

Figure 13. DPU model for interviews questions' analysis

The questions, which result from above analysis, can be seen in Table 6. The design parameters represent those that can be manipulated and questions formulated. However, several scenario parameters must be taken into account as well. Companies have their own habits and it may be difficult to change their opinions about the strategies that they use. What is more, some of rules, such as Cadastre's KLIC-online system, are dictated by law.
**Table 6. Interviews’ questions**

<table>
<thead>
<tr>
<th>Embodiments and scenarios that influence the question</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design:</strong> location’s coordinates; visualisation (analysis of drawings); <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>Where did you locate the test trenches?</td>
</tr>
<tr>
<td><strong>Design:</strong> amount of test trenches <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>Why did you choose that amount? What are distances between the test trenches?</td>
</tr>
<tr>
<td><strong>Design:</strong> location’s coordinates; visualisation (analysis of drawings), amount of test trenches; <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>What is your opinion about the idea of considering the shallow excavation as a test trench?</td>
</tr>
<tr>
<td><strong>Design:</strong> software <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>Did you use any aid to decide easier about number of test trenches or about the excavation? (I.e. software, Devices? Radars?)</td>
</tr>
<tr>
<td><strong>Design:</strong> number of damages <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>What were the results of your choices? Did any damage happen?</td>
</tr>
<tr>
<td><strong>Design:</strong> software, number of test trenches; <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>What do you think about the current information exchange system KLIC? Do you like it? Is it helping you? Would you change something?</td>
</tr>
<tr>
<td><strong>Design:</strong> visualisation (analysis of drawings), software, number of damages; <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>What do you think about the cooperation/communication at excavation place?</td>
</tr>
<tr>
<td><strong>Design:</strong> location’s coordinates; visualisation (analysis of drawings), software, number of damages; <strong>Scenario:</strong> user’s experience, practice rules, KLIC database and users itself</td>
<td>Could you tell me what would you like to change in the current procedures? Do you have any ideas what would help you to decide easier about test trench location?</td>
</tr>
</tbody>
</table>

**Performance**

Twelve interviews were conducted with excavation companies, network operators and government agencies. Their representatives differed in functions, which added to a broad overview on the problem discussions. The functions of interviewees are presented in Table 7.
Table 7. The functions of interviewees in the Companies

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>The function in the Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WION Inspector</td>
</tr>
<tr>
<td>2</td>
<td>Manager in the Operational Information Management department</td>
</tr>
<tr>
<td>3</td>
<td>Asset Manager</td>
</tr>
<tr>
<td>4,5</td>
<td>Designers</td>
</tr>
<tr>
<td>6</td>
<td>GPRs Specialist</td>
</tr>
<tr>
<td>7</td>
<td>FttH Engineer</td>
</tr>
<tr>
<td>8</td>
<td>Specialist of software design</td>
</tr>
<tr>
<td>9</td>
<td>Cables and pipes Coordinator</td>
</tr>
<tr>
<td>10</td>
<td>Group of Work Planners</td>
</tr>
<tr>
<td>11,12</td>
<td>Cables and Pipes Specialists (Network Operator)</td>
</tr>
</tbody>
</table>

Before the interview took place, the companies were asked to prepare examples of the project(s) they found challenging to locate test trenches. The interviews took approximately two hours and were based on the questionnaire presented in Table 6.

Results

Conducted interviews helped me to understand in practice how the excavation procedure is executed. Visiting Cadastre I filled in myself a KLIC notification, while participating in excavation process controls together with WION Inspectors. I experienced how excavation companies executed law and, while interviewing some other construction companies, I observed the process of digging test trenches.

The interviews showed the diversity of methods to select test trenches. The first difference is whether the decision is taken by designers or by contractors. Designers locate test trenches to check if there is a place for their design and, as a result, they can avoid unnecessary costs, changes in design and even project failures. In turn, contractors locate test trenches because they have to execute law and, in addition, they want to perform their work safely, without delays and without additional costs.

Methods used to decide about test trench location are presented in Table 8. They were grouped according to the test trenches decision steps distinguished in the chapter 1.3.3 - Current test trenches location system.
Table 8. Methods used to decide about test trench location

<table>
<thead>
<tr>
<th>Decision steps</th>
<th>Methodology (one method per step or combination of all or few methods)</th>
</tr>
</thead>
</table>
| **Data analysis** | • Using KLIC maps;  
  • Using decision-makers’ experience;  
  • Base on careful risk assessment (sometimes supported by computer algorithms);  
  • Base on internal databases of previously made damages. |
| **Site analysis** | • Using photo view (e.g. google earth, google maps, cyclomedia);  
  • Visiting the site. |
| **Use of new technologies** | • Marking test trenches on printed maps;  
  • Using other computer software to support analysis, spatial analysis and information exchange such as Geographic Information System (GIS), Computer-aided design (CAD), Building Information Modelling (BIM) and programming languages i.e. Python and JAVA.  
  • Using scanning techniques to support decisions about test trenches location such as Ground Penetrating Radars (GPRs) and Radio Detection.  
  • Using also other methods of utilities’ locations such as check holes (Dutch: proefgaat)  
  • Using internal databases to collect data;  
  • Using KLIC-app to read maps and share information about damages. |
| **Decision** | • Based on the collected data. Considering: project type, work type, actions’ type, knowledge about utilities depth, utilities materials, house connections, soil type, water level, present obstacles, sanitary fittings and land use.  
  • According to guidelines best practices (such as keeping 1,5m buffer);  
  • Influence by decision-maker experience  
  • Following best practices and locating test trenches on: (1) beginning and end of excavation area, (2) crossing points with many utilities, (3) places where path change, (4) every 200m on linear path and (4) places where utilities with dangerous content are buried. |
| **Reporting** | • On the piece of paper;  
  • Using AutoCAD (drawings of made test trenches, together with findings);  
  • Using spatial data analysis software such as GIS;  
  • Making photos of made test trench;  
  • Using 3D visualisation software, such as Infraworks;  
  • Generating written report from made decisions;  
  • Registering decisions in internal database and sharing among units involved in certain project. |

The diversity level of data is visualised in Figure 14. As can be seen, some companies store their data about planned and made test trenches just on a piece of paper. Others developed drawings using CAD software or used KLIC app developed by GOconnectIT. By using KLIC-app they contributed to the development of database of findings and to allow other users to plan their work better and safer. Some companies, who are interested in the new technologies, created their own Geographic Information System (GIS); a system that allows shared data between all users involved in the project so all can track the project performance.
and avoid misunderstandings. Online data sharing is especially helpful when many contractors are involved in the project.

How important a well-designed data sharing method is for effective test trench location can be noted by the example one interviewee presented (see Figure 15). Here, two contractors were involved. One thought the other was responsible for digging a test trench on the crossing point of sewage system with low voltage electricity lines. As the result, a test trench was not dug and, while performing excavation, damage was caused to electricity cables as they were buried deeper than expected due to a presence of an old tree. If these contractors could check from a system which test trenches had been dug, who made them and what was found, the damage could have been avoided.

Figure 14. Diversity in data representation A) Information store on the piece of paper; B) Data drew in CAD software with not clear location of test trenches, C) Using CAD software each test trench is marked on a map and afterwards drew together with uncovered utilities; D) KLIC-App developed by GOconnectIT (GOconnectIT, 2016); E) Internal software based on GIS which supports data storing and information sharing.
2.2.3. Workshops

During the interviews, companies presented their current projects and, hence, it was not possible to investigate how they deal with new, uncertain situations. Thus, the workshops used a decision-game to do this.

Goal

The workshops were performed in order to:

- Investigate how the decision-makers behave when they face new and/or uncertain situations;
- Check what reasons are behind made decisions;
- Understand decision-makers’ mindsets;
- Uncover the logic behind currently used strategies;
- Collect users’ needs for future support system.

Figure 15. Example of importance of data sharing between contractors.
**Design**

Workshops were based on a serious gaming techniques (Schell, 2015) to check the behaviour of the decision-makers when they are taking decisions under uncertainty. A game is defined as a *problem-solving activity, approached with a playful attitude* (Schell, 2015). The games are described as serious when they *contribute to the achievement of a defined purpose other than mere entertainment* (Susi, Johannesson, & Backlund, 2007).

Serious-games support decision-making by visualising and simulating real-world situations. The elements of the games, such as rules, goals, challenges and indicators, push players to use their experience and absorb new knowledge through solving problems individually, or in a team (van den Berg, Voordijk, Adriaanse, & Hartmann, 2017). Moreover, serious gaming can support knowledge and experience sharing, so that players can learn from each other by playing a game and discussing approaches and outcomes.

There are threads associated with serious-gaming design (van den Berg et al., 2017). The first thread refers to skills learnt by a player in a real-world situation. This is valuable when a game designer uses established procedures and theories and well-balanced theses across the game. Otherwise, the skills and knowledge used can cause errors. The second thread relates to the learning process throughout the game. If the game developers do not perform a questionnaire after playing the game one cannot be sure if the player acquired experience as planned while designing a game (van den Berg et al., 2017).

In order to deal with above-mentioned threads and designs, the game with the highest learning benefits developer must choose an effective design approach. Triadic game design approach (Harteveld, 2011), presented in Figure 16, can help the design of a good game. According to this approach, a good game is one that balances reality, meaning and play. Harteveld (2011) describes Reality, Meaning and Play as three separated worlds that are equally important, but the people there, their disciplines, as well as aspects and criteria, differ. In order to make a balance between these worlds, it is important to consider them simultaneously during the most critical moments of game design process: (1) prototyping, (2) testing and evaluating and (3) continual redesign. This is done until the requirements of the three worlds are met (van den Berg et al., 2017).

![Figure 16. TGD design space (Harteveld, 2011)](image)
**World of Reality** presents the connection of the game to a physical world, so players will not consider the tasks required impossible. If the designer adds few intuitive elements to the game, it will start to be meaningless and, as a result, players will be less enthusiastic and less interested in playing it. Thus, the design requires from the developer domain-specific knowledge.

**World of Meaning** is related to the learning objectives of the game and the values that should be achieved by playing a game and established for both players and observers. Without a meaning, players will get bored and lose enthusiasm and the observer will not be able to build conclusions from the observations.

**Worlds of Play** is related to the goals of the game and established rules. Developer must be creative while designing a game and come with the story, goals, rules and interactions that will keep players interested in the game and enthusiastic. There must be a balance between fun and learning.

There are four basic game elements that a developer can balance between these three worlds. Those elements are: (1) Mechanics, (2) Story, (3) Aesthetics and (4) Technology (Schell, 2015).

**Mechanics** includes procedures and rules of the game. There are many mechanics described in literature. Thus, only the ten most important and interesting will be mentioned here. These mechanics are (Schell, 2015): (1) Space, (2) Time, (3) Objects, Attributes and States, (4) Actions, (5) Rules, (6) Skill, (7) Chance, (8) Epic Meaning, (9) Viral Game Mechanics, and (10) Virtual items.

**Story** is connected with the game mechanisms. When the game story is established and developers know what they want to say through the game, the game mechanisms can strengthen that story.

**Aesthetics** describes what the game looks like. Depending on the story, the game can have multiple shapes. For instance, if the story takes place on a construction site, probably the board of the game and all associated objects, such as cards, pawns and dices, should be related to construction. A good design of board and elements’ can enhance the feeling of a player that the game is taking place in real-world.

**Technology** influences aesthetics of the game, its story and mechanics. It is, not only a high-technology, but also all materials that can be used to build a game.

Based on the serious-gamming theory and inspired by colleagues, I have developed a Test Trench Locations Decision Game. This approach was challenging, as the participants had to face situations they were not prepared for and to explain their choices. We provided them with a map of underground utilities, extracted from Cadastre’s KLIC system (Kadaster, 2016). It is the same map used every day by construction companies before and during excavation. On the map I superimposed the following projects: (1) building a new parking place, (2) placing new fibre cables and connecting them to houses and (3) replacing an old sewage system. In addition, I included obstacles, such as trees and waste containers, to make the assignment more difficult and to influence the utilities path. The game board, together with examples of the results, are shown in Figure 17.
Figure 17. Test Trenches Decision Game

The detailed description of scenarios is presented in Table 9.
Table 9. Description of scenarios used in Test Trenches Decision Game

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong></td>
<td>The design assignment was to replace the sewage system on the area, which is marked using the red colour. First, test trenches were planned in the office, without view on area. Afterwards, I located some trees in the area to check if that will influence the decisions. Scenario 1 is visualised in Figure 18.</td>
</tr>
<tr>
<td><img src="image" alt="Figure 18. Decision-game: Scenario 1" /></td>
<td></td>
</tr>
<tr>
<td><strong>2</strong></td>
<td>The assignment was to build a new parking area, together with three underground waste containers. Afterwards, the trees were added to check if that would impact on made decisions. Scenario 2 is visualised in Figure 19.</td>
</tr>
<tr>
<td><img src="image" alt="Figure 19. Decision-game: Scenario 2" /></td>
<td></td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>The assignment was to bury and connect fiberglass data transport cable to the houses. This example is interesting because statistical data and interviews uncovered that many times the decision-makers decided randomly about test trenches for data transport cables projects because the cost of damage is lower. Also, those cables are buried shallow, so, in decision-makers’ opinions, it is not necessary to check the presence of other utilities. In this example, trees were added, as well to check if the decision would change. Scenario 3 is visualised in Figure 20.</td>
</tr>
<tr>
<td><img src="image" alt="Figure 20. Decision-game: Scenario 3" /></td>
<td></td>
</tr>
</tbody>
</table>

In order to check the behaviour of individual players, each of them received the small map of each project. The map was covered by transparent foil to perform further decision comparisons. On the foil decision-makers could mark test trenches using markers. Each test trench had to have its number and explained in the form as shown in Figure 21.
When participants received the questionnaire, it was used to analyse if correct information was being extracted as it helped to look more into the uncertainties that the decision-makers wanted to discover in different situations by digging the test trenches. The following questions are included in the form:

- **Why do you use test trenches? What is the most important factor/goal for you when you decide about number and location of test trenches? Do you want to explain some uncertainties?**
- **What are the normal steps you follow when you point out the places of test trenches?**
- **What kind of uncertainties do you want to expose? What do you want to explain?**
- **Which issue/problem has an impact on your decisions about where to make the test trenches? Do the obstacles (for example trees, street lamps) have an impact on your decisions?**
- **Do the house connection have an impact on your decisions? Please explain why, Yes or why No.**
- **In which way do the Cadastre maps support your decisions? How can they help you?**
- **Which information could help you? What would you add to the Cadastre maps?**
- **Do you have ideas about possible requirements for the future support tool? Write below what is important for you in the tool design (write below what you wish from a “perfect” support tool)**

The participants were asked also to evaluate a meeting, so that the game could be improved.
**Results**

Based on the interviews and workshops inputs the currently used strategy as described and visualised is shown in Figure 6 in section 1.3 *Current test trenches location system*. It presents set of questions that decision-makers asked themselves when they decided about test trench locations. The importance of these questions can be described as follows:

- **Did you notice any obstacles that can influence the underground utilities’ path?**

  It is not only trees, ground water level and type of soil, can influence the location of the utilities, but also obstacles, such as drinking water points, or transformation stations, that can have an impact on utilities paths and depth. The main factors that decision-makers want to check are: (1) **The depth**: the depth can differ from the norms, (2) **The path**: the path can be different than presented on maps of underground networks, (3) **The material**: to check if the utility must be changed (i.e. asbestos) or its durability is low and, thus, it is not possible to use some equipment because of, for example, vibrations (impact on work plan).

- **Are there any high risk utilities which are draw on the KLIC maps? (i.e. high pressure gas)**

  In order to avoid damages the exact location, depth and type of material must be checked.

- **Are there any houses to which connections are not included on KLIC-maps?**

  The cross points with house connections must be checked to confirm it location. It is important also for work planning, for instance, test trenches are necessary if the ground piercing is planned.

- **Are there any cross-points where networks meet?**

  Check to answer for questions: What kind of utilities are exactly buried there and of what kind of material are they made of? What is the depth of those utilities?

- **Are the utilities buried linear?**

  Check to confirm the information presented on KLIC-maps.

- **Do you see on KLIC-maps the situations that may cause subsequent problems?**

  The decision-makers must be aware and dig test trenches in the places that look suspicious on KLIC-maps or look ominous while searching the excavation polygon.
The workshops emphasised the importance of the decision-makers knowledge, the skills and the experience. At the end of the workshops, I took from each participant the foils with located test trenches and compared them. In addition, I informed decision-makers that there are no bad answers and I would like to discuss with them their choices. Some differences and similarities could be noticed in test trenches location, as can be seen in Figure 22 (designers) and Figure 23 (contractors). Each test trench colour represents a different expert. Nevertheless, sometimes participants agreed with propositions of their colleagues, or they neglected it by giving solid arguments. The discussion uncovered that, besides some well-known best practices, decision-makers locate test trenches according to the situations they have faced in the past. This finding directed me towards deeper studies of behavioural psychology in order to describe the logic behind made decisions.

Figure 22. Test trenches marked by designers.
2.2.4. Projects’ observation

During my PDEng project I observed two excavation projects and once took part in site inspection together with WION inspectors.

Goal

I have observed the projects and ask questions to responsible construction managers and/or job planners in order to:

- Learn how seriously contractors treat the necessity of digging test trenches;
- Learn if companies execute law and notify excavation to Cadastre;
- Learn if test trenches are dug according to plans;
- Observe how the process of digging test trenches look like;
- Learn how the use of new technologies can support location of test trenches.

Observed Projects

**Project A:** The goal of the project was to build a highway between two Dutch cities. Tunnels and bridges were planned requiring careful risk assessment before excavation starts. One construction company, after passing health and safety tests, permitted me to observe how test trenches are dug and how detection tools are used to track utilities’ linearity. Examples of observations are shown in Figure 24.
Project B: It was located in the centrum of Amsterdam.

The goal of the project was to locate utilities using ground-scanning techniques (Ground Penetrating Radar and Radio Detection) and, afterwards, based on findings, locate test trenches and check-holes. The examples of observations are shown in Figure 25.

Project C: It includes all the projects that I have inspected together with WION inspectors. Among these projects the following work was performed: (1) New fiberglass connections and (2) New gas pipeline together with connection to houses. For some we observed the result of digging test trenches as shown in Figure 26.
**Results**

We did not find an example of using data sharing software during inspections. Companies used mostly tablets with KLIC-map and paper maps on which test trenches were marked. During one project, when a manager was asked about test trenches, he mentioned that they were dug already, but he did not remember exactly where. All projects visited during inspections were relatively small. It was noted that there was little attention given to test trenches. They are dug because law requires them and their amount is limited to minimum to not incur cost.

Different observation were given by Project A and B which are relatively big. There is much attention on careful risk assessment. Thus, before and while digging test trenches, the scanning techniques are used. In addition, companies used internal databases and software to store, present and share data. Nevertheless, it was noted by responsible construction managers that how carefully test trenches are dug and how information is extracted from them and stored, depends on the job planner. If the job planners manage their people poorly and do not put much attention on job quality, then the risk of causing the damage is higher, whereas, if the job planners are also good managers, they control their people and watch over performed work.

**2.3. Analysis of existing decision-making process**

In this chapter the data collected through literature studies, interviews, workshops and projects’ observations will be analysed from two perspectives: (1) analytical and (2) naturalistic. Analytical decision-making analyses are based on the Simon Decision-Making model (Simon, 1977) and, in turn, the naturalistic decision-making analyses are focused on decision-makers’ experience analysis using models developed by cognitive psychologists (Klein, 2008a).
2.3.1. Analytical Decision-Making Perspective

Method background

The information from this chapter were included in my conference paper (Racz, Van Buiten, & Dorée, 2016b).

Sometimes decisions are easy, and, at other times, difficult. Sometimes the decision entails heavy responsibilities, and, at other times, it is not as important as we first thought. Depending on their character, people can make independent decisions often or in part based on preferences from authority figures. Consider, as an example, the relation between bosses and workers. Workers might always agree with their bosses just because they consider them to be smarter and more important.

To make the decision means to make use of information and choose an option among the best available possibilities (Ishibushi & Nii, 2000). A decision-making process can be thought of as consisting of four phases: (1) intelligence phase, (2) design phase, (3) choice phase, and (4) implementation phase. These major phases are known as Simon’s rational decision making model (Turban & Aronson, 2001). The model is presented in Figure 27.

![Figure 27. The decision-making process as (Simon, 1977) adapted by (Turban & Aronson, 2001)](image)

The Intelligence Phase is the first phase of a decision process that focuses on data collection, case investigation and, subsequently, on problem identification, classification and statement. If the decision-makers are experienced, in the ideal situation, they will follow general work practices. Nevertheless, the
problems, which will have an impact on decisions, may appear while the work is proceeding. If the problems are correctly identified then accurate decisions can be made.

The Design Phase is focused on finding the possible solution(s) for the problem(s). In other words, it is the treatment phase. The decision-maker needs to understand the problem and provide the solution that will lead to a successful problem-solving. One method used to find the solutions consists of the creation of an accurate model of the identified problems. The model will frame the scenarios, which decision-makers consider could happen. Afterwards, it will guide them for the accurate paths during searching for alternatives.

During the Choice Phase the decision about the solutions is made. The decision is preceded by selection of the best alternatives, analysis of sensitivity and model testing.

The solution is implemented during the last step of the decision process; namely the Implementation Phase.

Analysis

Test trenches location strategy can be analysed in line with decision-making steps described by Simons. According to this model, the results obtained during literature studies, interviews, workshops and projects’ observations were analysed and are presented in Table 10.

Table 10. Analytical decision-making perspective on test trench location process

<table>
<thead>
<tr>
<th>Phase</th>
<th>Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelligence</td>
<td>Firstly, all the excavators use the KLIC-online system to receive information about underground networks, which are buried, on excavation polygons. In addition, the KLIC-viewer and KLIC-app are used to read the data. Secondly, during the first step of investigation all of the interviewees compare the received maps (and documents) with the design drawings. These help to detect the conflicts between the design and the situation under the ground. Following the detection of conflicts, the dialogue with the network operators begins and, either the design can be changed, or the utilities can be replaced. The next important step is the analysis of the excavation area. Many obstacles can be noticed during the analysis of the surroundings, which may impact on the decisions taken. The factors that can influence a decision are, for example: trees, paths, houses, rails and roads. Some companies support their decisions by using Ground Penetrating Radars (GPRs). Steps described above help to identify the problems, which can influence the decisions. The following factors can have an impact on making decisions:</td>
</tr>
<tr>
<td></td>
<td>• Kind of work that must be done: type of work, how deep is the excavation, what kind of technology is used to dig;</td>
</tr>
<tr>
<td></td>
<td>• Presence of hazardous underground networks on the excavation polygon, such as high-pressure gas pipeline;</td>
</tr>
<tr>
<td></td>
<td>• Presence of obstacles, such as trees, roots, rails, houses, roads;</td>
</tr>
<tr>
<td></td>
<td>• Presence of house connections; the information about house connections is still updated in KLIC system.</td>
</tr>
</tbody>
</table>
Some companies use internal databases, such as ArcGIS, to store all the data. The software helps in data comparison and makes the process easier when it is necessary to look into previous steps. What is more, the decision-makers have to consider that the situation under the ground can differ from the drawings. For example, the amount of cables (they can be placed in one duct) or the pipes and cables can be wider because of joints (i.e. socket-welded and butt-welded joints).

**Design Phase**

Considering the factors and problems mentioned in the intelligence phase, the group of decision-makers (designers, coordinators, work planers and, in case of necessity of precautions - network operators) decide about the number and location of the test trenches. They have to deal with an important question: “**how to get the maximum amount of information from the minimum number of test trenches, and at the same time avoid the danger and minimise the costs?**” Several good practices were noticed during the interviews. In order to obtain maximum information, the decision-makers:

- Compare the design with KLIC’s maps. This helps them see which utilities can be affected by design. The comparison and dialogue with network operators may result in decision changes or agreement with network operator about replacing the pipes or cables;
- Store data in the internal databases, as well as in applications like KLIC-app (develop by GOconnectIT). This can help analysis if similar cases were already considered in the past. The information about good practices, but also about previous mistakes, can help workers to improve their job. In addition, where damage occurs, steps are needed to look into the work to identify what was done wrong. The database also supports the coordinators to control the work that was made;
- Observe the surroundings in the excavation polygon to consider obstacles.

**Choice Phase**

A careful analysis helps to determine the number of test trenches and their location. However, the decision is changed many times after digging the first trial trenches. Sometimes, the experienced workers have the feeling that more test trenches should be done, for example, because they had already seen similar cases. In one example given during the interviews, three test trenches were planned, but finally fourteen were made and, in the last one, it was found that the pipe was not placed linearly.

Results showed that when many contractors work on the excavation polygon, misunderstandings occur during communications about who is responsible to make a test trench. Finally, nobody carries out that work and, as a consequence, damage is made to the network. A good practice noticed during the interviews is the placement of a cover on top of the pipes to warn workers that the network is located under it and they should dig carefully. This warning sign can help when test trenches have been planned at that precise spot and an unexpected network has been discovered.

**Implementation Phase**

The choice made can result in success or failure. Success means that the work was executed without causing any damage, and failure means that damage was made to the underground network. Depending on the company, the report of test trenches location is prepared using computer software tools, a piece of paper or else it is completely omitted.
Analytical analysis resulted in a first prototype of Decision Support System (DSS) built by the student from Muenster University: Lars Syfuss (Syfuss, 2017). Using the data, he built DSS with 3D Semantic Subsurface Utility Models. Our collaborative work was presented at the International Workshop on Computing for Civil Engineering (IWCCE) in Seattle (Racz et al., 2016a).

**Problem statement**

The SWOT analysis is the technique that is useful to present and analyse the strengths and weaknesses of the case under investigation. The SWOT analysis for currently used strategies to select test trenches location is shown in Table 11.

Table 11. SWOT analysis of currently used test trenches location strategies

<table>
<thead>
<tr>
<th><strong>Strengths</strong></th>
<th><strong>Weaknesses</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadastre’s KLIC system;</td>
<td>Data stored in forms or in different folders;</td>
</tr>
<tr>
<td>Comparisons between drawings and maps;</td>
<td>Careful risk assessment is not always performed because of time pressure, thus decision about test trenches is based only on decision-maker experience.</td>
</tr>
<tr>
<td>Use of software and new technologies;</td>
<td>The databases and online sharing software are not often used;</td>
</tr>
<tr>
<td>Experience decision-makers;</td>
<td>Reports about damages are not often registered;</td>
</tr>
<tr>
<td>Best practices included in guidelines.</td>
<td>Communication problems between different contractors in the project often occurred.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Opportunities</strong></th>
<th><strong>Threats</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Support data sharing between units involved in project;</td>
<td>Doubt among some decision-makers about necessity of digging test trenches due to development of ground scanning techniques</td>
</tr>
<tr>
<td>Support users through careful risk assessment;</td>
<td></td>
</tr>
<tr>
<td>Encourage decision-makers to use new technologies;</td>
<td></td>
</tr>
<tr>
<td>Support test trenches reporting process.</td>
<td></td>
</tr>
</tbody>
</table>
2.3.2. Naturalistic Decision-Making Perspective

The information from this chapter was included in my conference paper (Racz et al., 2017c).

Analytical analysis supported me through analysis that aimed to describe the strategies currently used for selecting test trenches location. I identified several problems (weaknesses), but also solutions to cure them. The analysis was presented to the Support Group whose members described phases and steps typically followed by them. Nevertheless, behind this strategy there is an experience of decision-makers that plays a significant role in final test trench location decision. Thus, in order to understand the logic behind the described strategy and made test trenches decisions, I performed Naturalistic Decision Making (NDM). These are elaborated in this section.

**Method Background**

Researchers often develop Decision Support Systems (DSS) from an analysis of several decision models. However, I observed that this erred people towards the development of the system itself and de-emphasised a focus on its users. The system would then represent an idealised example of reality by excluding actual users from the decision process (Blanchard & Fabrycky, 2011). NDM researchers consider the DSS development process differently (Klein, 2008b). First, current strategies are analysed to examine how people behave during extreme situations where there is time pressure, uncertainty, unexpected conditions and/or risk (Klein & Klinger, 1991), rather than just simply checking whether people were effective or not. Civil engineering projects seem natural candidates for such an approach. Engineers and workers always perform their job under time pressure. The rush commonly results in mistakes with potentially dangerous consequences. In addition, construction work puts considerable responsibility onto the persons involved, when the work must also be done within environment and health and safety regulations. Typically, problems do naturally arise during civil engineering projects. If these problems were correctly identified, an adequate response can be formulated.

Researchers have distinguished six types of problems (Ishizaka & Nemery, 2013; Roy, 1981): (1) The choice problem (select best option or reduce the set of options), (2) The sorting problem (classification into categories), (3) The ranking problem (from the best to the worst), (4) The description problem (option and their consequences), (5) The elimination problem (related to sorting problems), and (6) The design problem (identification of the goal or creating a new actions). Civil engineers often face these problems, while making decisions about work performance.

Even though modern technology helps to perform work more safely than in the past, there is always a risk involved. Some civil engineering works, such as excavation, are also very uncertain and require care. According to the literature (Lipshitz, Klein, Orasanu, & Salas, 2001), there are three forms of uncertainty: (1) inadequate understanding (insufficient situations awareness), (2) lack of information (incomplete or unreliable information) and (3) conflicted alternatives (difference between them is insufficient). Organisational units and people involved in the construction process have different experience and, even if they have the same data sources, their decisions may differ. Lipshitz (1993) identified nine NDM models. I would like to focus on three that, I believe, are applicable to the design project: (1) Rasmussen’s model
of cognitive control SRK, (2) Klein’s Recognition Primed Decision model (RPD) and (3) Recognition/Metacognition model (R/M).

Rasmussen differentiated three kinds of behaviour (Rasmussen, 1983): (1) Skill-based, (2) Rule-based and (3) Knowledge-based. Skill-based behaviour arrives from experience. The decision is made based on past information stored in the subconscious. In case of rule-based behaviour in decision-making, the unit will behave according to the rules set, because these have generated good results in the past. This kind of behaviour is typical for decision-makers who do not have enough experience, but know the rules needed to accomplish a task. Knowledge-based behaviour is assigned to new situations when there is no set of rules available. The units must first identify the problem, generate the alternatives to solve it and, finally, choose the best solution.

Psychologists Gary Klein, Roberta Calderwood and Anne Clinton-Cirocco created the RPD model to describe how people make decisions. Decision-makers based their decisions on experience by connecting the current situation with the solutions performed in the past (pattern-matching). There are three variations of RPD models that differ according to their complexity (Klein & Klinger, 1991): (1) Simple Match RPS, (2) Developing a Course of Action RPD and (3) Complex RPD Strategy. The RPD model cannot be used in the case of knowledge-based behaviour, multi-criteria analysis cases and Search-for-Dominance Structure (SDS) strategy (Klein & Crandall, 1996). Variation 1 describes a situation well known to decision-makers. Thus, they can easily simulate what the further scenarios are and notice the typical signs that indicate the use of particular solution. Conversely, in variation 2, the situation is not so easy to diagnose. Hence, decision-makers need to collect more data and/or assess the situation by looking into their past experience. Sometimes, decision-makers do not know which solution to select for the case (variation 3). However, in case of NDM methods, the choice of the best solution is not done by Multi-criteria Decision Analysis, but by generating a single action using mental simulation of possible scenarios. Nevertheless, even the most experienced decision-maker can make mistakes. The possibility of failure should always be considered. Human failures are distinguished by researchers (Embrey & Lane, 2005) from errors (which are related to the skill, rules and knowledge-based behaviour) and violations (which are exceptional or caused by routine). The types of errors are presented in Figure 28.
The Recognition/Metacognition (R/M) model, compared to the RPD, focuses on the situations when decision-makers fail, while recognising the case (Lipshitz et al., 2001). The incorrect situation recognition leads to the renewed data evaluation. Decision-makers need to elaborate situations (recognition), add missing data, and modify the strategy when there is: insufficient situations awareness, incomplete information or conflicted differences between alternatives (metacognition). The R/M model reconciles, both pattern-matching recognition, and problem-solving strategies (Azuma, Daily, & Furmanski, 2006).

**Analysis**

The interviews and workshops uncovered that decisions about the number and location of test trenches depended on the following factors: (1) stage of the project (orientation test trenches during design, test trenches dug before starting the excavation or test trenches dug when the repair to the utility is necessary due to system failure), (2) type of work (i.e. building a new road or replacing the sewage system), (3) actions taken (i.e. drilling, open excavation or trenchless methods), and (4) decision-makers’ and their experience.

Decision-makers used a set of good practices, such us digging test trenches, when there are doubts about the accuracy of utility maps, or when high risk utilities, such as gas pipelines, are present in the excavation area, or when many cables and pipes cross over one another.

During the workshop, we noticed how fast some decision-makers took decisions. This was clearly related to their knowledge and experience. In some cases, they could decide if the test trench was necessary, or not, because they had faced similar situations before. For example, if a water pump station was present on the excavation area, the experienced decision-maker knew the depth of associated utilities could
differ. Some decisions, such as checking the area up to 1.5 m from the excavation place, were influenced by (legal) rules (CROW, 2016) that establish best practices. Nevertheless, designers and contractors can face situations new to them. Furthermore, the decision as to whether an excavation should happen should not be made in a hurry, but proceed only after careful case-by-case analysis. If information was insufficient, then the information gaps need to be addressed before taking a decision, so as to reduce uncertainty (R/M model). Thus, the situation should be well identified, the tasks made clear and planned properly using the best available techniques (i.e. maps, ground radars and best practices).

The current behaviour of decision-makers is presented using the SRK model in Figure 29. It is based on the example of the water pump station discussed during workshop sessions. Only four of the twelve decision-makers decided it necessary to dig test trenches near the pump because the depth of the utilities can differ relative to the other parts of the excavation area. They supported their choice by using an example from their past experience (skill-based behaviour). Other participants agreed with their suggestion. The decision was also influenced by the set of rules (rule-based behaviour). To reduce the risk of failure, decision makers used, for example, the 1.5 m buffer. This ensures that no utility will be damaged while executing the work. Nevertheless, new situations could be identified using available technologies (knowledge-based behaviour). During the interviews, we observed cases where damage occurred because of a lack of a correct situation assessment. For instance, in one case, the age of buildings influenced the material and depth of the utilities and this was not taken into account by decision-makers.

Figure 29. Rasmussen’s model of cognitive control SRK for test trench location process (adopted from Rasmussen (1983))
Many strikes are attributable to the lack of the information on the utilities maps. However, the relation between SRK behaviours and the failures can be noted as well. The damages to the utilities could be avoided by correct assessment of the situation. Most are caused by:

- removing the trees;
- absence of the network operator supervisor,
- excavation machines (if utility marked on KLIC), and
- misunderstandings;

Experience sharing could be an interesting component of a future DSS. The excavation case could be analysed using data, not only from radars, maps, documentation and observations, but also by matching the situation to ones that had occurred in the past. The RPD and R/M models related to pattern-matching could be used by creating an experience database within the DSS. The new situations faced by decision-makers and best practices could be collected and updated. For example: how obstacles can influence the location and depth of utilities, the resistance of the material for vibrations, and so on. Based on the input information, the tool could look for patterns (using the RPD model variations) using algorithms and to present this to decision-makers by (e.g. warning signals). The information about previously dug test trenches can be also collected. So, if it is necessary to dig new test trenches, the decision-makers can have an overview of the past decisions and findings. Together with other techniques, this would help generate a more reliable risk assessment. A combination of analytical and naturalistic decision-models clearly could support better situation awareness, help to collect enough reliable information and, last, but not least, reduce uncertainty related to conflicts between alternatives approaches (i.e. dig one, two or three test trenches).

**Problem statement**

The knowledge and skills of decision-makers play an important role in the decision-process influencing how many test trenches will be dug and where they will be located. Currently, experience is not shared among decision-makers. As a result, mistakes are repeated and test trenches are not located in places which only a very experienced decision-maker could assess as high risk. Their experience levels differ. They often face new situations. These can involve poor decisions or incorrect assumptions if they have to analyse large amounts of data. Furthermore, the use of different techniques, such as detection tools, utility maps, visualisation programmes and data management tools, can support decision process. However, decision-makers ultimately assess the risk of damage. Many people involved in the excavation process are not sufficiently familiar with the use of ground scanning methods. This can result in further incorrect assumptions about the situation. Thus, full automation of decision-making on how and where to locate test trenches appears to be untenable. Neither is it desirable, as it prevents leveraging expertise from those directly involved.

**2.4. Conclusions**

The summary of the uncovered problems is presented in Table 12. Identified problems do not pertain to all design and construction companies. However, they were often notified during problem investigation.
<table>
<thead>
<tr>
<th>No.</th>
<th>Identified Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Data storing methods are not always sufficient and information is lost;</td>
</tr>
<tr>
<td>2</td>
<td>Risk assessment for small project and, in case of works on data-transport cables, is often poor. Nevertheless for other projects there is a lack of careful risk assessment due to time pressure. As a result, test trenches are based often only on personal judgments of decision-makers.</td>
</tr>
<tr>
<td>3</td>
<td>Communication problems when many contractors are involved in the project. It is not clear who is responsible for digging certain test trenches;</td>
</tr>
<tr>
<td>4</td>
<td>Often lack of data sharing between involved contractors;</td>
</tr>
<tr>
<td>5</td>
<td>Lack of experience sharing between construction and design companies;</td>
</tr>
<tr>
<td>6</td>
<td>Decision-makers represent different level of knowledge, skills and experience;</td>
</tr>
<tr>
<td>7</td>
<td>Many times employees are unfamiliar with the use of scanning techniques which results in incorrect assumptions and, consequently, in erroneous test trench location;</td>
</tr>
<tr>
<td>8</td>
<td>Computer support is not always used in order to visualised test trench location;</td>
</tr>
<tr>
<td>9</td>
<td>There is a doubt among some of decision-makers about necessity of digging test trenches with current level of development of ground scanning techniques. Hence, they dig test trenches simply to fulfil the law;</td>
</tr>
<tr>
<td>10</td>
<td>Poor reporting about performed test trenches location strategy. Often not made or stored in forms or computer folders.</td>
</tr>
</tbody>
</table>
3. System Requirements

The major step before performing design is the requirements specification as it defines stakeholders’ and users’ expectations and the needs. The requirements provide the foundation for system development and support system’s design when trade-offs must be done, or when changes are required in the development process (Hull, Jackson, & Dick, 2014). During the interviews and workshops the needs and expectations of the future Decision Support System’s (DSS) users were collected and evaluated together with the Support Group. This process is the subject of this chapter.

3.1. Requirements Engineering

Engineering literature (Hull et al., 2014) make clear that to define requirements well requires the problem be divided to manageable parts. There are variety of methods to support developers in gathering users’ needs and expectations as follows:

- Interviews with stakeholders;
- Workshops with decision-makers;
- Support Group meetings with stakeholders and decision-makers;
- Existing system analysis;
- Descriptive documentation studies;
- Prototyping.

Users’ goals were grouped hierarchically into five elements: (1) system element, (2) system, (3) business operations, (4) business management and (5) enterprise. Afterwards, they were transformed into needs and, finally, into requirements. Goals, needs and requirements are presented in Figure 30.
Figure 30. Users' goals, needs and requirements.
During the interviews goals and needs were gathered through the questionnaire, as described in the 2.2.2 Interviews. In turn, workshops scenarios encourage participants to share their expectation. Workshops were described in chapter 2.2.3 Workshops. The first meeting of the support group focused on requirements identification to confirm earlier information. Members of the group were asked to write DSS functions which, for them, had high, medium and low importance onto pink, yellow and blue cards. The results are presented in Table 13.

Table 13. Expectations and needs that emerged from Support Group's meetings

<table>
<thead>
<tr>
<th>Importance</th>
<th>Expectations</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Experience sharing;</td>
</tr>
<tr>
<td></td>
<td>Situation awareness (using GPS for positioning);</td>
</tr>
<tr>
<td></td>
<td>Motivation to use (regarding to concurrence on market);</td>
</tr>
<tr>
<td></td>
<td>Available database;</td>
</tr>
<tr>
<td></td>
<td>Precise data processing;</td>
</tr>
<tr>
<td></td>
<td>Exact interface determination;</td>
</tr>
<tr>
<td></td>
<td>Appropriate record (arguably/probably) of collected data;</td>
</tr>
<tr>
<td></td>
<td>Information sharing about the findings while digging test trenches;</td>
</tr>
<tr>
<td></td>
<td>Include the expression of share data;</td>
</tr>
<tr>
<td></td>
<td>Form of application (easy to use on construction site), help functions;</td>
</tr>
<tr>
<td></td>
<td>The tool must be used during preparation phase of the work;</td>
</tr>
<tr>
<td></td>
<td>Tell how many test trenches are necessary so client can determine the budget in advance;</td>
</tr>
<tr>
<td></td>
<td>Compulsory input by network operators and about house connections; compulsory test trenches for all the excavators; compulsory determining the anomalies; photos of made work; information about test trenches made my concurrencies (fixed price);</td>
</tr>
<tr>
<td></td>
<td>Workable, simple, easy to update, clear legend, easy to use, for both easy and complex projects;</td>
</tr>
<tr>
<td></td>
<td>Taking into account crossings with culverts, other crossing points, high voltage for which in case of damage the consequences are larger;</td>
</tr>
<tr>
<td></td>
<td>Objectify to making the intuitive decisions about location of the most important test trenches to make- that can make the conversation with the client about compensation of test trenches easier;</td>
</tr>
<tr>
<td></td>
<td>In case of gas pipeline: focus on the depth, the same for the medium voltage electricity cables;</td>
</tr>
<tr>
<td></td>
<td>Tool should allow for deviation of the suggested test trenches location if the risk of damage is consider (for example the medium risk on level of 30 and law of 35);</td>
</tr>
<tr>
<td></td>
<td>Decision-maker can give feedback on made choices;</td>
</tr>
<tr>
<td></td>
<td>Distinction of decision according to type of work;</td>
</tr>
<tr>
<td></td>
<td>Distinction depends of the phase of work (design or excavation);</td>
</tr>
<tr>
<td></td>
<td>Give the reason why this test trench was suggested (freedom of choice);</td>
</tr>
<tr>
<td></td>
<td>Distinction of importance of each test trench (may be necessary and a proposal);</td>
</tr>
<tr>
<td></td>
<td>Offer condition for making test trenches (e.g. know from the manager or perhaps from the department of environment and flood defence).</td>
</tr>
<tr>
<td>Medium</td>
<td>Distinction between old and in-service utilities.</td>
</tr>
<tr>
<td>Low</td>
<td>The client and contractor stay together behind the situation;</td>
</tr>
</tbody>
</table>
The second meeting discussed system prototypes as follows: (1) Lars Syfuss (Syfuss, 2017) Decision Support System, and (2) Risk assessment Decision Support System prototype developed by me. Decision-makers were impressed by Lars’s DSS. However, they all agreed the importance of users’ feedback and this cannot be automated. Lars’s DSS is visualised in Figure 31. In turn, DSS based on risk assessment was found by them to be an interesting solution as it does not supersede decision-makers, but supports them in making decisions. Nevertheless, they had several comments as to how the tool should be. The major requirement was that all operation must be mapped, so everyone involved will not have a problem using the DSS. My prototype is shown in Figure 32. The following remarks were shared during the meeting:

- The representation of risk should be graphical where the level of risk is presented using different colours i.e. red for high risk, orange for medium risk and green for low risk;
- Tool should focus on both design and construction phase;
- Segment division of the map should be re-thought, so that the user will receive precise location of test trenches;
- The project size and utilities’ slope should be considered;
- The risk assessment should take place on map, and score distribution should be automated (i.e. clicking on map);
- Tool must support decision-makers and not supersede them.

*Figure 31. Lars Syfuss DSS (Syfuss, 2017): A) Utilities at the University of Twente campus; B) System generated test trench location with high priority (green) and low priority (red); C) DWG file of subsurface utilities at University of Twente Campus; D) generated 3D semantic model*
Other needs and expectations are presented in Figure 30. *Users’ goals, needs and requirements*, were specified through analysis of current decision making strategy and problem investigation.

The process of the problem investigation and analysis, requirements engineering and initial prototyping directed me towards the development of the final solution. This chapter describes the final prototype of a Decision Support System (DSS). First, a brief overview will be given, then the system will be described and its architecture explained. Finally, the designed prototype will be presented and the chapter will be finalised with verification, validation and conclusions.

4.1. Overview of the developed Decision Support System

The Decision Support System is a computer-based tool to assist decision-makers, supporting them - rather than replacing them - to improve the effectiveness of decision-making (Blanning, 1979) in test trench location. Analysis shows problems appear in all decision-making stages. In the intelligence phase, where there is an emphasis on data collection, many companies do not combine several methods of data collection, but use only one or two of them. For instance, they use only KLIC maps of underground utilities and analyse excavation site by using programmes such as Google maps. Moreover, data are stored in several folders. Thus, there is a risk of missing important information. Next, often in the design stage, there is a poor risk assessment. This leads to incorrect assumptions and an absence of test trenches in high-risk spots. This is especially noticeable for the small projects and the projects related to data transport cables. Consequently, during the choice phase, some test trenches are omitted due to the different experience of decision makers. Experience is not shared between companies. Therefore, when decision-makers face new situations, they might not associate these with any higher risk of damages. Finally, there is often no reporting of test trench locations decision-making process as performed or, it is only documented on a piece of paper or using photos. In addition, communication problems were noticed in all stages; especially when many contractors are involved in the project. Communication problems between involved units can lead to misunderstanding and, subsequently, to excavation damage. The risk assessment solution was proposed as visualised in Figure 33.
The core of the system is a risk assessment. The generated risk map provides decision-makers with locations in which the damage is most probable and suggests test trenches are located there. Nevertheless, the designed DSS is not automated and requires users’ involvement and their feedback to make the risk calculation more accurate. Moreover, DSS assists decision-makers in data collection and supports them with data aggregation and situation visualisations. As the result, data and information, that can increase level of risk, are not missed (especially by less experienced decision-makers). The details about the system, its functions and components are described in following subchapter.

4.2. Glossary

The following abbreviation might appear in this chapter:

- **DSS**: Decision Support System.
- **H&S**: Health and Safety.
- **Obstacles**: elements that can influence the location of underground utilities, such as: trees, underground waste containers, sanitary fittings, transformation stations.
- **Decision-makers**: designers and contractors.
- **Python**: Open source programming language.
- **ArcPy**: Python site package, which provides code support for spatial data analysis.
- **Python Add-in**: plugin for ArcGIS which extends its functionality.
• KLIC system: A Cadastre’ utilities’ mapping system that provides the users with the maps of the underground space, together with an important documentation.

• KLIC-WIN: New version of KLIC system, which will be implemented in the beginning of 2018. Users will be provided with utilities vector data that will simplify the analysis process.

4.3. System Description

This section presents information about the choices of software, system functions, users’ characteristics, operational scenarios, system constraints and development risks.

4.3.1. System functions

In order to support and assist users in test trench location decision-making, the system must perform a number of functions often missed in current strategies. The functions were specified based on data gather through interviews and workshops and they result from requirements specified in chapter 3 - System Requirements. These functions are as follow:

• **Assisting**: DSS assists decision-makers in data collection with information vital because of its influence on the risk of damage. Thanks to this function, the information is not missed, especially when there is a time pressure; a frequent reason for errors, or when a less experienced decision-maker is in charge of final decisions.

• **Aggregation**: All collected data are stored in a database in the software. Compared to the current situation, where often data are located in different files, it ensures that information will not be missed.

• **Selection**: In order to ease the data collection process, DSS provides list of elements for some risk factors so decision-makers do not have to spend their time filing the forms. For instance, for factors such as, water level, users can choose among answers, such as high, medium and low. Moreover, when risk is calculated, DSS analysed each cell by selecting from a database the factors that are inside those cells and which increase the risk of damage.

• **Visualisation**: Collected data, as well as results of an analysis, are visualised on the map in 2D or in 3D. Decision-makers receive the visual overview of the situation on construction site, as well as the information about test trenches digging progress and findings when DSS is used online.

• **Equalisation**: DSS uses data collection from the experience database to calculate a risk of damage.

• **Simulation**: Risk is calculated by multiplying the probability of damage by its consequence level when a damage might occur. A generated risk map is the visual image of scenarios that could happen when decision-makers do not dig test trenches in the appointed spots. The simulation aims to make decision-makers aware of consequence of their decisions.

• **Compatibility**: Designed DSS is compatible with other engineering programmes, such as Computer Aided Design (CAD), Infraworks, Excel and FME, amongst others.

• **Learning**: Designed DSS is a self-learning tool. It requires the feedback from the decision-makers when they locate test trenches other than in the proposed places. Feedback has an influence on
risk scores estimated within the DSS as designed. Those scores were defined based on the experience of a group of decision-makers and experience of other experts may make them more accurate and, as a result, improve accuracy of a generated risk map. Also, the information provided after digging test trenches, and after performing excavation process, will influence the risk calculation. New situations faced by users, findings in test trenches and caused damages may indicate other factors, or their elements, that were not included during design, but they have major influence on the level of risk.

- Reporting: Currently, reports of test trenches are not generated and information are stored in different files. This makes it difficult to analyse the project performance and learn from any mistakes. Thus, designed DSS generates the report at the end of excavation process and sends information about new situations, findings in test trenches and damage caused to the experience database.

4.3.2. User’s characteristic and objectives

Decision-makers (designers and/or contractors) are the main users of the system as they take the final decisions about test trenches location. Nevertheless, the information is shared with units responsible for job planning and work execution. Moreover, as a precaution, the network-operator supervisor might be involved in excavation process. The knowledge, skills and experience of these experts differ. Thus, the challenge was to design DSS to make it clear and user friendly. The members of the support group emphasised that, in order to make the DSS easy for all type of future users, all actions must be mapped and complicated data gathering forms should be avoided.

4.3.3. Software

Many companies use ArcGIS as the computer support for construction projects. Moreover, it contains many functions that are applicable for Decision Support System design. Decision-making processes often relate to problems of data analysis of geographic spatial components. Geographic Information Systems (GIS), such as ArcGIS, can help in spatial data analysis by providing a variety of spatial data operation tools. Moreover, input and output data can be visualised in each operation step. This function of GIS support decision-makers who need to analyse the spatial aspects of their decisions (Keenan, 2008). The best example of spatial relations is a map where geographic objects are related to each other. This relation can be based, for instance, on a geographic referenced coordinate system. Other objects can be added to the map, related to other objects and, finally, analysed. For instance, the spring flooding from several years can be plotted on map. This will help distinguish hazard areas and, later on, to apply the best solution to the problem. ArcGIS allows the user to deal with large amounts of data and provide functionality that can help to analyse data using many toolboxes or programming languages such as Python. It is also possible for the user to extend the functionality of ArcGIS by building Add-in using Python programming language and the ArcPy library. Moreover, ArcGIS developers continuously add new functionalities to the programme to support users and their requirements. In addition, even users with low programming skills
can use freely the ArcGIS library and forum to access solution examples to apply in cases they are analysing.

There are two approaches of data representation in GIS (Keenan, 2008): (1) raster approach and (2) vector approach. Raster approach uses a bitmap to represent data. Thus, a map is represented by pixels on the grid. Users can add values to each cell in the grid so they can represent data using colours. The example output of such approach is the risk map of the area. A vector approach is the kind of geometric data representation solution. Similar to the Computer Aided Design programmes (CAD) the shape objects are drawn and to these objects information can be added by creating the attribute table. There are three main vector objects in GIS: points, lines and polygons (areas) (Keenan, 2008).

ArcGIS represents data in two-dimensional (2D) way. Nevertheless, users wishing to represent three-dimensional (3D) spatial data can use ArcGIS pro.

ArcGIS can be considered as a Decision Support System (DSS) as it provides the user with the possibility of data calculation, analysis and visualisation. The research studies of Jarupathirun and Zahedi (2005) suggest that GIS system helps in better decisions compared to decision-making using paper-maps or several digital maps (one map for each type of objects). Moreover, currently GIS can be integrated with other decision tools such as CAD or scripting programming languages. Hence, ArcGIS was chosen as a platform for Test Trench Location Decision Support System.

4.3.4. Operational scenarios

There are two operational scenarios, one for a design phase and one for a pre-excavation phase. During the design phase, test trenches are dug to ensure that design fits the proposed place and, in turn, during the pre-construction phase, test trenches are dug to fulfil the law, to confirm underground utilities location and to ensure that excavation create damages resulting in project delays and additional cost. Hence, users highlighted that the future Decision Support System should differentiate users and, consequently, provide them with a solution aligned to their reasons for test trench location. The operational scenario is visualised in Figure 34. The differences between them are twofold: (1) Choosing user and (2) Risk Map generation. When starting using the tool, users have to state their goal by choosing their role in the project. Subsequently, during risk calculations, there will be a significant change in the algorithm. So, for designers, the clashes between present utilities and a design are taken into risk calculations and factors, such as soil type or work type, are excluded, as they are only important for contractors. Differences between DSS for contractors and designers will be described in detail in chapter 4.4- System architecture.
4.3.5. Constraints

Utilities are currently presented as polylines. This influences significantly the risk calculations, as the situation presented in a computer might not correspond with reality. If case utilities are presented as vector data, each will have a special ID and, as a result, it will be possible to find the intersection between utilities and path changes. In addition, elements that are built from many polylines will dissolve and not disturb the calculation. The example of the street lamp is shown in Figure 35. It is built from 20 polylines, which has a major impact of increasing the level of risk in this spot.

Moreover, the current tool works using a simple algorithm. This must be transformed into a self-learning algorithm to improve risk calculations. In addition, other factors must be added, such as influence of situations (intersections with many utilities, path changes and path linearity), project phase (design or construction), which are currently not a part of the algorithm, due to polyline representation of data.

The plugin is designed using python programming language. It is complex to create a graphical user interface (GUI) using python in ArcGIS. Thus, the developed interface is simple compared to the one that could be achieved using other programming languages, such as Visual .NET or Java; both supported by ArcGIS as well.
4.3.6. Development risk

Development risk for the described project can be divided into prototype development and final system development. During the design, I faced the following development risks:

- **Schedule problems**: Concurrent to the design work, I had to follow course works. Thus, I risked not having enough time to work on the prototype. Furthermore, I had to schedule meetings with the support group. This was not easy given the limited availability of the group's members. There was a threat that I would not be able to gather data and feedback for the next design step.

- **Time pressure**: According to the Professional Doctorate in Engineering (PDEng) trajectory, one year was dedicated towards education. Thus, it was challenging to organise work and finalise design, verification and validation on time.

- **Budget problems**: I had to look for software not requiring large financial investments from the potential future users.

- **Requirements problems**: There were many requirements gathered during the problem investigation phase. It was a challenge to fulfill those requirements and design an effective and user-friendly tool. In addition, there was a risk should future users have expected a fully completed development of the products.

- **Data availability problems**: There was a threat of being able to gather all data to perform risk calculation. Members of the support group provided some data. Other data I had to search through open source databases or in the literature.

- **Knowledge and skills problems**: Problem investigation indicated computer-based support system as the most effective solution for a given problem. There was a risk I would not be able to obtain the necessary skills in time to apply them in my design, as I had no prior experience with programming.

In turn, future DSS developers will face following risks:

- **Technical risk**: A developer needs to improve the prototype of DSS and add advanced functionalities, such as self-learning. There is a question as to whether the information provided with prototype is sufficient to improve DSS and implement it. Furthermore, there is a risk regarding the maintenance of the DSS and the control of feedback and information provided by the users. The developer must ensure that information potentially compromising risk calculations could be not taken into consideration.

- **Business risk**: User representatives showed an enthusiastic interest in the tool during prototype development. However, there is a danger that companies may not want to implement it given their own decision systems, implementation schedules, necessity of training or for a lack of motivation. Thus, developer will need to find a way to encourage customers to use a tool to avoid its demise.

- **Customer risk**: There was a big concurrence sensed in the construction market that users’ will not want to share their experience and findings. Thus, DSS will not be able to learn from users and
collect data about new situations, findings and caused damages. Consequently, the risk algorithm will not be improved.

4.4. System architecture

It is important to describe the architectural knowledge of the system and its components while working on functional specification. First, it supports system’s architecture in the improvement process. Second, it simplifies the information sharing process with stakeholders. Last, but not least, it provides the developer with all necessary information about the system and, as a result, expedites the development process (Borches & Bonnema, 2010). In this subchapter the DSS’s architecture is described.

4.4.1. System architecture diagram

In order to help readers understand the system’s elements and communicate and clarify ideas about system’s structure, a system architecture diagram was prepared. This diagram is shown in Figure 36.

![System Architecture Diagram](image)

**Figure 36. The System Architecture**

The system is built from three types of elements: (1) Users, (2) Databases and (3) Problem Processing System. These interact between each other to provide information about the places where test trenches should be located. Absence of any of those elements would reduce the risk assessment accuracy or even make calculation impossible. The detailed information about system components is described in following subchapters.
4.4.2. System components, their attributes and relations between them

System component and relation between them is visualised in Figure 37.

The visualisation gives a general overview of components and their relations. Nevertheless, in order to understand their goals and attributes, a more detailed explanation is necessary. These components are described in more detail in Table 14.
Table 14. The System’s components, their goals and detail description

<table>
<thead>
<tr>
<th>GOAL</th>
<th>COMPONENT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support careful risk assessment and test trench location</td>
<td>The Problem Processing System</td>
<td>The system performs the main operations, such as probability score calculation, level of consequence calculation and, finally, the risk calculation. Based on the calculated risk, it suggests test trench location. Nevertheless, calculations cannot be performed without data. These are provided by users and stored in a database, as well as data stored in the experience database. The system divides the selected excavation area into small tiles (depending on user requirements about level of detail) and searches them to find which elements influence the probability/consequence level are present within them. In addition, the system checks if, within selected area, there are elements that are indicated from the experience database that increase risk of damage. These are marked on the map and incorporated into the algorithm as they can increase the level of risk. The system always requires feedback from users when they disagree over any proposed test trench location. However, it is important that the system controls user feedback to avoid false information disturbing the risk calculation process. Furthermore, the final test trench locations are shared with all units involved so they can track the digging progress.</td>
</tr>
<tr>
<td>Assist in data collection and support data aggregation.</td>
<td>Information database</td>
<td>This is the part of the Information database that includes excavation site information and project information. It aims to assist users in data collection so they will not omit information having a major influence on risk level. The system reminds users about uploading KLIC maps, select excavation polygon and provides ground-scanning result, if possible. Moreover, users are asked to define what type of work they will perform, what is the land use, water level, soil type and locate and define obstacles (i.e. trees, underground waste containers, sanitary fitting, transformation stations). All information is stored in databases to which users have easy access.</td>
</tr>
<tr>
<td>Support Experience sharing</td>
<td>Global Experience database</td>
<td>The base probability and consequence scores for factors that influence the level of risk were defined with experts while designing the system. Nevertheless, user feedback on generated risk and information about new risk factors might influence the scores, as the idea of the tool is that it will learn from users’ experience. Experience sharing is especially useful for less-experienced users who think the system may learn about the situations that have an impact on utilities location. It will also support more experienced users as underground space is very uncertain and it can bring multiple new situations. Furthermore, the information about previous damage and test trench findings might be stored in the experience database.</td>
</tr>
</tbody>
</table>
so that excavation can take place again in the same location and ensuring the awareness of next contractor will increase.

<table>
<thead>
<tr>
<th>Support visualisation</th>
<th>Risk map Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using the system, users receive a complex view on excavation site. Furthermore, the calculated risk is also projected on the map using colour description - red indicate high risk; yellow medium risk; and, green low risk. Colour representation even allows less educated users to understand a map and be careful while performing work.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Support test trench location</th>
<th>Test Trench Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated risk indicates places where it is necessary to locate test trenches due to high or medium level of risk. Test trenches might be automatically added to the map after risk calculation, but it must be done according to the procedure so perpendicular to the checked utility. Nevertheless, the system is a self-learning tool. Thus, users might disagree with it and indicate the necessity of digging test trenches in places that have low level of risk according to DSS. When users disagree with the system, they need to provide feedback so that system could learn from it.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Support information sharing</th>
<th>Performed Project information database</th>
</tr>
</thead>
<tbody>
<tr>
<td>The interviews and workshops indicated that planned test trenches are often omitted when many contractors are involved in the project and when it is not clear who is responsible for certain test trenches. Thus, in addition to supporting test trench location, the DSS should allow responsible decision-maker to share test trench location among involved contractors and track the progress by asking job planners and machines’ operators to provide information about progress of digging test trenches, findings in them and about any damage caused.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Support reporting</th>
<th>Report Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>While asking interviewees about reports of test trench decision-process, it was noted that many companies do not have such reports. Furthermore, any reports are often not generated, even for Cadastre when damage is notified. Thus, it is difficult to track the reasons of damages and improve risk calculation on additional factors that might be crucial for risk calculation. Hence, the valuable functions of the DSS would be generating report of all decision process. Some of reported information might be added to experience database as was indicated earlier in this table.</td>
<td></td>
</tr>
</tbody>
</table>

4.4.3. Users’ influence

The users have significant influence on risk assessment results because the system aims to support and assist decision-makers, rather than replacing them by automating the decision-process. As indicated on the system architecture diagram in Figure 36, there are two types of users: one that uses DSS to take
better decisions about test trenches location; and, one that uses it to perform their work. Among the first group are designers and contractors. The tool assists them in data collection and afterwards as they provide the feedback to the system when they disagree with risk assessment. Their knowledge, experience and skills differ. Thus, by using the DSS and providing feedback, they can learn from each other and increase awareness of less experienced colleagues. The second group of users are job planners, machines operators and network operators. The DSS helps them to track the project progress and, as a result, avoid miscommunication. In addition, they can indicate stage of work, findings, unexpected situations, and caused damages and, in this way, also contribute to improving risk calculation. In turn, network operators might indicate precautions where needed and use the DSS to control the location of their utilities. The ideal contribution of network operators to the system would be if they would agree to share the information about previous damages caused to their utilities and reasons for them.

### 4.5. Prototype Design

The final product of my PDEng Project was my design and development of the prototype of the Decision Support System with the system architecture as described in the previous sections. This prototype is a simplified version of the final tool and has various possible directions for any final development.

#### 4.5.1. Overview of the developed DSS

Figure 38 overviews the developed prototype and visualises as a flowchart the steps decision-makers take to generate a risk map and locate test trenches. Compared to the earlier system architecture, several elements are missed, such as user selection (design or pre-construction), project information sharing and report generation, to make development simple, given the limited time frame of the project. It was decided that the most important task was to fulfil the goal of the project; namely to focus on elements that by design could make test trenches location decision-making process even more efficient in the final DSS.

The section first describes the software and programming language used and then the various steps of a new Decision Support System. Finally, the designed prototype is verified and validated.
4.5.2. Software and programming language

The prototype was developed using ArcGIS software. This had several advantages as already mentioned. To make spatial data analysis more effective, to simplify data collection process and to automate some DSS functions, the Python programming language was used. Data collection support functions and risk assessment system were built using the ArcPy site package. This was specially developed for ArcGIS users who want to perform spatial data analysis using Python. The ArcPy package provides code completion, documentation, function, modules and class which can transform ArcGIS into a powerful spatial data analysis tool (Esri, 2017). In order to simplify the development of extended ArcGIS functionality a Python Add-in wizard (see Figure 39) was used. This add-in supports beginner python users to build classes, combo boxes and simple functions, such as reactions for a mouse click. The source code will not be shown in this report because of Intellectual Property Issues. Nevertheless, several algorithms were coded in Python using Notepad ++. These include algorithms for: (1) Data aggregation, (2) Excavation polygon generation, (3) Experience data base support and (4) Risk calculation and interoperation between them.
The map of the Netherlands was obtained from the open library of ArcGIS. In addition, some received data, such as utilities from KLIC map, were transformed to the shape format readable for ArcGIS. Thus, the utilities were uploaded to AutoCAD, saved in dwg format and, afterwards, using FME software, they were transformed to the shape file.

4.5.3. Data Aggregation

The first step that users need to conduct is data collection. Users are asked to add all available data, such as KLIC maps, results from ground scanning devices, design project and other information about excavation site and the project that they are dealing with. In addition, using obstacle location functions, they can locate excavation site elements that may increase the risk of damage. In the case of the developed prototype, only the tree location function was available. However, it is highly recommended that users have the possibility to define any obstacles they want to locate. This could be implemented using a menu with obstacle types. As indicated by experts, safety buffers are generated around utilities and obstacles because it is notified by Cadastre that the real location of elements might differ up to 1.5 m compared to the drawings.

The tool reminds the user to add information about factors that have high impact on increasing the risk of damage. Hence, combo boxes for land use, work type, water level and soil type where predefined. The combo boxes ensure careful site and project analysis and fasten the data collection process, as users do not have to upload information themselves, but only select from available options.
The developed DSS supports data aggregation and all collected data are stored inside software in databases. As a result, data are not divided and they might be easily access by decision-makers by selecting the element and opening its attribute table. The databases eases later calculations because the programme can search them and select the necessary information.

The overview of the data collection and the data aggregation is visualised in Figure 40.

Figure 40. The overview of data collection and data aggregation process
4.5.4. Excavation Polygon Generation

The developed system allows user to draw an excavation polygon. Moreover, the 1.5 meter buffer is generated, together with a polygon, as indicated in legislation (CROW, 2016). Generated excavation polygons, together with all added data, give the user images of the situation on an excavation site and provide information for further risk calculation. An example is shown in Figure 41.

![Excavation polygon generation](image)

Figure 41. The excavation polygon generation

4.5.5. Global Experience Database

The experience database is an important element of DSS. Feedback and information provided by users influences the probability and consequence scores used in risk calculation. In prototype development only the information about previously damage were uploaded to the database. However, it can be easily extended for additional information, such as new situations and test trench findings. This element of the system requires several improvements in order to support decision-makers in the way that it should really mean to. For prototype development, the self-learning function was omitted and the algorithm to enable
this was not built. The example of the experience database containing information about previously damages and their reasons is presented in Figure 42.

4.5.6. Risk Calculation

The risk calculation is performed using uploaded excavation and project information and information from experience database. It is performed in 5 phases:

- **Phase 1: Defining risk factors and consequence factors**
  Based on performed interviews, workshops and analysis the factors, which increase probability of damage, and factors, which increase the level of consequence in case damage occurred, were defined. Among the factors that increase the probability of causing a damage are: (1) utility type, (2) utility material, (3) project size, (4) work type, (5) land use, (6) water level, (7) soil type, (8) crossing and path changes, (9) previous incidents and (10) obstacles. In turn, level of consequence where damage occurred is checked for utility and land use from three perspectives: (1) project economy, (2) impact on environment and (3) impact on health and safety of works and people living in the neighbourhood of performed excavation. The detailed description of elements included in each factor is presented in Appendices 2 and 3.

- **Phase 2: Assigning damage probability and consequence scores**
  Together with WION’s inspectors (WION, 2008) the scores for each risk factor were defined and afterwards evaluated with the experts. The 1 to 10 scale was used to estimate the influence of each factor on increasing risk of damage. The explanation of the scale is provided in Table 15.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Likelihood</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Extreme risk of damage</td>
<td>Extreme consequences</td>
</tr>
<tr>
<td>8</td>
<td>Strong risk of damage</td>
<td>Strong consequences</td>
</tr>
<tr>
<td>6</td>
<td>Moderate risk of damage</td>
<td>Moderate consequences</td>
</tr>
<tr>
<td>4</td>
<td>Slight risk of damage</td>
<td>Slight consequences</td>
</tr>
<tr>
<td>2</td>
<td>Very low risk of damage</td>
<td>Very low consequences</td>
</tr>
<tr>
<td>1</td>
<td>Damage improbable</td>
<td>Not important</td>
</tr>
</tbody>
</table>

Table 15. The explanation of scale used to defined risk scores
The result of assigning probability and consequence scores are presented in detail in Appendices 2 and 3.

- **Phase 3: Saving scores in a programme library**
  The assigned scores are saved in different variables and are further used in the risk calculation. The user should have an impact on score values by providing feedback on assessed risk and by adding additional information to the experience database. Nevertheless, when the developed prototype scores are unchangeable the self-learning algorithm is not incorporated.

- **Phase 4: Generating excavation polygon tessellation**
  When users have already drawn an excavation polygon, they can divide it into small pieces depending on what level of detail they want to receive and perform risk calculation. They can chose between: low, medium and high levels of detail as calculated using Equation 1.

  \[ \text{Equation 1. The level of detail of the risk calculation} \]
  \[
  \text{Level of detail} = \frac{\text{excavation site area}}{K}
  \]
  where:
  \[ K = 200 \text{ when high level of detail} \]
  \[ K = 100 \text{ when medium level of detail} \]
  \[ K = 50 \text{ when low level of detail} \]

  In addition, a user might change the value of K if there is a demand for even more detailed calculation. Assessing the value of K could be an additional function to be added to the programme toolbar or information window.

- **Phase 5: Calculating Risk**
  First, the total damage probability score is calculated using Equation 2. The score value is as indicated in Appendices 2.

  \[ \text{Equation 2. Total damage probability score} \]
  \[
  \text{Total Damage Probability Score (TDPS)} = \text{Work Type score} + A \times (\text{Utility Type Score} + \text{Utility Material score}) + \text{Land Use score} + \text{Water level score} + \text{Soil type} + \text{Situation score} + \text{Obstacle score} + \text{Experience database elements scores}
  \]
  where,
  \[ A = \text{total number of utilities} \]

  However, as already mentioned, the developed prototype situation score (for intersection with other utilities, checking path linearity and path changes) was not included because utilities are saved as polylines and it is not possible to differentiate individual pipes, but only sections of pipes (there is no unique ID for each line or pipe). It will be possible with new KLIC-WIN to provide users with vector data. In addition, the experience database consists, at this moment, only of information about previous damages.
Calculation example:
The calculation starts from assigning score for work type which will indicate if calculations are made for work to be performed deeply or shallow and, as a result, which utilities are in danger while performing excavation. The example calculation will be performed for sewage work, which according to the Appendices 2 I have scored on level 8. Let us assume that in a checked cell within excavation polygon the following utilities are present: one sewage pipe (score 6) and one data transport telecom cable (score 8). The material of those utilities is consecutively concrete (score 5) and copper (score 5). Land use on this area is medium density single family residential (score 4), water level is low (score 2) and soil type is sand (score 2). There are no obstacles in the cell but there was one damage in this spot (score 6). Thus:

\[
TDP = 8 + 1 \cdot (6 + 5) + 1 \cdot (8 + 5) + 4 + 2 + 2 + 6 = 46
\]

Second, total damage consequence score was calculated using Equation 3.

**Equation 3. Total damage consequence score**

\[
TDCS = (\text{Economy effect score for utility} \\
+ \text{Environmental effect score for utility} \\
+ \text{H&S effect score for utility}) \cdot A \\
+ (\text{Economy effect score for utility in selected land use} \\
+ \text{Environmental effect score for utility in selected land use} \\
+ \text{H&S effect score for utility in selected land use})
\]

For instance, for the example mentioned in the total probability calculation and according to the Appendices 3 the calculation would be as follow: There is a sewage pipe and data transport cable in the medium family residential. Sewage has following scores: 3 for Economy, 6 for Environment and 6 H&S, in turn, data transport cable has consecutively 4, 2 and 2. They are in the residential area so scores for sewage pipe in the residential area are 2 for Economy, 4 for Environment and 4 for H&S whereas data transport cable has consecutively 4, 2 and 2. Thus, the calculation will be as follow:

\[
TDP = (3 + 6 + 6) \cdot 1 + (4 + 2 + 2) \cdot 1 + (2 + 4 + 4) \cdot 1 + (4 + 2 + 2) \cdot 1 = 41
\]

The total probability score is calculated by multiplying Total Damage Probability score with Total Damage Consequence Score as shown in Equation 4.

**Equation 4. Total Risk**

\[
TR = TDP \cdot TDCS
\]

For the described example, the total risk will have a following value:

\[
TR = 46 \cdot 41 = 1886
\]

The mentioned above equations are the part of the code. Thus, the only action a user needs to perform is to push the risk calculation icon as visualised in Figure 43.
Phase 6: Generating a risk map

The representation of the risk maps is done according to a pre-set template (a separate file with the maps). However, users can specify the risk values range and decide about the colour manually by changing layer properties in ArcGIS. As a default the programme displays risk in green-yellow-red colours, where green indicate law risk, yellow medium risk and red high risk. The risk map is a perfect tool to visualise calculated risk and users with different levels of education can easily read it.

An example of a risk map is presented in Figure 43. In addition, users may check using python window what is to be found in each cell and what was the major contributor to the total probability and to the total consequence.
4.5.7. Locating Test Trenches and evaluating assessed risk

The prototype DSS does not display test trenches on the map, but rather leaves that decision to the decision-makers. Nevertheless, were a self-learning algorithm to be introduced, it would be valuable if test trenches appeared in the most risky spots. To see how this might work I asked members of the support group to locate test trenches without a risk map and subsequently on the risk map. In addition, I asked them to provide feedback on the places that they disagreed with the tool and as it would be made in the final tool. The experts were enthusiastic about this idea and they found this very valuable that their experience is used and they can influence the location of test trenches. The results of this exercise are shown in Figure 44.

As can be seen in Figure 44, the experts (each of them represented by different colour), located test trenches in the places indicated by a DSS as high and/or medium risk. Furthermore, they provided feedback on three spots where they disagreed with system suggestions.

4.6. System validation

One goal of the support group meetings was to check if designs would meet customer actual needs. Received feedback, opinions and suggestion helped to reveal errors in each design step and, consequently, avoid failure of the final system. Each part of the DSS was tested separately and, in the end, the whole tool was judged by the experts. System parts’ were tested during the meetings using serious gaming techniques (data collection, data aggregation and the excavation polygon generation) and the first prototype of a tool was tested using prepared mock-ups. Finally, support group members were invited to try the final prototype and verify whether it met their requirements. The requirements were checked after
each meeting with the support group. The analysis showed that designed DSS meets following requirements, as mentioned earlier in chapter 3-System Requirements:

I. **Updatable:** One of the core ideas of the tool is that it should learn from users’ experience and it would be easy to update on new information. In addition, the risk map gives the possibility, not only to support users in test trench location, but also in construction projects in general. When ground-scanning techniques reduce the number of dug test trenches, the DSS could be used to support these users in developing the area checking strategy.

II. **Innovative:** It is innovative tool because it allows users to conduct all decision operations within one system when earlier approach had to employ several software.

III. **Affordable:** most construction companies use ArcGIS and they would not have to spend additional cost on implementing the DSS.

IV. **Reliable:** Results of workshops show that users mostly agree with the tool, indicating only a few spots where they disagreed with the system. Nevertheless, that can be easily improved by introducing a self-learning algorithm to a DSS.

V. **Fast:** Because all decision steps take place with one system and the user is assisted by a tool through decision-process, the test trenches are located much faster than previously

VI. **Accurate:** ArcGIS warned users when data added had different geographical coordinates.

VII. **User-friendly:** All decision-steps take place on the map and risk is represented using colour scale. Therefore, users with different education levels can use the DSS.

VIII. **Compatible:** ArcGIS is compatible with other engineering programmes, such as AutoCAD, Infraworks, Excel, FME and many others.

IX. **Supportive:** Designed DSS support data collection, data aggregation, experience sharing, data sharing, visualisation and knowledge development

X. **User depended:** Users are not excluded from the decision-process and can actively take part it.

**4.7. System verification**

Workshops with support groups, as well as workshop conducted during ZoARG Symposium, which took place 19th of October 2017 at University of Twente, indicated that the designed system prototype proposed test trenches location in places that corresponded with their choices and experience. The feedback received from experts shows that they mostly agree with the risk distribution for any given example. In addition, they showed enthusiasm when they were informed about improvements that would have to be introduced to the prototype in order to increase efficiency of designed Decision Support Systems.

In addition to workshops, the experts were asked during the symposium to comment on the DSS that was presented to them. Many positive comments were received indicating that the idea of Decision Support System based on careful risk assessment and supports data collection, data aggregation, experience sharing and information sharing would find the application as designed supported by most construction companies.
4.8. Discussion and conclusion

The functional specification of the Decision Support System has been described and, subsequently, the prototype developed. During the development of the prototype verification and validation activities took place. The fulfilment of requirements was confirmed at each design step during meetings with experts and Support Group through discussion or workshops based on serious gaming techniques. The DSS was validated through workshop where users were invited to try the system and asked to provide feedback on assessed risk. The real project was used as an example for analysis. Moreover, verification and validation were repeated with a bigger group of future users during a workshop at the 2nd ZoARG Symposium at University of Twente on 19th October 2017. The verification can be accomplished through tests on a construction site after the prototype is improved for the elements and functions described in functional specification. Verification and validation showed that designed DSS does meet future users’ needs and provides information congruous with expert’s experience. In addition, users indicated that this DSS can help them to increase workers awareness about a risk and, in the future, it can be used to assist in building strategies for using ground scanning devices.
5. Conclusions and Recommendation

The final chapter concludes my work. This two-year project gave me the opportunity to expand my knowledge about the excavation process, to improve my personal and professional skills, to share some lessons and to recommend future developments of DSS and its implementation.

5.1. Conclusions

Digging test trenches is one method used to confirm the exact location of the cables and pipes. Often, the decision about their number and location appears random and driven by the personal judgments of individual decision makers. The interviews and workshops conducted uncovered strategies used by the decision-makers (designers and contractors). They used good practices, such as digging test trenches, when there is uncertainty about the accuracy of utilities maps, when high-risk utilities are present, or when many cables and pipes cross over one another. The regulatory rules and other guidelines can also help to reduce uncertainty (e.g. the rule of adding the 1.5 m checking buffer to ensure that the excavation project will not damage utilities).

The knowledge and skills of decision-makers both play an important role in the decision-process. It influences how many test trenches will be dug and where they will be located. The use of different techniques, such as detection tools, utility maps, visualisation programmes and data management tools can support the decision process. However, decision-makers ultimately assess the risk of damage. Their experience levels differ. They often face new situations. These can involve poor decisions or incorrect assumptions if they have to analyse large amounts of data. Many people involved in the excavation process are not sufficiently familiar with the use of ground scanning methods. This can result in further incorrect assumptions about the situation. Full automation of decision-making regarding how and where to locate test trenches appears to be untenable. It is also not desirable, as it prevents leveraging expertise from those directly involved. A combination of analytical and naturalistic decision-making elements within one DSS seems to be an interesting and viable option.

Designed DSS aims to support decision-makers in test trench location. System is a computer-based tool to assist decision-makers in making decision, and to support them, rather than replace and improve the effectiveness of decision-making. The core of the system is a risk assessment. The ArcGIS software was chosen as a platform for Test Trench Location Decision Support System. The tool aims to assist decision-makers in data collection and support data aggregation, situation visualisation, risk assessment, test trench location, experience sharing, information and reporting. All these have an impact on the efficiency of location test trenches. The proposed DSS was described in the form of functional specification and the final prototype was design. The product’s verification reaffirmed that designed DSS fulfilled users’ requirements. The requirements’ fulfilment is proved in Table 16.
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Explanation</th>
<th>Proof methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enterprise needs</td>
<td>Careful risk assessment helps to reduce the number of test trenches. Moreover, experience sharing increases decision-maker’s skills and knowledge and, consequently, test trenches are located in spots that previously might not have been considered.</td>
<td>Tested by experts during support group meetings and by experts who joined ZoARG Symposium 2017 using serious gamming methods. And Confirmed through intensive discussions with value management workshop elements</td>
</tr>
<tr>
<td>Damage reduction</td>
<td>The risk map increases risk awareness of decision-makers who locate test trenches, as well as workers who work on construction site.</td>
<td></td>
</tr>
<tr>
<td>Business needs</td>
<td>The code was built to automate some DSS functions. The defined variables can be easily changed and additional functions can be added. Moreover, situations can be visualised in 3D.</td>
<td></td>
</tr>
<tr>
<td>Innovative</td>
<td>The tool can be used to increase awareness of workers on construction sites and, in the future, to build strategies of locating underground utilities using ground scanning devices.</td>
<td></td>
</tr>
<tr>
<td>Affordable</td>
<td>ArcGIS is already used by many construction companies so they do not have to implement new software.</td>
<td></td>
</tr>
<tr>
<td>Efficient</td>
<td>Test showed that decision-makers mostly agree with tool’s suggestions</td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>ArcGIS can be shared online and used on tablets on construction site.</td>
<td></td>
</tr>
<tr>
<td>Stakeholder’s needs</td>
<td>Indicated risk places were confirmed by experts during workshops</td>
<td></td>
</tr>
<tr>
<td>Reliable</td>
<td>Tool speeds up the decision process because it assists and supports users in all decision steps and replaces using multiple software.</td>
<td></td>
</tr>
<tr>
<td>Fast</td>
<td>Tessellation of excavation site allows for detail analysis of construction sites.</td>
<td></td>
</tr>
<tr>
<td>Precise</td>
<td>ArcGIS ensure the coordinates and can be connected with GPS devices.</td>
<td></td>
</tr>
<tr>
<td>Accurate</td>
<td>All actions take place on maps and risks presented using colours that can be used by different users.</td>
<td></td>
</tr>
<tr>
<td>User-friendly</td>
<td>Supports data aggregation and visualisation, as well as knowledge, skills and experience development through presence of several databases and self-learning function</td>
<td></td>
</tr>
<tr>
<td>System’s needs</td>
<td>Supports data aggregation and visualisation, as well as knowledge, skills and experience development through presence of several databases and self-learning function</td>
<td></td>
</tr>
<tr>
<td>System element needs</td>
<td>ArcGIS allows sharing data online that was added to functional description of the tool.</td>
<td></td>
</tr>
</tbody>
</table>
The objectives defined at the beginning of the project have been achieved. The currently used strategies were defined and analysed looking at their strengths and weaknesses. In addition, the logic behind those strategies was uncovered by using multiple techniques to understand decision-maker’s mindsets. Ultimately, the final prototype solution was developed. The functions of Decision Support System were explained in the Functional Specification and the prototype was designed and developed. Finally, both the defined tool functionality and the prototype were verified and validated.

5.1.1. Lessons learned

**Design and construction companies**

Behind the strategies for test trench location is the experience of decision-makers and all other units involved in the construction process. It is possible to locate test trenches more effectively and receive the maximum information from the minimum number of test trenches. Nevertheless, it must be done collaboratively. Experts need to share their knowledge and experience in order to contribute to reduction of underground damages. The less experienced decision-makers may learn from their experience colleagues about the situations that should have made them aware of a high risk of damage. All learning processes evolve and even an experienced specialist may learn about new situations on an excavation site that increase risk. Without expert’s contribution the designed DSS would not be able to improve the risk calculation and there will be always an uncertainty about utilities location.

**Network operators**

The risk assessment was inspired by systems implemented in network operators’ companies. It would be valuable if their systems could be combined with the designed DSS and contribute to the experience database. It would allow both construction companies and network operators to more effectively control excavation process.

**Government**

The implementation of the Decision Support System would demand some legislation updates regarding experience sharing to motivate companies to contribute to the global good.

5.2. Recommendation for future implementation of the DSS

The prototype as designed has room to improve several of the functions described in the functional specification and system architecture. The tool should have self-learning skills to improve risk calculation. Actions should be worked out to encourage construction companies to share experience. The risk calculation algorithm should be improved and updated by a specialist in mathematics. The algorithm should take into account the depth of digging, perform actions, number of utilities, their material, utilities intersection, path changes, presence of old utilities and information about situation provided by the experience database.

Finally, before implementing DSS, it should be tested for several months on real construction projects.
5.3. In closing

The designed prototype is a starting point to improve test trench location. It needs several adjustments before it could be used on construction sites. As many utilities were buried a long time ago, many uncertainties remain regarding their location. The most important factor is to encourage all construction companies and network operators to work as one big team and to share their knowledge and experience. By learning from each other we can reduce uncertainty and teach new generations of decision-makers.
6. Literature


CROW. (2016). *Schade voorkomen aan kabels en leidingen. Richtlijn zorgvuldig grondroeren van initiatief-tot gebruiksfas*e. Retrieved from The Netherlands:


Health and Safety Authority. (2010). *Code of Practice for avoiding danger from underground services*. Retrieved from Dublin:


Syfuss, L. (2017). *Generation of a semantically-rich model that supports qualitative spatial reasoning in the domain of subsurface utilities from heterogeneous data sources*. (Master), University of Muenster, Muenster.


7. Appendices

Appendix 1. The overview of educational activities
## Appendix 2. Damage probability score

<table>
<thead>
<tr>
<th>Global Parameter</th>
<th>Parameter</th>
<th>Attributes</th>
<th>Attribute Weight</th>
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<tr>
<td><strong>Utility Type</strong></td>
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</tr>
<tr>
<td></td>
<td>Water system</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Data Transport</td>
<td>Telecom</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio/TV</td>
<td>8</td>
</tr>
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<td></td>
<td>Gas pipeline</td>
<td>High pressure (40-80 bar)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium pressure (1-8 bar)</td>
<td>2</td>
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<td></td>
<td></td>
<td>Low pressure (&lt;0,1 bar)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Electricity Cables</td>
<td>Medium voltage (3 t/m 25 kV)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low voltage (0,4 kV)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Public Lighting (OV)</td>
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<td></td>
<td>Heating system</td>
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<td></td>
<td>Industry pipelines</td>
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<td>6</td>
</tr>
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<td>Others</td>
<td>-</td>
<td>2</td>
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<tr>
<td><strong>Utilities within 1,5 m buffer</strong></td>
<td>Utility's material</td>
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<td></td>
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<td>Asbestos-cement</td>
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<td>Stoneware clay</td>
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<td>Concrete</td>
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<td></td>
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<td>Fiberglass</td>
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<td></td>
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<td>Medium</td>
<td>6</td>
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<tr>
<td></td>
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<td><strong>Work Type</strong></td>
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<td></td>
<td>Bestratingwerk</td>
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<tr>
<td></td>
<td></td>
<td>Bodemsanering</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Bouwwekzaamheden</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CAI kabel leggen</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Duikers leggen enz.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grondwerk/bouwrijp maken</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Handholes plaatsen</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>HDPE buis leggen</td>
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</tr>
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<td></td>
<td></td>
<td>Horizontale leiding leggen</td>
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<td>O.V. wekzaamheden</td>
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<td></td>
<td>Onbekend/diverse</td>
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<td></td>
<td>Huisaansluitingen maken</td>
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</tr>
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<td></td>
<td></td>
<td>Ruiilverkaveling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stobben frezen</td>
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<tr>
<td></td>
<td></td>
<td>Tanks/putten/containerts in-of uitgraven</td>
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</tr>
<tr>
<td>Medium risk work</td>
<td>High risk work</td>
<td>Land use</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>----------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>Bodemonderzoek/sonderingen</td>
<td>Bodemonderzoek/sonderingen</td>
<td>Conservation Open Space i.e. Parks</td>
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</tr>
<tr>
<td>Bomen rooien/planten</td>
<td>Bomen rooien/planten</td>
<td>Agriculture</td>
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<td>Funderingswerk</td>
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<td>Gasleiding leggen</td>
<td>Gasleiding leggen</td>
<td>Medium Density Single Family Residential</td>
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<td>Hekwerk plaatsen</td>
<td>High Density Single Family Residential</td>
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<td>Kabels/leidingen leggen</td>
<td>Kabels/leidingen leggen</td>
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<td>Leggen hoogspanning</td>
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<td>Mantelbuis leggen</td>
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<tr>
<td>Palen/masten plaatsen/verwijderen</td>
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<td>Sloopwerkzaamheden</td>
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<td>Industry Zone</td>
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<td>Werk aan bestaande leiding</td>
<td>Waterleiding leggen</td>
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<td></td>
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<tr>
<td>Damwand/beschoeiing slaan</td>
<td>Zinker maker</td>
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**Excavation area**

<table>
<thead>
<tr>
<th>Excavation area</th>
<th>Land use</th>
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<tr>
<td>No use</td>
<td>Conservation Open Space i.e. Parks</td>
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<td>Agriculture</td>
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<td>Low Density Single Family Residential</td>
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</tr>
<tr>
<td>4</td>
<td>5</td>
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<td>Medium Density Single Family Residential</td>
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<tr>
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<td>6</td>
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<td>8</td>
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<td>Community Facilities i.e. hospital, schools</td>
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<td>Water Level</td>
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<td>Low</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Soil Type</td>
<td>Medium</td>
</tr>
<tr>
<td>-------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Type A (clay)</td>
<td>6</td>
</tr>
<tr>
<td>Type B (silt)</td>
<td></td>
</tr>
<tr>
<td>Type C (sand)</td>
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</table>

<table>
<thead>
<tr>
<th>Situations</th>
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<tr>
<td>Crossing point with many utilities</td>
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<tr>
<td>Crossing point with one utility</td>
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<td>Changes on the path</td>
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<td>Linear path</td>
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<td>Previously damage occurred there</td>
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<tr>
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<table>
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<tr>
<td>2</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>3 and more</td>
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</table>

<table>
<thead>
<tr>
<th>Obstacles within 1,5 m buffer</th>
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<tbody>
<tr>
<td>Trees</td>
<td>5</td>
<td></td>
</tr>
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<td>Canals</td>
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<td>4</td>
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<td>Street Lamps</td>
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<td>Underground Waste Containers</td>
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<td>5</td>
</tr>
<tr>
<td>Sanitary Fittings i.e. pumps, hydrants</td>
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## Appendix 3. Damage consequence score

<table>
<thead>
<tr>
<th>Utility Type</th>
<th>Global Parameter</th>
<th>Parameter</th>
<th>Attributes</th>
<th>Sub attribute</th>
<th>Economy Attribute Weight</th>
<th>Environment Attribute Weight</th>
<th>H&amp;S Attribute Weight</th>
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<td></td>
<td></td>
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<td>Water system</td>
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<td>4</td>
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<td></td>
<td>Data Transport</td>
<td>Telecom Radio/TV</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<td>Gas pipeline</td>
<td>High pressure (40-80 bar)</td>
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<td>8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gas pipeline</td>
<td>Medium pressure (1-8 bar)</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gas pipeline</td>
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<td>5</td>
<td>4</td>
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<tr>
<td></td>
<td></td>
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<td>Electricity Cables</td>
<td>High voltage (50/110/150 kV)</td>
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<td>2</td>
<td>4</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Electricity Cables</td>
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| Sewage system           | 5       | 4        | 4      | 4      | 4      | 4          | 4          | 3          | 3                     |
| Water system            | 7       | 4        | 4      | 4      | 4      | 4          | 4          | 3          | 3                     |
| Heating system          | 5       | 3        | 4      | 4      | 4      | 4          | 4          | 3          | 3                     |
| Industry pipelines      | 7       | 6        | 7      | 7      | 7      | 7          | 7          | 6          | 6                     |
| Telecom                 | 5       | 2        | 4      | 2      | 2      | 4          | 4          | 2          | 2                     |
| Radio/TV                | 2       | 2        | 2      | 2      | 2      | 2          | 2          | 1          | 1                     |
| Gas HP                  | 6       | 6        | 10     | 6      | 6      | 10         | 10         | 5          | 5                     |
| Gas MP                  | 6       | 4        | 7      | 4      | 4      | 7          | 7          | 4          | 4                     |
| Gas LP                  | 5       | 5        | 6      | 5      | 5      | 6          | 6          | 4          | 4                     |
| Electra HV              | 6       | 4        | 7      | 4      | 4      | 7          | 7          | 6          | 6                     |
| Electra MV              | 6       | 4        | 6      | 4      | 4      | 6          | 6          | 6          | 6                     |
| Electra LV              | 5       | 4        | 4      | 4      | 4      | 4          | 4          | 4          | 4                     |
| Public Lighting (OV)    | 2       | 3        | 2      | 2      | 2      | 2          | 2          | 2          | 2                     |
Appendix 4. First prototype of DSS presented on second meeting of the support group together with map that was used to define the probability of damage and consequence scores.

Workshop map:
WELCOME ON THE TEST TRENCHES' LOCATION WEBSITE

Dear user,

We are very happy to welcome you in our Test Trenches' location website. Do you have a problem to decide where to dig test trenches and how many of them?

DON'T WORRY! WE WILL HELP YOU!

Our method is based on 4 stages (see image on the right):

1. Data collection: We will ask you to add all project information: kind, melding, design layers, other layers and documentation. Based on those information the map of excavation area will be created.

2. Risk assessment: Map will be divided into segments for which the level of risk of damage will be calculated. In order to calculate risk you will be asked to fill the questionnaire. Moreover, the data from experience data base will be used. In the end you will receive the map with the level of risk.

3. Test trench location: Based on风险管理 in stage 2 test trench location will be proposed using multi-criteria analysis.

4. Visualization: Location will be visualised using 2D or 3D technique. User can influence a decision, however, you have to notify why you change the proposed location.

During the process you are supported by information from experience data base. Please, after you will dig your test trenches and finalize the excavation process on the area share with other users your findings (found utilities, photos, videos, made damages and their reasons, proposed changes etc.).

How to start?
In order to start click USERS in the menu. Then login or create a new user account.

Contact us: proefsleuf@gmail.com
Below showed tables were used only for the workshop and they were not planned as the part of DSS as all actions should take place on the map:

Risk assessment
Appendix 5. Publications
Decision Support for Test Trench Location Selection with 3D Semantic Subsurface Utility Models
P. Racz¹, L. Syfuss², C. Schultz², M. van Buiten¹, L. olde Scholtenhuis¹, F. Vahdatikhaki¹, and A. Dorée¹

¹Construction Management and Engineering, University of Twente
²Institute for Geoinformatics (IFGI), University of Muenster

ABSTRACT
Subsurface utility construction work often involves repositioning of, and working between, existing buried networks. While the amount of utilities in modern cities grows, excavation work becomes more prone to incidents. To prevent such incidents, excavation workers request existing 2D utility maps, use detection equipment and dig test trenches to validate their accuracy and completeness. Although test trenches are of significant importance to reveal information about subsurface conditions, the process of determining their location, number and size is not explicated by experts to date. This study therefore aimed to explicate the reasoning and logic behind the selection of utility test trenches, and to formalize this in a semantically-rich utility model. To this end, we conducted interviews with experienced excavator operators. We then derived heuristics and rules that the experts used to determine trench locations. Such rules related to, for example, the layout of the excavation site, and the type of utilities, and accuracy of available data. Based on these rules, we integrated various incomplete sources of data, and generated a 3D utility model that could generate several alternative construction situations. We used queries to identify the most suitable location for a test trench. The resulting answers to queries helped optimize the test trench selection process. Our prototype demonstrates that the identified rules (1) facilitate the generation of semantically rich 3D utility models, and (2) support test trench decision making.

1. INTRODUCTION
Reliable information about subsurface utilities is essential for planning and conducting subsurface construction operations, such as placing new utilities, or maintaining and replacing existing utilities. One central concern when such information is not reliable is the risk of damaging existing infrastructure. Such errors are not only costly and time consuming; they pose a serious risk to public safety and operations crew personnel. Negative effects of striking a utility include environmental pollution, delays in the construction project, interference in public activities, e.g. traffic delays, and, in the most tragic scenarios, human injury. The Netherlands’ Cadastre, land Registry and Mapping Agency (Kadaster) announced that 33,000 damages were made to Dutch utilities in 2015. Although down compared to previous years, the cost of reparations are still substantial, i.e., approximately €30 million per year (Kabel en leiding overleg KLO, 2016).

One technique for establishing reliable information is by making test trenches (or trial trenches) in carefully selected locations, i.e. to physically expose the existing utilities by digging exploratory trenches. Each test trench costs time and resources, and provides the opportunity to confirm or invalidate current information about the utilities in question. Thus, decision makers face a trade-off between the number of test trenches (in carefully selected locations) and more accurate and complete information about the location of subsurface utilities.
Our research focuses on improving decision support for subsurface utility construction operations planning. We investigate the (often implicit) methodology that practitioners exercise in test trench location selection. Our key contributions are as follows:

- we have conducted expert interviews with experienced excavator operators, and through these interviews, we have identified heuristics and rules employed by experts for test trench location selection (Section 3);
- we have formalized and implemented these rules as a prototype software tool for test trench location selection (Section 4).

We demonstrate how a semantically-rich model can be used to derive a plausible 3D spatial representation based on 2D data sources such as schematics and ground-penetrating radar readings.

2. BACKGROUND AND RELATED RESEARCH

There is scant research literature investigating principles, and industry practices, of test trench location selection. The focus is mostly oriented towards virtual test trenches and detection tools such as Ground Penetrating Radars (GPRs) and Electro-Magnetic Locating (EML) (Jones, 2010). However, detection tools will not provide complete certainty. Obstacles, soil type, ground water, material, depth, among other factors, can cause disturbances and decrease accuracy of a ground scan.

The problem of determining test trench location is well known to practitioners. The perceived importance of digging test trenches is exemplified by national excavation damages prevention programs such as ‘Call before you dig’ in United States (US), PAS 128:2014 standard in United Kingdom (UK) and “Reduction of Damage to Utilities and Careful Excavation” (ReDUCE) in the Netherlands. All of these programs indicate that solely using detection tools is insufficient. Careful data analysis, on-site exploration and utilities location verification by digging test trenches are also necessary. Pollock (2009) describes ‘keyholes’ as an alternative to test trenches: small, minimally invasive holes through which operators access utilities while remaining on the surface e.g. using long-handled tools. They can be dug in places with relatively low risk and uncertainty to confirm the results of ground scanning. Keyholes are smaller than test trenches, and thus less invasive, faster to execute, and cheaper. In this case too, the location of keyholes must be carefully determined to reduce the risk of mistakes and damages.

In generating 3D semantic models from 2D input schematics we build on numerous lines of research, such as efforts to generate 3D visualizations of subsurface utilities based on 2D schematics (Du et al 2006, Döner et al 2011). Hijazi et al (2011) employs the geographic markup language CityGML ADE (Becker et al 2013) as a basis for modelling interior utility models.

3. TEST TRENCH LOCATION DECISION MAKING

We have conducted several interviews and two workshops with decision-makers (designers and contractors) as well as with network operators and developers of excavation support applications. We initiated contact with the specialist participants through the support of the University of Twente and through inspectors from Agentschap Telecom. All of the expert participants are working in Dutch civil engineering companies. We had the opportunity to talk not only with engineers but also with employees who dig test trenches, and for whom the effect of oversights in decision making can have the greatest impact.
Interviews. We asked interviewees to prepare examples of projects they found interesting from the perspective of test trench determination. These were further discussed during interviews in eleven civil-engineering companies. The interviews took place from March to June 2016. Each interview session took approximately two hours.

Workshops. For the workshops, we adopted a different approach. Instead of analyzing examples prepared by the participants, we decided to challenge the specialists by asking them to locate test trenches in three project scenarios that we had prepared beforehand. We divided the workshop into two sessions. The first session took place in July 2016 and focused on decisions made by designers. The second session took place in October 2016 and focused on analyzing the decision strategies of contractors. Both meetings were performed with six participants and each took approximately 3 hours.

We used serious gaming techniques (Schell, 2015) in order to check the specialists’ behavior while they were making decisions under risk and uncertainty. They had to face the following situations: (1) build a new parking place, (2) place new fiber cables and connect them to houses and (3) replace an old sewage system and build a new bicycle road together with a bicycle bridge above a channel. For each of these projects, decisions about test trench locations had to be taken. The game board and some examples of the results are shown in Figure 1.

Summary of Findings. We identify the following key challenges faced by decision-makers across projects:

- some important test trenches were overlooked by experts. (i.e. risk utilities);
- opinions differed on the exact positioning of test trenches (e.g. deciding to prioritize locations where a map indicates a linear path of a utility, or rather locations with a change in this linearity);
- opinions differed on the number of test trenches required, keeping in mind the additional cost, effort and risk of damage with each additional test trench;
• managing uncertainties and risk, particularly with respect to aligning the reality of the situation with the situation presented in maps and indicated by GPR measurements;
• the presence of obstacles (i.e. tree roots, waste containers, street lamps and so on);
• time pressure and deadlines.

The importance of these factors may differ depending on the decision-maker and type of work. Designers dig test trenches to check if there is enough space for the project in order to avoid changes and unnecessary costs. In the case of contractors, test trenches are dug to verify if the work can be performed safely and swiftly. Thus, besides the utilities’ location and depth, other factors are critically important such as the materials (e.g. accounting for vibrations), type of connections (e.g. accounting for changes in depth) and work type (such as piercing, drilling, trenchless methods, open excavation etc.).

A substantial amount of variability is to be expected across projects regarding procedures for test trench determination. Despite this, a fairly coherent picture emerges from our analysis of the interviews and workshops. Specifically, it indicates that the following steps (Figure 2) must be taken in order to choose the location of test trenches:
• data analysis (i.e. utilities’ maps);
• site analysis (i.e. ground conditions and obstacles);
• detection (GPR and other detection equipment, data bases);
• safety checking (i.e. applying a 1.5 m spatial buffer region).

Figure 2. Decision making for test trench location selection.
4. PROTOTYPE SUBSURFACE UTILITY MODEL

Based on the findings from our interviews and workshops we have formalized principles of test trench location selection as a prototype decision support software tool. Given 2D schematic data about subsurface utilities (e.g. AutoCAD DWG files) our tool generates a conceptual model with 3D geometric representations as a basis for suggesting test trench locations. In the input file, utilities are represented as polylines and other 2D curves, and the category of each utility is attached as an attribute. Our tool generates the associated pipes, and the component sections and joints, as objects in the new model. It then generates 3D geometric representations of each section and joint based on the utility type and the associated 2D geometry in the input file.

Figure 3 illustrates a class diagram of the concepts in our model. Our model is based on the CityGML UtilityNetworkADE (Becker et al. 2013). We explicitly specialize the types of cables and pipes, define components that compose utilities, and separate spatial representation from object concepts, i.e. a utility can be assigned multiple alternative representations simultaneously such as 2D schematic, coarse 3D, detailed 3D, etc. Moreover, we model salient obstacles and other environmental features such as trees. Finally, we also explicitly model the region of location uncertainty as a spatial artefact (Bhatt et al. 2012) of distribution components, i.e. the region of space in which the utility may in fact be located. Information about dug test trenches is fed back into our model and reduces the size of the uncertainty region.

Generating plausible 3D geometries is an iterative procedure. We use the well-established Dutch guideline NEN 7171-12009 as a basis for programming background knowledge about the expected spatial properties of different types of utilities. The guideline specifies industry-standard diameter ranges, depth ranges, and free space requirements for (a) types of utilities (central antenna devices, data transport, electricity, water, gas, heat, and sewage), according to (b) categories of roads (residential, main road, industrial area roads, rural roads). We implement this background knowledge as properties associated with utility classes that must be satisfied when generating 3D models, i.e. spatial constraints.

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1 Our prototype system is implemented in Java (SE version 8). The input data is in the Netherlands mapping spatial reference system Amersfoort / RD New (EPSG:28992). All input data files have been transformed to ESRI Shapefiles (.shp) using AutoCAD (version 2016) and QGIS2 (version 2.16). All experiments were run on a desktop PC with Windows 10 Pro 64bit, Intel 3.6GHz, 16GB RAM.
Our iterative algorithm is as follows. Initially each utility section is assigned a default diameter, minimum depth, and minimum required surrounding free space, according to NEN guideline; e.g. the sewer utility type requires an inclination in the flow direction. The system then vertically rearranges the utilities to prevent any intersections or violations of the minimum free space requirement, which are deemed to be conflicts that need to be resolved (Figure 4).

The algorithm resolves conflicts by moving utilities deeper until all constraints are satisfied. Utilities must remain within specified minimum and maximum depths according to the type of utility. We define slack as the distance between the current depth and maximum depth of a utility; some utility types do not have a maximum depth. First, the algorithm does a pairwise comparison of each utility. If the minimum distance \( d \) between a given pair of utilities \( a,b \) violates the intersection or free space requirements, then the necessary vertical displacement \( d' \) between \( a,b \) is computed that would resolve the conflict. The utility with the most slack is then displaced by \( d' \). The procedure continues until a fixpoint is reached, i.e. no constraints are violated, or alternatively, a utility does not have enough slack to satisfy the constraints, i.e. the model can not satisfy all constraints simultaneously.

**Empirical Evaluation.** We evaluate our prototype with real-world data describing the 2D locations of different subsurface utilities at the University of Twente (Figure 5(a)). The data is in the form of AutoCAD (.dwg) files and encompasses eight types of utilities: drinking water, sewer pipes, low pressure gas pipes, high and low voltage electricity cables, telephone cables, fiber glass, and public lighting. The semantic 3D model generated by our prototype software tool is illustrated in Figure 5 (b). In total, our generated model resulted in 43,499 utility sections and 42,059 joints. Our algorithm for generating the 3D model (including utility rearrangement) took 304.23 seconds to complete (approximately 5 minutes). We emphasise that in this prototype we have not attempted to optimise algorithm runtime; we anticipate significant increases in runtime performance in subsequent versions of our tool.

**Automated suggestions of viable test trench locations.** Based on our analysis of the expert interviews, we have developed an algorithm that finds test trench locations according to geometric relations of subsurface utilities and the excavation region. Importantly, when our tool suggests a location, it also provides the rationale for the decision, i.e. making the reasoning process explicit. The algorithm searches the model for the following cases listed below; each case is implemented as an IF-THEN rule that, when satisfied, implies the location of a potential test trench with an assigned priority score. The algorithm combines locations into higher-priority locations when they coincide i.e. when two locations are within an adjustable threshold distance:
We executed our algorithm on an extract of the Twente utility dataset illustrated in Figure 6. In total, our algorithm suggested 135 test trenches, ranked according to priority. The top 30 test trenches were taken to be high priority (Figure 7). The runtime was 3.51 seconds.

5. CONCLUSIONS AND FUTURE PERSPECTIVES
We have presented our investigation into the principles and practice of test trench location selection. Based on our interviews and workshops with specialists in excavation and subsurface operations management, we identified key challenges and factors that experts face in test trench location selection, such as an inability to always reliably identify risk utilities, and managing competing opinions on the most effective criteria for selecting locations. We identified the most common criteria that experts employ when selecting test trench locations, and formalized the
rational, expected utility properties, and IF-THEN rules for test trench location selection in a decision support software tool. Our software tool generates a 3D semantic model of subsurface utilities based on input 2D schematics (such as AutoCAD files), and presents a comprehensive list of plausible locations, with explicit justification (i.e. the logic that the tool employs is readily accessible to the user), and a suggested prioritization.

On the software tool front, we are not claiming that decision support tools can guarantee, for example, that all risk utilities will be identified. Instead, our aim is to shift the tedious and cognitive burden of manually checking many numerical details away from practitioners based on the data available (i.e. relying on attributes that define utility types in a 2D DWG file); such tools can identify errors in a model that contradict common-sense: sewer pipes necessarily have an inclination, they have a certain expected diameter, and are placed at certain depths in the ground. If a given subsurface utility model contradicts these facts the software system can alert the practitioner, with accompanying visualisations, and practitioners can directly query the model in a more meaningful way, e.g. “identify regions where trees are near to planned gas pipe installation areas”. Our next step is to develop our system using rule-based reasoning frameworks in the context of declarative spatial reasoning and logic programming (Bhatt et al. 2011), to facilitate the rapid and principled addition of new formal IF-THEN rules and reasoning tasks.

ACKNOWLEDGEMENTS
We gratefully acknowledge the support, time, and effort of the specialists that participated in our interviews and workshops, and the support of the Agentschap Telecom inspectors and the University of Twente in facilitating contact with industry experts.

REFERENCES
Naturalistic decision-making perspective on uncertainty reduction by civil engineers about the location of underground utilities

Paulina RACZ, Marc VAN BUITEN, and André DOREE
University of Twente
Drienerlolaan 5
7522NB Enschede
The Netherlands

p.racz@utwente.nl; m.vanbuiten@utwente.nl; a.g.doree@utwente.nl

ABSTRACT
Modern engineers must perform their work carefully to avoid damaging buried underground utilities. Before starting ground works the exact location of pipes and cables must be confirmed. Current detection equipment still cannot provide complete certainty and requires extensive training in order to obtain the correct data. Digging test trenches remains an important practical tool to interpret subsurface conditions, but deciding on the number and location of test trenches is problematic. Decisions seem to be taken randomly and are based mostly on intuitive judgments. We conducted interviews and workshops in order to uncover the strategies used to select test trench location. Our results show that choices are influenced significantly by decision-makers’ experience. We describe our findings using Rasmussen’s Skills-Rules-Knowledge model. We propose that any future decision support system should combine elements from both analytical and naturalistic models.

KEYWORDS
Decision-Making; Civil Engineering; Test Trenches; Naturalistic Decision Models

INTRODUCTION
Excavation work demands that modern engineers take many precautions. They must schedule their works in such a way that existing underground utilities will not be disturbed. This is a challenge, given that underground spaces have become increasingly busy. Many types of cables and pipes, underground infrastructures, precious fauna and flora, as well as archaeological findings, can make excavation work difficult. Underground utilities, particularly, and depending on their content, can cause many problems. Damages to high-risk pipes and cables (e.g. gas pipelines, the sewage system, industry pipelines and/or high-voltage electricity cables) can have profound impacts on the environment and the health of workers and people living and working in the area neighbouring the excavation area.

Ground Penetrating Radars (GPRs) and Augmented Reality (AR) technologies are used by engineers to improve the safety of excavation procedures. However, these technologies are costly and still do not provide complete certainty. Furthermore, even if maps and plans of underground utilities are available, the information contained by these sources might be incorrect. Therefore, test trenches are often dug to confirm the exact locations. These trenches are variously described as test holes (Canada), trial holes (UK and US), potholing (Australia) and proefsteunen (the Netherlands). They all have the same goal: to establish precisely what is underground before excavation starts.

There is always doubt as to where to locate test trenches. Utilities’ maps, GPRs and AR support those decisions. Nevertheless, it is the responsible decision-makers (designers, contractors) who make the final choice. The process of selecting the test trench location appears to be random and mostly based on the personal judgment of an individual. This exerts considerable pressure on these decision-makers faced with meeting deadlines and faced with the nagging uncertainty about the actual location of subsurface utilities and the risk of excavation damage to the utilities. The problem is well known to practitioners. However, there is a dearth of information about locating test trenches in the scientific literature which is surprising given the importance of digging test trenches that is readily apparent from various national excavation damages programmes, such as “Reduction of Damage to Utilities and Careful Excavation” (ReDUCE) in the Netherlands, PAS 128:2014 standards in United Kingdom (UK) or “Call before you dig” in United States (US).

The analysis in this article examines the Dutch excavation context and where clarity of test trenches location strategy is one major goal of the Dutch Government. The Netherlands has a national digital mapping system (referred to as “klic”). This system was developed by the Cables and Pipes Information Agency (Cadastre) and
provides the excavator with maps of utilities in the area of interest, together with necessary documentation. In spite of this, damage to underground utilities persists. According to the data provided by Cadastre, almost 33,000 cases of damage were recorded involving Dutch utilities in 2015 and the cost of their repairs mounted to €30 million per year (Kabel en leiding overleg KLO, 2016). The Underground Networks Information Exchange Act (WION), together with klic, provides a solid foundation for making decisions. The WION describes the steps that excavators must follow before breaking the surface, and the klic system supports them with the relevant maps. Before excavation starts it is mandatory for a request to be sent to Cadastre. The agency will provide the excavator with necessary maps, together with important documentation (e.g. about precautions). In Figure 1, the klic system is presented.

![Figure 1. The klic system in the Netherlands (Groot, 2008)](image)

New European regulations, such as Infrastructure for Spatial Information in the European Community (INSPIRE), as well as feedback from klic users, allow Cadastre to receive feedback to improve the system. As a result, the klic-win system was developed that is slowly being implemented to provide users with location data in vector format to create data sets with added value, such as 3D visualizations (Kadaster, 2016). The authors intend to develop a Decision Support System (DSS) for selecting test trenches to help decision-makers minimize risk and uncertainty during excavation and, as a result, reduce the number of cases where excavation damages underground utilities.

To achieve this goal, it is necessary to optimize the current decision-making strategy. This, in turn, requires careful analysis of current strategies, logic and decision-makers’ behaviour. To that end, interviews and workshops were conducted. The purpose of those meetings was to check how people make decisions when factors such as risk, uncertainty and time play an important role. The research showed that on many occasions mental simulations conducted by decision-makers leading to their subsequent choices, were aligned with the degree of their expert level (i.e. expert vs novice). In this article, we investigate how decision-makers use their experience to decide on where to locate test trenches and whether it is possible to use Naturalistic Decision Models (NDM) as a decision support tool for Civil Engineering.

The structure of this article starts by outlining the background information of Naturalistic Decision Making models. Then, the methodology used to collect the data is described. Subsequently, the results of analysis are presented. The paper finishes with conclusions.

**BACKGROUND ON NATURALISTIC DECISION MAKING (NDM) MODELS**

To make a decision entails using information to choose between options from amongst the available possibilities (Ishibushi & Nii, 2000). On many occasions, researchers develop Decision Support Systems (DSS) from an analysis of several decision models as we did also (Racz, Van Buiten, & Dorée, 2016). However, we observed that this approach directed us more towards the development of the system itself and de-emphasised a focus on its users. The system would then represent an idealized example of reality by excluding actual users from the decision process (Blanchard & Fabrycky, 2011). NDM researchers consider the DSS development process differently (Klein, 2008). First, current strategies are analysed to examine how people behave during extreme situations where there is time pressure, uncertainty, unexpected conditions and/or risk (Klein & Klinger, 1991), rather than just simply checking whether people were effective or not. Civil engineering projects seem natural candidates for such an approach. Engineers and workers always perform their job under time pressure. The rush commonly results in mistakes with potentially dangerous consequences. In addition, construction work puts considerable responsibility onto the persons involved when the work must also be done within environment and health and safety regulations. Typically, problems do naturally arise during civil engineering projects. If these problems were correctly identified, an adequate response can be formulated.

Researchers have distinguished six types of problems (Ishizaka & Nemery, 2013; Roy, 1981): (1) The choice problem (select best option or reduce the set of options), (2) The sorting problem (classification into categories), (3) The ranking problem (from the best to the worst), (4) The description problem (option and their consequences), (5) The elimination problem (related to sorting problem), and (6) The design problem (identification of the goal)

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1 University of Twente, Reggefiber and other partners created the ReDUCE program (Reduction of Damage to Utilities and Careful Excavation). This programme is realised to promote careful approaches in construction and maintenance of the underground infrastructure, by investing in the development of new methods and technologies that prevent excavation damages (Reggefiber & University of Twente, 2015). The analysis are part of a PDEng (Professional Doctorate in Engineering) project entitled “Improved strategies, logic and decision support for selecting test trench location”.

2
or creating a new actions). Civil engineers often face these problems while making decisions about work performance. Even though modern technology helps to perform the work much more safely than in the past, there is always a risk involved. Some civil engineering works, such as excavation, are also very uncertain and require care. According to the literature (Lipshitz, Klein, Orasanu, & Salas, 2001), there are three forms of uncertainty: (1) inadequate understanding (insufficient situations awareness), (2) lack of information (incomplete or unreliable information) and (3) conflicted alternatives (difference between them is insufficient). Organisational units and people involved in the construction process have different experience and, even if they have the same data sources, their decisions may differ. Lipshitz (1993) identified nine NDM models. We would like to focus on three that we believe are applicable to the design project: (1) Rasmussen’s model of cognitive control SRK, (2) Klein’s Recognition Primed Decision model (RPD) and (3) Recognition/Metacognition model (R/M).

Rasmussen differentiated three kinds of behaviour (Rasmussen, 1983): (1) Skill-based, (2) Rule-based and (3) Knowledge-based. Skill-based behaviour arrives from experience. The decision is made based on past information stored in the subconscious. In case of rule-based behaviour in decision-making, the unit will behave according to the rules set because these had generated good results in the past. This kind of behaviour is typical for decision-makers who do not have enough experience, but know the rules needed to accomplish a task. Knowledge-based behaviour is assigned to new situations when there is no set of rules available. The units must first identify the problem, generate the alternatives to solve it and, finally, choose the best solution.

Psychologists Gary Klein, Roberta Calderwood and Anne Clinton-Cirocco created the RPD model to describe how people make decisions. Decision-makers based their decisions on experience by connecting the current situation with the solutions performed in the past (pattern-matching). There are three variations of RPD models that differ according to their complexity (Klein & Klinger, 1991): (1) Simple Match RPS, (2) Developing a Course of Action RPD and (3) Complex RPD Strategy. The RPD model cannot be used in case of knowledge-based behaviour, multi-criteria analysis cases and Search-for-Dominance Structure (SDS) strategy (Klein & Crandall, 1996). Variation 1 describes a situation well known to decision-makers. Thus, they can easily simulate what the further scenarios are and notice the typical signs that indicate the use of particular solution. Conversely, in variation 2, the situation is not so easy to diagnose. Thus, decision-makers need to collect more data and/or assess the situation by looking into their past experience. Sometimes, decision-makers do not know which solution to select for the case (variation 3). However, in case of NDM methods, the choice of the best solution is not done by Multi-criteria Decision Analysis, but by generating a single action using mental simulation of possible scenarios. Nevertheless, even the most experienced decision-maker can make mistakes. The possibility of failure should always be considered. Human failures are distinguished by researchers (Embrey & Lane, 2005) from errors (which are related to the skill, rules and knowledge-based behaviour) and violations (which are exceptional or caused by routine). The types of errors are presented in Figure 2.

![Figure 2. Types of errors (adopted from Embrey and Lane (2005))](image)

The Recognition/Metacognition (R/M) model compares to the RPD focuses on the situations when decision-makers fail, while recognizing the case (Lipshitz et al., 2001). The incorrect situation recognition leads to the renewed data evaluation. Decision-makers needs to elaborate situation (recognition), add missed data and modify the strategy when there is: insufficient situations awareness, incomplete information or conflicted differences between alternatives (metacognition). The R/M model reconciles both pattern-matching recognition and problem solving strategies (Azuma, Daily, & Furmanski, 2006).

**METHODOLOGY**

We conducted eleven interviews and two workshops with decision-makers (designers and contractors), as well as with operators, data specialists, network operators and developers of applications for construction engineering industry.
Interviews for the first stage of project were held between March and June 2016. We prepared a set of questions and asked interviewees to prepare example(s) of projects that they found interesting regarding locating test trenches. To extract information about the user experience, practice rules, decision results and strategies we questioned each specialist about the number and location of test trenches, the reasons for decisions, opinions, support aids, results, communication and suggestions about changes. Each interview session took approximately two hours.

Workshops were divided into two sessions; one with six designers and (afterwards) one with six contractors. This division resulted from interviews when we noticed that the decisions made by designers and contractors were different (due to different stages of project). The first session took place in July 2016 and the second in October 2016. Both were based on serious gaming techniques (Schell, 2015) to check the behaviour of decision-makers when taking decisions under uncertainty. This approach was challenging as the participants had to face situations they were not prepared for and to explain their choices. We provided them with a map of underground utilities, extracted from Cadastre’s klic system on which we superimposed the following projects: (1) build a new parking place, (2) place new fibre cables and connect them to houses and (3) replace an old sewage system. For each project, they had to decide how to locate test trenches and place them on map using transparent foils. We included obstacles, such as trees and waste containers, to make the assignment more difficult and influence the utilities path. The game board, together with examples of the results, are shown in Figure 3.

![Figure 3. Workshop session with decision-makers](image)

To analyse the collected data and information we used analytical and cognitive approaches to provide us with interesting results to generate further ideas about DSS design. In addition to the NDM model described earlier we also used the following methods: (1) The Design Process Unit (DPU) and Design for eXcellence approach (DfX) (Becker Jaruregui & Wessel, 2013), (2) System Engineering (Blanchard & Fabrycky, 2011), (3) Simon’s Rational Decision-Making Model (Simon, 1977), and (4) Multi-criteria Decision Analysis (Ishizaka & Nemery, 2013). We discuss our results and adopt a NDM perspective in the following section.

RESULTS

During the interviews and workshops we observed a number of good and bad practices. The best practices showed that, in order to decide about the number and location of necessary test trenches, the following techniques needed to be combined:

- Data analysis (i.e. maps of underground utilities);
- Site analysis (i.e. ground conditions and obstacles);
- Detection tools (i.e. ground scanning tools);
- Use of best practices (i.e. provided by guidelines);
- Computer support (i.e. visualization tools and data bases to store data).

Only a few companies we interviewed used the combination of these methods, with others using just one or two methods. Clearly, using judgments is not incorrect. The experience, skills and knowledge of decision-makers are important to the decision process. Nevertheless, all best practices (experience, computer support, ground scanners, and utilities maps) can and should be joined together and used, not only by experts, but also by novices who might otherwise assess the excavation case wrongly.

It was interesting for us to check why damages still occurred, despite the fact that test trenches were dug. We analysed the most frequent cases of damage to assess whether the errors were due to poor risk assessment, a lack of data or due to rushed activities. The damage to utility services that occurred most often were: (1) mechanical damages, (2) damages to house connection, (3) damages while fibre cables were connected to houses, (4) damages to data-transport cables, (5) damages due to lack of information on utilities maps, (6) damages to disconnected utilities, (7) damages when tree was pulled together with utilities, (8) damages due to absence of Network Operator.
supervisor, (9) damages due to ground conditions (soil type, reduce visibility), and (10) damages while digging test trenches.

Those results directed us towards an analysis of decision-makers’ behaviour. The interviews and workshops uncovered that decisions about the number and location of test trenches depended on the following factors: (1) stage of the project (orientation test trenches during design, test trenches dug before starting the excavation or test trenches dug when the reparation to the utility is necessary due to system failure), (2) type of work (i.e. building a new road or replacing the sewage system), (3) actions taken (i.e. drilling, open excavation or trenchless methods), and (4) decision-makers’ and their experience.

Decision-makers used a set of good practices, such us digging test trenches, when there are doubts about the accuracy of utility maps, or when high risk utilities, such as gas pipelines, are present in the excavation area or many cables and pipes cross over one another. Designers dig test trenches to check if there is enough space to perform the project and to avoid unnecessary cost and changes. In contrast, contractors dig test trenches because they want to keep deadlines and to perform their work safely. To achieve this, they have to confirm, not only the location and depth of the utilities, but also check their material (e.g. resistance for vibration) and type of connections (e.g. can have impact on utilities depth).

During the workshop, we noticed how fast some decision-makers took decisions. This was clearly related to the knowledge and experience they had. In some cases, they could directly decide if the test trench was necessary or not, because they had faced similar situations before. For example, if on the excavation area a water pump station was present, the experienced decision-maker knew the depth of associated utilities can differ. Some decisions, such as checking the area up to 1.5 m from the excavation place, were influenced by (legal) rules (Crow, 2013) established according to best practices. Nevertheless, designers and contractors can face situations new to them. Furthermore, the decision as to whether an excavation should happen should not be made in a hurry, but proceed only after careful case-by-case analysis. If information was insufficient, then the information gaps need to be addressed before taking a decision so as to reduce uncertainty (R/M model). Thus, the situation should be well identified, the tasks made clear and planned properly using the best available techniques (i.e. maps, ground radars and best practices).

The current behaviour of decision-makers is presented using the SRK model in Figure 4.

![SRK Model](image)

Figure 4. Rasmussen’s model of cognitive control SRK for test trench location process (adopted from Rasmussen (1983))

Figure 4 is based on the example of the water pump station, which was discussed during workshop sessions. Only four of the twelve decision-makers decided that it was necessary to dig test trenches near the pump because the depth of the utilities can differ relative to the other parts of the excavation area. They supported their choice by using an example from their past experience (skill-based behaviour). Other participants agreed with their suggestion. The decision was also influenced by the set of rules (rule-based behaviour). To reduce the risk of failure, decision makers used, for example, the 1.5 m buffer. This ensures that no utility will be damaged while executing the work. Nevertheless, new situations could be identified using available technologies (knowledge-based behaviour). During the interviews, we observed cases where damage occurred because of a lack of a correct situation assessment. For instance, in one case, the age of buildings influenced the material and depth of the utilities and this was not taken into account by decision-makers.
Many strikes are attributable to the lack of the information on the utilities maps. However, the relation between SRK behaviours and the failures can be noted as well. The damages to the utilities caused by:

- removing the trees;
- absence of the network operator supervisor;
- excavation machines (if utility marked on klic), and
- misunderstandings;

could be avoided by correct assessment of the situation.

Experience sharing could be an interesting component part of a future DSS. The excavation case could be analysed using, not only data from radars, maps, documentation and observations, but also by matching the situation to ones that had occurred in the past. The RPD and R/M models related to pattern-matching could be used by creating an experience database within the DSS. The new situations faced by decision-makers and best practices could be collected and updated, for example: how obstacles can influence the location and depth of utilities, the resistance of the material for vibrations, and so on. Based on the input information, the tool could look for patterns (using the RPD model variations) using algorithms and to present this to decision-makers by (e.g. warning signals). The information about previously dug test trenches can be also collected. So, if it is necessary to dig new test trenches, the decision-makers can have an overview of the past decisions and findings. Together with other techniques, this would help generate a more reliable risk assessment. A combination of analytical and naturalistic decision-models clearly could support better situation awareness, help to collect enough reliable information and, last, but not least, reduce uncertainty related to conflicts between alternatives approaches (i.e. dig one, two or three test trenches).

CONCLUSIONS

Digging test trenches is one method used to confirm the exact location of the cables and pipes. Often, the decision about their number and location appears random and driven by the personal judgments of the individual decision makers. The interviews and workshops conducted uncovered strategies used by the decision-makers (designers and contractors). They used good practices, such as digging test trenches when there is uncertainty about the accuracy of utilities maps, when high-risk utilities are present, or when many cables and pipes cross over one another. The regulatory rules and other guidelines can also help to reduce uncertainty (e.g. the rule of adding the 1.5 m checking buffer to ensure that the excavation project will not damage utilities).

The knowledge and skills of decision-makers both play an important role in the decision-process. It influences how many test trenches will be dug and where they will be located. The use of different techniques, such as detection tools, utility maps, visualisation programmes and data management tools, can support decision process. However, decision-makers ultimately assess the risk of damage. Their experience levels differ. They often face new situations. These can involve poor decisions or incorrect assumptions if they are having to analyse large amounts of data. Many people involved in the excavation process are not sufficiently familiar with the use of ground scanning methods. This can result in further incorrect assumptions about the situation. Full automation of decision-making regarding how and where to locate test trenches appears to be untenable. Neither is it desirable, as it prevents leveraging expertise from those directly involved.

A combination of analytical and naturalistic decision-making elements within one DSS seems to be an interesting and viable option. Pattern-matching could give additional input for decisions, especially when decision-makers lack experience or when new situations have to be faced. An experience database could be created by the users and updated by adding information about the best practices, findings, failures, obstacles that influence the location of utilities and digging test trenches. The DSS could search the database to find similar cases to the project under consideration. Moreover, based on all collected data and conducted analyse, the risk of damage (including the case where test trenches are not used) can be calculated.

We argue that DSS which collects all the necessary data, analyses them, visualises them and, in addition, compares them with best practices and previous experience, can reduce all of the aforementioned three forms of uncertainty mentioned in the literature (Lipshitz et al., 2001) (inadequate understanding, lack of information and conflicted alternatives). The system of pattern matching within the tool can be based on the RPD model by comparing the current situation with others in the database (variation 1), requiring additional input information (variation 2), or informing about the necessity of “evaluation of course of actions” by, for instance, risk calculation of the generated scenario (variation 3). The RPD model can be supported by using the R/M model and inform the users about any deficiency in information which is needed to generate a viable solution. Of course, these ideas await further elaboration and testing. Nevertheless, we are confident that they will help shape the thinking about tomorrow’s DSS for selecting the nest locations for test trenches.

ACKNOWLEDGMENTS

We would like to thank all the companies and their representatives who participated in the interviews and workshops and who supported us with their knowledge regarding the excavation process of selecting test trench locations.
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To dig or not to dig: How to determine the number and location of test trenches

A Case Study

Paulina Racz, Marc van Buiten, André Doree
University of Twente
Drienerlolaan 5
7522NB Enschede
The Netherlands
p.racz@utwente.nl; m.vanbuiten@utwente.nl; a.g.doree@utwente.nl

Key words: decision-making, test trenches, excavation, excavation damages

Abstract: To confirm the exact location of underground utilities, engineers can rely on maps of underground systems at the excavation polygon, as well as technologies, such as Ground Penetrating Radars (GPRs). However, differences may exist between maps and reality. As a result, it is necessary to confirm the exact location of the underground systems by digging test trenches. This article focuses on the analysis of currently used strategies to determine the location of test trenches. Data were gathered through a literature review and interviews conducted at several companies in the Netherlands. Results indicate that companies devise their own particular, and often ad-hoc, strategies to decide. All of them are based on the drawings received from the Cables and Pipes Information Agency. The preliminary results hint at several “best practices”, which are elaborated. Weaknesses are identified and discussed. These findings serve as input for our current (follow-up) research on strategy improvement to obtain the maximum amount of information out of the minimum number of test trenches.

1. INTRODUCTION

The underground space is becoming increasingly busy. Many kinds of cables and pipes are buried under the ground. Excavation has become challenging for today’s engineers. They have to schedule operations in a way
that will not cause damages to the existing networks. Since several of the pipes and cables were buried a long time ago, the actual location does not always match the position according to the drawings. New technologies such as ground penetrating radars and 3D visualization (Schall, Junghanns, & Schmalstieg, 2010) are used to help to confirm the exact location of the underground utilities. However, radars are costly and do not give complete certainty. As a result, test trenches are used to confirm the exact location of underground networks in many countries such as Canada (test holes), USA and UK (trial holes), Australia (potholing), Netherlands (“proefsleuven”). Drawings and radars are merely supporting tools which help to decide where shallow trenches are necessary. Several guidelines about damage prevention are in place in those countries. These guidelines present rules about the dimension and distances between test trenches. In the Netherlands, the underground network extended over approximately 2 million km in 2013 (GPKL-Het Gemeentelijk Platform Kabels en Leidingen, 2013). This will probably only increase in the coming years. During the same year 40,000 damages to the Dutch underground network were reported (GPKL-Het Gemeentelijk Platform Kabels en Leidingen, 2013). The number presumably decreased slightly over the last two years thanks to the national Underground Networks Information Exchange Act, commonly referred to as WION (WION, 2008) and the improvement of the Klic application, implemented by the Cables and Pipes Information Agency (Cadastre). The legislation act describes the rules about activities that must be accomplished before, during and after excavation. Once an excavation request is sent to Cadastre, the excavator will receive information about the existing networks in the area. Figure 1 presents a schematic overview of Klic.

![Figure 1](image)

Before breaking the surface, it is necessary to confirm the exact location of the underground networks. Due to legal requirements (WION) and technological limitations of electronic devices, confirmation of underground system locations has to be done by digging test trenches. The decision process about determining the location and number of test trenches is not easy and often appears to be random, resulting in many damages to underground systems. What is more, every excavation, even the hand digging, can cause
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damages. In an ongoing project, we aim to develop a decision support tool which will make the decision process easier and more reliable.

This article presents findings from the preliminary stages of this project, and in particular focuses on the analysis of strategies used to select test trench location. Data were gathered through literature review and interviews conducted at several companies in the Netherlands. Interviews with representatives of several companies were conducted. Before each interview, the representative was asked to prepare an example of a project where they had to decide about the number of test trenches and their location. Each case was discussed during the interview. Other examples were also shared what gave the opportunity to compare the strategies depending on the situation. That results of this first stage are described in this article.

The structure of this article is straightforward. Section 2 outlines background information on decision-making processes in general and excavation procedures in the Netherlands. The research method is described in section 3. Results are in section 4. Finally, conclusions are presented in section 5.

2. BACKGROUND

2.1. Decision-making process

Sometimes decisions are easy, and at other times difficult. Sometimes the decision entails heavy responsibilities, and at other times it is not as important as we first thought (for example, which dress to wear for an important meeting). Depending on their character, people can make, independent decisions, but often the decision, at least in part, based on preferences from authority figures. Consider as an example, the relation between bosses and a workers. Workers might always agree with their bosses, just because they consider them to be smart and more important.

To make the decision means to make use of information and choose an option among the best available possibilities (Ishibushi & Nii, 2000). A

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1 University of Twente, Reggefiber and other partners created the ZOARG program (Dutch: Zorgvuldige Aanleg en Reductie Graafschade). This program is realized to promote careful approaches in construction and maintenance of the underground infrastructure, by investing in the development of new methods and technologies that prevent excavation damages (Reggefiber & University of Twente, 2015). The analysis of strategies currently used to select the location of test trenches is part of a PDEng (Professional Doctorate in Engineering) project entitled “Improved strategies, logic and decision support for selecting test trench location”. 
decision-making process can be thought of as consisting of 4 phases: (1) intelligence phase, (2) design phase, (3) choice phase, and (4) implementation phase. These major phases are known as Simon’s rational decision making model (Turban & Aronson, 2001). The model is presented in Figure 2.

![Decision Making Process Diagram](image)

**Figure 2.** The decision-making process as (Simon, 1977) adapted by (Turban & Aronson, 2001)

The Intelligence Phase is the first phase of a decision process and it focuses on the data collection, case investigation and subsequently problems’ identification, classification and statement. If the decision-makers are experienced persons, in the ideal situation, they will follow general work practices. Nevertheless, the problems, which will have an impact on decisions, may appear while the work is proceeding. If the problems will be correctly identified the accurate decision can be made.

The Design Phase is focussed on finding the possible solution(s) for the problem(s). In other words, it is the treatment phase. The decision-maker needs to understand the problem and provide the solution that will lead to a successful problem solving. One of the methods used to find the solutions consists of the creation of an accurate model of the identified problems. The model will frame the scenarios, which decision-makers consider that can happen. Afterwards, it will guide them for the accurate paths during searching for alternatives.

During the Choice Phase the decision about the solutions is made. The decision is preceded by selection of the best alternatives, analysis of sensitivity and model testing.
The solution is implemented during the last step of the decision process named Implementation Phase.

The decision-making in civil engineering project impose heavy responsibilities on the decision-makers (Turskis, G., Kalibutas, & Barvidas, 2007). The question: ‘Where and how many test trenches should I locate in the excavation polygon?’, is a good example of such responsibilities. The test trenches are the shallow trenches dug to confirm the exact location of the underground utilities. If the decision-maker choose not enough amount of test trenches to the case, the risk of damage to the underground systems will increase. Contrarily, if too many test trenches are dug that will expose the contractor to higher costs of the process. Depending on the case the decision-makers will have to choose the best option from the possible alternatives by taking into account the information that they have already possessed. To choose the correct solution from the variety of alternatives the Decision Support tool can be used. (Omar F.M., 2009).

This kind of tools can have the form of computer-based systems. The decision-makers very often have to rely on their experience, judgments and intuition which in case of failure, can have significant consequences. The types of Decision Support Systems (DSSs), that are used to support complex problems are as follow (Druzdzel & Flynn, 2002):

- Database management systems (DBMS): are used to store the data. The user can analyse them and provide the relevant solutions to the problem.
- Model-base management system (MBMS): the data that were stored by DBMS can be easily transformed into the information that will support the decision-maker.
- Dialog generation and management system (DGMS): are used to manage the dialog (interface) between the user and Decision Support System.

2.2. Excavation procedure in the Netherlands

Excavation damages are defined as mechanical damages to underground networks which result from the contact with an object. (Technology Subgroup of the Operations&Environment, 2011). Their magnitude depends of the shape of the object together with the provided power. Damages can be made to the external coating of pipe or cable and other network equipment, but they can also take another form such as dents, scrapes, cuts or punctures (Technology Subgroup of the Operations&Environment, 2011). Damage can occur in every phase of the utilities life cycle. What is more, damages are not always discovered during excavation and can occur in the future. Durability
of utilities decrease when the coating gets injured and other factors such as corrosion, pressure, fluid stream, intrusion can have higher influence on them. As a result, catastrophic failure can appear when is least expected.

In the Netherlands, an excavation notification must be sent to Cadastre by Klic-online application before any excavation works. The excavator has to ensure that an investigation has been performed into the exact location at the excavation polygon. It is important to send the notification on time (at least three but not earlier than twenty working days before the beginning of the work). Cadastre will send the data within two days. The excavator has to ensure that the area information received from the Agency are presented at the excavation polygon.

It is also necessary to check if any extra precautions are needed. In a positive case, the additional precautions will be indicated and the user will be asked to contact the network operator. Pipes and cables can be found even 1,00 m away from the position indicated in the plots. Because of that inaccuracy, it is necessary to determine their exact location on site. In case a deviation in the position of the pipes is detected, this information should be reported to Cadastre. The length of test(trial) trench is approximately 1,00 m on both sides of the theoretical location (CROWN, 2000). There can be a reason to deviate from standard dimensions described in the guidelines (Groot, 2008). In some situations additional rules must be applied, for example in case of pipes with dangerous content (such as gas or chemicals) or in case of utilities with a high value (such as major communication lines). The information about the precautions for networks can be found in the Klic-viewer application. The excavators have to contact the network operator to receive information about how the work must be carried out. The network operators have to ensure precautions (if necessary) within 3 working days from that time. It is important that network operators ensure all precautions, so it is necessary to make that clear in the agreement with them. Any doubts should be consulted with the them to avoid the possibility of damages.

So, when the test trenches are necessary? The test trenches are necessary for open excavation when the theoretical horizontal position of network’s elements is situated wholly or partly (Groot, 2008):

- Within the planned excavation profile or monitoring area;
- Within the horizontal distance of 1,50 m on both side of the planned excavation.

For vertical drilling, sounding or installation of piles or sheet piles when the theoretical horizontal position of network’s elements is situated wholly or partly (Groot, 2008):

- Within the location of the diameter of drilling or probing or at the location of projected piles installing;
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- Within the horizontal distance of 1,50 m from the outer diameter of the projected ground drilling, probing, projected piles or sheet piles.

When are test trenches NOT necessary? Test trenches are not necessary for open excavation, vertical drilling or probing or installing piles and sheet piles when the theoretical horizontal position of network’s elements is situated (Groot, 2008):
- Completely outside of horizontal distance of 1,50 m on both side of planned excavation;
- Completely outside of 1,50 m from the outer diameter of the projected ground drilling, probing, projected piles or sheet piles.

In case of trenchless techniques it is necessary to contact the network operator and consult how to proceed to determine the exact location of the network and determine the necessary precautions. For vertical drilling, probing or installing piles and sheet piles it is necessary to contact the operator as well in order to confirm proceeding, in case the horizontal position of networks components is expected to be more than 1,50 m below ground level. When the excavation takes place with shallow ground water level, it may be not possible to proceed work by using test(trial) trenches in order to determine the exact location of network. For that situation the excavator has to contact the network operator. If the excavators will no adhere to the procedures they will have to pay a fine.

3. RESEARCH APPROACH

Guidelines are available to help decide about test trenches location. These support the excavator on technical issues (Groot, 2008), (Crow, 2013). However, the technical guidelines are not enough to make reliable decisions. It is necessary to look into the decision consequences resulting from previously made decisions (Bennet & Bennet, 2008). We have conducted interviews with the units involved in the decision-making process about test trench location to examine currently used strategies. The goal of the first round of interviews was to get familiar with currently used strategies, identify the problems and investigate how to obtain the maximum amount of information out of the minimum number of test trenches.

The Design Process Unit (DPU) approach (Becker & Wessel, 2013) was used to structure questions for the interviews (see Figure 4). DPU is part of other design method DfX (Design for eXcellence), as presented in Figure 3. DPU can be defined as the knowledge which is compulsory to design. The design parameters are properties of the artefact that can be manipulated to achieve the performance. Opposite, the scenario parameters describe the
properties that cannot be changed and have to be considered in the design. The performance is pulling both the design and scenario and it assesses the quality of the analysis (Becker & Wessel, 2013). There are 5 categories of DfX methods: (1) Guidelines, (2) Checklists, (3) Metrics, (4) Mathematical models, and (5) Overall methods (Becker Jauregui & Wessel, 2011).

The questions, as a result of the analysis, can be seen in Table 1. The design parameters represents the parameters which we can manipulate. Due to them, the questions are formulated. However, several scenario parameters must be taken into account as well. Companies have their own habits and it may be difficult to change their opinions about the strategies that they use. What is more, some of the rules, such as using Cadastre Klic-online system, are dictated by law.
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Table 1. Interviews’ questions result from DPU

<table>
<thead>
<tr>
<th>Embodiment and Scenario that influence the question</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design:</strong> location’s coordinates; visualization (analysis of drawings); <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>Where did you locate the test trenches?</td>
</tr>
<tr>
<td><strong>Design:</strong> amount of test trenches <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>Why did you choose that amount? What are distances between the test trenches?</td>
</tr>
<tr>
<td><strong>Design:</strong> location’s coordinates; visualization (analysis of drawings), amount of test trenches; <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>What is your opinion about the idea of considering the shallow excavation as a test trench?</td>
</tr>
<tr>
<td><strong>Design:</strong> software <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>Did you use any aid to decide easier about number of test trenches or about the excavation? (software? Devices? Radars?)</td>
</tr>
<tr>
<td><strong>Design:</strong> number of damages <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>What were the results of your choices? Did any damage happen?</td>
</tr>
<tr>
<td><strong>Design:</strong> software, number of test trenches; <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>What do you think about the current information exchange system Klic? Do you like it? Is it helping you? Would you change something?</td>
</tr>
<tr>
<td><strong>Design:</strong> visualization (analysis of drawings), software, number of damages; <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>What do you think about the cooperation/communication at excavation place?</td>
</tr>
<tr>
<td><strong>Design:</strong> location’s coordinates; visualization (analysis of drawings), software, number of damages; <strong>Scenario:</strong> user’s experience, practice rules, Klic database and users itself</td>
<td>Could you tell me what would you like to change in the current procedures? Do you have any ideas what would help you to decide easier about test trench location?</td>
</tr>
</tbody>
</table>

Ten interviews were conducted with excavation companies, network operators and government agencies. The representatives of this units differed in functions what helped to have a broad overview on the discussed problem. The function of interviewees in the company are presented in Table 2. The results of interviews are discussed in the Results section below.
Table 2 The functions of interviewees in the Companies

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>The function in the Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WION Inspector</td>
</tr>
<tr>
<td>2</td>
<td>Manager in the Operational Information Management department</td>
</tr>
<tr>
<td>3</td>
<td>Asset Manager</td>
</tr>
<tr>
<td>4</td>
<td>Designer</td>
</tr>
<tr>
<td>5</td>
<td>Designer</td>
</tr>
<tr>
<td>6</td>
<td>GPRs Specialist</td>
</tr>
<tr>
<td>7</td>
<td>FttH Engineer</td>
</tr>
<tr>
<td>8</td>
<td>Specialist of software design</td>
</tr>
<tr>
<td>9</td>
<td>Coordinator</td>
</tr>
<tr>
<td>10</td>
<td>Group of Work Planners</td>
</tr>
</tbody>
</table>

4. RESULTS

The results will be discussed according to the phases of the decision-making process model presented in Figure 2 (see point 2.1). This section concludes with SWOT analysis of the currently used strategies.

4.1. Intelligence Phase

Firstly, all the excavators use the Klic-online system to receive information about underground networks which are buried on excavation polygons. In addition, the Klic-viewer and Klic-app are used to read the data. An example of a map received by using the Klic-online system is shown in Figure 5.

![Example of map presented in the Klic-viewer](image)

Secondly, during the first step of investigation all of the interviewees compare the received maps (and documents) with the design drawings. These
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help to detect the conflicts between the design and the situation under the ground. Following the detection of conflicts, the dialogue with the network operators begins and either the design can be changed or the utilities can be replaced.

The next important step is the analysis of the excavation area. Many obstacles can be noticed during the analysis of the surroundings, which may have an impact on the taken decisions. The factors that can influence a decision are: trees, paths, houses, rails, roads and so on. Some of the companies support their decisions by using Ground Penetrating Radars (GPRs). The frequency of use depends on the amount of money that the company can invest. Many times the GPRs are used only to calculate the depth and confirm the path of the networks which were already uncovered by test trenches. However, some representatives have doubts about the usefulness of digging test trenches. They justify their opinions that GPRs are non-invasive and as a result better to detect underground utilities. Nevertheless, the GPRs are costly and do not provide total certainty.

Steps described above help to identify the problems which can influence the decisions. The following factors can have an impact on making decisions:

- Kind of work that must be done: type of work, how deep is the excavation, what kind of technology is used to dig;
- Presence of hazardous underground networks on the excavation polygon, such as high-pressure gas pipeline;
- Presence of obstacles such as trees, roots, rails, houses, roads;
- Presence of house connections; the information about house connections is still updated in Klic system.

Some of the companies use internal databases, such as ArcGIS, to store all the data. The software helps in data comparison and makes the process easier when it is necessary to look into previously taken steps. What is more, the decision-makers have to consider that the situation under the ground can differ from the one which is presented on the drawings. For example, the amount of cables (they can be placed in one duct) or the pipes and cables can be wider because of joints (i.e. socket-welded and butt-welded joints).

4.2. Design Phase

Considering the factors and problems mentioned in the intelligence phase, the group of decision-makers (designers, coordinators, work planers and in case of necessity of precautions- network operators) decide about the number and location of the test trenches. They have to deal with an important question: ‘how to get the maximum amount of information from the minimum number of test trenches, and at the same time avoid the danger and minimize the costs?’.
Several good practices were noticed during the interviews. In order to obtain maximum information, the decision-makers:

- Compare the design with Klic’s maps that help them to see which utilities can be affected by the execution of the design. The comparison and dialogue with network operators may result in decision changes or agreement with network operator about replacing the pipes or cables;
- Store data in the internal databases, as well as in applications like Klic-app (develop by GOconnectIT), which can help to analyse if similar cases were already considered in the past. The information about good practices but also about previous mistakes can help workers to improve their job. In addition, in case a damage is made to the network it is possible to look into steps taken and see what was done wrong. The database also supports the coordinators, to control the work that was made;
- Observe the surroundings in the excavation polygon to consider obstacles.

4.3. Choice Phase

A careful analysis helps to determine the number of test trenches and their location. However, the decision is changed many times after digging the first trial trenches. Sometimes, the experienced workers have the feeling that more test trenches should be done, for example, because they had already seen similar cases. In one example given during the interviews, three test trenches were planned, but finally fourteen were made and in the last one, it was found that the pipe was not placed linearly.

Results showed that when many contractors work on the excavation polygon, some misunderstanding can occur in the communication about who is responsible to make one of the test trenches. Finally, nobody carries out that work and, as a consequence, damage is made to the network.

A good practice, which was noticed during the interviews, is placing a cover on top of the pipes, as is shown in Figure 6. This cover warns the workers that the network is located under it and they should dig carefully. That warning sign can help in case any test trench has been planned at that precise spot and an unexpected network has been discovered.
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![Image](167x622 to 286x763)

Figure 6. Underground utilities together with the red cover in the test trench

4.4. Implementation phase

The choice made can result in success or failure. Success means that the work was executed without causing any damage, and failure means that a damage was made to the underground network. The interviewees admitted that sometimes the report of damage is not registered and the information about the damage after it was repaired was missed. During the interviews a database with information about damages in the year 2015 was presented. About 70% of the damages were completely registered by the Network Operators, and other 30% of them were only reported.

A report which describes the decision process for the test trenches location and details how the works were done is often not prepared.

4.5. Analysis SWOT of the current system.

SWOT analysis is the technique which is useful to present and analyse the Strengths and Weaknesses of the case under investigation. The SWOT analysis for currently used strategies to select test trenches location is shown in Table 3.
Table 3. Analysis SWOT of currently used strategies

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadastre’s Klic system;</td>
<td>Databases are not obligated by law;</td>
</tr>
<tr>
<td>Comparison between drawings and maps;</td>
<td>Sometimes decision is based on judgments</td>
</tr>
<tr>
<td>View on excavation area;</td>
<td>The databases are not often use;</td>
</tr>
<tr>
<td>Internal databases.</td>
<td>Reports about damages are not often registered;</td>
</tr>
<tr>
<td></td>
<td>Misunderstandings;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global database for proceeding the excavation; Educational meetings and guidelines</td>
<td>If the use of database is not required by law it will not be used.</td>
</tr>
</tbody>
</table>

The Cadastre’s Klic-system is unarguably one of the strongest points of the currently used strategies. Digital maps together with documentation are received from one unit which work as a bridge between excavators, network operator and government agencies. The system provides the support for decision-makers in civil engineering. As a result, they are able to compare the drawings with maps. Afterwards they can confirm the information during inspections in the area and include observations in analysis (for example the presence of obstacles). In addition, some of the companies use internal databases as well as applications to store the information.

However the several weaknesses were observed as well. Klic-app is nowadays improved in addition functions. For example soon it will be possible to store the data about test trenches in the cloud. Nevertheless, the users are not obligated by law to use it. What is more, the internal databases are not used by every company and information about made decisions is many times lost. In case of some companies only comparison between drawings and maps is done, what seem to be insufficient. Moreover, the decisions are many times changed because of intuitions of the workers. The lack of support tool can influence the communication in the excavation place what result in misunderstanding about responsibilities. In addition, the reports are often not registered and afterwards it is not possible to analyse the mistakes.

To receive maximum amount of information from the minimum number of test trenches, all companies should use a global database. That can direct them towards the best practices, help to avoid the same mistakes, as well as confirm if other works were executed in that area in the past. Education meetings should be organized as well, and the guidelines should be published to make the excavators aware of the importance of test trenches. Nevertheless,
a global database will not work if the information sharing is not required by law.

5. CONCLUSIONS

In this article we have reviewed current strategies to determine the number and location of test trenches on construction sites. Results indicate that careful data analysis and observation of the surroundings are needed. It is difficult to analyse large amounts of data. Moreover, information can be lost which result in faulty decisions. Arguably successful practices showed that database software, such as ArcGIS, facilitated informed decision-making. The database helped excavators to store data, analyse previously made decisions, avoid the same mistakes and also to control the work. What is more, the database would help to prepare a good report about the decision process which was applied to the case. In this report, the information about test trenches can be included. Currently, the quality of the reports about the decision process differs between companies (in some cases reports were even not prepared).

During some of the interviews, the interviewees showed doubtfulness about the necessity of digging the test trenches. Due to that, it might be important to prepare some meetings with the excavators to explain why the test trenches plays an important role in underground system confirmation, and what are the advantages compared to using only ground penetrating radars.

In some of the companies it was noticed that there is a lack of communication between the contractors. A database, with open access for all the units involved in the excavation works, can help to follow the work process. In addition, the good practice guidelines can help to solve this problem.

The subsequent interviews are directed at determining best strategies used to select test trench location, as well as to identify the problems that excavators are struggling with. Meanwhile, a possible new strategy will be developed and tested. The goal is to improve currently used strategies and make the decision process easier and more reliable!

6. ACKNOWLEDGMENT

The work is supported by Agentschap Telecom and Reggefiber. We would like to thank especially Frank van Bree and Robert-Jan Looijmans for supporting us with their knowledge and organize the interviews meetings in several companies.
7. REFERENCES


To dig or not to dig? Improved strategies, logic and decision support for selecting test trench locations

Waar graaf ik mijn proefsleuf? De ontwikkeling van een beslissingsondersteunend model voor locatiebepaling van proefsleuven

Article for Blog en innovatiemagazine Pioneering

Paulina Racz, PDEng trainee University of Twente, department of Construction Management and Engineering

The underground space is increasingly busy. The subsurface contains not only precious fauna, flora, and archeological findings but also many cables and pipes. For modern city engineers, it is, therefore, challenging to conduct their work in a way that will not damage underground infrastructure. Data from the Dutch Kadaster (Cables and Pipes Information Agency in the Netherlands), shows that 33,000 damages to underground utilities were reported in 2015. Only the direct costs of this damage are up to 30 million euro.

To avoid damages, excavation processes must be preceded by the exact confirmation of the location of utilities. They, therefore, use utility maps (KLIC-tekeningen) and detection tools to address the question: To dig or not to dig? However, those tools do not guarantee absolute certainty since some utilities can be located inaccurately on maps, or may be missing completely. Also, detection tools may show incorrect information due to positioning failures, and difficulty of locating utilities in all soil types. To cope with these problems, test trenches (Figure 1) are dug to update or confirm (the accuracy of) underground utility information.

![Figure 1. Test Trench (in Dutch: proefsleuf)](image)

The combination of techniques such as, maps analysis, detection systems and test trenches can decrease the risk of damage. Practice shows, however, that test trenches are often located randomly based on the personal judgment of individuals. Unquestionably, the experience of these specialists is an important asset in the decision-making process. It should, however, be used correctly to determine a suited location for a test trench. To date, such knowledge is not used systematically adequately.
University of Twente, Reggefiber and other partners created the ReDUCE program (Reduction of Damage to Utilities and Careful Excavation; Dutch: ZoARG). Within this program, many projects are centered on careful excavation approaches. My project is part of this program and is entitled, *Improved strategies, logic and decision support, for selecting test trench locations*. It focuses on the problem outlined above. The aim of my work is to develop a Decision Support System (DSS) that helps make faster and more reliable decisions about the location of a test trench. I started my project in November 2015 and I plan to finalize it by November 2017. During the first year, I conducted several interviews and workshops (see Figure 2) to gather data, identify problems, specify requirements, and to study the designers’ and contractors’ behavior.

![Figure 2. Workshop session with decision-makers](image)

First results indicate multiple strong and weak points of the current practice. Weak points are, for example: (1) insufficient or incorrect information on utilities maps, (2) differences between required number of test trenches, (3) incorrect risk assessment, (4) difficulty in dealing with large amounts of data, (5) misunderstanding between contractors and (6) insufficient use of experience. While developing the DSS I will, therefore, focus on the consequent elements: (1) data collection, (2) risk assessment, (3) experience sharing, (4) visualization and (5) multi-criteria analysis. Improvements of those elements hopefully help designers and contractors to make informed decisions about the location of test trenches, and ultimately help reduce the number of excavation damages.